Rotary Switched Reluctance Actuator: A Review on Design Optimization and Its Control Methods

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ABSTRACT

A switched reluctance actuator (SRA) is a type of electromagnetic stepper actuator that is gaining popularity for its simple and rugged construction, ability of extremely high-speed operation and hazard-free operation. SRA gained supremacy over permanent magnet actuators due to the fact that its building material are relatively low cost compared to the expensive and rare permanent magnets. SRA is already making its debut in automotive, medical and high precision applications. However, many parties are still oblivious to this new age actuator. This paper reviews the latest literature in terms of journal articles and conference proceedings regarding the different design parameters and control method of SRA. The impact of the parameters on the performance of SRA are discussed in details to provide valuable insight. This paper also discussed the advantages of various novel SRA structure designs that prove to be a huge contribution to the future technology. It is found that several design parameters such as the air gap when kept minimum, increases torque value; while increasing number of phases in SRA minimizes torque ripples. Increased stator and rotor arc angles will increase torque, not to mention a larger excitation current can also achieve the same effect. Researches are often done through Finite Element Method (FEM) analysis to verify the optimized design parameters before fabrication, whilst experimental procedures are executed to verify the simulation results. To ensure smooth phase switching and improved torque output, intelligent controllers are employed in speed control and direct torque control (DTC) methods of SRA.

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1. INTRODUCTION

Actuators are mechanical or electro-mechanical devices that provide controlled and sometimes limited movements or positioning. These motions can be rotational or linear movements. These actuators can be operated electrically, manually, or by various fluids such as air, hydraulic and others [1],[2]. The electromagnetic actuator is a trending actuator which allows actuation motion with the supply of an electrical signal. A simple example of electromagnetic actuator is microelectromechanical systems (MEMS) magnetic actuator for microfluidic positioning in biomedicine, pharmaceutics and biotechnology [3],[4].

A actuator can be categorized as a subdivision of actuators that provides rotational movement. Fundamentally, the working principle of an electromagnetic actuator is by converting electrical energy to magnetic field, then through magnetic field interactions, produces electromagnetic force that drives a mechanical part (rotational motion). Possessing simple and robust structures, electromagnetic actuators are well known for their high actuation force and displacement, also includes the capability to operate in high speed modes [5]. Apart from that, these actuators can function optimally in harsh environments, such as automobile industries, for instance, induction, permanent magnet and direct current (DC) actuator [6]. However, the most significant drawback of electromagnetic actuator is that it faces high power dissipation during long operations, sacrificing its high actuation force due to the fact that the air gap between electromagnet and armature increases, drastically decreasing the electromagnetic force [5]. To overcome these problems, an electromagnetic actuator without permanent magnet, namely the rotary switched reluctance actuator (SRA) will be discussed in this paper. The SRA does not implement any rare-earth material or highly expensive permanent magnets. SRAs provide inherent fault tolerances, making them extremely suitable for automotive and aerospace applications [7],[8].

Figure 1 shows an example of the structure of a 6/4 SRA [9]. Switched reluctance actuator (SRA) fundamentally consist of three (3) main elements; i.e:(i) stator; (ii) rotor and (iii) coil winding. Conventionally, two stator poles at opposite ends are configured to form one phase. Figure 1 SRA has a 3-phase, 6 stator poles and 4 rotor poles. The number of rotor poles are chosen to be different to the number of stator poles. Both the stator and rotor have salient poles. The number of poles presence on stator depends on the number of phases for operation. The SRA shown has a concentrated typed phase windings.

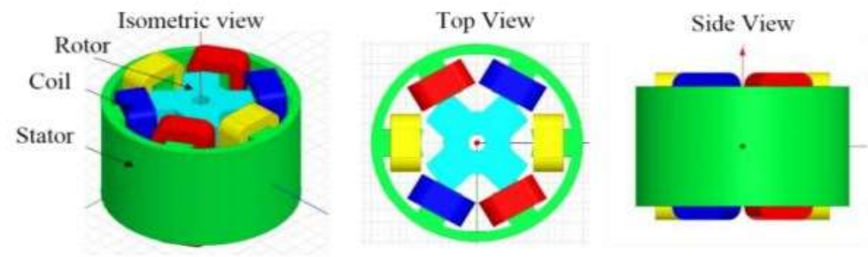


Figure 1. Design of conventional SRA [9]

From Figure 1, the SRA design parameters are varied to obtain the optimized design for high torque and large angular motion; i.e.: air gap, number of phases, number of stator poles, number of rotor poles, rotor arc angles, stator coil windings and excitation current. Therefore, in this paper several SRA design topologies and its control strategies are reviewed and compared in details. In Section 2, the design parameters and their impact on the performance of SRA will be discussed. In Section 3, the use of finite element method (FEM) analysis in SRA research is highlighted. In Section 4, the control strategies for SRA will be discussed. Finally, conclusions are presented in Section 5.

