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A Review on Intelligent Control Strategies for Accomplishment of High Performance SynRM Drive

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Abstract

Synchronous reluctance motors (SynRMs) have been shown in recent studies to be a promising technology. As a result, research has been going on increasingly into SynRMs drive systems. Recent advances in motor modelling have led researchers and industries to investigate and categorize the best control techniques for this motor drive systems. The behavior of this motor has been enhanced and optimized for many applications with the development of contemporary drives with varying speeds and power electronics converters. Induction motors, switch reluctance motors, and permanent magnet motors can all be replaced with Synchronous Reluctance Motors (SynRM). In terms of efficiency, torque, and power density, they surpass similarly sized induction motors. They are easy to build, maintain and controllable. This paper broadly discusses the comprehensive review of SynRM with different other machines available based on various performance aspects; and also, the different control strategies adopted in controlling of torque, speed and velocity in applications driven by this motor has been explored e.g. Torque control, velocity control and field- oriented control.

Keywords: GFDM, Maximal Ratio Transmission, symbol error rate, Rician fading, Weibull Fading, 5G network.

1. Introduction

The increase of industrialization and using of fossil fuels to power industry, transportation, electricity generation, home heating and cooking accounts for approximately 65 percent of humans in producing higher levels of greenhouse emissions and toxic effect on human health. These harmful gases are also changing the climate tremendously. Thus, with these rapid environmental changes, people are searching for alternative ways so as to reduce its impact on environment. This led researchers in finding alternative improvements in the field of electrical machines and are focusing on technological innovation in order to boost industrial development and technological advancement. Synchronous reluctance machines (SynRMs) have drawn attention in the past few years resulting in better performance for traction and electrical aircraft applications [1-2]. They use less rare-earth minerals which is simple to design with high robustness and less costly in terms of manufacturing. These recent advancements in its motor structure help manufacturers to choose SynRM over other machines in saving energy and utilizing low materials. They can produce maximum torque per ampere, has higher efficiency and can run at constant-power speed range. Furthermore, it lacks rotor cage or Permanent Magnet (PM) losses, which allows continuous torque higher than that of an Induction Motor (IM) of the same size, thus, provides its huge applications in Electric Vehicles (EVs). Considering its superiority from other motors, it has been used in applications such as centrifugal machines, conveyor systems, fans and pumps, cranes, compressors, elevators, crushers, and general machines (servo pumps, extruders and winders [3]. SynRM has the property of line-start capability where the shorted rotor winding causes damping effect and reduces its efficiency by 10 %. But in case of variable-speed drives (VSDs), it does not have this effect and are very efficient when used for high-speed applications [4-5]. As a result, SynRMs are commonly used in industry as part of their drive package.

Based on the extensive literature review, some of the important research articles results and outcomes is being discussed further. A solar photovoltaic (PV)-battery integrated system for the light electric vehicle (LEV) based on SynRM motor drive with longer range and proposes Maximum power point tracking (MPPT) control technique based on incremental conductance (InC) approach for obtaining maximum power from a PV array which the motor receives power from the battery/ PV array via a voltage source inverter (VSI) [6-7]. The modelling and simulation for a pure electric vehicle using propulsion chain uses two SynRMs for propelling the vehicle rear wheels whereas voltage source inverter and control systems controls both the motor speed and the electronic differential controller (EDC). The Particle Swarm Optimization (PSO) technique is used to specify the optimal parameters of the cascade controllers for controlling the motors [29, 30]. Space Vector Pulse Width Modulation (SVPWM) techniques for controlling the direct and quadratic axes voltages with SynRM including speed and torque with different frequencies and load conditions has also been discussed [6, 8-12]. Various drives used in EVs & HEV mainly AC and DC which includes permanent magnet synchronous motor (PMSM), Induction motor (IM), Switched reluctance motor (SRM), Brushless DC motor (BLDC) have been presented [13-14]. These motors are fed by different power electronic converters such as DC-DC converter, DC-AC converters per the supply requirements [15-17]. Different electric motors have been studied and compared to see the benefits of each motor and the one that is more suitable to be used in the EV applications [15-18]. After studying and analyzing research contributions by various authors in relation to SynRM, it can be concluded that SynRM has been

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used for a long period in controlling of various applications in the field of Light Electric Vehicles, Hybrid Electric Vehicles and its property shows superior performance when compared to other machines, so it has been used in driving Electric vehicles with different control techniques such as MPPT, PSO, and others. The major focus of this paper is to present the readers with the key aspects of torque, velocity, and field-oriented control strategies of SynRM motor, which have been classified further based on control loop block diagrams and applications.

