International Journal of Science and Engineering Invention (IJSEI)
Volume 09, Issue 02, February 2023,
*https://doi.org/10.23958/ijsei/vol09-i02/236*

**Original article**

# A Review of Torque Ripple Minimization Strategies in Switched Reluctance Machines

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Received 30 January 2023; Accepted 20 February 2023; Published 25 February 2023

## Abstract
Switched reluctance machines (SRMs) have proven to be reliable, efficient and cost effective over other conventional motors. However, its major drawback lies in its highly nonlinear characteristics which makes it to produce torque ripples, acoustic noise and vibration. A number of methods have been proposed for the minimization of the ripples produced by either changing and improving the structure and geometry of the motor or via a number of control strategies. Artificial intelligence techniques have also been explored for the minimization of these ripples. This paper reviews the state of the art on various control strategies for torque ripple minimization of the SRM. It is expected that this review paper will serve as an underlying platform for researchers meaning to traverse control of SRMs for further improvement.

***Keywords:*** ***switched reluctance machines, torque ripple minimization, torque.***

## I. Introduction

The SRM is making rapid progress in the industry and has become a highly popular machine of choice due to its robust and simple structure, high torque to inertia ratio, low cost, high efficiency and reliability, fault tolerance capabilities and suitability for variable speed operations. The SRM as a Motor is well known for over 150 years whereas the generating mode, SRG has created considerable interest of recent [1]. The SRM is referred to as a doubly salient pole due to the salient pole structure of its stator and rotor [2]. This is not unconnected with the fact that the machines have no brushes and Permanent Magnet on the rotor and this makes it robust and able to operate at very high speeds. The machine is commercially applied in washing machines, vacuum cleaners, water pumps, automatic doors, hybrid electrical vehicle, automotive application, electrified power train, starter generator, turbocharger application, gas turbine textile machines, and a host of others [3].

However, despite these advantages, the SRM has a number of disadvantages which has limited its wider applicability. Some of the disadvantages include: its highly nonlinear characteristics due to its salient pole structure and magnetic saturation along the flux path [2,3]. This non-linearity causes torque ripples, vibrations and acoustic noise which are all undesirable. As a result, it has become imperative for researchers to devise a means of reducing these undesirable characteristics- majorly the torque ripple- so as to close the existing gap between the conventional machine and the SRM.

Two methods are primarily used for torque reduction: the first is to improve the magnetic design of the motor by modification of the structure and geometry of the SRM. The second method uses advanced electronic control techniques. In the first method, the reduction in torque ripple is usually obtained by changing the structure of the stator and rotor poles [4], however this has a corresponding effect on the motor torque. In the electronic approach, control parameters such as voltage and current levels, turn off and turn on angles are optimized. This method is also at the expense of average torque as the machine will not attain the optimal power levels. Figure 1 depicts the various methodologies for torque ripple minimization (TRM).

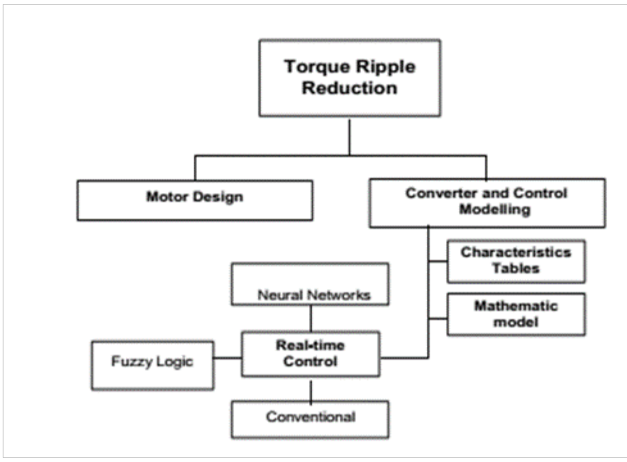


**Fig.1: TRM methodologies** [4]

Extensive research has been carried out on the various TRM methodologies. [5-9] optimizes motor design of the SRM while [10-13] utilizes advanced electronic control methods.

Torque-production mechanisms for switched reluctance motor drive are both current and position dependent. [14] Shows an earlier method of torque ripple minimization where the shape of the torque/angle/current can be determined by a series of static and dynamic measurements. The author in [15] employed a by-cubic interpolation to model the nonlinear data by experimentation and optimal pre-calculation of the position of a four phase 4kW SRM. The result produced a torque controller with low toque ripple.