2. EFFECT OF DESIGN PARAMETERS OF SWITCHED RELUCTANCE ACTUATORS

2.1. Structure Designs

The structure concepts of SRA (switched reluctance actuator) are gaining innovative improvements throughout these past few years. One of these designs that stood out among conventional structures is the axial SRA with segmental rotor [10],[11] where the stator and rotor cores are laminated into disk shape. The stator tooth consist of double-width teeth used for coil windings and standard-width teeth which instead of using for coil windings, are specifically designed to provide the circuit for the flux path. The rotor on the other hand is made up of a series of segmental rotor blocks, which are embedded into an aluminum body. These unique configurations successfully enhance flux linkage to increase torque output by 16.57%. Figure 2 shows the design concept of the SRA with segmental rotor.

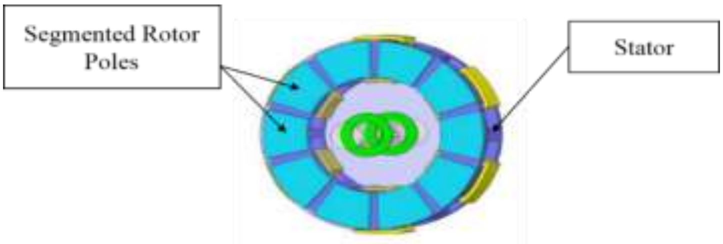


Figure 2. Structure of an axial SRA with segmented rotor [10]

Multilayer SRA with magnetically independent layers is also developed [12] where a number of independent SRAs are connected with a common shaft. The design will deliver greater torque output due to its multiple numbers of SRA rotating as one. Figure 3 shows the design structure of a multilayer SRA with 4 independent 4/4 SRAs.

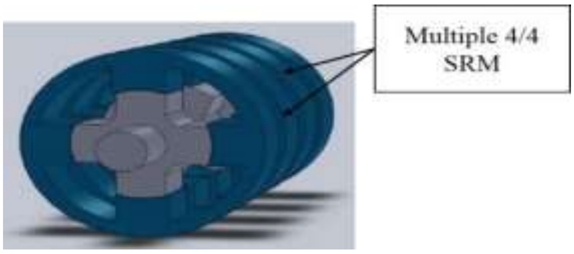


Figure 3. Structure of multilayer SRA [12]

Another novel design is the pancake-shaped axial-flux SRA [13] which has several c-cores with individual windings instead of conventional stator poles. This design provides various advantages such as high torque and power density, maximum thermal dispersion, convenient replacement of damaged c-cores, easy coil winding and reduced copper losses. Figure 4 shows the structural drawing of the c-core and rotor poles of the pancake-shaped SRA.

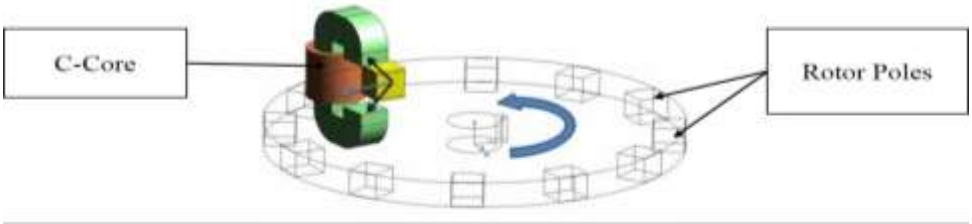


Figure 4. Structure of pancake-shaped axial-flux SRA [13]

A novel bearingless switched reluctance actuator (BLSRA) with double stator is also introduced [14]. The design includes an inside stator to generate radial force to suspend the rotor and an outside stator which produces rotational torque. The main advantage of double stator is the decoupling control between radial force and torque, in addition to the constant radial force at the arbitrary rotor position using a constant current value.

As a conclusion, conventional SRA rotor and stator structures are undergoing improvements with the development of novel designs such as segmented rotor, multilayer SRA and others which can effectively increase torque output and minimize the greatest flaw of SRA, torque ripple. These new designs are evolving based on the needs of SRA in various industrial and engineering fields.

2.2. Phases of SRA

A conventional 3-phase driven rotary switched reluctance actuator demands a command scheme that, sequentially, energizes actuator phases, thus allowing the actuator to rotate continuously. Torque production is not dependent on the current direction; instead the rotational torque depends on the continuity of the current supply [15]. Increasing the number of phases in SRAs provide similar advantages as multi-phase electrical actuators, hence leading to extensive researches for automotive applications, notably for hybrid electrical vehicles [16],[17]. Multi-phase SRA displays enhanced torque production, increased fault tolerant capability and decrease in vibration and noise [18],[19].

SRAs are typically driven by 3-phase current supply; however there are also designs on 2-phase SRAs [20]. This design successfully reduced core loss and increased torque production but have the downside of providing unidirectional rotation only. Figure 5 shows the structure design of a 2-phase 4/3 driven SRA.

