Review of Linear Switched Reluctance Motor Designs for Linear Propulsion Applications

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Abstract— **Linear switched reluctance motor (LSRM) and its applications in different industries have been an interesting research topic for the past few years. LSRMs have proved to be a suitable alternative in a variety of applications requiring linear motion. However, its use is not that popular which instigated an active interest in the evolution of newer LSRM configurations. Enhancement in its propulsion force along with the reduction in force ripples, weight, acoustic noise, and vibration have been the main objectives in recently proposed LSRM designs. In this paper, recently proposed LSRM designs are reviewed and analyzed. The paper presents a one-stop introduction and a complete update to the designs, both in terms of qualitative and quantitative parameters. In addition, it takes into account the challenges in the implementation of these designs. Based on a detailed comparison of these designs as presented in this paper, an appropriate design can be chosen for a given application.**

Index Terms— **Linear switched reluctance motor, Motor design, Linear motion, Industrial applications.**

I. INTRODUCTION

LINEAR switched reluctance motor (LSRM) is one of the most researched motors due to highly desirable features suitable for industrial use. This motor has been designed for applications requiring linear motion such as conveners, elevators, rail transit vehicles, photovoltaic power generation, direct-drive wave energy conversions, motorized ventricular devices etc. The use of linear motors supersedes rotary motors in such applications because of production of linear motion with gearless direct transmission and fewer mechanical losses [1]. Linear induction motor and linear synchronous motors are widely preferred for linear applications [1],[2]. However, in view of advantages like low cost, simple construction, high starting force and high fault tolerances, LSRMs are receiving much wider attention both, in terms of designs and control schemes. LSRMs exhibit limitations such as high force ripples, more weight, complex control, high acoustic noise and vibrations [3]-[4]. Consequently, for the past few years, efforts are directed to develop LSRM designs not only to overcome these limitations but to improve its propulsion force as well.

Many LSRM designs have appeared in the literature. These designs have their own merits and demerits from viewpoint of application requirements. As of now, no literature is available which comprehensively reviews the aforementioned designs thereby stipulating their comparative advantages and limitations.

This paper aims to present a complete review of all LSRM designs proposed with the exclusive objective of improving its performance limitations. Analysis of these designs is specifically carried out on the following basis:

- Structural modifications for different applications
- Improvement in propulsion force obtained
- Reduction in force ripples, volume, and noise

In addition, this paper provides a comprehensive reference list for researchers in relation to LSRM designs for different applications. Although the development of designs has been accompanied by advancement in control schemes, this paper focuses only on structural modifications suggested for LSRM with their consequences.

The paper is organized as follows. In section II, basic constructional and working details about LSRM are given. Classification of various LSRM designs proposed so far is discussed in section III. This section is divided into 5 sub-sections. Each sub-section is dedicated to a particular type of modification suggested in the LSRM structure. To elaborate on these modifications, sub-sections are divided into sub-sub-sections to describe variations in different modifications. Comments are then made on them based on qualitative and quantitative parameters. The summary of these designs is presented in section IV in the form of discussions. Concluding remarks are given in section V.

II. BASIC LINEAR SWITCHED RELUCTANCE MOTOR

Basic LSRM mainly consists of three major parts: stator (S), translator (T) and excitation windings (W) as shown in Fig. 1 [2]-[4]. Out of stator and translator, one moves while the other remains stationary during operation. The LSRM is generally mounted with concentrated copper windings that can be wound either on stator or on translator. Both the stator and translator are constructed with ferromagnetic material and have teethed structure. This double salient structure varies reluctance between them. Thus, whenever a phase is excited, the moving part aligns its teeth with stationary teeth to provide minimum reluctance path to the flux flowing inside the motor.

Depending upon the direction of flux flow (Ø) with respect to the direction of motion, basic LSRM is classified as

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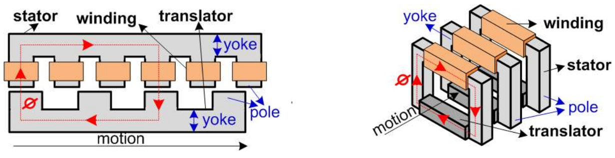
longitudinal (LLSRM) and transverse LSRM (TLSRM) [1],[2].

In LLSRM, stator and translator are arranged longitudinally so that the flux flows in-parallel with the direction of motion as marked in Fig. 1(a) while in TLSRM, the direction of flux remains perpendicular to the direction of motion during its entire operation as shown in Fig. 1(b).



(a) (b)

Fig. 1. Basic LSRM structure (a) LLSRM (b) TLSRM.

The basic design though possesses simple construction, high starting torque however, it suffers from high force ripples, bulky construction, high acoustic noise and vibrations [3]-[4]. Force ripples occur in LSRM due to the formation of dips in force profile during sequential switching of excited phases while LSRM produces acoustic noise and vibrations due to its double saliency [2]-[4].

A slight modification in the basic parts of this design has proven its effectiveness in overcoming these drawbacks. The different LSRM designs that were proposed by modifying its basic structure are discussed further in the following section.

III. CATEGORIZATION OF PROPOSED MODIFICATIONS IN LSRM'S BASIC STRUCTURE

In different designs given in the literature, modifications are generally proposed in one of its basic parts i.e. either stator (S), translator (T) or excitation winding (W) including yokes and poles as shown in Fig.1

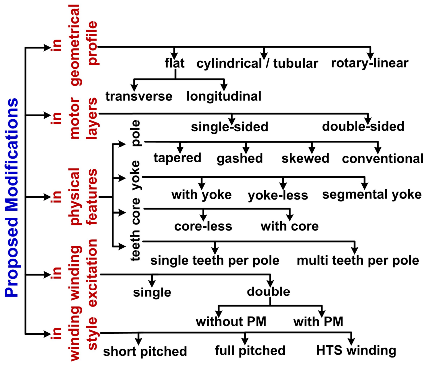


Fig. 2. Categorization of LSRM designs.

