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A Review: Design Variables Optimization and Control Strategies of a Linear Switched Reluctance Actuator for High Precision Applications

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Article Info	ABSTRACT
	This paper presents the review of design variables optimization and control strategies of a Linear Switched Reluctance Actuator (LSRA). The introduction of various type of linear electromagnetic actuators (LEA) are compared and the advantages of LSRA over other LEA are discussed together with the type of actuator configurations and topologies. The SRA provides an overall efficiency similar to induction actuator of the similar rating, subsequently the friction and windage losses are comparable but force density is better. LSRA has the advantage of low cost, simple construction and high reliability compare to the actuator with permanent magnet. However, LSRA also has some obvious defects which will influence the performance of the actuator such as ripples and acoustic noise which are caused by the highly nonlinear characteristics of the actuator. By researching the design variables of the actuator, the influences of those design variables are introduced and the detail comparisons are analyzed in this paper. In addition, this paper also reviews on the control strategies in order to overcome the weaknesses of LSRA.

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1. INTRODUCTION

Linear electromagnetic actuators (LEA) is a mechanism that generate linear motion due to the interactions of the magnetic fields and electromagnetic thrust. The major advantage of electromagnetic actuators over the conventional actuators is that it is almost maintenance free which is due to the absence of mechanical part such as gears [1]. In general, LEA can be classified as linear brush DC actuators (LDCA), linear induction actuators (LIA), linear synchronous actuators (LSA), linear solenoid actuators (LSoA) and linear switched reluctance actuators (LSRA) [2].

The configurations of the LEA can be divided into transverse flux and longitudinal flux configurations [1], [3], [4]. Longitudinal flux configuration occurred when the flux lines and movement of the actuator is in parallel while transverse flux configuration occurred when the plane with flux lines is perpendicular to the motion of the actuator.

The typical design of LEA can be characterized as three topologies: (i) Planar Single Sided; (ii) Planar Double Sided; (iii) Tubular. By comparison, the tubular topology of LEA has greater force density compare to planer topology actuator due to lesser flux leakage and tubular topology actuator minimized the stray magnetic field in the direction of travel along the stator and mover part [5]. Hence, the thrust force and

magnetic flux of the tubular topology actuator will be larger compare to planar single sided and planar double sided LEA.
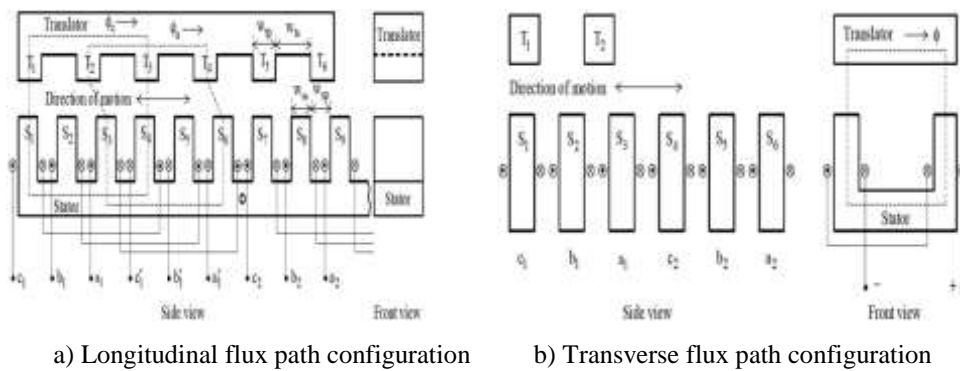

a) Longitudinal flux path configuration   b) Transverse flux path configuration

Figure 1. Configuration of LEA [1]

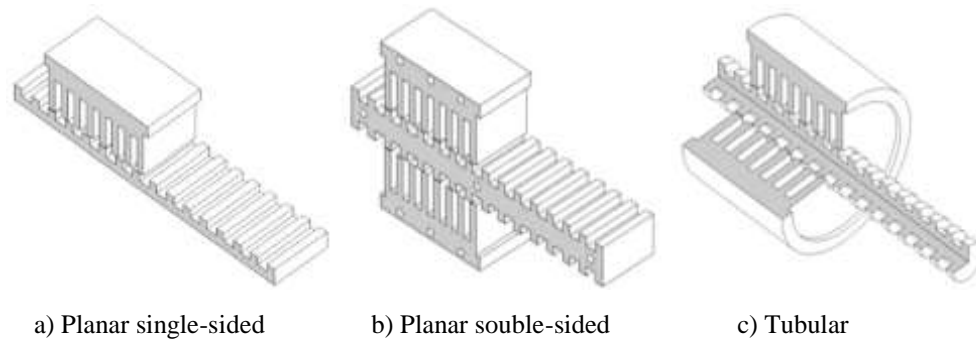a) Planar single-sided   b) Planar souble-sided   c) Tubular

Figure 2. LEA topologies [3]

In addition, the LEA can be built with permanent magnets (PMs) or without PMs. All types of LEA can use PMs to increase the thrust of the actuator except induction actuators. In fact, the high energy PMs have essentially improves the thrust of the actuator but the usage of PMs will directly increase the cost of the actuator. A qualitative comparison and performance indexes of LEA with different topologies is shown in Table 1. By comparison, LSA with PMs and LSRA provide a higher force density than LIA. Then, the tubular topology of LSA provides better force density than flat topology and lowest loss to thrust ratio. However, the applied of the PMs increase the cost of the actuators.