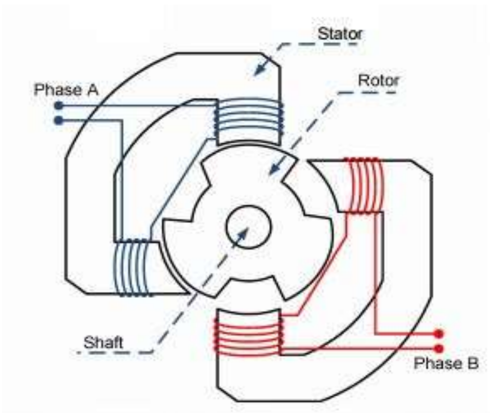
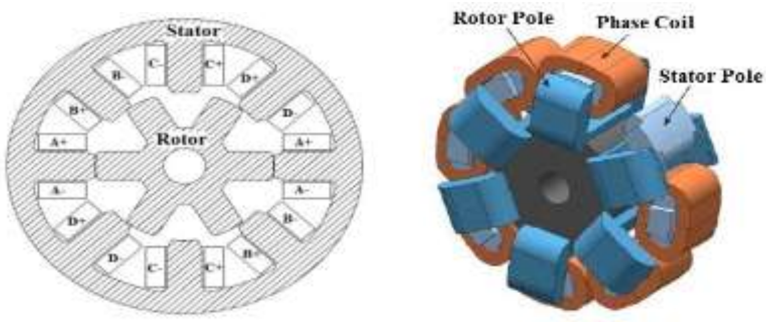


Figure 5. 4/3 SRA driven by 2-phase current supply [20]

There are also studies on the design of SRA powered by 4-phase current supply [21]. A modular 4-phase SRA is able to eliminate low frequency torque ripple due to asymmetric mutual coupling between adjacent phases [22]. Figure 6 shows the design of a conventional 4-phase 8/6 SRA and a modular 4-phase 8/6 SRA for electric vehicle application.



(a) (b)

Figure 6. (a) Conventional 8/6 SRA driven by 4-phase current supply. (b) Modular 8/6 SRA driven by 4-phase current supply [22]

The 5-phase SRA are uncommon but there are studies on such design structures such as the axial-flux 5-phase SRA [13]. This design consists of 15 c-cores which functions as stator poles, each with individual coils that make up three repetitions of five phases. SRAs up to 6-phase are achievable where researchers are proposing methods to optimize torque ripple due to mutual coupling between phases of the actuator [23]. Other 6-phase SRA research includes the study on converter topology which combines the advantages of both asymmetric half bridge converter and split phase converter [24] for low-cost and high-performance converters.

Generally, the increasing number of phases allows higher torque output and decreasing torque ripple. SRAs which exceed 3-phase provide significant advantages however; the control method for these additional phases will become much more complicated. Henceforth, it must be managed delicately to ensure consistent and effective phase switching.

2.3. Number of Stator and Rotor Poles

The number of stator and rotor poles varies according to the needs and applications for the SRA. The most common is the 6/4 SRA [25], with increasing poles up to 12/8 [26] or 12/14 [27] and even other combination numbers of stator and rotor poles, depending on the usage purpose of the SRA. The number of poles affects the acoustic behavior significantly [28]. Higher ratio of stator to rotor poles provides lower efficiency due to its high maximum power density [29]. However, high ratios of stator to rotor poles have the advantage of noise and vibration reduction, in addition to reduced radial force [30]. It is also proven that higher ratio stator and rotor poles will increase the thrust force [31],[32]. Figure 7 shows the efficiency comparison of 6/4, 12/8 and 18/12 SRAs at 15000 revolution per minute (rpm).

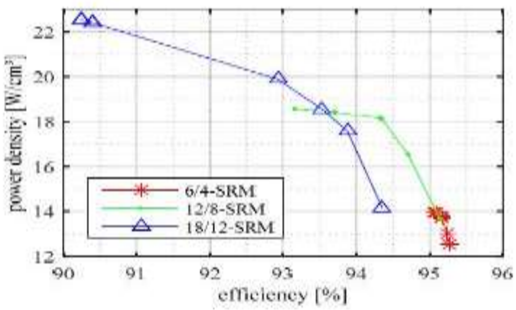


Figure 7. Graph of power density against efficiency for different pole configurations at 15000rpm [29]

It can be concluded that the 12/8 SRA is the optimized conventional design as it provides great efficiency with a decent maximum power density [29]. Low pole ratio designs deliver high efficiency but low power density. High number of pole pairs provides low efficiency but high maximum power density and better acoustic behavior. Hence, the objectives and operating condition of the SRA serves as an important input in choosing the suitable number of pole ratio for different applications.