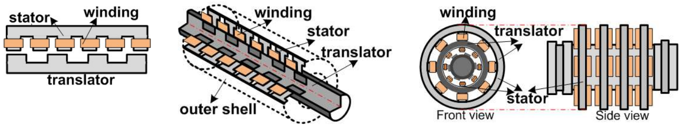
To understand different proposed modifications in detail, the studied designs presented here are classified based on modified physical part as given in Fig. 2. Various alterations in studied designs are mainly classified as:

- Modification in geometrical profile
- Modification in motor layers
- Modification in physical features
- Modification in winding excitation
- Modification in winding style

It is important to mention that different papers have followed different terminologies for describing modifications proposed in LSRM. However, to follow common terminology for comparative analysis of these designs, the moving part of LSRM is termed as translator and the stationary part is termed as stator in further descriptions. All these designs are differentiated by using different numbers that are preceded by the letter "D" e.g D-1, D-2, etc. This is done only for the ease of referring. Detailed analyses of these modifications are discussed further in the section.

A. *Modifications in Geometrical Profile*

Depending upon its use, LSRM's profile can be flat, cylindrical/tubular or rotary-linear. These geometries are shown in Fig.3. Various topologies are proposed with these geometries. These are described from design D-1 to D-22.



(a) (b) (c)

Fig. 3. LSRM (a) flat (D-1) (b) cylindrical (D-2) (c) rotary-linear (D-3).

1. *Flat Geometry*

Flat geometry as shown as D-1 in Fig. 3(a) is one of the widely proposed geometry for producing linear motion. The D-1 is a 6/4 flat LSRM with 4 translator poles over 6 stator poles [2]. Flat LSRM can be either LLSRM or TLSRM as shown in Fig. 1. Many forms of these geometries are found in the literature. The D-4 shown in Fig.4 (a) is used for horizontal propulsion, which is a 6/8 LSRM with windings on the translator [5]. Fig. 4 (b) shows D-5, which contains 4 levitation modules (LM) along with windings on the translator to simplify the levitation control mechanism [6]. Thus, D-5 is more suitable than D-4 for the transportation system, however with a heavier translator.

(a) (b) (c) (d)

Fig. 4. Flat LLSRM (a) D-4 (b) D-5 (c) D-6 (d) D-7.

The D-6 as shown in Fig. 4 (c), is reported in [7] for high precision applications. In this, translator phases are decoupled to reduce the flux path and, span of the translator phase aligns itself with alternate stator teeth. It not only reduces mutual inductance between windings but also eases the excitation control. However, the installation of this configuration is slightly complicated due to the absence of a common yoke.

Using this phase decoupling design, a very thin D-7 is reported in [8] for use in microscopes, alignment apparatus, inspection systems etc. As shown in Fig. 4(d), in D-7, the stator is flattened to accommodate windings while translator is in the form of a replaceable thin sheet with no windings.

D-4 to D-7 are designs of flat LLSRM. However, plenty of designs for flat TLSRMs are also available in the literature for different applications. D-8 to D-14 shown in Fig.5 represents the transverse section of TLSRMs.

In D-8 [9] shown in Fig. 5(a), a C-shaped translator is used with an I-shaped stator. However, it contains windings on both translator limbs, which mainly improves flux distribution inside the core with only two airgaps. But it also increases winding weight and cost. In D-8, common yoke is not present to tie different transverse sections, which is a general trend in TLSRM designs. Yokeless designs increase installation difficulty. Thus, to overcome that, D-9 is proposed with a similar configuration as D-8 but with a common yoke connecting all translator sections. This design is proposed for rail transit applications in [10]. In both D-8 & D-9, windings are installed on both limbs.

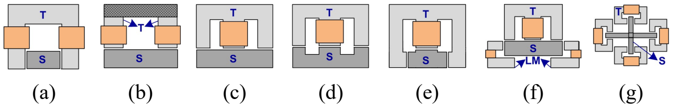


Fig. 5. TLSRM (a) D-8 (b) D-9 (c) D-10 (d) D-11 (e) D-12 (f) D-13 (g) D-14.

To reduce winding complexity and cost, D-10 is proposed with an E-shaped translator and an I-shaped stator [11]. However, it increases the number of airgaps to three. Also, not much weight saving can be seen due to thicker central limb. Though, copper saving is a plus point here. In D-11, the stator is slightly modified to E-shape by giving two notches in the I-core, which reduces its weight [12]. Moreover, the translator remains E-shaped, as in D-10. This design is proposed for rail vehicles where translator is mounted on a common platform.

In D-12 [13], the stator is similar to D-11, however, size is slightly reduced to accommodate extended translator limbs as shown in Fig.5(e). It is suitable for applications having less space for stator installation. These designs are further enhanced by adding LM in D-13 as shown in Fig. 5(f) [14]. This design is proposed to reduce control requirements in levitation-based applications. TLSRMs are generally known to produce less force with fewer force ripples as compared to LLSRMs. Thus, to increase its force, a four-sided D-14 is proposed in [15] as shown in Fig. 5(g). In this, the four-sided translator is fitted with a thin segmental stator consisting of small round ferromagnetic chips mounted on a four-sided thin plate forming the stator yoke. It surely increases its force production, however at the cost of a bulky translator with increased copper weight.

2. *Cylindrical or Tubular Geometry*

These LSRMs are generally fitted inside a cylinder where the connected shaft acts as a translator to produce linear motion as shown in Fig 1(b) as D-2. In D-2 [16], the stator contains windings to flow the flux perpendicular to the motion direction. Moreover, the translator contains a basic structure. This design is proposed for linear compressors.

Generally, such geometries are reported for use in ventricular medical equipment. In D-15 [17] shown in Fig. 6(a), a similar decoupled phase flux structure of D-6 is used for stator. While teethed translator is mounted on its shaft. Design D-16 [18] shown in Fig. 6(b), is like D-15 in many ways. The only difference is in stator phase poles span.

In D-17 [19], the basic structure is used for both stator and translator which is same as given in D-1. However, the force is increased by mounting windings on both stator and translator as shown in Fig. 6(c). However, this increment must be at a cost of increased copper usage.