In [16], the authors used PWM control techniques to reduce torque ripples by using a current control strategy during commutation. [17] proposes a ripple minimization strategy based on the Sliding Mode Control (SMC) which compensates the low frequency oscillations in the output of the torque. This method employed a completely analog system as it uses a sensor to sense the position of the rotor. [18] Implements a simple method by minimizing the ripple independent of the stator structure. Also, TRM was achieved independent of the machine design using Finite Element Analysis (FEA). In [19], a novel method of segment type SRM with two-steps skew/slide rotor to reduce torque ripple was proposed. The machine characteristics was compared to the experimental machine. In this method, however, there was a reduction in the average torque of the machine. [20] Improves the dynamic performance of the SRG by employing criteria based on machine design parameters and structure of the geometry. With this defined, an optimal pointer to SR topologies for TRM was obtained in addition to the imposition of a magneto motive force (MMF) from a trapezoidal phase reference. This was synchronized with the rotor position and the torque ripples shown to be effectively minimized.

Another well-known control approach to torque ripple minimization is the Torque sharing Function (TSF). The TSF method regulates the torque production of the individual phases to distribute the reference torque among all the phases, while keeping the sum of all the individual torque references equal to the required torque [21][22-25] employs Torque control techniques for ripple minimization. [26-28] employs a TSF for reducing torque ripples in SRM. An attempt has been made in [29] to minimize the torque ripple of an SRM through current profiling using a combination of machine design and control algorithm. Simulation of the dynamic model in MATLAB/Simulink environment considering machine nonlinearities, electrical and magnetic loss and mutual coupling was done and experimental verification validated showing a good correlation between experimental results and simulation. However, efficiency of the SRM was conceded to be able to meet desired torque ripple improvements.

Aide Xu et al [30] compared the optimized scheme of the Direct Torque Control, DTC and Direct Instantaneous Torque Control DITC with a new method based on Model Predictive Flux Control, MPFC to reduce Torque ripple in SRM. They found that this approach can only partly overcome the torque ripple as compared with the Optimized DTC and DITC methods. In [31], Nan Wu et al presented a Torque Ripple Minimization strategy in SRM for application in water pumping using Model Predictive Control, MPC. They found that the presence of MPC makes the use of a converter unessential, thereby reducing cost. A third order response surface model was applied to build a multi objective function considering efficiency improvement and torque ripple reduction was described in [32], simulation and experimental results returned a good compromise between SRG high efficiency and low torque ripple.

Satisfactory control performance is difficult to achieve using traditional controllers such as the proportional, integral and/or derivative (PI, PD, and PID) controllers as they can only be tuned to obtain desired performance under a specific set of operating conditions. However, its performance deteriorates significantly as the operating conditions vary with increasing nonlinearity of the SRG. Hence, artificial intelligence control techniques such as Fuzzy Logic (FL) [33-38], Artificial Neural Network (ANN) [39], Bacteria Foraging Optimization (BFO) [40] Genetic Algorithm (GA) [41] are employed for torque ripple minimization which allows for better performance. [42-44] gives an extensive review/literature survey of related approaches adopted for torque ripple minimization in SRM drives. This work will focus on a review of the various research work carried out on the SRG and their control strategies

### II. Electromechanical structure of SRG

The SRM has a structure where both its rotor and stator poles protrude into the airgap (salient pole). The rotor and stator poles are made up of steel laminations and only the stator poles have windings concentrated round them [39]. Also, there exists no permanent magnet (PM) on the rotor, but rather, a gear like chunk of laminated steel. This lack of PM and windings on the rotor means the magnetic field has to be created from a source of external supply [40]. The stator pole windings are connected in series with the opposite stator poles to form a phase. Some typical SRG configurations include a three phase 6 stator, 4 rotor 6/4 machine configuration, a four- phase 8/6, three- phase 12/8 machine, etc. [41] Figure 2 shows a conventional four phase 8/6 and three phase 12/8 SRM.