2.4. Air Gap

The gap distance between stator and rotor, also known as air gap, is a varying factor in the design of SRAs. Gaps in SRAs is naturally unavoidable and they contain air. Typically, air gap can be as small as 0.1mm up to 0.3mm or more. Such gaps are often undesirable because air has high resistance to the flow of magnetic flux. Thus, the value of air gaps must be minute but sufficient enough to prevent contact between the stator and rotor, taking into considerations of manufacturing tolerances on their dimensions, or deformation caused by radial forces resulting from rotary motion and looseness in supporting bearings. Larger air gaps provide smaller torque output [33], hence ideally air gap should be as small as possible. Air gap of SRA is considered to be well-balanced, that is if:

a. The rotor outer and stator inner diameters are according to fabrication dimensions precisely.
b. The stator inner surface and the rotor outer surface are concentric.
c. Relative eccentricity is absent between the stator and rotor axes.
d. There is no tilt between the stator and rotor axes.

However, due to fabrication tolerances, air gap non-uniformity occurs, which are 5% to 10% of the relative eccentricity of the air gap between the stator and rotor axes, in addition to a concentricity error of 5% to 10% of the air gap is considerably typical [34]. Figure 8 shows the two types of air gap non-uniformity, rotors having relative eccentricity and concentricity error. Table 1 and 2 shows the torque values for various relative eccentricities and concentricity error values.

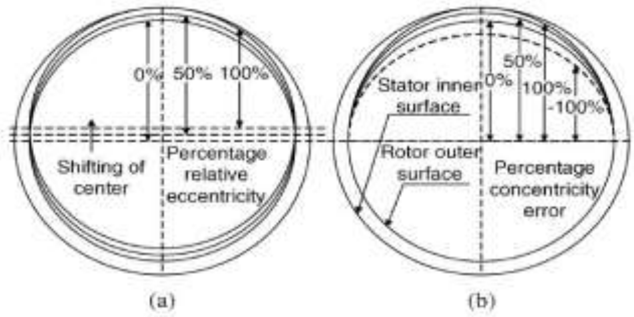


Figure 8. (a) Rotor with relative eccentricity (b) Rotor with concentricity error [35]

Table 1. Torque Ripple at Various Relative Eccentricities [35]

Relative Eccentricity (%)	Torque Ripple (%)	Relative Eccentricity (%)	Torque Ripple (%)
0	27.37	25	29.15
5	27.77	50	38.56
10	28.11	75	50.84
20	28.70	95	54.66

Table 2. Average Torque and Torque Ripple For Concentricity Error in One Half of the Rotor and Elliptical Rotor at an Excitation of 10A [35]

Error	-50%	-10%	0%	10%	75%	95%
	Concentricity error in one half of the rotor					
T_{avg}	8.79	9.58	9.69	9.86	11.72	13.26
T_{ripple}	31.77	29.69	27.93	31.50	52.70	54.73
	Concentricity error in both halves of the rotor (Elliptical rotor)					
T_{avg}	7.92	9.43	9.69	10.0	14.25	16.66
T_{ripple}	36.31	31.52	27.93	34.38	67.00	73.10

Higher relative eccentricity will produce higher average output torque, but with greater torque ripple. At higher relative eccentricity, there are also more significant harmonics present, resulting in undesirable noise and vibrations. A higher magnetic flux saturation occurs at the location of a smaller air gap in the case of eccentricity [36]. A higher average output torque and torque ripple is generated due to the increase in concentricity error in the positive direction.

As a conclusion, smaller air gap provides less reluctance for magnetic flux flow, producing higher torque output. Air gap is optimized to a range between 0.2mm up to 0.5mm where these values are more common [37]-[39]. Regardless, air gap should be sufficient in different SRAs to prevent contact of rotor and stator during operation, and also include fabrication tolerances.

2.5. Stator Coil Windings

The SRA stator coil windings can differ from its winding pattern and number of turns, impacting the performance of the actuator differently. One unique way for coil winding is the toroidal winding method. The winding consists of wire wounded around a donut-shaped ferromagnetic material. The process for toroidal winding is practically more convenient and simpler, providing a higher filling factor compared to conventional windings. Toroidal winding allows direct exposure of the windings, enhancing machine thermal performances [40]. Research showed that utilizing a proper coil connection and switching sequence, toroidal winded SRA is able to yield a 50% higher output torque than conventional windings [41]. By using smaller outer diameter copper wires for toroidal windings, the decrease in wire cross-sectional area will significantly increase the copper losses, but however still provide an increased in torque output, concluding that toroidal windings displayed competitive advantages against conventional windings.

The number of turns in stator windings will affect the magnetic field intensity, H. Hence, decreasing the number of the turns contributes to a lower magnetic field intensity and results in lower torque values [42]. However, more winding turns provide more resistance. At prolonged operations of SRA, the increase in number of series turns causes a decrease in efficiency at high rotational speed due to the significant increase in copper loss [43]. Table 3 shows the test results for two SRAs with different number of turns at 6000 rpm.