In D-18 shown in Fig. 6(d) [20], is proposed for wave energy conversion. In this, phase windings are mounted on a translator with permanent magnet (PM) blocks. In D-18, two phases are excited at a time to introduce mutual inductance in the magnetic circuit. In addition, the salient pole stator remains stationary with no windings.

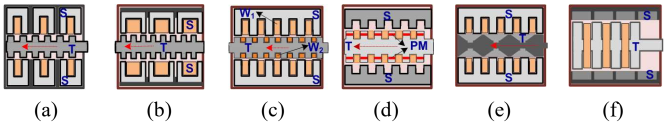


Fig. 6. Tubular (a) D-15 (b) D-16 (c) D-17 (d) D-18 (e) D-19 (f) D-20.

D-19 [21],[22] is proposed for generation application as shown in Fig. 6(e). In D-19 basic structure is used for stator. However, a segmental structure is proposed for the translator in which trapezoidal blocks of ferromagnetic material are fitted on a shaft made of non-ferromagnetic material. This not only reduces the inner flux path to reduce losses but also reduces the translator weight.

A slight modification is done in D-19 [23] as shown in Fig. 6(f) as D-20. In this design, segmental stator design is proposed with rectangular ferromagnetic blocks. Windings are mounted on the translator that increases translator weight.

3. *Rotary-Linear Geometry*

Rotary-linear SRMs (RLSRMs) are generally designed for applications requiring both rotary and linear motion simultaneously. Position control of solar PV panels can be an example of such an application. Fig.1(c) shows the structure of an RLSRM as D-3 [24]. In this design, outer and inner stators are inserted into a tube. The 3-phase inner stator produces rotary motion while the 4-phase outer stator produces linear motion and exerts a force on the translator that acts as a shaft. It uses both longitudinal and transverse flux paths during its operation. Rotary and linear motions are separately controlled to monitor the movement of solar PV panels.

The RLSRM given in [25] is shown in Fig. 7(a) as D-21. In this, two stacks of stators (S_1 & S_2) are reported. Rectangular blocks are mounted on the shaft to produce rotary and linear motion simultaneously. Both these motions are controlled independently. Each stator and translator pair correspond to 6/4 SRM.

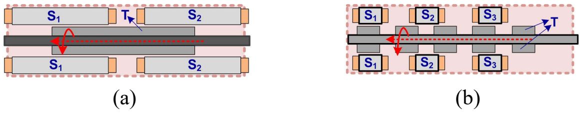


Fig. 7. Rotary-Linear LSRM (a) D-21 (b) D-22.

D-22 is a slight modification in D-21, as proposed in [26] shown in Fig. 7(b). In this, three stator stacks (S_1, S_2 & S_3) are reported. Every stator stack consists of 4-phases with 4 poles/phase. In addition, small rectangular blocks are mounted on the shaft to form different stacks of translators. Every translator stack consists of 12 poles to produce rotary motion. Three stator stacks act as three phases to produce linear motion. Translator produces both linear and rotary motions.

B. *Modifications in Motor Layers*

The designs discussed so far contain only one layer of stator and translator. These are therefore known as single-sided

LSRM (SSLSRM). They not only produce propulsion force but also produce repulsive/ attractive force perpendicularly to the motion direction because of their flat geometry. The applications requiring complete nullification of perpendicular/normal force need double-sided LSRMs (DSLSRM). They cancel net normal force by producing two equal and opposite forces. Also, their geometry doubles the propulsion force. Many designs are proposed for DSLSRMs.

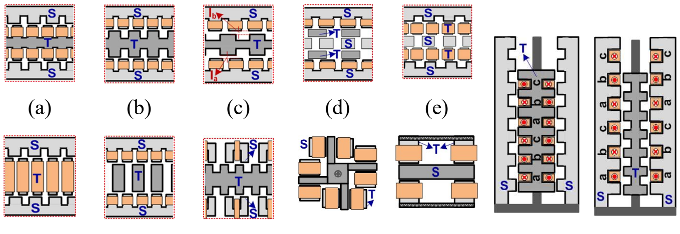

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Fig. 8. DSLSRM (a) D-23 (b) D-24 (c) D-25(d) D-26 (e) D-27 (f) D-28 (g) D-29 (h) D-30 (i) D-31 (j) D- 32 (k) D- 33 (l) D- 34.

In D-23 proposed in [27], D-1 is joined back to back as shown in Fig. 8(a). This design uses a 6/8 configuration in which the translator moves with the windings. The design was studied for elevator application. In D-24 [28], 6/8 LSRM is mentioned, which is similar to D-23. However, D-24 contains windings on the stator instead of the translator as shown in Fig. 8(b). This is done to decrease the translator weight. Fig.8(c) shows D-25 eccentric DSLSRM reported in [29] with different airgaps. This design is used to study air-gap eccentricities due to constructional flaws.

D-26 is a 6/4 LSRM proposed in [30] for high force density applications. It contains a stator that is divided into three parts as shown in Fig. 8(d). The middle stator consists of individual rectangular blocks with no yoke. Other two yoked stator parts contain windings. Whereas translators are yoke-less with rectangular blocks mounted between the stator partitions. This increases the airgaps to 4. Also, its installation is quite tricky.

D-27 [27] is like D-26, with a 6/8 configuration. In this, windings are mounted on a translator instead of a stator as shown in Fig. 8(e). D-28 is also reported in [27] as shown in Fig. 8(f). In this, yokeless translator contains windings. However, the stator with yoke does not contain any windings. Thus, translator weight is comparatively less as compared to D-23, however, its installation is slightly complex as there is no space given to fix the translator. To overcome the challenges of this design, D-29 is proposed in [28] as shown in Fig. 8 (g). In D-29, the yoked stator is wound with windings whereas, the yoke-less translator contains no windings.