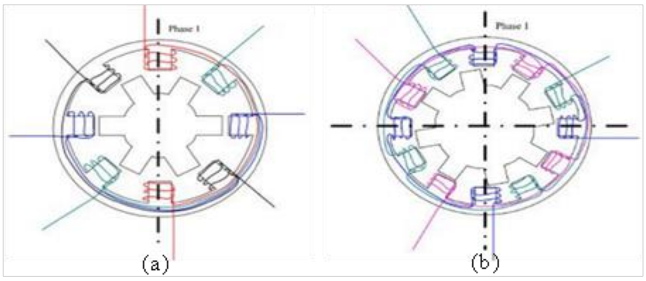


**Fig.2: Switched reluctance generator structure (a) four-phase 8/6, (b) three-phase 12/8** [3]

### III. Background on torque ripple

Torque ripples are inherent in SRMs due to the salient structure and excessive magnetic saturation of the machine. Its flux linkage, inductance and torque are highly coupled with a rotor position and phase current [48]. These features make the SRG to be highly nonlinear. This nonlinearity thus introduces high torque ripples, vibrations and acoustic noise during the operation of the SRM. By neglecting the effect of magnetic saturation, an idealized induction profile is obtained [21]. The torque relationship between the idealized inductance profile and phase current is as shown in figure 3.

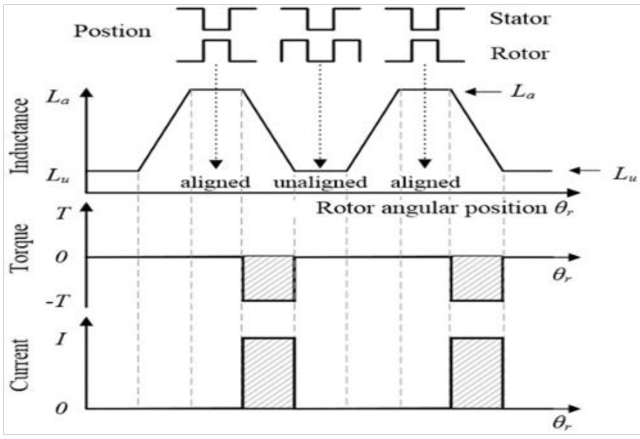


**Fig. 3: Torque relationship between the idealized inductance profile and the phase current.** [21]

Torque ripple is defined as the difference between maximum and minimum total instantaneous torques expressed as percentage of average torque [48].

$$Torque_{rip.}\ \% = \frac{T_{inst\,(max)} - T_{inst(min)}}{T_{ave}} \quad \ldots\ldots\ldots(1)$$

Where $T_{inst}$ is the instantaneous torque produced during every switching and $T_{ave}$ is the average torque value.

Torque ripples in the SRM is mainly caused due to the switching of phase currents into its windings and the highly nonlinear nature of phase inductance variation when the rotor rotates. With the successive phase windings excited in sequence to produce continuous rotation, the total torque is the sum of the torque generated due to the currents in the outgoing phase and the current in the incoming phase. The torque pulsations are thus encountered at the instants of current switching from one active phase to the other. These currents are controlled independently.

$$T(\theta, i) = \frac{1}{2} i^2 \frac{dL(\theta,i)}{d\theta} \quad \text{.........(2)}$$

The total instantaneous torque of motor is given by sum of all the individual phase torques.

$$T_{total} = \sum_{phases} T_{phases}(i, \theta) \quad \text{.........(3)}$$

The average torque expression is thus obtained by integrating equation (3) over a time interval T.

$$T_{ave} = \frac{1}{T} \int_0^T T_{total}\, dt \quad \text{.........(4)}$$

Where: $\theta$ is the Rotor angle, $i$ is the phase current, L is the Phase inductance, $T_{ave}$ is the average Torque and $T_{total}$ is the total Torque.

## IV. Review of torque control techniques

**1. Changing motor geometry and structure**

[49] Proposes a new stator pole shape with non-uniform airgap and a pole shoe on the rotor pole for the minimization of the torque ripple. Numerical analysis using finite element method (FEM) and optimization was carried out with the optimized stator and rotor giving a reduced torque ripple. In [50], an effective torque mitigation technique for double stator switched reluctance motor (DSSRM) using rotor shape optimization technique was presented. This method was based on shape optimization of the rotor for redistribution of the flux so that the inductance profile has smoother variation as the rotor poles move into alignment with excited stator poles. However, this method results in lower torque pulsations without significant reduction in the average torque. [51] Describes a proposal for a new stator pole face having a nonuniform air-gap and a pole shoe attached to the lateral face of the rotor pole. These additions minimize the undesired torque ripple. The effects of each design parameter were investigated using a time-stepping finite-element method. The parameters were optimized by utilizing response surface method (RSM) combined with (1+1) evolution strategy. It was shown, through numerical tests, that the optimized shape gives higher average torque and drastically reduced torque ripple.