Table 1. Qualitative Comparison and Performance Indexes of LEA with Different Topologies [2]

Type of Actuator	Force Density	Force Density	Force Density	Force Density
Linear induction actuator (flat)	Low	High	Average	High
Linear induction actuator (tubular)	Low	Average	Average	High
Linear synchronous permanent magnet actuator (flat)	Good	Low	High	Moderate
Linear synchronous permanent magnet actuator (tubular)	Very Good	Very Low	Average	Moderate
Linear switched reluctance actuator (flat)	Good	Average	Average	High

Hence, Tubular LSRA will be an alternative choice to replace the LSA with PMs due to the lower cost and improved force density even though the force density is lower than actuators with PMs. The schematic structure of the tubular LSRA is shown in Figure 3. LSRA is an attractive alternative candidates on many applications such as propulsion railway transportation system [6], active vehicle's suspension system [7], left ventricular assist device [8], precision motion control [9]-[10] and direct-drive wave energy

conversion [11]. LSRA does not attract the interest among the researchers due to nonlinearity characteristic, large thrust force ripples, high acoustic noise, vibration and low thrust force-volume density [12]–[16]. However, the increasingly advancement of the control strategies able to overcome the LSRA weaknesses which started to gain the interest of researchers for further research on the LSRA.
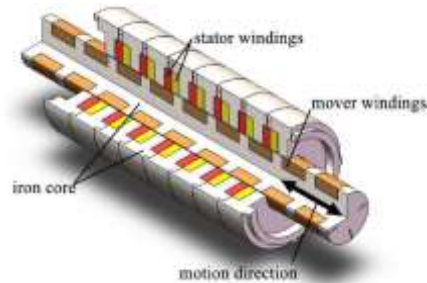

Figure 3. Schematic structure of tubular LSRA [17]

The development of the linear actuators today has started to focus on the LSRA. Other than that, the increase in the demand the SRA on industrial and automation process is mainly due to the advantages of the SRA compare to other type's actuator. As a kind of linear actuator, LSRA has achieved a great development due to its simple structure, low cost production, good fault tolerance, absence of mechanical processing, lack of windings on either the stator or mover structure, high reliability in harsh environment and capability to operate in elevated temperature [1], [18]-[24].

In general, the structure of LSRA consists of three major parts which are the stator, mover and windings. For a linear type of switched reluctance actuator, the windings can be set at either stator or mover. The thrust force and motion of the actuator is produced due to the tendency of the mover to reach a position where the inductance of the stator is maximized while the reluctance is minimum [25]-[26].

The LSRA produced lower thrust force compare to the actuator with PMs for approximate 60% [3]. In order to improve the thrust generated by the LSRA, the optimization design variables of the electromagnetic actuator is an important aspect. The modification on the different design variables may increase or decrease the thrust force, magnetic flux and the saturation of the LSRA. There are many design variables that can be changes to obtain the optimized value with larger thrust such as pole length, pole width, pole pitch, pole shape, windings turn, number of phases, air gap, excitation current and coil diameter. Hence, the optimized design variables must be obtained in order for the LSRA to generate a larger thrust force with lower volume as possible. This paper reviews the introduction to the linear electromagnetic actuator specifically LSRA topology, influence of design variables to thrust force and actuator control strategies for both position control and velocity control for high precision application.

2.   DESIGN VARIABLES OF LSRA

For LSRA, there are many variables that can be optimized and will influence the actuator performance. Figure 4 shows the three dimensional view and main dimensions of LSRA which require optimization for actuator design. A LSRA with high thrust force and low force density often used as the reference to optimize the actuator variables to achieve desired performance, i.e.: (i) translator pole width, b_s, (ii) translator pole pitch, c_s, (iii) translator pole length, l_s, (iv) stator pole width, c_p, (v) stator pole shape, (vi) stator pole length, l_p, (vii) air gap between stator and translator, g, (viii) number of winding turns, n, (ix) number of phases and coil diameter, d_{coil}. In the next section, the reviews will discuss on the influence of the design variable of LSRA to its output.
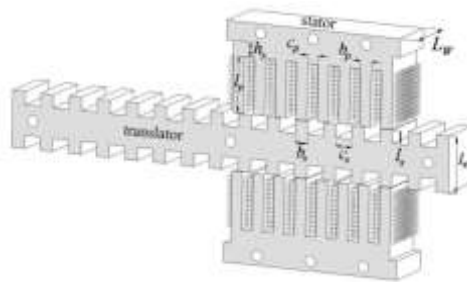
Figure 4. Three dimensional view and main dimensions of LSRA [27]

2.1. Influence of Translator Pole Width, b_s

Lenin et al. [28] described the influence the translator pole width on single-sided LSRA as in Figure 2(a). The increasing of the translator pole width will directly increase the average generated thrust force by 0.25N for every 1mm. The increase in the thrust force when a larger translator pole width is applied is due to the larger available area for magnetic flux to flow through from stator to translator which directly increase the magnetic field of the actuator. However, the mass of the translator will be increased as the translator pole width increased. Hence, the force density of the actuator designed will reduce when the translator pole width was increase.