For further improvement, D-30 is reported in [31] as shown in Fig. 8(h). In D-30 stator has decoupled design of D-6 with windings but the translator does not contain any winding. The stator teeth span is such that it aligns with consecutive translator teeth. The design is proposed for railway shunting channels. However, an increase in the installation cost of stator segments may be an issue. To increase the force and introduce the four-quadrant operation, a four-sided DSLSRM design is reported in [32] as shown as D-31 in Fig. 8(i). In this, all the four DSLSRMs contain basic structure of D-28. This ripple-free design is studied for application in active suspension systems.

The D-9 is arranged in two layers to form D-32 DSLSRM shown in Fig. 8(j) [10]. Unlike previous longitudinal designs, this is a transverse DSLSRM with a yoked translator. The stator is kept yokeless. This design is proposed for rail transit. However, TLSRMs are known to produce less force with less ripples as compared to LLSRMs. Therefore, its comparative performance with LLSRM needs attention. D-33 is reported for vertical propulsion wave energy conversion application in [33]. In D-33, the translator contains full-pitched winding as shown in Fig. 8(k). This enables dual phase excitation, to produce mutual inductances. D-34 is also reported for vertical propulsion in wave generator applications [34]. However, in D-34 stator contains full-pitch windings to introduce mutual inductance in its magnetic circuit by enabling dual excitation. The winding free translator is used to reduce its weight.

C. *Modifications in Physical Features*

To overcome the limitations of basic design, many modifications in physical features are suggested in the literature. These modifications mainly include variations in pole shapes, yoke, core and teeth, which are discussed further.

1. *Pole Variation*

Fig. 9(a) shows the basic pole structure as P-1. All the designs studied so far contains P-1 shapes. However, this shape suffers from saturation and flux fringing at the edges. This also gives comparatively higher ripples, acoustic noise and vibrations during motor operations.

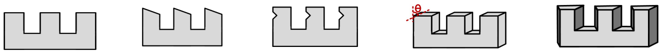

(a) (b) (c) (d) (e)

Fig. 9. Pole variation (a) basic (P-1) (b) tapered (P-2) (c) gashed (P-3) (d) skewed (P-4) (e) modified skew (P-5).

To overcome them, tapered poles (P-2) reported in [35] are shown in Fig. 9(b). Tapering is found to reduce force ripples and vibrations. Gashed poles (P-3) shown in Fig. 9(c), are used in stator in [36]. This is proposed for reducing force ripples and stator weight. However, the use of P-3 shows an increment in propulsion force also, due to reduction in ripples.

Fig. 9(d) shows skewed stator poles (P-4) that are used in [37],[38]. The P-5 in Fig. 9(e) shows a modified form of these skewed poles. Both P-4 and P-5 are comparatively studied in [38] to establish that P-4 gives better force density as compared to P-1. Whereas, P-5 increases force density and reduces pole weight. These are some of the variations in stator pole structure to obtain performance enhancement of LSRMs.

2. *Yoke and Core Variation*

Many variations in yoke and core construction are available in literature. The main objectives of these variations are either to reduce translator weight or to reduce constructional cost.

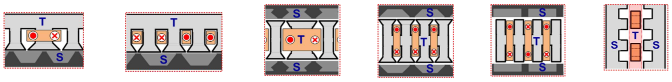

(a) (b) (c) (d) (e) (f)

Fig. 10. Yoke/core variation (a) D-35 (b) D-36 (c) D 37 (d) D-38 (e) D-39 (f) D-40.

An E-shape core in Fig. 10(a) as D-35, is reported for translator phases [39]. This reduces the flux path. In D-35, stator consists of trapezoidal segments of ferromagnetic material fitted on a block of non-ferromagnetic material. Translator slots are semi-enclosed to increase airgap flux.

Another variation is proposed in [39] named D-36 here. In this, a basic translator is used with semi-enclosed slots as shown in Fig. 10(b). However, the stator is same as reported in D-35. Full-pitch windings are used on the translator. The same design is given in [40]. Th only difference is that the stator and translator are interchanged.

Fig. 10(c) shows a D-37 variation in which the segmental stator of D-35 and D-36 is connected on both sides to form DSLSRM [41]. However, the shape of the segment is slightly changed to increase the grip of every segment on the non-ferromagnetic block. The translator in D-37 is yokeless with different I-core segments arranged with concentrated windings. These winding poles are separated from each other with additional thin I-cores. Translator slots are semi-enclosed for even spreading of airgap flux.

D-38 shown in Fig. 10(d), used the segmental core of D-35 and D-36 on both sides to form a DSLSRM [42]. It uses a basic translator with semi-enclosed slots. Toroid windings are wound on the translator to reduce its inner flux path.

Another modification D-39 reported in [23] is shown in Fig. 10(e). In D-39, rectangular ferromagnetic segments are used in the stator core instead of trapezoidal segments of D-38. In this, toroid winding is used. However, translator winding slots are rectangular-shaped. Fig. 10(f) shows D-40 with a core-less translator as in [43]. Its translator uses high-temperature superconducting (HTS) windings encased in a container with supercooling liquid. The basic stator on both sides of the translator forms a DSLSRM that is aligned vertically. It is proposed for vertical propulsion.

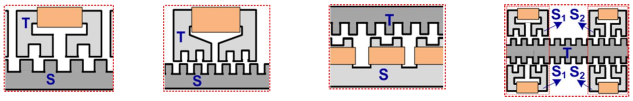
3. *Teeth Variation*

The teeth variations are generally proposed for reducing propulsion force ripples. Fig. 11 (a) gives D-41 reported in [44],[45]. In D-41, the translator consists of decoupled phases to reduce flux path as well as mutual inductance as in D-6. However, here each translator pole contains two teeth. This reduces the translator and stator teeth width that further reduces the ripples. Its stator contains a basic shape. A similar design with a slight modification is given in [46] in which the translator consists of aluminum to further decrease its weight.

In D-42 shown in Fig. 11(b), the same decoupled translator is reported as given in D-41 [47]. However, D-42 is proposed to move in an x-y plane instead of a straight line. Also, the translator consists of two sets of three-phase windings with three teeth per translator pole. Whereas stator consists of a teethed sheet laid in an x-y plane that is formed from laminated silicon steel blocks mounted on an aluminum base.