**2. Indirect torque control**

Torque in AC machines can be controlled by converting torque reference into equivalent phase current references. In an SRM, torque can be indirectly controlled by controlling the current. This methodology of torque control in an SRM is called the indirect torque control. Figure 4 shows a basic block diagram of this technique.

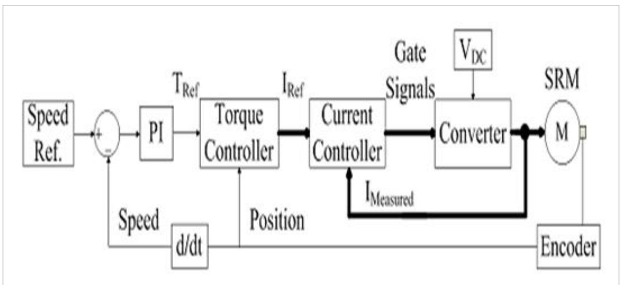


**Fig.4: Indirect Torque Control for SRM [44].**

However, as a result of torque dependence on rotor position, the torque to current conversion is very difficult to achieve in SRMs. It therefore becomes very difficult to obtain an analytical expression between the torque, current and rotor position. Existing methods in literature for the torque to current conversion in SRMs includes the use of look-up table to store the torque-current -rotor position characteristics [52]. In [53], a torque control method that was based on exponential function to reduce torque ripples was proposed. This method directly translated the reference torque into the reference current using the torque formulae and lookup table. The system was verified on a simulation model of a 3kw 12/8 poles switched reluctance motor. Results obtained show the effectiveness of the proposed method in reducing torque ripples. [54], reports a research based on determination of optimum geometry that minimizes torque ripple. The effect of magnetic circuit parameters on the torque ripple over a wide speed range was undertaken. The prediction of torque-position and permeance -position characteristics of a doubly-salient magnetic structure as a function of exciting MMF for a specified normalized position was also studied. However, simplifying assumptions such as the fact that the magnetic circuit behind the doubly-salient air gap region having negligible MMF drop making the airgap to be subject to an excitation level dictated by the phase current and constant excitation level irrespective of position gives an oversimplification of the problem and allows far reaching conclusions to be drawn.

In [55], neural network was used to extract the data required to predict the torque produced by a given geometry and excitation so that the static torque curve can be obtained and torque ripple reduced. Neural network is used because the objective function cannot be explicitly expressed as a mathematical function of the objective variables However, this method requires intensive online computations and its prediction accuracy is very low.

The authors in [56] used a method of indirect torque control and Iterative Learning control (ILC) by distribution of the motor torque among the phases using TSF and converting the phase torque references to phase current references. However, due to linear magnetization characteristics, an invertible torque function was obtained which leads to torque error as the motor enters into magnetic saturation. Thus, the authors introduced ILC to add a compensation current to the nominal phase current references so that torque error was eliminated.

**3. Direct torque control**

The DTC scheme avoids the complex process of torque-to-current conversion which is common in indirect torque control scheme. DITC comprises a digital torque hysteresis-controller, which generates the switching signals for all activated machine phases. The reference torque is compared with the actual generated torque and given to a hysteresis torque controller which outputs torque increase or decrease. If the torque generated by the motor is less than reference torque, the torque is increased by turning on the top and bottom switches of the converter to enter into state 1. If the torque developed is more than the reference, then it is reduced by turning off either top or bottom switch or both the switches to enter into state 0 or -1[57]. A block diagram of DITC is shown in Figure 5.