2.2. Influence of Translator Pole Pitch, c_s

Kou et al. [29] stated that the flux density of tubular LSRA will directly affects the cogging force and thrust characteristic of the actuator with the changed of the translator pole pitch. The flux density of the actuator will rise when the translator pole pitch increase. In addition, the cogging force and thrust characteristic of the actuator also will increase when translator pole pitch increase due to the changes in the magnetic flux density in the actuator. The influence of translator pole pitch can be clearly observed when the actuator produced the thrust force for approximate 700N with 10N of cogging force for 7mm of translator pole pitch. When the pole pitch is increased to 19mm, the generated thrust force is approximate 1600N with 60N of cogging force. The increased in the thrust force and cogging force when increasing the translator pole pitch is due to larger reluctance occurred as the translator tooth is further away from stator tooth. So, the SRA produce larger flux density to move the translator to a position to achieve minimum reluctance and maximum inductance. Hence, the increase of the translator pole pitch results in the larger thrust force.

2.3. Influence of Translator Pole Length, l_s

In the study of Lenin et al. [28] on single-sided LSRA and Amoros et al. [27] on double-sided LSRA, the study found that increasing the length of the translator pole will improve the average thrust force. The coils of the designed actuator is located at the translator part. In order to improve the actuator's magnetic field strength and generated thrust force, lengthening the translator pole directly increase the useful available area for the winding turns which contact with the translator pole. Hence, longer translator pole length will increase the magnetic flux of the actuator which improve the thrust force at the same time. The study by Lenin shows 50N of propulsion force generated with translator pole length of 42mm. However, when the translator pole length was increased to 52mm, the propulsion force significantly gave higher propulsion force; 125N respectively. Although the average thrust force can be improved by lengthening the translator pole length, nonetheless further increment of the translator pole length will not influence the thrust force due to magnetic flux saturation. Hence, it can be depicted that when saturation occurred, increase of the length will not produce any gain in the propulsion force for high excitation current.

2.4. Influence of Stator Pole Width, c_p

SRA is known to have issues on larger force ripple generation due to phase switching. One of the important criteria in designing an electromagnetic actuator is the handiness to produce maximum average thrust force with low force ripple. By varying the stator pole width, the actuator able to produce larger average thrust force with lower force ripple [28]. Nevertheless, when the stator pole width is increased, the average thrust force produce has found to be reduced after a certain width due to dead zone [28]. The dead zone happened when the maximum inductance occurred with no contribution on the generation of propulsion force. The dead zone will be larger with the increase on the absolute difference between the stator and translator pole width [30].

From Table 2, it is found that the average thrust force will increase as stator pole width increase until a significant value of 19mm where there is reduction in the average thrust force. On the other hand, the force ripple also reduce as the stator pole width increase but the force ripple increase again after 19mm. So, the increase in the stator pole width will increase the actuator induction continuously but not improvement on average thrust force and force ripple.

Table 2. Comparison of Average Thrust Force and Force Ripple for Various Stator Pole Widths [28]

c_p (mm)	Fmin (N)	Fmax (N)	Favg (N)	% Ripple	Lmin (H)	Lmax (H)
16	67.33	124.87	100.39	60.38	0.02972	0.08626
17	67.91	124.70	101.07	57.68	0.03019	0.08658
18	68.23	124.57	101.10	55.88	0.03071	0.08683
19	68.32	124.11	101.30	53.41	0.03125	0.08700
20	68.28	124.34	100.86	56.16	0.03184	0.08713
21	67.88	123.90	100.63	55.67	0.03246	0.08725

2.5. Influence of Stator Pole Shoe and Pole Shape

There are some major issues that arise in designing a LSRA due to high force ripple and acoustic noise generated. A few numbers of methods were used by researchers in order to improve the both single-sided and double-sided LSRA performances. The most common strategy used was to design an advance controller to reduce the ripple and noise in the actuator [31]-[35]. However, the design of the controller is complex and complicated. Hence, another two approaches are used for ripple reduction which are; i.e.: (i) determine the waveform of the input excitation current profile by using an electronic control of power controllers or (ii) change the geometrical structure of the stator or translator pole [28], [36].

Lenin et al. have proposed the force profile improvement through the geometrical modification on the stator poles by introducing the pole shoes on the stator poles [28], [36]-[39]. The conventional stator pole is rectangular in pole shape is shown in Figure 5a [30]. However, other polar shapes and pole configurations can be used either in primary or secondary. Lenin et al. proposed the modification on the stator poles by introducing the stator pole shoe as shown in Figure 5b [28], [36]. Ganesh et al. described the actuator performance by presented the skewed poles [37] as shown in Figure 5c and tapered poles [38] as shown in Figure 5d. On the other hand, Santo et al. suggested the changes on the stator poles shape with round pole as in Figure 5e and wedge pole as shown in Figure 5f [40].
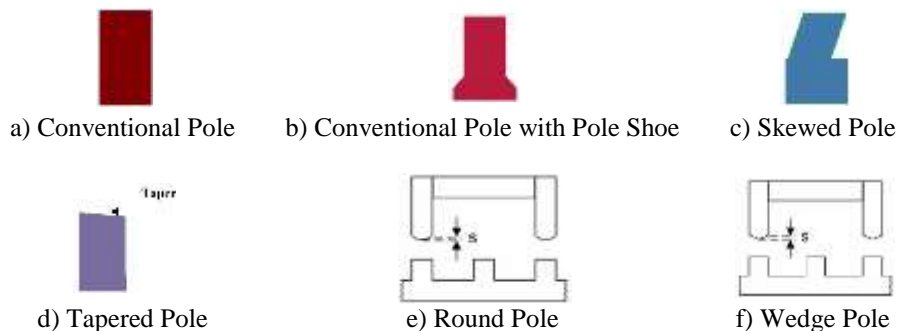