In D-43 shown in Fig.11 (c), each stator pole contains a notch to virtually increase the number of teeth, without increasing the number of phases [48]. This notch, therefore, divides the flux into two parts. In addition, translator teeth are more as compared to stator teeth. This increases the stator slot size to accommodate more windings. This design is mainly proposed to increase force and reduce ripples.

Fig. 11 (d) shows D-44 design [49]. It is given with two sets of stators (S_1 and S_2). Both sets have the same construction as D-41 translator. S_1 and S_2 both are controlled independently. The S_1 is fixed whereas the translator moves as a primary mover. The S_2 is also movable and serves as secondary mover. It tests the controlling of two stators on a common platform.



(a) (b) (c) (d)

Fig. 11. Teeth variation (a) D-41 (b) D-42 (c) D-43 (d) D-44.

D. *Modifications in Winding Excitation*

Designs in previous discussion are all excited by windings that are either wound on translator or on stator to make them singly excited. However, to further make its force comparable to other popular linear motors dual excitation is suggested.

1. *Dual Excitation without Permanent Magnet (PM)*

One alteration suggested for dual excitation is shown in Fig. 12(a) as D-45 [50]. In D-45, D-41 design is taken with stator and translator both wounded with winding sets W_1 and W_2.

(a) (b)

Fig. 12. Dual Excitation without PM (a) D-45 (b) D-46.

D-46 shown in Fig. 12(b) is reported in [51]. It is a basic 6/8 LSRM of D-3. However, the only difference is that both translator and stator contain windings.

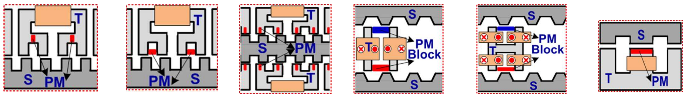
2. *Dual Excitation with Permanent Magnet (PM)*

To further increase the force, many variations are suggested with PM. Fig. 13(a) shows D-47 with flux decoupling similar to D-41 [52]. However, in D-47, PM blocks are inserted vertically in translator poles along with windings. The use of PM blocks with windings increases the air-gap flux that further increases the force. The D-48 suggested in [54] is shown in Fig. 13 (b). It is also similar to D-41. However, here PM blocks are inserted between two teeth of translator pole.

In D-49 given in [53], the D-41 translator is connected on both sides to form a DSLSRM and the stator is of a basic shape. The translator contains two teeth/pole. It also contains PM blocks along with windings. The PMs are inserted vertically in every translator teeth as shown in Fig. 13(c).

Fig. 13(d) gives D-50 with basic stators [54] with trapezoidal-shaped teeth. Its translator is yokeless with windings. Each translator phase consists of a pair of I-shaped limbs that are decoupled from other phases, to reduce flux path. Each pair of limbs is wound with positive and negative windings. PM blocks are fitted horizontally in between these limbs to complete the phase excitation. D-51 contains the same stator structure as D-50 as shown in Fig.13(e). Its translator phases are yokeless and decoupled from each other [54]. Each phase consists of an H-shaped core, where each limb of ‘H’ contains windings. PM blocks are inserted horizontally between upper and lower gaps of ‘H’.

A D-52 is a TLSRM proposed in [55]. This design is proposed for railways with translator on the vehicle as shown in Fig. 13(f). Each translator phase contains PMs along with windings. Both stator and translator contain E-shape sections.



(a) (b) (c) (d) (e) (f)

Fig. 13. Dual Excitation with PM (a) D- 47 (b) D-48 (c) D-49 (d) D-50 (e) D-51 (f) D-52.

Dual excitation with PM gives better force as compared to single excitation; however, with the increased cost. Also, the insertion of PM blocks increases control complexity as the extra mechanism is required to control the activation and deactivation of PMs during every phase excitation.

E. Modifications in Winding Style

Different LSRMs discussed so far either contain concentrated windings, which are short-pitched windings or contains full-pitched windings. Short-pitched windings are commonly used for different applications. Also, in [56], basic LSRM is wound with double-layer windings. These windings are fitted in semi-enclosed slots not only to reduce the overall stator length and force ripples but also to increase its force. The designs that consider dual-phase excitation, are generally wound with full-pitch windings. D-33, D-34 and D-36 contain full-pitch windings. When dual-phase excitation is used, mutual inductance becomes significant in the magnetic circuit. However, due to the overlapping of phase excitations, force ripples are drastically reduced. In D-40, HTS windings are wound on a core-less translator to increase force. However, it may lead to an increase in its cost.

IV. DISCUSSIONS

Based on the analysis of different LSRMs designs presented in previous section, comments can be made on qualitative and quantitative parameters of these modifications. A summary of these modifications is presented in Table 1. The modifications given in LLSRM make it suitable not only for railways but also for very tiny applications like microscopic instruments. Different TLSRMs with different core modifications are suggested not only to reduce translator weight but also to reduce copper usage. Three and four-sided TLSRMs are also presented for improving its force performance.

Modifications in cylindrical LSRM are given to achieve propulsion force with reduced cost for use in medical equipment. Different RLSRMs that produce both rotary and linear motion simultaneously are altered mainly for controlling the motion of solar tracking plates in PV panels. Different DSLSRMs are given to maximize the force using two SSLSRM back to back. Due to their symmetry, the normal forces produced by two SSLSRMs get cancelled. This not only doubles the propulsion force but also reduces the ripples. The DSLSRMs are generally preferred for elevator applications and wave energy conversion. Bulky constructions are their major drawback. Many yokeless DSLSRMs are thus presented to reduce weight. However, their size is still questionable. TLSRMs are also converted to DSLSRM. Four such DSLSRMS are connected to form a different design for high precision applications. These are proposed for railway propulsion and active suspension systems.

