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A review on linear switched reluctance motor

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Summary. Switched reluctance motors have been extensively studied by researchers for their unparalleled advantages in many applications. The linear versions have been developed around the world in the last couple of decades because of attributes similar to that of rotary switched reluctance motor(RSRM). Owing to their frugal design, robust built and high force density, the linear switched reluctance motor (LSRM) has had significant stages of development and optimization. The flexibility in design and operation makes LSRM a prime contender for any linear motor-actuator application. This paper provides a bird's eye view across its developmental stages and its various aspects in design, analysis and control. The following content discusses the salient points of research and the contribution by researchers in this field.

Key words: linear switched reluctance motor, design, analysis, control

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Introduction

Linear Motors are preferred as industrial drive system because they eliminate the requirement of auxiliary mechanical drives. This tackles the persisting problem of backlash in gears (motion converters) and losses in compressor-pipes-valves (pneumatic drives). Linear synchronous and induction drives lack accuracy in low speed operation due to their design constraint in pole pitch and operating frequency [11]. Being predominantly position controlled, linear switched reluctance motor troubleshoots the problem of accuracy of control. Moreover, the inherent winding design allows a high fault tolerance in the machine [30]. Industrial research for variable reluctance motors only began with the advent of semiconductor technology, although the first motor running on this principle has been established in 1838 by W. H Taylor [55]. As the performance boosted with the use of microprocessor controlled switching, variable reluctance motors began to be regarded as a high speed variant. In 1988 Takamaya et al. [53], [54] developed a linear motor based on the principle of variable reluctance. Analytical tools developed for the RSRM, has been popularly adopted for the LSRM. With this, extensive research on electromagnetic analysis of LSRM has been documented which utilizes tools like reluctance network, finite element method and neural networks. Development of control algorithms obtained a smoother operation by reducing cogging or ripple force, often experienced in a variable

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reluctance machine. This accelerated their application in several fields ranging from elevator drives [34], [35], generators [57], transportation rails ([37], [5], [29]) ocean wave energy harnesser [56], actuators [12], driver for automatic door [18], medical applications [41] only to name a few.
The present work discusses the various flexibility in configuration, algorithms of design, tools of analysis and adopted control methodologies of LSRM, in brief.

Selection of Configurations

A LSRM can simply be seen as radially cut open form of a RSRM offering an abundance of configuration flexibility [32]. An elemental set of a LSRM essentially comprises a primary (ferromagntetic poles coiled in current carrying windings) and ferromagnetic secondary, separated from the primary by an air gap. The set of above mentioned assembly is repeated, often connected by yokes, which allows magnetic flux to travel in closed loop. The primary and secondary are separated by a sufficient air gap, the dimension of which, is critical to machine performance. Windings are placed either on the stator or the translator. When the stator houses the winding, it forms the primary and the configuration so obtained is referred to as active stator configuration (primary). This configuration has been adopted in developing actuators, drives for doors, industrial rails ([11], [53], [57], [12], [18], [41], [32], [2], [17], [9], [43]). Similarly, when the translator houses the windings, the configuration is called an active translator or primary mover. Liu and Kuo [37] developed a LSRM for wagon wheel which uses an active translator assembly, the likes of which has been popularly adopted in several applications ([34], [35], [29], [56], [39]). In applications such as material handling system where the displacement is short, an active stator configuration is preferred. While in transportation system involving long rails, active translator configuration is adopted as it reduces cost [36].
LSRMs can be broadly classified as in the way the magnetic flux path is oriented with respect to the direction of motion. With this knowledge, further flexibility in configuration is achieved. When the magnetic flux path and the direction of motion are parallel to each other, the configuration is termed as longitudinal flux (LF) configuration. Contrarily, when they are perpendicular to aech other, the configuration so obtained is called transverse flux (TF) configuration. Corda and Skopljak [11] elaborated on both configuration features of LSRM, derived from a RSRM. Darabi et al. [14], [15] has compared LF and TF configurations based on secondary weight, thrust and levitation forces. In the study, the LF configuration developed more levitating force with a lower secondary mass than the TF configuration. Lim and Krishnan [34] and others ([35], [32], [18], [17], [9], [43]) has used a LF configuration as a model to study for its mechanical stability thereby optimize its performance characteristics. Liu and Kuo [37], Baoming et al. [5] and Liu et al. [40] has used a TF configuration to drive a wagon on wheels which obtained promising results in application.
The LSRM designs based on an open RSRM structure, consists of a single primary and secondary ([53], [54], [5], [32]). In such configuration, the system has to deal with high attractive force which is difficult to control [14], [38]. Researchers adopted a twin symmetric primary design that eliminates the unbalanced attractive force ([34], [35], [56], [18], [2], [9], [26], [6]). Further exploration in flexibility of configurations such as intermediate core [17], yokeless systems ([34], [35], [17]) and permanent magnet embedded hybrid motors [7], [4] obtained better performance characteristics like mass to force ratio and reduction in force ripple. Also, a unique cylindrical LSR actuator introduced by Corda and Sko-