a) Conventional Pole   b) Conventional Pole with Pole Shoe   c) Skewed Pole

d) Tapered Pole   e) Round Pole   f) Wedge Pole

Figure 5. Geometrical structure of stator poles [36]–[39]

The purpose of modifying the structure of the stator pole was proposed to reduce the force ripple, stator volume and mass while providing a better force density. Lenin et al. [28], [36] studied the availability of stator pole shoe in LSRA. The pole shoe used in the stator able to increase the average force linearly until 4mm; where after that saturation occurred with no significant change in average thrust force. In 2015, Ganesh et al. [37], [38] found that the skewed pole and tapered poles proposed able to increase the generated thrust force by the actuator. Based on these findings, both skewed pole and tapered pole generated thrust force of 0.5N higher than conventional pole with force ripple reduction by approximately 27% for tapered pole. In comparison, the round pole and wedge pole proposed by Santo et al. [40] are found that the conventional stator pole provide better thrust force generation with 66N compare to the round pole and wedge pole with 58N and 51N. Meanwhile, Jamil et al. [41] introduced a number of notch to the stator pole for torque ripple minimization. The proposed technique was found that stator with three notches has lesser torque ripple

compare to stator with two (2) notches. Based on the reviews. stator pole shoes or pole shape with larger surface area had improve the thrust force due to increase of more magnetic flux flow.
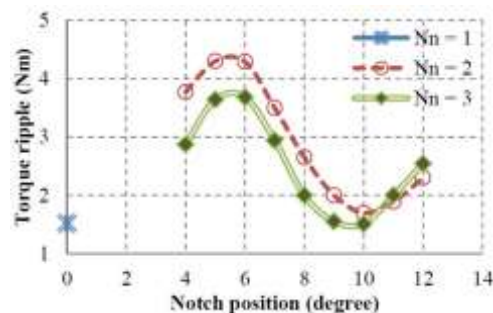

Figure 6. Influence of stator notch to the torque ripple reduction [41]

2.6. Influence of Stator Pole Length, l_p

Lenin et al. [28] and Amoros et al. [27] have studied the influence of stator pole length to the average thrust force of an actuator. The LSRA able to provide a higher average thrust force by increasing of the stator pole length. While, Fahimi et al. [42] found that smaller stator pole length will lead to higher natural frequency in the actuator which will cause the deformation of the stator. Moreover, reduction of the stator pole length will reduce the available area for the windings. Thus, the increased of the stator pole length will increased the available area for the coils. Consequently, the magnetic flux density and output thrust force can be improved. However, longer stator pole length means the volume of the actuator is larger which reduces the torque density of the actuator [43]-[44]. So, Goto et al. [43] proposed that the stator pole length need to be optimize with longer stator pole length before the torque density gradually reduced. The actuator produced torque density of 45Nm/L with the stator pole length of 17mm. At pole length 22mm, the torque density increases to 46Nm/L, while at pole length 34mm the torque density reduced to 40.5Nm/L respectively.

2.7. Influence of Air Gap, g

In order to increase the efficiency of the actuator, the reduction of the air gap thickness is an alternative method for increasing the propulsion force without affect the actuator dimension [30]. As a general rule, smaller air gap thickness able to produce larger propulsion force. The thrust force produce is an attraction or propulsion force between the stator and mover due to the tendency of a magnetic circuit to restructure itself in order to achieve smallest reluctance. The actuator reluctance will increase with the air gap thickness and the magnetic flux diminishes as the co-energy content [4], [45]-[46]. Moreover, larger air gap thickness will leads to reduction in the magnetic flux between poles due to the increasing in the reluctance which then resulting in smaller inductance and reduced thrust force. As a comparison, actuator with larger air gap thickness has the benefit of less ripple and more suitable for application that require smooth motion. Calado et al. [47] study the relationship of air gap to thrust force where 97N of thrust force was generated with 2mm of air gap. When the air gap was increased to 4mm, the thrust force reduced to 90N and the further increased of air gap to 8mm causes the generated thrust force to decrease rapidly to 60N. Even though smaller air gap able to generate large propulsion force, however there are two issues with small air gap thickness; i.e: (i) narrow air gap make the manufacturing becomes difficult which leads to high cost of manufacturing and (ii) smaller air gap thickness increases the force ripple. [48]. Hence, an optimized parameter for the air gap thickness is crucial in order to design an actuator that capable to generate large thrust force, smaller force ripple and able to provide smooth motion.