Different pole shapes are proposed for minimizing ripples and weight. Variations in yoke and core structures are also done not only to reduce weight but also to reduce losses by reducing the inner flux path. In coreless design, superconducting windings are used mainly to increase their propulsion force. Teeth variations with 2 to 3 teeth/pole are given mainly to reduce ripples. Designs with windings on both stator and translator are also given. This increases force but at the cost of increased copper usage.

PMs are used with windings for high-force applications. PMs are fitted to increase air-gap flux. PM not only increases the cost but also increases the control requirement.

Different winding styles are seen in designs including short-pitch and full-pitch. Full-pitch windings enable dual-phase excitation to introduce mutual inductance in the circuit. The pros and cons of these modifications are summarized in Table 1 along with their suggested applications. This table can be used as a one-stop review of LSRM design modifications proposed so far in the literature. This can also be used to choose suitable motor designs for different applications.

V. CONCLUSION

As linear switched reluctance motors continue to gain increasing importance for both high force and low force applications, many researchers have proposed specific structural modifications for intended applications. Also, newer designs have been proposed offering high precision performance with comparatively reduced size and manufacturing cost as compared to other popular linear motors. In this paper, a review of different modifications suggested so far in the LSRM structure is presented. Based on the review, it can be concluded that in the process of increasing force and reducing ripples, various compromises are involved such as:

- Bulkiness of DSLSRMs & SSLSRMs due to LM modules
- Increased size of three-sided and four-sided TLSRMs
- Complex installation of yokeless stators and translators
- Questionable rigidity of segmental stator and translators
- Increase in cost with superconducting windings
- Increased cost and control complexity due to PM blocks

In this paper, qualitative and quantitative features of different LSRM designs have been discussed and a comparison has been made so as to facilitate a well-informed selection of a suitable design for a given application. In addition, the paradigm presented in the paper will also help to evaluate the LSRM designs that will be proposed in the future.

TABLE I
SUMMARY OF MODIFICATIONS SUGGESTED IN STUDIED LINEAR SWITCHED RELUCTANCE MOTOR DESIGNS

Modification Type	Design Type		Various advantages obtained	Suggested application	Concerns
Modification in geometrical profile	Longitudinal	D-1, 4 to7	• simple structure with use of PM • loss reduction, reduce control needs • molded in very thin size • cost cutting, weight reduction • rotary & linear motion together	• rail transport, microscopes • alignment apparatus • inspection systems • ventricular equipment • solar PV panels	• more weight due to LM • increased cost due to PM • more converter needs for RLSRMs • fixing of yokeless designs
	Transverse	D-8 to 14			
	Cylindrical	D-2, 15 to 20			
	Rotary-Linear	D-3, 21,22			
Modification in motor layers	single-sided	D-1 to 22	• increased force with zero normal force • decreased ripples, cost & weight	• elevators, suspension system • railways, wave generator	• bulky structure • fixing yokeless designs
	double-sided	D-23 to 34			
Modification in physical features	pole	P-1 to 5	**pole variation:** • reduced ripples & vibrations • more force with cost & weight saving **yoke and core variation:** • weight and cost saving, increased force • reduced losses & ripples **teeth variation:** • reduced ripple, saturation & vibration • increased force & reduced weight	• rail transit systems • elevators • horizontal propulsion • vertical propulsion • industrial automation	• installations of yokeless designs • saturation at teeth edges • increased production cost
	yoke & core	D-35 to 40			
	teeth	D-41 to 44			
Modification in excitation	Double (w/o PM)	D-45 to 46	• increased force • reduced ripples and reduced weight	• high-force density • horizontal propulsion	• more copper & more cost • complex control
	Double (w PM)	D-47 to 52			
Modification in winding style	full pitch	D-33,34,36	• reduced stator length, ripples & cost • increased force & winding efficiency • temperature resistant winding	• smooth &vertical propulsion • elevator, wave generators • horizontal propulsion	• cryogenic requirement in HTS windings
	HTS	D-40			

REFERENCES

[1] I. Boldea, L. N. Tutelea, W. Xu and M. Pucci, "Linear Electric Machines, Drives, and MAGLEVs: An Overview," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 9, pp. 7504-7515, 2018.

[2] Byeong-Seok Lee, Han-Kyung Bae, P. Vijayraghavan and R. Krishnan, "Design of a linear switched reluctance machine," *IEEE Transactions on Industry Applications*, vol. 36, no. 6, pp. 1571-1580, 2000.

[3] X. Xue, K. W. E. Cheng, Z. Zhang, J. Lin and N. Cheung, "A Novel Method to Minimize Force Ripple of Multimodular Linear Switched Reluctance Actuators/Motors," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 3859-3862, 2012.

[4] N. C. Lenin, R. Arumugam," Vibration analysis and control in linear switched reluctance motor", *Journal of Vibroengineering*, vol. 13, no. 4, pp. 662-675, 2011.

[5] H. K. Bae, B.S. Lee, P. Vijayraghavan and R. Krishnan, "A linear switched reluctance motor: converter and control," *IEEE Transactions on Industry Applications*, vol. 36, no. 5, pp. 1351-1359, 2000.

[6] W. Hao, and Y. Wang, "A brief analysis of a bearingless linear switched reluctance motor with mover structural decoupling design", *IEEJ Transactions on Electrical and Electronic Engineering*, vol.14, pp.652-653, 2019.

[7] A.E. Espírito-Santo, M.R.A. Calado, C.M.P. Cabrita, "On the influence of the pole and teeth shapes on the performance of linear switched reluctance actuator", *COMPEL - The international journal for computation and mathematics in electrical and electronic engineering*, vol. 30, no. 2, pp. 412-430, 2011.

[8] K. Sato, "Novel Compact Linear Switched Reluctance Motor with a Thin Shape and a Simple and Easily Replaceable Mover", *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, vol.7, no.3, pp 295-304, 2013.

[9] D.S.B Fonseca, C.P.Cabrita, M.R.A. Calado, "A new methodology for dynamic performance simulation of a new linear switched reluctance motor based on geometric dimensions", in *Proc. of 6th WSEAS International Conference on Power Systems*, Lisbon, Portugal, September 22-24, 2006, pp. 84-89.