The outline of this paper is arranged: firstly, the major motor technologies, construction, its operating principles, comparison of motors' performance in terms of cost and environmental impact and applications are discussed in section 2; secondly, section 3 dwells the SynRM mathematical modelling; section 4 aims to focus on different control techniques based on various criteria are thoroughly analyzed. Finally, section 5 summarizes the major findings and future scope.

2. Synchronous Reluctance Motor

The theoretical and experimental research of SynRM is being evaluated in this paper. It is one such types of synchronous electric motors where the torque has been generated due to difference in magnetic conductivities between the direct axes and quadrature axis of the rotor. Field windings or permanent magnets are usually absent in these type of motors [19]. It draws lots of interest for a great number of researchers since 1923 [19]. This research has been extended in the hope that it will contribute further to this field [20]. Power electronics communication and mechanical communication are the two primary categories of electrical machines [21-23]. This motor comes under non-excitation with continuous field under power electronics communication. For controlling SynRM, Maximum Torque Per Ampere (MTPA) method is a common approach that can be proposed.

The constructional feature of this machine consists of a stator and a rotor where the stator is made up of a frame and a core with a winding. The windings can be arranged in both distributed as well as in concentrated manner. The rotor can be classified into three types: an axially laminated rotor, a transversally/ radially laminated rotor and a rotor with prominent salient poles which are segmented.

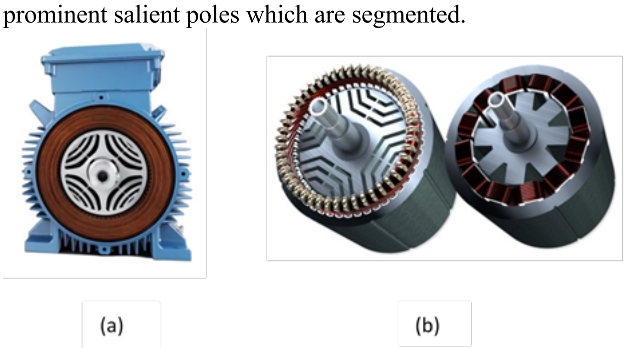


Fig. 1. Constructional view of Synchronous Reluctance Motor (SynRM) (b) Types of SynRM with axially and transversely laminated [9].

Fig. 1 shows: (a & b) The constructional diagram of SynRM with axially and transversely laminated. When an alternating current passes through the stator windings with the rotor keeping constant, a rotating magnetic flux is produced from the three phase coils. The magnetic flux is directed toward the magnetic resistance with the lowest value. The rotor has a property to align with the flux of stator but as this flux tends to rotate in tshe direction with the lowest magnetic resistance, the rotor lags behind the stator and starts rotating. As a result, the rotating magnetic flux develops a reluctance force and ends up producing a rotational torque termed as reluctance torque.

Despite the absence of permanent magnets, SynRM can be considered a subclass of the permanent magnet machine. Its feature is identical to Interior Permanent Magnet Synchronous Motor (IPMSM) without taking into account the flux generated by permanent magnets. As a result, it only produces reluctance torque and follows principle of reluctance only. Furthermore, the rotor performance depends on its construction and the arrangement of flux barriers inside the rotor. With air within, the goal of these flux barriers is to achieve a high saliency ratio [24-26] can measure the machine's strength in the field when it is weakening and for determining the amount of torque it can produce. Maximum efficiency of the motor is reached when the barriers to flux are following magnetic field lines as close as possible.

Some features of SynRM are listed below:

1. Simple and reliable in rotor construction: The rotor is made of sheet electrical metal steel plates punched into a package with no bars and magnets with a short-circuited winding which makes it more robust and cost- effective with a low rotor inertia [24-25].
2. Low heat: Due to absence of currents in the rotor winding, heat produced is negligible thus operated in cold rotor condition with no losses resulting in longer durability of the motor and allowing nominal torque to be loaded 2.5 times greater than IM [21, 27].
3. Absence of magnets: As this motor uses less rare earth metals in the construction of the electric motor, the cost price is lower, and its maintenance becomes easy with no magnetic forces present.
4. Low rotor moment of inertia: This electric motor has lower moment of inertia thus allowing to accelerate faster and conserving more energy with no windings or magnets were found present in the rotor.
5. Controlling the speed: Desired speed control of this machine can be obtained over a wide range as it operates on a frequency converter, and it can withstand continuous load without additional cooling.