2.8. Influence of Winding Turns, n

There are two factors that will influence the magnetic flux, inductance and thrust force of the actuator; i.e.: (i)number of winding turns and (ii) excitation current. The various coil turns will determine the value of the generated thrust force by the actuator. Hence, increasing the number of winding turns will improve the thrust force, magnetic flux and inductance of the actuator, respectively [49]–[52]. The increasing of the winding turns can improve the generated thrust force but field saturation will occurred where further increase in the number of turns after exceeding the saturation point will has less influence to the magnetic

flux and thrust force[53]-[54]. The magnetic flux, Φ of the actuator can be derived from the as in Equation (1) [55].

$$\phi = \frac{F}{R} = \frac{Ni}{R}$$

(1)

where F is the magneto motive force, R is the reluctance, N is the number of winding turns and i is the excitation current. From Equation (1), the increase in either the number of winding turns and excitation current able to increase the magnetic flux and generated thrust force. On the other hand, the decreasing in the reluctance will increase the generated thrust force as well. Then, the number of winding turns can be expressed as a function of the actuator dimensions as [55];

$$N = \frac{h_{cu}l_2 K_{ff}}{A_w}$$

(2)

$$K_{ff} = \frac{S_{copper}}{S_{total}}$$

(3)

where h_{cu} is the thickness of copper, l_2 is the coil's length, k_{ff} is the filling factor, A_w is the cross-sectional of single wire, S_{copper} is the cross-section of the wires and S_{total} is the overall cross-section of the coil. However, increase in the number of turns leads to an increase of the slot area and magnetic core volume which will reduce the efficiency for the desired application. According to the study of Teixeira et al. [30], three winding turn with 120, 226 and 264 turns are compared. The highest value of winding turns with 264 turns was found to have the highest thrust force with 970N compare to 226 turns with 705N; and 150 turns with 320N. This indicates higher winding turns results in higher thrust force.

2.9. Influence of Number of Phases

A reluctance actuator will generate the thrust force due to the tendency of the translator part to move to a position where the inductance of the excited windings is maximum and reluctance is minimum. In order for the electromagnetic actuator to provide a controlled continuous motion, the required minimum number of phases is three (3) where the phases can be connected either in series or parallel connection [56]-[57]. Other than that, increasing the number of phases result to reduction of the cogging force[58]. Hence, the minimization of the detent force then reduces the vibrations, acoustic noise and ripple factor of the actuator. At the same time, the motion smoothness of LSRA is improved and the control system for positioning is simplified [3]. Furthermore, the increase of the phase numbers will also improve the thrust force due to the effect of cogging force reduction. Nevertheless, with the increased of the phase numbers, the system will become more complex, which then requires more complex strategies to control the excitation current and phase shifting since the phase is activated independently each time [59]. Figure 7 depicts the influence of phase numbers to the ripple factor where two (2) phases actuator has twice larger ripple factor compare to three (3) phase's actuator.
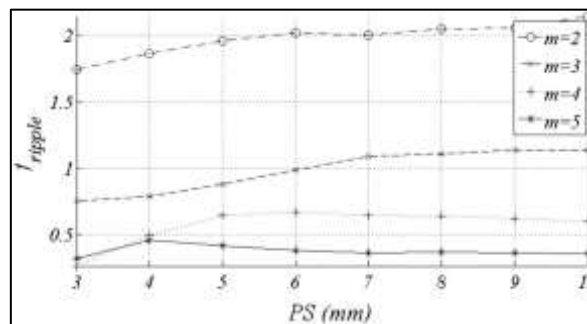

Figure 7. Effect of phase numbers to ripple factor [3]

2.10. Influence of Coil Diameter, d_{coil}

In SRA, the peak force generated by the actuator are caused by the excitation current. Therefore, the coil diameter is an important parameter that will directly affect the coil length and generated thrust force. A larger coil diameter will produce coil with lower resistance per unit length [60]. Nevertheless, the larger coil diameter will cause an unnecessary coil thickness to the LSRA. Figure 8 depicts that the maximum peak force remains the same and does not increase further when the coil diameter was larger than 2mm. Thus, the rate of thrust force to volume can be improved by increasing the coil diameter which leads to lower resistance. However, the excitation current apply to the coil must not exceed the rate of driving capability based on the Standard Wire Gauge (SWG). Hence, the diameter of the coil is chose based on the excitation current needed in order to fulfill the rate of driving capability [61]. Even though theoretically has proves that larger wire diameter will has lower resistance and hence larger thrust force but studied shows that further increased in the wire diameter may not satisfy the condition of thrust force [48]. R. Othman et al. found that the increase in the coil size will cause the flux density of actuator to be reduced [62]. As a conclusion, optimization of the coil diameter is an important parameter in designing the electromagnetic actuator.
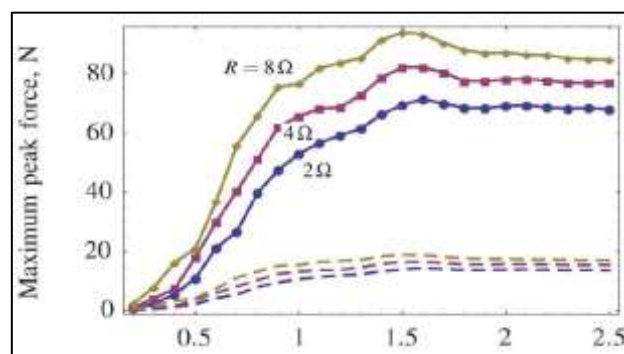

Figure 8. Effect of coil diamater on maximum generated thrust force for three coil impedance [60]

3.   CONTROL METHOD

LSRA is a new type of actuator that has high liability due to the low cost and simple construction. However, the major issues of a SRA are the excessive force ripples and vibrating noise compared to the conventional machines [63]-[64]. Hence, the control strategy of the actuator is crucial in order to overcome the disadvantages. Based on studies, many types of controllers have been proposed and applied to SRA mechanism; i.e: modified PID control, intelligent control, linearization control and two degree of freedom control. In this section, comparison of these controllers is discussed with respect to their design structure and controller performances.