[10] F. Daldaban, U. Nurettin , "A novel linear switched reluctance motor for railway transportation systems", *Energy Conversion and Management*, vol. 51, no. 3, 2010, pp. 465-469.

[11] Y.Avşar, A. Fenercioğlu, "structural analysis of linear switched reluctance motor designed EIcore", *The Online Journal of Science and Technology*, vol. 6, no.3 pp. 64-68, 2015.

[12] G. Baoming, A. T. de Almeida and F. J. T. E. Ferreira, "Design of Transverse Flux Linear Switched Reluctance Motor," *IEEE Transactions on Magnetics*, vol. 45, no. 1, pp. 113-119, 2009.

[13] Y. Avşar, A. Fenercioğlu, "Force analysis of linear switched reluctance motor with modular core structure", *International Scientific Conference UNITECH 2015*, pp.172-174, Gabrovo, Bulgaria, 20-21 Nov. 2015.

[14] F. Daldaban, N. Ustkoyuncu, "A new linear switched reluctance motor with MagLev effect," in *Proc. 2009 International Conference on Electrical and Electronics Engineering - ELECO 2009*, Bursa, 2009, pp. I-420-I-422.

[15] M. Vatani, S. Ahmadi, M. Mirsalim and A. Khorsandi, "Performance Analysis of a Novel Linear Switched Reluctance Motor with Transverse-Flux and Four-Sided Structure," in *Proc. 11th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC)*, Tehran, Iran, 2020, pp. 1-5.

[16] X. Xue, K. W. E. Cheng and Z. Zhang, "Model, Analysis, and Application of Tubular Linear Switched Reluctance Actuator for Linear Compressors," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 12, pp. 9863-9872, 2018.

[17] J. Llibre, N. Martinez, B. Nogarède and P. Leprince, "Linear tubular switched reluctance motor for heart assistance circulatory: Analytical and finite element modeling," in *Proc. 2011 10th International Workshop on Electronics, Control, Measurement and Signals*, Liberec, 2011, pp. 1-6.

[18] J. Corda, "Analytical optimisation of electromagnetic design of a linear (tubular) switched reluctance motor", in *Proc. of the XVII International Symposium on Electromagnetic Fields in Mechatronics, (ISEF 2015)*, Valencia, Spain, 10-12 Sep. 2015.

[19] W. Li, C. Chen, L. Yan, Z. Jiao and I. Chen, "Design and modeling of tubular double excitation windings linear switched reluctance motor," in *Proc. IEEE 10th Conference on Industrial Electronics and Applications (ICIEA),* Auckland, 2015, pp. 1686-1691.

[20] J. Du, P. Lu and X. Yang, "Analysis and modeling of mutually coupled linear switched reluctance machine with transverse flux for wave energy conversion," in *Proc. 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, 2016, pp. 1-6.

[21] X. Huang, Z. Lin and X. Xiao, "Four-quadrant force control with minimal ripple for linear switched reluctance machines", *CES Transactions on Electrical Machines and Systems*, vol. 4, no. 1, pp. 27-34, 2020.

[22] D. Wang, C. Shao and X. Wang, "Design and Performance Evaluation of a Tubular Linear Switched Reluctance Generator with Low Cost and High Thrust Density," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 7, pp. 1-5, 2016.

[23] T. Higuchi, Y. Yokoi, T. Abe, N. Yasumura, Y. Miyamoto and S. Makino, "Design analysis of a segment type linear switched reluctance motor," in *Proc. 2017 11th International Symposium on Linear Drives for Industry*

Applications (LDIA), Osaka, 2017, pp. 1-4.

[24] S. Li, K.W.E. Cheng, J. Zhu, Y. Zou, "Design and application of a decoupled rotary-linear switched reluctance motor for concentrated photovoltaic power generation", *IET Electric Power Applications*, vol.12, no.7, pp. 908-915, 2018.

[25] J. Pan, F. Meng, G. Cao, "Decoupled control for integrated rotary–linear switched reluctance motor", *IET Electric Power Applications*, vol. 8, no.5, pp. 199-208, 2014.

[26] I. Benita, M. Ruba, L. Szabo, "A Rotary-Linear Switched Reluctance Motor for Advancd Industrial Applications", PCIM Europe 2011, pp. 947-9512, 17-19 May 2011, Nuremberg, Germany.

[27] N. S. Lobo, H. S. Lim and R. Krishnan, "Comparison of Linear Switched Reluctance Machines for Vertical Propulsion Application: Analysis, Design, and Experimental Correlation," *IEEE Transactions on Industry Applications*, vol. 44, no. 4, pp. 1134-1142, 2008.

[28] J. Garcia-Amorós, P. Andrada, B. Blanqué, "Design Procedure for a Longitudinal Flux Flat Linear Switched Reluctance Motor", *Electric Power Components and Systems*, vol.40, no.2, pp. 161-178, 2011.

[29] Q.Wang, H.Chen, R. Nie, "Unbalanced normal force reduction in the eccentric double-sided linear switched reluctance machine", *IET Electric Power Applications*, vol. 10, no.5, pp. 384-393, 2016.

[30] U. S. Deshpande, J. J. Cathey and E. Richter, "High-force density linear switched reluctance machine," *IEEE Transactions on Industry Applications*, vol. 31, no. 2, pp. 345-352, 1995.

[31] E. M. Barhoumi, M. Hajji, B. B. Salah, "Design of a double-stator linear switched reluctance motor for shunting railway channels", *Turkish Journal of Electrical Engineering & Computer Sciences*, vol. 22, pp. 302-314, 2014.

[32] Z. Zhang, N. C. Cheung, K. W. E. Cheng, X. Xue and J. Lin, "Direct Instantaneous Force Control With Improved Efficiency for Four-Quadrant Operation of Linear Switched Reluctance Actuator in Active Suspension System," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 4, pp. 1567-1576, 2012.