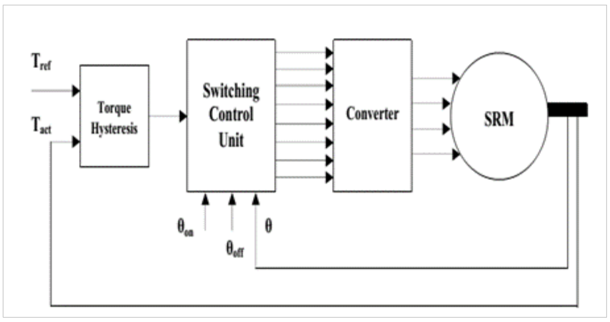


**Fig. 5: Simple Block diagram of DITC [58]**

In [59], the authors employed the direct instantaneous torque control (DITC) to control the motor torque by means of switching table whose inputs are signals of flux and torque error. DITC does not use any current waveform to inhibit torque ripple, but directly regulates the instantaneous torque. [22] Employs a new instantaneous torque controller by adding a PI controller before the instantaneous torque controller and a change in commutation zones. It is expected that the PI controller will produce higher error values which leads to an early response of the torque hysteresis regulators. The integral gain contributes to reduce the steady state error. As a result, the instantaneous torque controller is able to anticipate future torque values and thus execute proper control action to avoid exceeding the torque ripple limit. The author then simulated the PI-DITC model in MATLAB/Simulink environment and the effectiveness of the method established when compared to experimental results. However, the effectiveness of the proposed model was only tested in low speed drives as its effect on high speed SRM drives requires further research. [60] Investigated a DITC for switched reluctance drives. It implemented DITC without the use of the rotor position estimation system. The digital torque hysteresis controller employed the reference torque and instantaneous torque value to generate the switching signals for the converter based on predefined switching angles.

In [61], a novel Lyapunov function-based direct torque controller (DTC) to minimize the torque ripple in an SRM drive system is presented. The Lyapunov function based direct torque controller was proposed in this paper to avoid the nonlinear dynamic relationship between the applied phase voltage and the resulting motor torque for a DTC and also the fixed sampling frequency which results in large amount of torque ripples. The hysteresis controller applies full positive negative values of the dc-link voltage to the phase winding, at variable switching frequency to keep the output torque within a narrow band of the reference. In the Lyapunov function-based controller, the feedback gain is varied using a heuristic technique as the stability of the proposed controller is ensured by the direct method of Lyapunov. Experimental results for a 1-hp, 4-phase SRM demonstrates the efficiency of the proposed torque control scheme. Despite the simple structure of DITC, it requires complex switching rules for smooth torque generation during commutation. In addition, its control performance is dependent on the switching rules and sampling period in the digital controller.

## 4. Torque sharing function

In the Torque Sharing Function (TSF), torque production for the individual phases is regulated so as to distribute the reference torque among each of the individual phases while at the same time keeping the sum of all individual torque reference equal to the required torque [21]. TSF s are usually classified according to the various functions that are used to implement them. Some of these functions are; linear based [15] which resulted in a single-input, linear, decoupled output torque controller that provided a low torque ripple; cubic [56]; sinusoidal [16]; in which torque produced by the phases, during phase commutation changes with the rotor position; and exponential. However, a major drawback of this method is that effect of back emf and incremental inductance was not considered [62]. The primary objective for the selection of TSFs is in minimizing torque ripple and maintaining the torque sharing. Since selection of TSF will be influenced by the phase current reference, a secondary objective of the TSF is to minimize copper loss. [60-63] reports several TSF for the minimization of torque ripples in SRMs.

Figure 6 shows a block diagram of TSF torque minimization scheme.