3.1. Modified PID control

The PID controller is widely used in speed and position control applications due to its simplicity, easy tuning and ruggedness. There are many classical techniques proposed and used for designing and tuning the parameters of the PID controller such as trial-and-error, Ziegler-Nichols method, Cohen-Coon method and Tyreus & Luyben method [65]-[66]. However, the applied of the conventional PID controller will reduce the positioning performances due to the highly nonlinearity characteristic of the switched reluctance actuator. Thus, in order to implement the knowledge of linear controller to a nonlinear system, the system require to undergo linearization control [67]-[68]. Hence, M. Maslan et al. proposed a new controller to overcome the challenge with respect to the precision control by introducing the linearizer unit [68]. Figure 9 shows the block diagram of modified PID control system with linearizer unit.

The linearizer unit is added to suppress the high nonlinearity of the driving characteristics while canceling the negative influence between the PID controller and the actuator. Then, the amplitudes of the excitation current to the coils are obtained from the output of linearizer unit in relation to the thrust force and position. On the other hand, Hama et al. have studied on the nonlinear PID control with feedforward element [69]. The nonlinear PID control includes a proportional element and derivative element through a gain scheduled to minimize the mover vibration which express as a error signal and time derivative of an error signal. In addition, the nonlinear PID control has a conditional integrator as a function for steady state error minimization in the system. Furthermore, the feedforward element for cogging force and friction

element was added into the system to overcome the influence of the cogging and friction to the system. The block diagram for nonlinear PID compensator with feedforward element is shown in Figure 10.
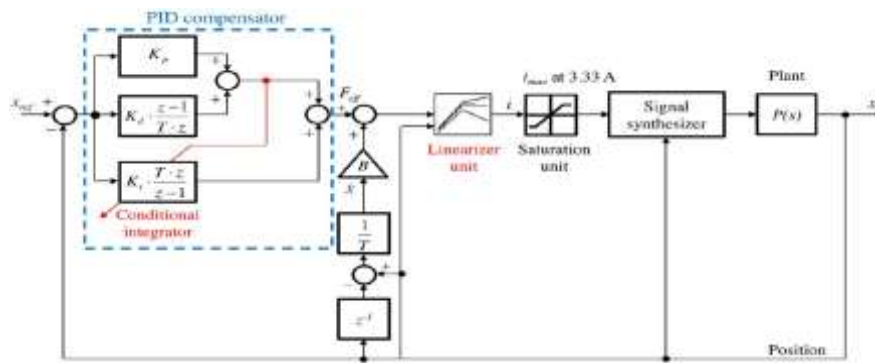

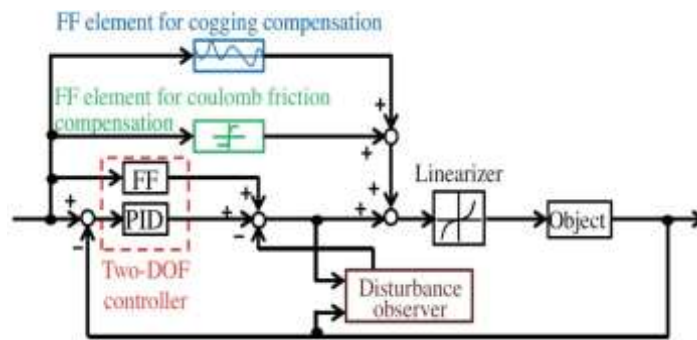Figure 9. Block diagram of PID control system with linearizer unit [68]

Figure 10. Block diagram of nonlinear PID compensator with feedforward element [69]

Moreover, Zaafrane et al. presented the used of PI controller, hysteresis controller and force distribution function (FDF) for the purpose of speed control [70]. The combination of control system for the nonlinear switched reluctance actuator enable the performance to be improved due to hysteresis controller will control the excitation current, speed control done by a PI controller while the FDF is used for force control and ripples reduction. Next, the Bang-Bang control has been proposed for the open loop control of SRA to reduce system overshoot and eliminate the oscillations [71].