pljak [11], based on an active stator TF configuration where a solid ferromagnetic shaft with rings formed the actuator body delivered a high force per unit volume. Pan et al. [49] has developed an asymmetric skewed geometry which later was developed further for planar motors [46].Interestingly, attractive force has been harnessed efficiently to achieve magnetic levitation [14]. Application oriented manipulation in design for magnetically levitated system has been carried out by incorporating hybrid magnets by Kakinoki et al. [27].

Design of LSRM

Performance characteristics of a LSRM directly depend on the design of geometrical as well as electrical parameters of the machine. Lee et al. [32] derived a power equation to relate electrical power and geometrical parameters of LSRM. The power equation is derived from a fine tuned rotary counterpart which can be further exploited to optimize the design. LSRMs are often operated at saturation conditions for optimum performance. Hence it is essential to analyze as per the condition of operation. Baoming et al. [5] obtained a similar power equation for a TF configuration which incorporates an overloading factor. A modification in power equation by Pan et al. [49] relates the geometric variables for the skewed asymmetric teeth profile with the power input. The geometric variables are further studied for optimization by Wang et al. [57]. The above mentioned formulation of power equation, set the guideline to determine the geometrical parameters of the machine under specific power input. Impact of different shape profiles on the performance characteristics have been studied by several researchers. Takayama et al. [54] has observed a sharp drop in the force profile along the stroke length of a LSRM, when the pole width is reduced beyond the width of the primary. No commendable profile change has been recorded with increase in pole width of the secondary. Hence, to avoid peak material saturation, the pole width of secondary should not be less than that of primary [36]. EspÃrito-Santo A.E. et al. [21] elaborates on the effect of pole shapes on the performance characteristics where different pole shapes are studied under identical phase current excitation. The finite element study reveals that the different pole shapes deliver force profiles which can be exploited for a wide range of operation. Liu and Chen [36] classifies a set of feasible operation polygons for machine dimension, from where pole pitch and pole sizes of both LF and TF configurations are optimised. An objective function, formulated to minimize the work done sets geometric constraints on the pole dimensions. Fonseca et al.[22] too adopted a feasible polygon in its pre-design step to estimate pole sizes. Amoros and Andrada [3] has studied the impact of geometrical parameters on the performance of a double sided LSRM which incorporates a similar feasible polygon to analyse the influence of pole width. The study reveals that the primary pole width had more influence on performance characteristics and influences the higher peak and average force values. Elevarasan et al. [20] conducted a study on a gashed pole LSRM to study its impact on force ripple and mass reduction of stator while Lenin and Arumugam [33] observes a reduction of force ripple by incorporating stator pole shoe in their LSRM. The above section thus provides a diverse range of design algorithms emphasizing on power equation.