2.1 SynRM and its different applications

Some of the contribution of SynRM in practical applications are discussed below:

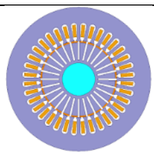
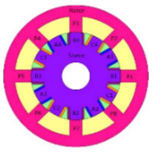
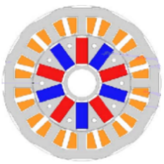
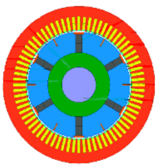
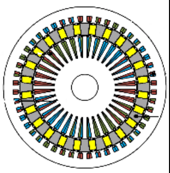
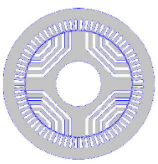
1. Originally designed as a line-start synchronous AC motor for use in applications requiring synchronous speed.
2. These motors have probable utilization in the textile industries and were powered by a single voltage source.
3. Due to enhanced durability, the motor is commonly employed in high-speed aerospace applications.
4. They are also utilized in aircraft applications as noise is not an issue because vibrations are generally muted out at high speeds [15].
5. In terms of production and operation, simplicity and adaptability are key features of this motor.
6. Higher efficiency and torque density, higher overload capacity and lower rotor temperature.
7. SynRM technology is appealing for high-speed applications and generators.
8. It is very new to the industrial market in comparison to other machine types leading to less adoption.
9. SynRM has been replacing IMs in companies like ABB particularly for use in pump applications such as heating and

air conditioning, as well as ventilation, due to its maximum power density and higher efficiency [26].

2.2 Comparison of SynRM with other machines

Different types of AC drives based on Synchronous Reluctance Motor have lately been launched on the market. Back in 1923, there is a concept that with improved rotor design and improvements in power converters, these motors are applicable for industrial purposes. SynRM power density is lower than that of PMSMs but higher in case of Induction motors. When compared to IM and IPMM, the ratio between base and maximum speed of SynRM is rather low. As a result, the machine has a small area of steady power. Considering the same, pumps and fans are considered as suitable applications for SynRM because they operate at a single operating point. Permanent magnets are avoided to avoid demagnetization and to simplify overall machine management. Due to absence of electrical induction in free-running loads or in times of maintenance, unlike permanent magnets, fewer precautionary measures are required [23]. In comparison to a PMSM, SynRM has lower power factor (cos φ), necessitating a large sized inverter. The required higher currents in the stator
windings partially offset the missing ohmic losses in the rotor windings, resulting in enhanced efficiency.
Table 1 shows the comparison of SynRM machines with oater machines based on the different aspects.

Table 1. Comparison of SynRM with other machines

Machine types	Stator and rotor structure	Efficiency	Cost	Rpm/ Torque	Applications	Maintenance
IM [15, 18, 25, 32]		86.42%	Less	1500rpm/ 14.48 Nm	Used in variable speed drives for pumps, trains, fans and general automation.	Less
SRM [4, 18, 25, 32]		90.00%	More	1500 rpm/ 14.40 Nm	Used in Machine tools: planers, vertical lathes, drilling machines.	Less
PMSG[4, 24, 28, 34]		75.00%	Less	1500 rpm/ 13.58 Nm	High efficiency drives (aerospace, automotive industry).	More
SEIG [4,22, 24, 30, 35]		80.25%	More	1500rpm/ 14.20 Nm	Enables the wind turbine to run at its maximum Cp for a wide range of wind speeds.	Less
DFIG [5, 25, 28, 32]		80.00%	Less	1500 rpm/12.78 Nm	Used to control the reactive and active power separately, or to control the power factor of wind turbines.	More
SynRM [5, 12, 32, 35]		94.42%	Less	1500 rpm/ 14.00	Because of their superior efficiency and power density, they are used in pump applications such as heating and air conditioning and also for ventilation.	Less

3. Mathematical Modelling of SynRM

Constructional features mainly include stator and rotor windings. The stator winding is of three phases in nature which are connected in star or delta and is made of silicon steel stampings. The rotor windings are made up of ferromagnetic material since the rotor has to align with stator magnetic material as per reluctance principle, therefore the reluctance of the rotor windings must be least.

Here, the combined expressions of voltage across the stator winding are given in eqn. (1) [5].

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \frac{d\Psi_a}{dt} \\ \frac{d\Psi_b}{dt} \\ \frac{d\Psi_c}{dt} \end{bmatrix} \quad (1)$$

Where:

- v_a, v_b, v_c = Phase voltages of stator winding.
- R_s = Equivalent resistance across each stator winding.
- i_a, i_b, i_c = Phase currents flowing across the stator winding.
- Ψ_a, Ψ_b, Ψ_c = Magnetic fluxes that links each winding of the stator.
- Ψ_a, Ψ_b, Ψ_c = Magnetic fluxes that links each winding of the stator.