Rafael et al. presented an adaptive PID controller for speed control [72]. The proposed controller designed based on the Takagi-Sugeno fuzzy system with some simplifications. The controller with adaptive algorithm tends to have the advantage of simplicity on algorithm structure and lesser processing resources compared with the intelligent or hybrid system. Furthermore, the adaptive PID controller does not require any PID calibration. The controller also able to quickly compensate the disturbance that appear in the actuator.
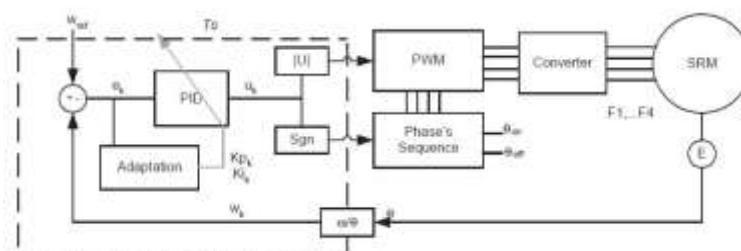

Figure 11. Block diagram of adaptive PID control system [72]

Srivastava et al. suggest the speed and position control of the switched reluctance actuator with a cascaded controller of advanced PI and PD controllers [73]. The PI controller is used to provide a fast transient response while eliminating the steady state error for speed control. Then, the PD controller will be function to counteract the delay effect and overshoot in the position response due to the utilized of integration of the PI controller.

3.2. Intelligent control

Intelligent controls are widely used in nonlinear system such as SRA in order to obtain high precision positions and speed control. Yao et al. applied a fuzzy neural network modeling to learn the nonlinear static position-torque-current and flux linkage characteristics for torque control of the SRA [74]-[75]. Then, torque distribution function was used to calculate the phase torque and the ANFIS inverse torque model to obtain optimize current waveform. In order to achieve ripples minimization, adaptive sliding mode current controller will control actual phase current waveform by tracking the desired phase current waveform to generate the most similar current waveform.

Li et al. proposed a instantaneous torque control based on radial function neural network (RBF) [76]. The optimization of the current waveforms with respect to different speed and torque is learned from dynamic simulation for RBF neural network offline training. Then, then trained RBF neural network is used for the obtained the relationship between speed, torque and position to current nonlinear mappings of torque control. The experimental results show that the control strategy able to minimize the ripples while provide high control accuracy.
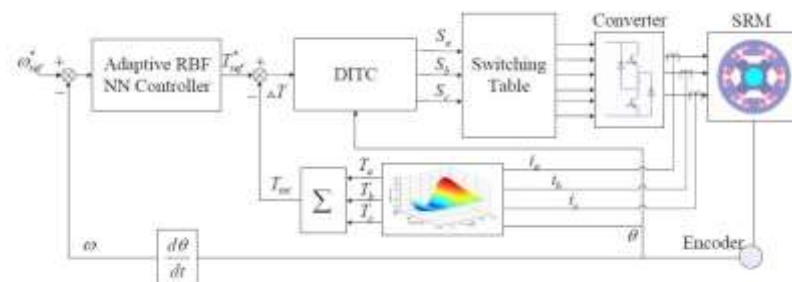

Figure 12. Configuration of adaptive RBF neural network ontroller of SRM [76]

3.3. Position Control

There are various control methodologies that are proposed to evaluate the position control of the actuator. The most common and simplest control methodology that requires less computational effort is using the lookup table [77]-[80]. Then, the sliding mode theory is the second method which can be used to evaluate the position control of the actuator [79].

Lookup table method is the most simple and effective position control strategy for low cost implementation. In these control method, various nonlinearities of the actuator in the motion system are taken into account. This method able to linearize the relationships between thrust force, current and position in switched reluctance actuator [81]. However, there are some assumptions made when implement this control method which are the system model is assumed to be precise and no nonlinear friction behaviors occurred. Hence, the lookup table able to produce and show the position control and characteristic of the actuator. Nevertheless, this control method only provides good performance for long and medium distance travel.

Yuichi et al. [82] proposed the position control method with Magnetic Non Linearity Control (MNLC) by considering the magnetic nonlinearity of the actuator. Gan et al. [83] presented the position control of SRA with a current-thrust force-position lookup table and a linear optical encoder to observe the motion profile of the actuator. The system used the look up tables which include the relationship between excitation current, motion profile and torque profile with variation of rotor position to design the controller for torque control and phase switching control. Then, the lookup table with reference torque at different rotor position is then used to determine the three phase reference currents. Figure 13 shows the position control diagram with the used of lookup table.
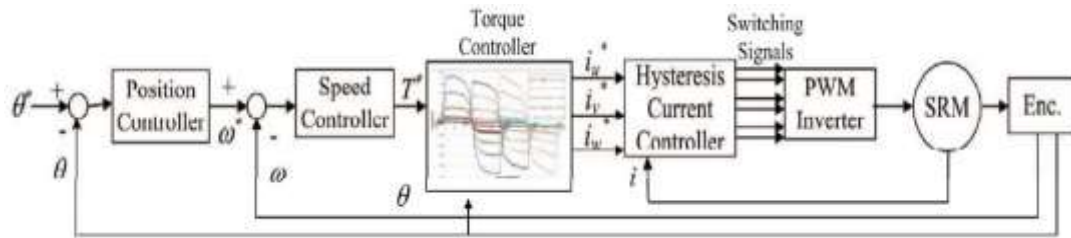
Figure 13. Position control diagram with lookup table in torque controller [82]