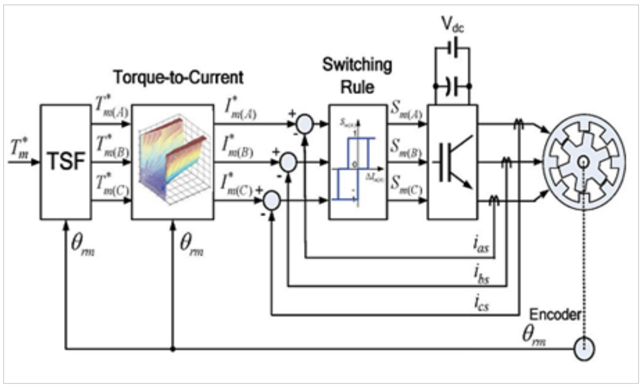


**Fig.6: Block diagram of torque minimization with TSF** [27]

An off line TSF for ripple reductions in SRM was proposed in [28] with two secondary objective functions; minimization of copper loss and derivatives of current references. A Lyapunov factor was used to compare with the convention. This factor was selected based on a trade-off between the copper loss and torque-speed performance. The comparisons were made in terms of operating efficiency and toque-speed performance. With the machine operating in both saturation and magnetic linear regions. Results obtained shows the reduction in torque ripples of the SRM with no corresponding increase in phase current reference and thus no increment in copper loss. [64] employs an online TSF for torque ripple minimization in SRM drives. In this, two modes are defined during commutation. These are modes for the absolute rate of change of flux linkages for incoming and outgoing phases. The total torque was determined by the phase with lower absolute rate of change of flux linkages rather than the phase with higher.

The proposed TSF was verified via both simulations and experiments. Results obtained show that the proposed TSF has higher average torque, and much lower torque ripples compared to conventional TSFs. A torque ripple minimization scheme using a TSF based FLC is presented in [36]. This method gives the robustness at the torque error and uncorrected data of the TSF such that when the torque ripple is generated, FLC compensated the error instantaneously. This method has the added advantage that the controller can track the torque under a wrong TSF condition.

[11] presents a valuable approach to select a reasonable TSF in order to implement TRM control to realize large speed range and high operating efficiency. It proposes an improved TSF for torque ripple minimization in SRM and compares the linear, sinusoidal, cubic and exponential TSFs with their effects of turn on and overlap angle on two optimization criteria which are the maximization of speed and minimization of copper loss for a given torque. From the evaluation of the four TSFs, the effective rate-of-change of the flux linkage and the copper loss were found to be dependent on both the turn-on angle and the overlap angle for a specific torque. GA was thus used to optimize these two criteria so as to minimize both the effective rate-of-change of flux linkage (maximize the speed range) and the square of rms current (minimize the copper loss). The paper presented valuable approach to select a reasonable TSF in order to implement TRM control to realize large speed range and high operating efficiency.

## 5. Intelligent controllers for torque ripple minimization

Intelligent controllers such as neural network, fuzzy logic, genetic algorithm and other artificial intelligence based techniques are used to implement adaptive control for torque ripple minimization in SRM drives. The basic premise in the intelligent controller is the incorporation of online learning involving the simultaneous excitation of more than one phase winding and the use of fuzzy adaptive system to represent current as a nonlinear function of phase [43].

[65-71] reports on the adaptive neuro fuzzy logic controller for torque ripple minimization. [66] presents an application of

adaptive neuro-fuzzy (ANFIS) control for switched reluctance motor (SRM) speed. This method has the advantages of expert knowledge of the fuzzy inference system and the learning capability of neural networks. The author in [67] proposes using the ANFIS for torque ripple reduction of SRM drive. The proposed system was simulated using MATLAB/Simulink and simulation results compared with single layer SRM show a significant reduction in speed settling time as well as motor torque ripples. In [72], an adaptive neuro fuzzy inference system for torque-ripple reduction in switched reluctance machines is presented. Fuzzy parameters were initially chosen randomly and thereafter adjusted to optimize the control. The controller produces smooth torque up to the motor base speed. The torque is generated over the maximum positive torque-producing region of a phase thus increasing the torque density and avoids high current peaks.

Genetic Algorithm (GA) is a bio- inspired optimization algorithm that has been used in many complex engineering problems based on its ability to attain near optimum solutions. However, GA suffers from long processing time to find optimum solution and may sometimes attain a local minimum instead of global minimum. In spite of this, it has been successfully implemented in various torque ripple minimization methodologies. In [73], GA is applied for optimal design of PI controller coefficient considering minimum torque ripple as a cost function in simulation tests. Result obtained via MATLAB/Simulink simulation was validated with an 8/6 SRM. A control mechanism for torque ripple minimization of SRM is presented in [41] which reduces the torque ripple using non-dominated sorting GA (NSGA-II). This is a modified version of NSGA-I. The control scheme consists of a proportional-integral (PI) speed controller in the outer loop, PI current controller in the inner loop along with control of turn on and turn off angles for a 3 phase, 6/4 switched reluctance motor. Statistical performance of the Integral Squared Error (ISE) parameters for 20 independent trials of the SRM are considered with results showing that NSGA-II based controllers give better performance in terms of lesser torque ripple and quick settling time. However, this method has only been validated by simulation.