The permanent magnet, excitation winding, and three phase stator winding are given in eqn. (2) [24].

$$\begin{bmatrix} \Psi_a \\ \Psi_b \\ \Psi_c \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

Where:

- L_{aa}, L_{bb}, L_{cc} = Self-inductances of winding of the stator.
- $L_{ab}, L_{ac}, L_{ba}, L_{bc}, L_{ca}, L_{cb}$ = Mutual inductances of this stator winding.
-

$$\theta_e = N\theta_r + rotor\ offset \quad (3)$$

$$L_{aa} = L_s + L_m \cos(2\theta_e) \quad (4)$$

$$L_{bb} = L_s + L_m \cos(2(\theta_e - {2\pi}/{3})) \quad (5)$$

$$L_{cc} = L_s + L_m \cos(2(\theta_e + {2\pi}/{3})) \quad (6)$$

$$L_{bb} = L_s + L_m \cos(2(\theta_e + {2\pi}/{3})) \quad (7)$$

$$L_{ab} = L_{ba} = -M_s - L_m \cos(2(\theta_e + {\pi}/{6}) \quad (8)$$

$$L_{bc} = L_{cb} = -M_s - L_m \cos(2(\theta_e + {\pi}/{6} - {2\pi}/{3})) \quad (9)$$

$$L_{ca} = L_{ac} = -M_s - L_m \cos(2(\theta_e + {\pi}/{6} + {2\pi}/{3})) \quad (10)$$

Where:

- θ_r = Mechanical angle of the rotor.
- θ_e = Electrical angle of the rotor.
- $\emptyset$ = Rotor offset when rotor electrical angle is defined w.r.t. d-axis.
- L_s = Self-inductance per phase of the rotor.
- L_m = Induction fluctuation of the stator.
- M_s = Stator mutual inductance.

Here, the Park transformation, P is defined as

$$P = \begin{bmatrix} cos\theta_e & \cos(\theta_e - {2\pi}/{3}) & \cos(\theta_e + {2\pi}/{3}) \\ -sin\theta_e & -\sin(\theta_e - {2\pi}/{3}) & -\sin(\theta_e + {2\pi}/{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (11)$$

The electrical angle depends on mechanical angle of rotor in which

$$\theta_e = N\theta_r + rotor\ offset \quad (12)$$

Where:
N = Number of poles
θ_r = Mechanical angle of rotor
After applying Park's transformation to eqn.(1), these equations arise

$$v_d = R_s i_d + L_d \frac{d_{i_d}}{dt} - N\omega i_q L_q \quad (13)$$

$$v_q = R_s i_q + L_q \frac{d_{i_q}}{dt} - N\omega i_d L_d \quad (14)$$

$$v_0 = R_s i_0 + L_0 \frac{d_{i_0}}{dt} \quad (15)$$

$$T = \frac{3}{2} N(i_q i_d L_d - i_d i_q L_q) \quad (16)$$

Where:

- i_d, i_q and i_0 = d-axis, q-axis and zero- sequence currents, given by

$$J\frac{d\omega}{dt} = T - T_L - B_m \quad (17)$$

Where:

- i_d, i_q and i_0 = d-axis, q-axis and zero- sequence currents, given by

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (18)$$

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = P \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (19)$$

Where:

- i_a, i_b, i_c = Stator currents
- v_d, v_q and v_0 = d-axis, q-axis and zero- sequence voltages, given by

Where

- v_a, v_b, v_c = Stator voltage.

$$L_d = L_s + M_s + \frac{3}{2} L_m \quad (20)$$

$$L_q = L_s + M_s - \frac{3}{2} L_m \quad (21)$$

$$L_0 = L_s - 2M_s \quad (22)$$

- R_s = Stator resistance per phase
- N = Number of rotor pole pairs.
- T = Rotor torque.
- B_m = Rotor damping.
- ω = Mechanical speed of the motor (rotational).
- J = Rotor inertia.

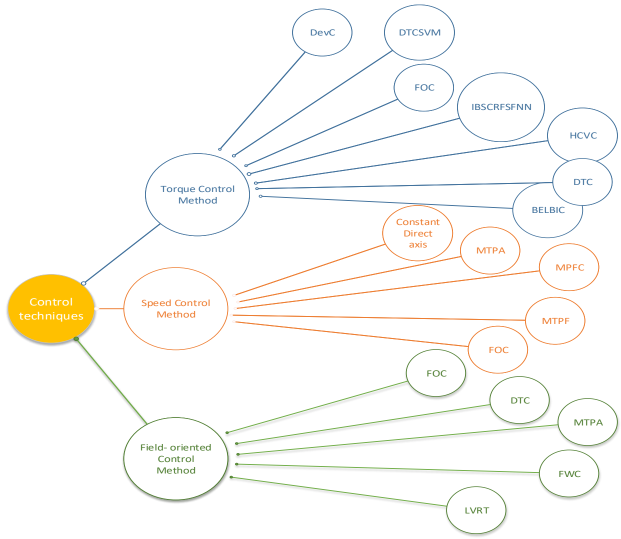


Fig. 2. Classification of different motor control techniques [28].