Table 3. Comparison of Test Results for Two Different SRAS at 6000 RPM [43]

	SRA1	SRA2
Number of series turns	13	17
Winding resistance (Ω)	0.054	0.103
DC side voltage (V)	500	500
Shaft output (kW)	47.8	46.9
Torque (Nm)	74.8	74.6
RMS current (A)	68.8	80.3
Copper loss (W)	918	2267
Efficiency (%)	92.9	91.3

At high speed operations of SRA with greater number of winding turns, the build-up in back electromotive force results in the reduction of actuator output power and the actuator efficiency will decrease too. Toroidal winding is a more effective winding method than conventional approach because it provides better thermal dispersion and better torque performance. With each increasing number of winding turns, up to even 120 turns [27], the magnetic field intensity will increase correspondingly, hence producing a larger torque output for SRA.

3. FINITE ELEMENT METHOD (FEM) ANALYSIS

The finite element method (FEM) is a computer-based numerical technique used to determine approximate solutions to boundary value problems for partial differential equations. It basically breaks down a large complex problem into smaller simpler equations called finite elements. Then it solves these small equations and reassembles them into the large system that models the original problem. This method is often practiced in engineering field to study structures and components under various conditions. FEM is used to augment experimental testing before prototyping is carried out [44].

FEM is used to study new SRA rotor design that consists of notched teeth on the torque ripple effect [45]. The rotor design is varied by its notch width and position after studying the flow of flux. The proposed design is able to reduce a maximum torque ripple of 4.4%. Figure 9 shows the FEM model with notched teeth rotor of different width.

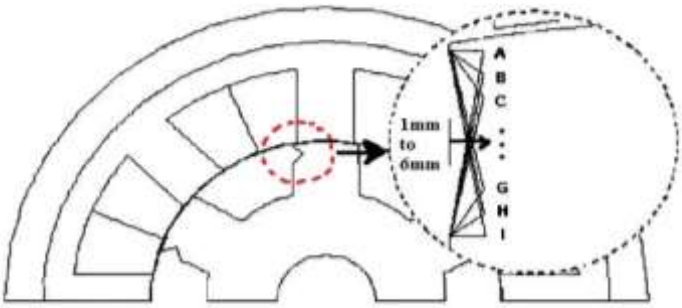
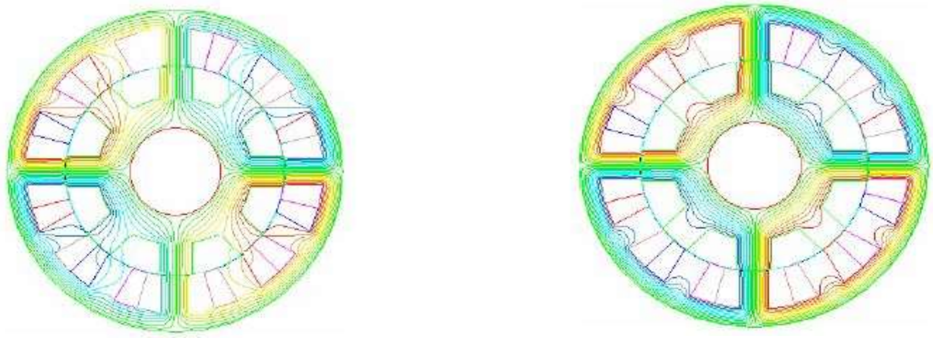


Figure 9. Design of rotor with different dimensions of notched teeth [45]

Manual calculations can be carried out to determine the permeance in SRA [46], however, FEM analysis can be used to simplify the study of air gap permeance and flux linkages of SRA in details [47], including mutual coupling and saturation [48]. Manual analyses are made, before verifying the calculations using FEM analysis. Such analysis leads to new discovery such as the self-flux linkage and mutual flux linkage in the two channels of the same phase are not the same. Neighboring channels exert mutual coupling of almost equal magnitude but in different directions. Figure 10 shows the FEM analysis of magnetic flux distribution of a dual-channel SRA at aligned (0°) position with single and both channels excited.



(a) (b)

Figure 10. Magnetic flux distribution of dual-channel SRA (a) one channel excited (b) both channels excited [48]

Researchers also applied FEM analysis to study SRA variations such as rotor eccentricity to determine its impact on power losses [49], torque and flux density [50], [51]. These losses included ohmic losses, hysteresis losses, eddy- current losses and iron losses. Further studies included the reduction of rotor eccentricity effects using winding methods [52]. A winding method which utilizes two parallel branches with neighboring coils in series and an equalizer is found to reduce the unbalanced magnetic forces (UMF) effectively. Figure 11 shows hysteresis and eddy current losses in rotor and stator with dynamic eccentricity (DE) and static eccentricity (SE).