Other than that, sliding mode control is one of the technique that commonly used for evaluate the position control of nonlinear actuator such as electromagnetic actuator. Sliding mode control is a nonlinear control technique that alters the dynamics of nonlinear system by applying the discontinuous control signal to force the SRA slide along the boundaries of control structure of actuator in normal behavior. In this method, the thrust force of the SRA is generated by switching the two phases and the motion of the translator is move based on the resolution of designed actuator [79]. The sliding mode consists of two parts which are sliding mode and reaching part (non sliding part). Sliding part is where the trajectory asymptotically tends to moves toward the origin of the phase plane. Mean while, reaching part is the trajectory starting from any position on the phase plane which moves towards a switching line in finite time [84]. Through the sliding mode control, a sliding surface S can be designed so that the state trajectories of the plant when restricted to S have the desired tracking behavior and maintain the stability of the closed-loop system. In addition, sliding mode control can determine the switching control law to drive the state trajectory to maintain the S surface [85]. Moreover, the extended state observer is used with sliding mode control able to estimate the system uncertainties and nonlinear perturbation to study the position control [86]. . However, sliding mode control technique will experienced some oscillations phenomenon with finite amplitude and finite frequency due to the fast dynamics. The fast dynamics tends to neglected the ideal model and the utilization of digital controllers with finite sampling rate caused the phenomenon of oscillations. [87].
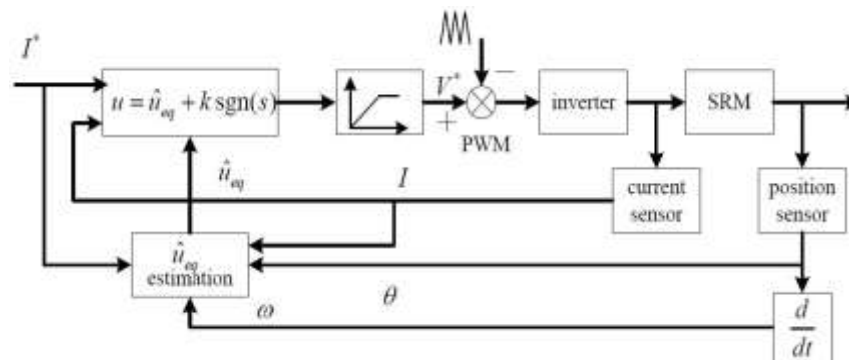

Figure 14. Block diagram of SRM sliding mode current controller [67]

3.4. Velocity Control

The velocity control and braking of the actuators are results from the excitation current switches turning on and off. Velocity control is used to compare the actuator motion speed with the reference speed. The velocity of the linear switched reluctance actuator can be obtained by applying a simple position derivative [8], [88]-[89]. A current reference will produced from the speed control then compared with the actual phase current [90]. Since there is speed ripple occurred in the actuator, a low-pass filter is capable to reduce the speed ripple due to roll off over the cutoff frequency of the mechanical system [91]. On the other hand, J.F. Pan et al. proposed an Auto Disturbance Rejection Speed controller (ADRC) for the purpose of speed control due to the ability to adapt to parameter variation [92].
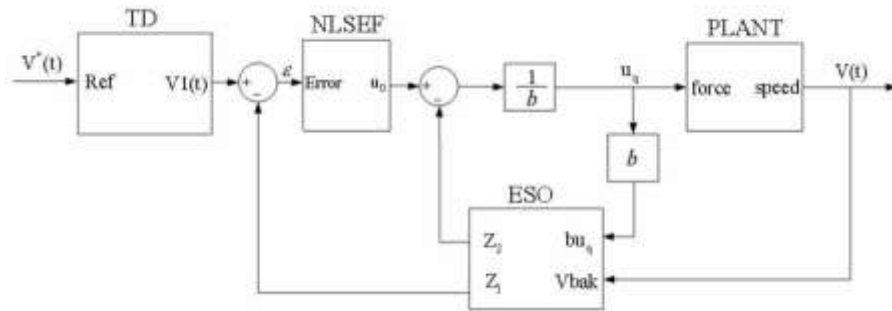
Figure 15. Velocity control with ADRC block diagram [92]

4.   CONCLUSION

In this paper, a review on the design variables optimization and control strategies of linear switched reluctance actuator (LSRA) is presented. The study found that LSRA is an alternative technology that can replaced linear synchronous actuator (LSA) which contain the permanent magnets (PMs) due to high cost on the magnet material. Moreover, the tubular topology of LSRA has higher force density compare to the conventional flat topology. Various LSRA design variables from stator tooth width to mover tooth pitch and air gap between stator and mover have been investigated. Design study have shown that the design variables discussed in the paper has a significant influence on thrust force capability, force density, cogging force, force ripple and mostly importantly the variables also have an impact on the vibration and acoustic noise. Hence, the study on LSRA position control, speed control and ripple reduction is of great importance. The highly nonlinearity of the LEA and LSRA make the actuator hard to be controlled in precision applications. Nevertheless, the improvement and development in advance control strategies such as PID controllers and various intelligent control theories overcome these issues. Therefore, the research on the optimizing the design variables and suitable controller must be done to ensure the LEA and LSRA able achieve the operation of high speed and high precision applications. As the recommendation, the design optimization of LSRA variables will able to overcome and reduce the ripple force and acoustic noise of the actuator. Hence, the controller design for the LSRA will simpler and for apply to achieve the high precision control of LSRA.

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