4. Types of control techniques

SynRM can be controlled using different types of techniques such as torque control, vector control and field-oriented control method which their performance analysis can be done using these techniques [22]. The vector control methods include control of current for current angle and direct axis control. MTPA (Maximum torque per ampere), MTPF (Maximum torque per flux), and MPFC (Maximum power factor control) can all be used to regulate the constant current angle [29]. The SynRM is driven by a current- controlled PWM voltage source inverter, which is controlled by a PI controller. These control techniques have been simulated in MATLAB environment. Under certain conditions, the simulation displays excellent results when managed by these control methods and can be used for driving high-performance applications such as electric automobiles, tractions and so on. Fig. 2 shows the classification of different approaches based on these three control techniques.

4.1. Torque control techniques of SynRM

For synchronized reluctance machine control using this technique, a high-voltage battery is fed to the machine across a controlled three-phase converter [30]. A velocity source is applied across the load which is ideal and angular in nature. A control subsystem is proposed in the system for controlling of current. It consists of a current controller based on PI controller which is a closed loop for controlling current and an outer loop subsystem for controlling the torque. Here, MTPA strategy is used at every instant for converting references torque to current where torque steps are used both in the generator and motor modes. The author uses deviation-based torque management of SynRM drives [31]. To generate linear and simple correlations between diverse machine signals, the proposed control system employs a normalized deviation model. As a result, unique deviation equations replace the commonly employed proportional-integral current regulators. Thus, the suggested approach offers electric drives benefits such as control system simplicity, parameter independence, and no controller tweaking. The control performance of the control system is also compared with that of a field-oriented control scheme based on PI controller [32]. It results in reduction of control complications, such as the number of conventional controllers, and the elimination of machine parameter dependency in other electrical drives. Under an automatic search of the MTPA strategy, the author proposes Speed Control Modes (SCM) and Torque Control Modes (TCM) of SynRM drives based on emotional controllers and space vector modulation where the controller's performance is then compared to that of an optimized traditional PI controller under various operating situations [33]. In both TCM and SCM, the suggested method's superiority, such as fast dynamic, simple implementation, and robustness to parameter fluctuations and external disturbances is demonstrated [29]. Furthermore, the proposed MTPA technique demonstrates a consistent and quick response to operating point changes.

A sliding mode-plus-PI controller is devised for torque and flux control, respectively, to preserve DTC transient and robustness qualities [34]. In actuality, a variable structure controller for direct torque and stator flux regulation is used, based on the conventional DTC principle. Fig. 3 shows a block schematic of the suggested efficiency-optimized VSC-DTC for sensor less SynRM drives. The stator flux is orientated and controlled in this drive. The torque and the stator flux magnitude s are the two control variables. An outer speed control loop with a PI speed controller produces torque reference [34]. The VS-DTC controller in the inner loop calculates the most appropriate stator voltage vectors to direct the torque and flux to their references.

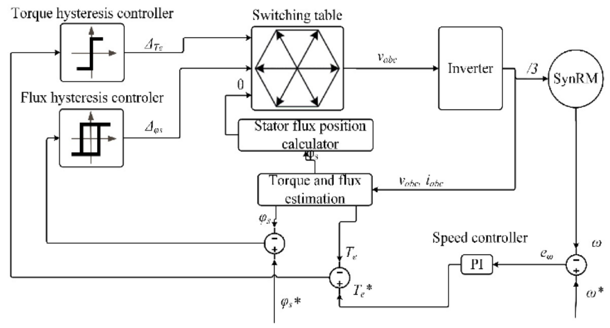


Fig. 3. Block diagram showing Direct Torque Control Method in SynRM [26].

This controller shows superior performance than other controllers in terms of high dynamic control. It prevents using of current regulator which makes it possible for attaining higher transient in controlling the torque performance and uses the stator resistance for allowing robust control of the motor. Considering its fast dynamic responses, it has been implemented in servo applications. Most customers who prefer to obtain transient response than steady response in running this motor often adopted this control method.

Table 2 shows the different torque control techniques of SynRM along with its benefits. Intelligent back stepping control employing a recurrent feature selection fuzzy neural network (IBSCRFSFNN) control approach has been shown to be more efficient since the sampling interval is 1 ms, requiring less control time and providing the best speed response.

4.2. Speed Control Techniques of SynRM

This method is similar to that of torque control methods. The only difference is that the rotor angular velocity of a SynRM can be controlled using this technique. Here, a high-voltage battery is fed to the machine across a controlled three-phase converter. Instead of a velocity source applied across the load on torque control method, an ideal torque source is applied across the load [25-26]. An additional multi-layered PI cascaded control structure is present in the current controller [4]. The author proposed a control subsystem consists of an outer control loop for controlling angular velocity and two inner loops for controlling of current. It can be categorized as constant direct axis current control and constant current angle control [4]. In constant current angle control, different control methods include MTPA, MTPF and MPFC [7]. The parameter findings such as response time, peak stator current, and torque ripple can be compared based on the better performance of various control approaches [18]. The outcomes of the study will help in determining when and under what conditions each of the above-mentioned vector control techniques may be employed in high-performance drive systems including electric cars, traction and ship propulsion, among others.