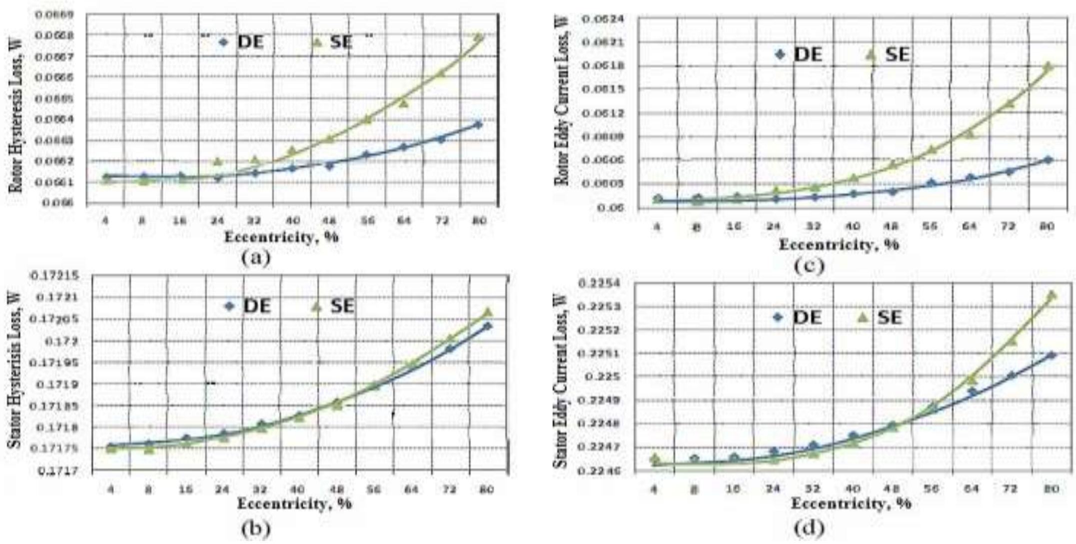


Figure 11. Losses in SRA with DE and SE, hysteresis loss in (a) rotor (b) stator, eddy current loss in (c) rotor (d) stator [49]

The geometrical parameters of SRA such as internal diameter of stator, rotor pole breadth and others are studied through FEM [53]. The torque characteristics are compared so that future development of SRA designs can be optimized to produce the best performance. The shape of rotor core contributes significantly to the average torque and torque ripple effect. The breadth of stator pole impacts greatly the shape of output torque against the rotor angular position.

Through FEM analysis, several parameters are optimized in a 6/4 SRA such as winding turns, air gap thickness and specific dimensions of the rotor and stator [31]-[32]. The rotor and stator arc angles are also optimized through FEM analysis [9]. As a conclusion, FEM analysis is a fundamental and powerful method to analyze different designs in SRA research. It is often used to verify calculations and optimize new SRA structures before prototyping is carried out, for example to investigate different winding techniques, geometrical varieties, rotor arc angle and other parameters.

4. CONTROL METHOD
4.1. Speed Control

The control method for SRA is particularly complex because it is a non-linear system. Typically, the speed of rotor is used as the input to the controller, known as speed control. The speed error of the system response is feedback into the controller which will then control the voltage or current to achieve the reference speed. There are some notable research of 'intelligent' controllers which exercise the use of fuzzy logic controllers [54]-[56]. There are also other research done on neural network for its self-adaptation capabilities [47] and also hybrid system combining fuzzy logic and PI or PD controllers [58], [59]. A classical PID controller can also be enhanced with parameters adaptation capabilities for the speed control of SRA [60], which does not require any adjustments or calibration for the PID controller. The adaptive algorithm implemented is based on a fuzzy system with a Takagi-Sugeno inference mechanism with some slight alterations for a fast response system. Figure 12 shows the block diagram for fuzzy logic controller. Figure 13 shows the control system for an adaptive fuzzy-PI controller. Figure 14 shows the block diagram for the adaptive PID speed control system.

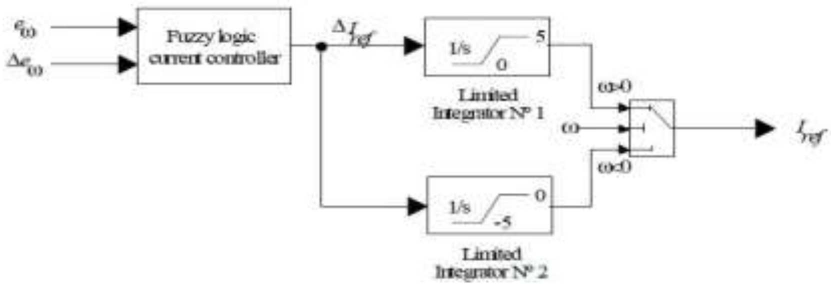


Figure 12. Block diagram for fuzzy logic controller [55]

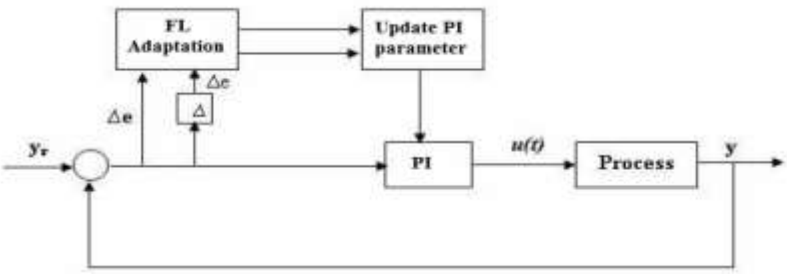


Figure 13. Control system for an adaptive fuzzy-PI controller [58]