Analysis of LSRM

Design analysis of LSRM incorporates analytical and numerical algorithms commonly used for the RSRM. A popular method of developing an analytical model is the reluctance network model from which magnetic flux linkages are estimated. Significant development in such network models ([37], [29], [17], [9], [43], [6], [49], [51], [47], [1]) have resulted in better accuracy. However, finite element analysis still remains the most accurate method to obtain performance characteristics of the machine. Estimating reluctance from flux tube method ([12], [32], [17], [9], [6]) is popularly used to calculate reluctance or permeance deterministically, as a function of displacement of mover, to track changes of inductance with position [10]. Chen et al. [9] has estimated the distribution of magnetic flux linkage in the air gap for six special mover positions. Gauss-Seidel iteration method with fixed phase current has been used to determine the distribution of flux linkages. Lee at al. [12] uses a bisection method to narrow down the variables by iterating for the mmf supplied to the system. Fonseca et al. [22] adopts the Runga Kutta method to calculate the distribution of flux linkages while Lee B S. [31] evaluates magnetic flux linkage by applying conservation of magneto-motive force in the system. Finite Element Analysis/Method (FEA or FEM) is the most proficient alternative in analysing the flux linkage characteristics. Researchers ([34], [35], [29], [12], [2], [17], [43], [21], [20], [33], [47], [28], [13], [60], [16]) have adopted 2D finite element analysis to calculate thrust and levitation forces in LSRM. Barhoumi et al. [6] has compared the proposed efficient reluctance network with FEM results which delivers considerable accuracy. Lee et al. [32] demonstrates 2D results for a single stator LF LSRM in aligned and unaligned positions. Due to approximation of geometry in 2D, the primary variables in the weak formulations are approximated which is inconsistent with the practical model. In 2D, the flow of current is assumed in only one plane but in practice, the coil windings carrying current are wound in 3D space. Such approximations lead to error in result. A 3D finite element analysis carried out by ([5], [39], [14], [15], [26], [6], [49], [19]), provides better accuracy of results with experimental data. Zhang et al. [58] has compared the variation in static force as obtained by 2D and 3D FEA for short stack length LSRMs. Zou et al. [60] has studied on deformation and acoustic noise production of a skewed teeth secondary attributed to normal force, which uses FEA. Pan et al. [50] analyses core losses for a planar switched reluctance motor with time stepping finite element method. Ganji and Askari [25], with the help of FEM, has carried out an extensive analysis on full pitched, short pitched and conventional LSRMs. Takayama et al. [53] has focused their attention on validation of formulation of thrust force by experimental results by using a matrix of ribbon-like hall effect sensor and semiconductor type sensor, both in 2D and 3D analysis. The concept of partial magnetic flux is established and held responsible for maximum contribution to thrust/propulsion force. Liu et al. [40] determines the stability of a TFLSRM with as a passive stator configuration primarily adopted to be used as a bogie for transportation purposes. Eigen values of the state space equation involving closed form equations of voltage, velocity and motion are obtained, the solution from which ensured stability. Thermal characteristics under different phase current operation has been studied by [2] and [8]. Dalbadan and Ustkoyuncu [13] used a combined form of Artificial Neural Network (ANN) and Fuzzy Interference system(FIS), in a LSRM to analyze performance characteristics of a LF-LSRM. Chen et al. [9] has used a back propagation feed forward neural network and coupled it with genetic algorithm to handle six mover position, current and corresponding magnetization flux linkage.

Control

The need of any SRM or LSRM is to be able to achieve the maximum torque or the thrust force and this can be done by designing a converter which has fast fall and rise time. There are various typologies of converters that have been used by the researchers to make this possible, for example, R-Dump converter, C-Dump converter, C-Dump with freewheeling converter, asymmetric converter, series passive converter, parallel passive converter and split source type converter [42], [24]. Among various available topology of the converter the best available option for this operation is an asymmetric bridge converter. Asymmetric bridge converter for a single coil can be used many times in the same DC rail depending on the number of coil required to be controlled independently[45]. Once the topology of the converter is fixed, the challenge is to have a proper control over mover position. In any control scheme of LSRM generally there exists three control blocks namely position control block, current control block and PWM inverter block. However due to nonlinear relationship of force, position and current, it is required to have a linearization block in between to have a proper control of position ([28], [19], [44], [52], [23], [59], [48]) . The easiest way of achieving linear behavior is to use look up table or force distribution function. The look-up table or force distribution function can be constructed either experimentally or numerically based on the inverse relationship between force position and current.

Conclusion

This article aims at delivering a quick glance of vital development stages focusing on the application of LSRM. A brief discussion on design flexibility and their adaption by researchers leads to a review of design algorithms already at place. Analytical approaches are documented for comparison and design validation. Several aspects associated with performance optimization are also mentioned. An effort has been made to correlate each section so as to provide a designer with a broader picture of LSRM and further exploit its features.

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