Fig. 4 shows the block diagram of speed controller used in SynRM. It consists of a current controller of a constant value in the inductive axis where excitation of direct axis is kept at a constant value for maintaining machine flux and excitation of the quadrature axis is changed for controlling the torque of the motor. This control mainly focuses on implementing the current controller thus by taking the direct and quadrature suitable axis excitation values for finding the inverter switching configuration in any control system [35].

Table 3 shows the different speed control techniques of SynRM along with its benefits. After studying the responses of each approach, it was determined that the Maximum torque per flux (MTPF) control is the best option since it has the least rising time of 0.13s relative to other approaches.

Table 4 shows the different speed control techniques of SynRM along with its benefits. Based on the results of the study, it can be claimed that field-oriented control is more successful in terms of torque response. It also results in a smaller motors, lower costs, and lower power consumption. Besides from that, the four-quadrant operation seems to be another attracting attribute.

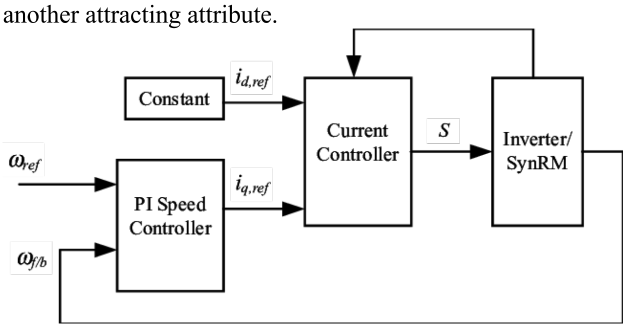


Fig. 4. Block diagram showing Speed Control Method in SynRM [35].

Table 2. Different torque control techniques of SynRM.

S. No	Control techniques	Performance parameters	Benefits
1	DTC space vector modulation (SVM) [30]	Speed increases with the response after 0.7s, and there is 0.8% overshoot.	Switching state patterns have been improved
2	Deviation base torque control (Dev C) [5]	Has faster dynamic response of 3.5 ms which is 28 % faster than FOC.	Has faster dynamic response, more accuracy and simpler compared to FOC.
3	PI controller base Field Oriented Control (FOC) [24]	Has dynamic response of 2.5 ms.	Uses optimized PI controllers which is reliable for optimization methods.
4	Intelligent back stepping control using recurrent feature selection fuzzy neural network (IBSCRFSFNN) [36]	The sampling interval of speed control loop is found to be less than 1 ms requiring less control effect.	Requires less control effort compared to sliding mode control. Lower costs than traditional systems, more efficiency, a more robust system that is more reliable and flexible, and the ability to mimic human deductive thinking.
5	Brain Emotional Learning based Intelligent Controller (BELBIC) [34]	1. Has fast dynamic response than VC (vector control) based tuned PI control which is about 3 ms without overshoot. 2. It provides continuously steady decoupling flux which is poor and has significant overshoot, in case of PI. 3. Has low ripple torque and rich convergence which is low while convergence is poor in case of OCC-PI (optimal conventional controller). 4. Can track the speed step command and at t=0.4s zeros speed error, without any overshoot which shows about t=0.7s in conventional PI control.	1. Has very fast response, simple implementation and robustness with respect to disturbances and parameter variations. 2. Switching state patterns have been improved. Has zero steady state error, without under/over- shoot, higher adaptiveness, fast tracking & high convergence but has significant under/over-shoot, lower adaptiveness and low tracking in case of PI.
6	Direct Torque control (DTC) [30]	1. Shows speed response of 200 ms with acceleration up to 4000 rpm having load torque of 3 Nm. 2. Deceleration with elimination of the 3 Nm load–torque showing response time of 600 ms.	1. Does not require position of stator flux vector as hysteresis controllers are employed and the approach is simple and robust. 2. Does not necessitate the use of a pulse-width modulator. 3. Suitable for control with simple positioning application.

7	Hysteresis Current Vector Control (HCVC) [34]	1. Shows speed response of 200 ms with acceleration up to 4000 rpm having load torque of 3 Nm. 2. Deceleration with elimination of the 3 Nm load–torque showing response time of 600 ms.	1. In the steady state, the torque reference tracking is error-free. 2. It produces lesser torque and current ripples than the DTC. 3. More suitable for control application with precise position.