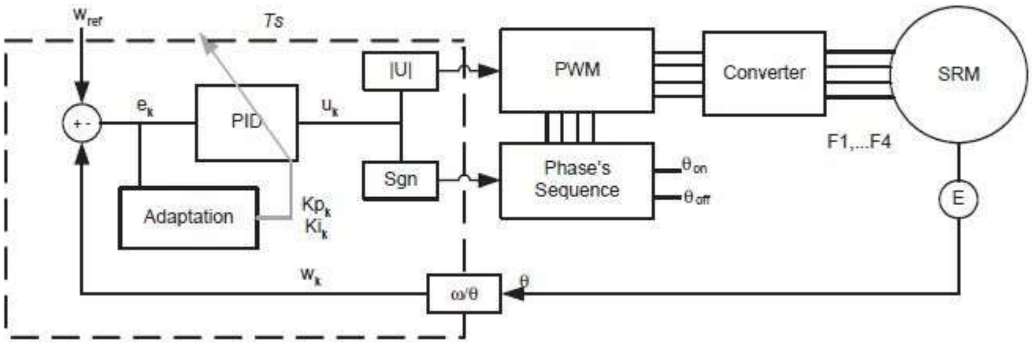


Figure 14. Block diagram for SRA adaptive PID system [60]

There are also fuzzy-PID controllers developed for speed control using Mamdani inference mechanism [61]. Compared with a conventional PID controller, the fuzzy-PID controller provides more stable rotational speed through uniform electromagnetic torque. Figure 15 shows the block diagram for hybrid fuzzy-PID controller.

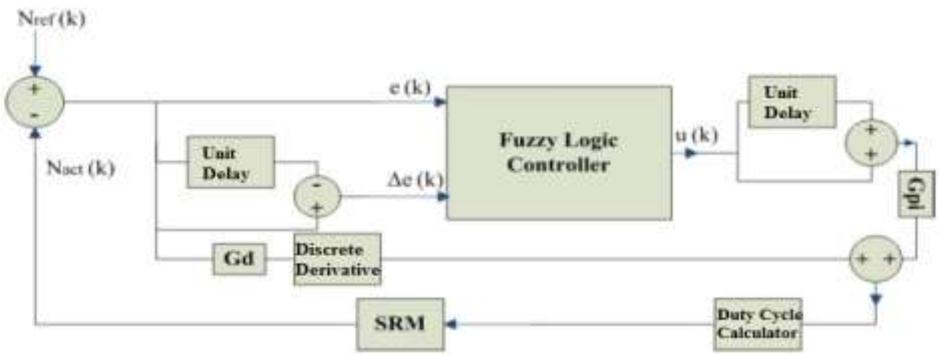


Figure 15. Block diagram for hybrid fuzzy-PID controller [61]

A unique dwell angle control method is also introduced to minimize torque ripple and vibrations in SRA through the control of excitation current [62]. The method enables a smoother current switching for better torque performance. Figure 16 shows the block diagram for the dwell angle feedback control system.

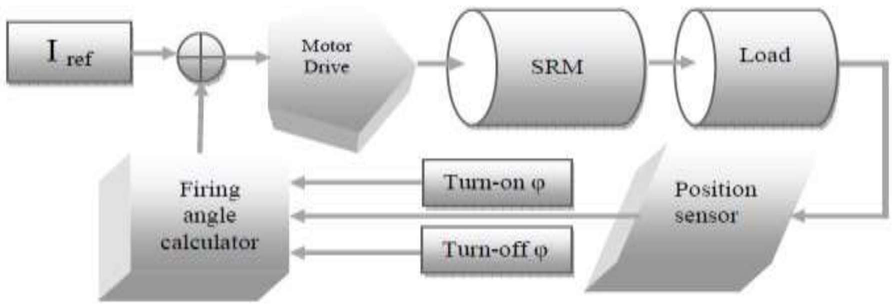


Figure 16. Block diagram for the dwell angle feedback control system [62]

Speed control is a more common approach in SRA control methods. Conventional PI, PD and PID controllers are able to allow SRA to function normally, however these controllers are still lacking in providing the desired performance. Due to this, the use of hybrid controllers such as fuzzy-PID and even neuro-fuzzy controllers are researched intensively as these controllers provide a more robust control over the phase changing and speed of SRA. Though a more complex system, hybrid controllers provide enhanced torque output and minimal torque ripple effect.

4.2. Direct Torque Control

Direct torque control (DTC) is a method used in 3-phase alternating current (AC) electric actuators to control the speed through the management of torque. The process includes estimating the magnetic flux and torque using calculations based on the measured value of voltage and current. There are multiple works on DTC for SRA, such as direct adaptive fuzzy control system which implements the Takagi-Sugeno structure [63] and a novel control strategy which is operation point dependent phase torque splitting [64], hence allowing effective torque ripple reduction. Figure 17 shows the block diagram for direct torque control driving system using adaptive fuzzy controller.