[74] proposes a torque minimization scheme using a combination of Seeker Optimization Algorithm and Finite Element Method (FEM). The author used spline interpolation to fit continuous curve to energy-angle points from which torque was calculated by differentiation. An appropriate independent geometrical variable for the motor optimization was selected and a suitable objective function obtained. In [75], a simulation electromagnetic model was introduced using ANSYS finite element package for the SRG. The results explicitly show that the flux density waveforms were completely non-sinusoidal. The authors further observed that the optimal turn- on and turn- off angles obtained depended totally on the speed of the rotor.

[76-80] employs Particle Swarm Optimization (PSO) in order to solve the problem that the current stochastic and deterministic optimization methods have not yet obtained the perfect solution to. It describes the design optimization procedure of SRM using the improved PSO with the objective of maximizing average torque and minimizing torque ripple. It optimizes the motor design and achieves satisfactory results. Naggar H.S., in [81] introduced a new method of Maximum Power Point Tracking, (MPPT) of SRG for wind system in which the classical Hill Climb Searching HCL was modified using Artificial Neural Network, (ANN) under a wide range of speed variation and was a success. However, the authors established that a malfunction can occur as a result of rapid change in wind speed. [82] compared Multi Objective Particle Swarm Optimization (MOPSO) technique with Artificial Neural Network, (ANN) and there was a significant improvement in the efficiency of the system and torque ripples were minimized with MOPSO. A simulation of SRG driver in MATLAB/Simulink and a real time control of the SRG on a Digital signal processor kit (DS1103) to determine the performance of the SRG was presented in [83]. The output voltage of the SRG was controlled by a Proportional-Integral (PI) voltage Controller. The results in this paper established that changes in phase currents were affected by selecting the turn-on and turn-of angles of the SRG. Table 1 presents a brief tabulated review of some control strategies implemented in SRMs with their limitations.

**Table 1: A tabulated review of some control strategies considered in SRM with their constraints.**

| Referense | Title | Methodology | Finding | Remarks | Limitation |
|---|---|---|---|---|---|
| Amissa Arifin et al, 2012 | State of the Art Switched Reluctance Generator | A review of recent development of SR machine operating in generating mode in both low and high speed operations | Due to its geometry simplicity and advantages such as robustness, absence of permanent magnet and windings on the rotor, etc, the SRG is a good candidate for variable speed operation | Further research is required to fill the commercial gap on SRG with the aid of a comprehensive modelling software. | To analyse the machine thoroughly, various changes on the parameters have to be made which may be time consuming and may incur high cost. |
| Mohamed E.Metally, 2017 | Sensorless Control of SRG with Maximum Power Extraction Wind Driven Based on MO-PSO | A modified Multi objective PSO was used for wind maximum power point tracking MPPT and ripple minimization. MOPSO technique was compared with ANN and the result shows great improvement with MOPSO | Simulation result support the feasibility of the proposed Torque ripple minimization and MPPT with Sensorless control technique. | The modified MOPSO improves the overall efficiency and minimizes the Torque Ripples | Torque Ripples not completely eliminated. There is still room for improvement |
| Pedro Jose dos Santos Neto et al., 2018 | Design of computational Experiment for Performance Optimization of SRG in Wind Systems | Computational experiment is applied to determine Optimal Firing angles and DC link voltage. A third order response surface model based on space filling designs is applied to build multi objective function. Hysteresis and | Simulation and experimental result show a good compromise between SRG High efficiency and low Torque Ripple. | The technique reduces computational effort and provides a clear massive Data simulation framework. | System Efficiency was more prioritized than Torque Ripple Reduction |