[33] J. Du, D. Liang and X. Liu, "Performance Analysis of a Mutually Coupled Linear Switched Reluctance Machine for Direct-Drive Wave Energy Conversions," *IEEE Transactions on Magnetics*, vol. 53, no. 9, pp. 1-10, 2017.

[34] J. Du and D. Liang, "Optimal performance study of mutually coupled linear switched reluctance generators in wave energy conversion," in *Proc. International Conference on Electrical Machines and Systems*, Beijing, 2011, pp. 1-5.

[35] V.G. Sampath, R. Elavarasan, N.C.Lenin, and R. Arumugam, "Design and Experimental Verification of Linear Switched Reluctance Motor with Tapered Poles", *Applied Mechanics and Materials*, vol. 787, pp. 878–882, 2015.

[36] R. Elevarasan, N. C. Lenin and R. Arumugam, "Analysis of Linear Switched Reluctance Motor having gashed pole," in *Proc. IEEE 2nd International Conference on Electrical Energy Systems (ICEES)*, Chennai, 2014, pp. 168-170.

[37] N. C. Lenin, R. Arumugam, "Design and Experimental Verification of Linear Switched Reluctance Motor with Skewed Poles", *International Journal of Power Electronics and Drive System*, vol. 6, no. 1, 2015, pp. 18-25.

[38] V.G. Sampath, R. Elavarasan, N.C. Lenin, R. Arumugam, "A Novel Skewed Linear Switched Reluctance Motor – Analysis and Design", *Applied Mechanics and Materials*, vol.787, pp. 874–877, 2015.

[39] B. Ganji, M.H. Askari, "Analysis and modeling of different topologies for linear switched reluctance motor using finite element method," *Alexandria Engineering Journal*, vol. 55, no. 3, pp. 2531-2538, 2016.

[40] N. Vattikuti, R. Vandana and B. G. Fernandes, "A novel high force density linear Segemented switched reluctance machine," in *Proc. 34th Annual Conference of IEEE Industrial Electronics*, Orlando, FL, 2008, pp. 1083-1088.

[41] D. Wang, C. Shao, X. Wang and X. Chen, "Design and Performance Comparison of a Bilateral Yokeless Linear Switched Reluctance Machine for Urban Rail Transit System," *IEEE Vehicle Power and Propulsion Conference (VPPC)*, Hangzhou, 2016, pp. 1-5.

[42] D. Wang, X. Du, D. Zhang and X. Wang, "Design, Optimization, and Prototyping of Segmental-Type Linear Switched-Reluctance Motor with a Toroidally Wound Mover for Vertical Propulsion Application," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1865-1874, 2018.

[43] T. Hirayama, S. Yamashita and S. Kawabata, "Design and Analysis of Linear Switched Reluctance Motor with Coreless HTS Excitation Windings for Ropeless Elevator," in *Proc. 21st International Conference on Electrical Machines and Systems (ICEMS),* Jeju, pp. 1879-1884, 2018.

[44] J. F. Pan, N. C. Cheung and Y. Zou, "An Improved Force Distribution Function for Linear Switched Reluctance Motor on Force Ripple Minimization With Nonlinear Inductance Modeling," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 3064-3067, 2012.

[45] W.C. Gan and N. C. Cheung, "Design of a linear switched reluctance motor for high precision applications," in *Proc. IEEE International Electric Machines and Drives Conference (IEMDC)*, Cambridge, MA, USA, 2001, pp. 701-704.

[46] S. W. Zhao, N. C. Cheung, W. Gan, J. M. Yang and J. F. Pan, "A Self-Tuning Regulator for the High-Precision Position Control of a Linear Switched Reluctance Motor," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 5, pp. 2425-2434, 2007.

[47] J. F. Pan, N. C. Cheung, W. C. Gan and S. W. Zhao, "A Novel Planar Switched Reluctance Motor for Industrial Applications," *IEEE Transactions on Magnetics*, vol. 42, no. 10, pp. 2836-2839, 2006.

[48] N. Prasad, S. Jain and S. Gupta, "Design and Analysis of a New Improved Force Linear Switched Reluctance Motor for Transit Application", *IETE Journal of Research*, 2019.

[49] J. F. Pan, Y. Zou and G. Cao, "An Asymmetric Linear Switched Reluctance Motor," *IEEE Transactions on Energy Conversion*, vol. 28, no. 2, pp. 444-451, 2013.

[50] L. Yan, C. Li and Z. Jiao, "A novel flat linear switched reluctance motor with doubly-excited windings," in *Proc. 20th International Conference on Electrical Machines and Systems*, Sydney, NSW, 2017, pp.1-5.

[51] L. Yan, C. Li and Z. Jiao, "Design and modeling of double excitation windings linear switched reluctance motor," in *Proc. IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*, Harbin, China, 2017, pp. 1-5.

[52] H. Sun, Y. Chen, C. Ma et al., "A novel design and electromagnetic analysis for a linear switched reluctance motor", *Electrical Engineering* , vol. 101, pp. 609–618, 2019.

[53] Y. Fan and B. Zhang, "Performance analysis of a hybrid linear switched reluctance machine," in *Proc. IEEE International Magnetics Conference (INTERMAG)*, Beijing, China, 2015, pp. 1-1.

[54] D. Shen, R. Cao, M. Lu and E. Su, "Investigation on A New Double-sided Permanent Magnet Linear Switched Reluctance Motor," in *Proc. 22nd International Conference on Electrical Machines and Systems (ICEMS)*, Harbin, China, 2019, pp. 1-6.

[55] Cheng-Tsung Liu, Kun-Shian Su and Jyh-Wei Chen, "Operational stability enhancement analysis of a transverse flux linear switched-reluctance motor," *IEEE Transactions on Magnetics*, vol. 36, no. 5, pp. 3699-3702, 2000.

[56] R. J. Modi, D. U. Shah, P. N. Kapil, "Force Profile Comparison for Various Stator Teeth Configurations and Translator Material in Linear Switched Reluctance Motor (LSRM)", in *Proc. of the World Congress on Engineering WCE*, vol. 1, July 5-7, 2017, London, U.K.

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