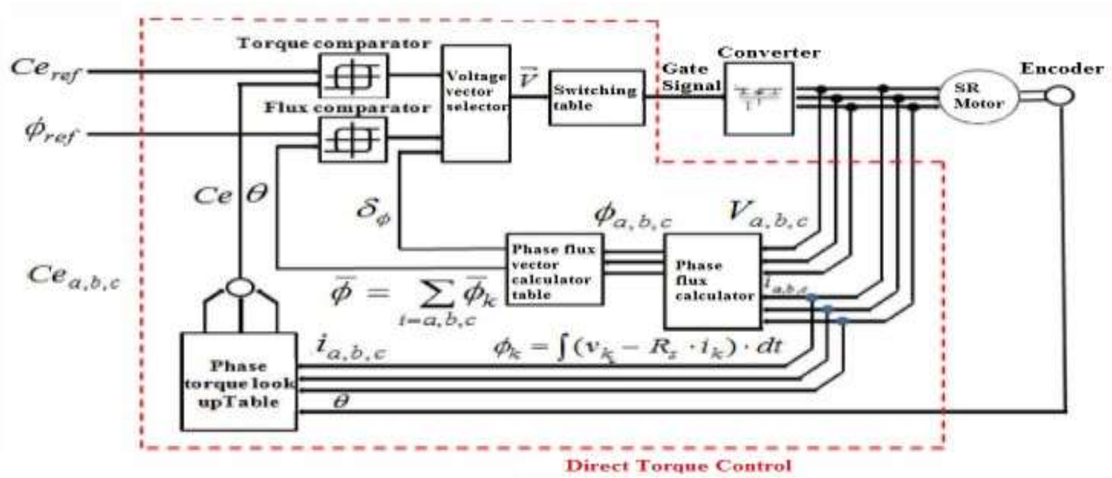


Figure 17. Block diagram for direct torque control driving system [63]

In a comparative study of various torque control methods, DTC, direct instantaneous torque control (DITC) and current profiling methods are studied [65].The current profiling technique provides the advantage of minimum phase root mean square (rms) current. As for DITC method, the phase transition can be kept at a minimum value. However, the downside of it is both schemes require rotor position information to turn on and off the phases. DTC scheme on the other hand does not require rotor position information, but high phase rms current is required to produce the desired torque compared to other control schemes. The DITC control method has an inherent property of torque ripple minimization [66]. Figure 18 shows the block diagram of DITC control system.

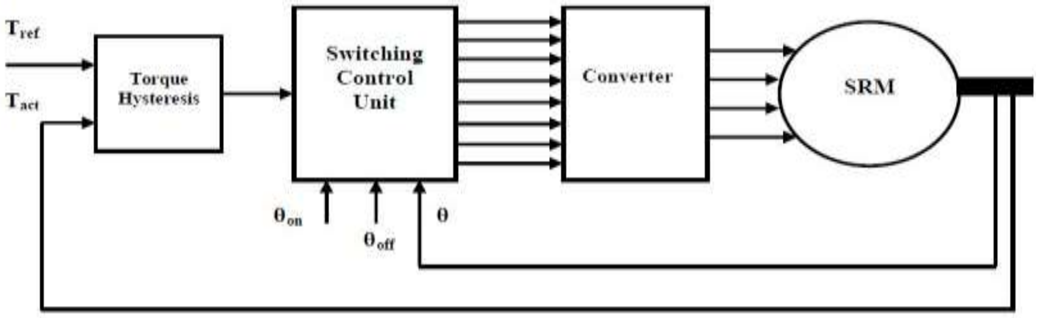


Figure 18. Block diagram of DITC control system [66]

Researches on DTC method are very limited because this approach requires more procedures such as the calculation of torque and current in order to control the speed of the rotor. DTC is more complicated as the torque value is derived from measured voltage and current compared to the speed control method, where the rotor speed is read through a sensor and controlled directly.

5. CONCLUSION

The SRA possesses a great deal of potential for automotive, medical and high precision applications. The paper has collected valuable knowledge on SRA to provide information on the impact of different parameters in SRA. This paper explained the use of FEM analysis and different control methods in SRA. It is found out that some authors have successfully introduced notable SRA designs such as segmented rotor and multilayer SRA that provide the foundation to the future development of this actuator. The air gap of the rotor must be kept minimal to enhance torque and the increasing number of phases in SRA decreases torque ripple. Simulations are done through FEM analysis before prototyping is done and the results are also compared through experimental procedures. Speed control is a more common control method compared with DTC because DTC requires additional calculations of torque and magnetic flux. The SRA may have its own flaws, but current efforts are in progress to overcome these weaknesses. With its simple construction and high speed capabilities, the SRA is definitely a valuable asset in future technology.

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