Table 3. Different speed control techniques of SynRM.

Sl. No	Control techniques	Performance parameters	Benefits
1	Constant direct axis current control [4]	Performance under starting load shows faster torque response than MTPA by 50 μsec.	Faster torque response.
2	MTPA (Maximum torque per ampere) [4]	Shows faster torque response of 1.68 ms during starting.	Maximum torque ripple efficiency is found to be 6.45 %.
3	MPFC (Maximum power factor control) [4]	Shows torque response of 1.36 ms during starting.	Current drawn is found to be higher than MTPA and MTPF control.
4	MTPF (Maximum torque per flux) [4, 15]	Rise time for torque response is 0.13s which is faster than MTPA & MPFC having rise time of 0.77 ms and 0.26 ms.	During starting, the fastest response was shown with rising speed.
5	DTC [32]	When the load is changed from 3Nm to -3Nm, the torque response displays 0.5s and 1s at the initial load.	1. It shows reduced response time compared to the FOC scheme. 2. DTC shows faster response and suitable change in load.
6	FOC [32, 35]	Shows better tracking of the reference speed with no overshoot.	1. It shows more significant peak torque than DTC. 2. It has better steady state behavior without ripples.

Table 4. Different field-oriented control techniques of SynRM.

Sl No.	Cotrol Techniques	Performance parameters	Benefits
1	Field oriented control [37]	i.Has 60% higher torque ripple than DTC during high torque operation. i.Phase current goes close to zero as the torque goes to zero.	1. Torque response is improved. 2. Torque control at low frequencies and low speed. 3. Dynamic speed accuracy. 4. Reduction in size of motor, cost and power consumption. 5. Four quadrant operation. Short-term overload capability.
2	DTC [37]	i.The torque ripple is between 15% − 30%. i.Phase currents are considerably high.	1. It does not require any external measurements of the mechanical location of the rotors like that of FOC. 2. The method is simple because no current regulators, rotating reference frame transformations, or PWM generators are required.
3	MTPA control [33]	With a rated load of 0.6 Nm, the speed response is 1000 rpm, with a peak starting torque of 0.98 Nm	Generates the greatest amount of torque for a given operational current.

4	Field weakening control [6, 9, 33]	Peak starting torque is roughly 0.98 Nm, with considerable overshoot in transient conditions due to the transient peak power being less than the motor's maximum power.	Increases speed of the synchronous reluctance motor above its rated value with reduced torque.
5	Low Voltage Ride Through (LVRT) SynRM-based Wind Energy Conversion systems (WECS) method [38]	With a wind speed of 9 m/s, the generator spins at 1875 rpm, producing 1 kW of power which attains maximum yield.	Maximum power is harvested from the wind turbine when the motor is driven at an optimum speed using this technique.

4.3. Field- oriented control techniques of SynRM

SynRM stator currents are controlled using this control approach, which is represented by a vector. This is based on transforming three- phase co-ordinate of speed and time to two-phase co-ordinate (d and q axis) which are time invariant. The output of the projections is comparable to that of a regulated DC machine [24]. Two constant components are given as input references: torque and flux, which are aligned with the q-axis and d- axis, respectively. As a result, these two coordinates [26] are used to transform the three phases. Thus, a variable d-q current control, current controller which is speed invariant and variable speed loop gain controller are proposed in this technique. Using a SynRM as a generator, the author uses Low Voltage Ride Through (LVRT) for a variable speed grid-connected WECS [38]. A hill climbing algorithm is used in the WECS to track maximum power points. The system's LVRT capability is implemented using three separate control techniques under three-phase grid fault conditions: modulation index control, de-loading, and crowbar protection. These approaches have been tried in a Simulink/MATLAB environment, with promising results for LVRT implementation in a SynRM based WECS [38].

Fig. 5 shows the block diagram for implementing Field-Oriented Control in SynRM. In order to achieve dq-axis current control, FOC requires a position/speed observer, when other controllers or observers require an accurate motor model. For obtaining high-performance current vector and position estimation, FOC control requires a powerful Motor Control Unit and a high-precision current sensor, which adds up the cost of electronic device drives [15]. Furthermore, this vector control technique requires a greater carrier ratio compared to scalar control, implying that FOC control necessitates a higher IGBT switch frequency, raising the IGBT and cooling component costs.

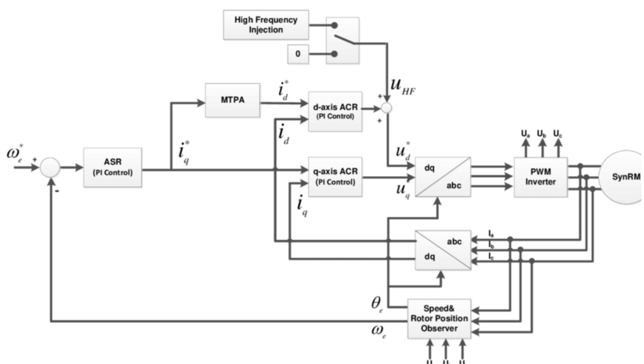


Fig. 5. Block diagram showing Direct Torque Control Method in SynRM [26].