| | | | | | |
|---|---|---|---|---|---|
| | | single pulse current control are applied for low and high speed operation respectively | | | |
| Naggar H. Saad et al., 2018 | Artificial Neural Controller for Torque Ripple Control and Maximum Power Extraction for wind System Driven by Switched reluctance Generator | Modified Toque Ripple Minimization algorithm of 4-phase 8/6 poles SRG using ANN control, also MPPT was carried out using the classical hill search Technique in ANN | Results show good response of the system to the wind speed changes. Generator current is symmetrical and nearly smooth the electromagnetic torque has smoothed waveform with minimum torque ripples. | Simulation results show good agreement and feasibility of the technique for TRM and MPPT | Although the MPPT technique does not depend on the load, system and wind characteristics, it could malfunction under rapid change in wind speed. |
| Aide Xu et al, 2019 | A new Control Method Based on Direct Torque Control (DTC) and Model Predictive Control (MPC) to reduce Torque Ripple in SRM | Control Methods based on DTC and MPC are used to reduce Torque ripple in SRM | It was found that the new approach can partly overcome the compared with the optimized DTC and DITC METHODS | Simulation and Experimental results are carried out in steady state and dynamic state to demonstrate the validity of the new approach | DITC has large peak currents and complicate hysteresis rules, because firing angles needs to be optimised online from different conditions, the process needs lots of simulation and experimental tests. |
| Zeki Omac et al, 2021 | Control of Switched Reluctance Generator in Wind Power System Application for Variable Speeds | Simulation of SRG driver in MATLAB/SIMULINK was performed and real time implementation control of SRG was carried out on a Digital signal processor to determine the performance of the controller. Output voltage was also controlled by a PI voltage Controller | Simulation results were accurate when compared with experimental results.it was also found that selecting turn-off angle after un-aligned rotor position and the Changes in Phase Current turn-on angle before aligned position increases the phase current of the SRG. | Changes in Phase currents are effected by selecting turn-on and turn- off angle. | Wasn't tested on a fixed speed wind turbine generator |
| Hojjat Hojiabadi et al, 2021 | Multi-Objective Optimization and Online Control of SRG for wind Power Application | Optimization of turn-on and turn- off angles in the offline mode using PSO algorithm to control system in the online mode with linear interpolation. | it was found that the system has simple structure, low execution time, and efficient convergence rate that are independent of machine characteristics | Ultimately, the simulation results of a typical 3-phase 6/4 generator using MATLAB confirmed the validity of the presented control strategy that can find applications in the future. | The effect of firing angles were not studied simultaneously as seen in some previous work. |

A comprehensive summery of Torque Control Techniques presented in this paper; showcasing there features, advantaged as well as limitations are as shown in Table 2.

**Table 2: Summery of the features, advantages and limitations of torque control techniques of the SRMs.**

| | Features | Advantages | Limitation |
|---|---|---|---|
| Changing Motor geometry and structure | -Provides low starting current.<br>-high torque | -low energy use | -difficult to control<br>-low torque pulsations with no significant reduction in average torque |
| Indirect torque control | -Torque is indirectly controlled by controlling the current | Directly translates reference torque into reference current using torque formula and lookup table | -complex torque to current conversion system.<br>Difficult to obtain analytical expression between the Torque, Current and rotor position. |
| Direct Torque Control | -directly regulates the instantaneous torque.<br>-does not use current ripple to inhibit torque ripple.<br>-adds a PI Controller before the instantaneous Torque controller | -integral gain reduces steady state error. | -model was only tested on low-speed drives. Its effect on high-speed drives requires further research. |

| | | | |
|---|---|---|---|
| Torque Sharing Function | -reference torque is been distributed among the individual phases.<br>-sum of all individual torques still remains equal to the required torque. | -minimizes copper loss<br>-high operating efficiency and large speed range. | -does not consider effect of back emf and incremental conductance. |
| Intelligent controller | Intelligent controllers incorporates online learning involving the simultaneous excitation of more than one phase winding. | Results obtained were satisfactory and by far the best out of the five. | Sometimes, does not easily converge due to its non-linear characteristics. |

**V. Challenges and future recommendation**

SRMs are gradually becoming a good alternative compared to the conventional Permanent magnet machines. This is not unconnected with their low cost, Robustness, high speed, among others; despite these advantages however, its market attractiveness is highly reduced due to its non-linear characteristics that brings about torque ripples and noise which are both undesirable.

The generating mode of SRMs require a substantial amount of study in other to harness the full potential of the machine. Researchers are expected to work extensively on the Machine as it has very vast research area and too little attention. This will in turn improve its production and bring it more into the market.

## VI. Conclusion

Due to the growing interest in SRM drives owing to their suitability for direct drive application, as well as its low cost, researchers recognize the need to resolve the high torque ripple and acoustic noise associated with this drive. A brief overview of related literature and published work on the torque ripple reduction and control of switched reluctance motor drives has been presented in this paper.

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