5. Types of control techniques

Nowadays, several industries are trying to adopt variable speed drive applications which are showing more efficiency, robustness and allows precise control in the field of high-performance applications.

Even though, adopting of VSDs in motors increases costs to the manufacturers, it has been used both in variable and fixed speed drive applications for attaining maximum efficiency. In fact, use of low energy materials can also reduce the cost for the same drive which are operating in same ratings. Researchers are trying to find solutions in developing more advanced and robustness control showing better performances through findings and innovations in most industries in the near future [28]. Thus, they focus mainly on these areas for obtaining the desired performances and improved economy:

- Optimal motor design,
- Optimal converter design, and
- Optimal controller design.

The control unit has an important role in estimating the system performance of any electric drive system. It will decide the reliability of the system which can be categorized as below:

- Input modules – It converts analog to digital converters and sense the input variables coming from electrical and mechanical sensors or transducers.
- Output modules – It provides continuous switching sequences for e.g. Pulse Width Modulation (PWM) modules.
- Peripherals modules – Programming and exchanging of data is performed in this module.
- Main processor – Here, control algorithms are executed and processed in this unit.

In order to obtain a high efficiency motor performance, the control unit plays a significant role. Use of frequency converters controlled by microprocessors increase the robustness and performance of the motor. Whereas use of VSDs often associate a high frequency current flowing into the system resulting with some considerable losses which requires more precise control of the motor. Thus, with SynRM using the frequency converters for powering, researchers are trying to focus mainly in this particular control area. They aim in increasing the robustness, reducing the current and torque ripples, reducing the losses and improve dynamic responses of the motor with smooth transition between different speed regions [28].

6. Conclusion and Future works

With the advancement in industrialization and adoption of improved technologies, different optimization techniques for utilization of energy have been adopted over the past years. When employed alone in drive systems due to theoretical and practical constraints, motor control methods may not ensure an appropriate degree of all control elements such as, good robustness, quick dynamic, minimal torque ripple, and precise tracking. As a result, electric drive research and development activities are updated on a regular basis in order to stay up with technical breakthroughs and provide superior service. With SynRM having its wide range of application with VSDs, more intelligent control strategies are expected to be developed for maintaining the highest efficiency of the motor throughout a wide speed range while providing desired performance in both transient and steady-state conditions. This paper discussed various approaches for other motor technologies that can be modified and applied for enhancing the performance of synchronous reluctance motor where the torque, speed and field-oriented method has been adopted as well as recommendations for further study.

Based on the extensive survey conducted above on control techniques, author is trying to recommend the most competent approach and their significance, as illustrated in Table 5.

Table 5. Optimal selection of control techniques of SynRM based on the performance.

Sl.No	Type of control techniques	Best Approach	Significance
1	Torque control	IBSCRFSFNN	Requires less control time and shows faster speed response.
2	Speed control	MTPF	Has maximum efficiency with minimum rising time.
3	Field-oriented control	DTC	Has minimum torque ripple and exempt the use of external requirements.

From the discussed torque control techniques, it has been found that IBSCRFSFNN control approach is more efficient with sampling interval of 1 ms, requiring less control time and providing the best speed response. Similarly for speed control, MTPF method results in having more efficiency with minimum rising time of 0.13s and DTC approach for field-oriented control with minimum torque ripple and use of any external requirements like current regulators, rotating reference frame transformations, or PWM generators are excluded relative to other approaches.

Variation in motor parameters has a direct impact on machine controllability in SynRM thus, control strategy to avoid these difficulties should be developed. It is possible to assess and increase the controller's resistance to external disturbances, such as strong load torques. According to the study, excessive torque ripples in SynRM drive systems are one of the primary concerns when compared to alternative technologies where high quantity of torque ripple causes pulsation and vibration, which can result in low system efficiency as well as noise in the environment.

The following are some of the future scopes that can be adopted:

1. Identifying solutions and ideas for decreasing torque ripples from a design and control standpoint.
2. Given the wide range of SynRM with VSDs applications, more intelligent control strategies can be developed for obtaining amazing efficiency of these motors over a wide speed range with desirable performance in both directions.

Therefore, in view of research and the major application sectors like for industries, SynRM manufacturers, E-mobility, SynRM drive systems would be a need in future for more sophisticated and intelligent control techniques which can lead to achieve the desirable efficiency and performances of this machine.

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