Analysis and modeling of different topologies for linear switched reluctance motor using finite element method

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Abstract In the present paper, an electromagnetic simulation model is introduced for the conventional type of linear switched reluctance motor (LSRM) in which the dynamic characteristics of the motor are predicted precisely by carrying out 2D finite element (FE) transient analysis using ANSYS FE package. The simulation model is created totally in ANSYS parametric design language (APDL) as a parametric model and it can be used easily for different designs of the conventional LSRMs. Introducing linear switched reluctance motor with segmental translator as a new type of LSRM, performance principles and design criteria are presented for two various topologies of this motor. Carrying out 2D FE transient analysis, dynamic characteristics of these two motors are predicted and compared to those obtained for the conventional LSRM.

1. Introduction

Due to exclusive features of switched reluctance motor (SRM) including simple and robust structure, absence of permanent magnet and windings on rotor, low manufacturing cost, high operation reliability, appropriate performance over a vast range of speed and high output power/weight ratio, special attention has been paid to this motor in the last three decades [1,2]. Structure and performance principles of LSRMs are very similar to that for the rotary SRM and therefore it can be utilized appropriately as a suitable candidate for traction force applications because of all above-mentioned features.

However, the researchers have concentrated mostly on the rotary SRM and not many works have been reported for electromagnetic modeling and design aspects of LSRMs.

A comprehensive magnetic equivalent circuit has been developed for the LSRM in [2] which can be used properly for doing analysis and design of LSRM. A design algorithm is presented in [3] for the longitudinal field LSRM with multiple air gaps. Introducing a transverse flux type of LSRM is considered in [4] and its important electromagnetic characteristics including inductances and force are predicted using finite element method (FEM). A linear switched reluctance actuator based on cylindrical variable reluctance configuration has been introduced and constructed in [5]. A standard design procedure is described in [6] for a single-sided and longitudinal flux-based LSRM. A design algorithm is introduced for the double-sided, double-translator LSRM in [7]. A LSRM drive is designed and manufactured in [8] for a test track of autono-
mous railway vehicles. Construction of LSRM is considered in [9] and its behavior is experimentally verified with two control methods.

In the present paper, an electromagnetic simulation model is developed for conventional type of LSRM with FEM using ANSYS FE package. The simulation model is created totally in APDL as a parametric model usable for various designs. In addition, linear switched reluctance with segmental translator is introduced and two different topologies for this motor are described. The simulation results are presented for these motors and they are compared to those for conventional type of LSRM. At the following, the developed electromagnetic simulation model is introduced in Section 2. Two different topologies for linear switched reluctance with segmental translator are described in Section 3. The simulation results are presented in Section 4 and the paper is concluded in Section 5.

2. Electromagnetic simulation model for LSRM

In order to predict the dynamic characteristics of the LSRM using ANSYS FE package, the FE model of the motor must be created and coupled to the external circuit as it is shown for the three-phase LSRM in Fig. 1. This LSRM can be considered equivalent of a rotary 6/4 SRM and selection of two extra poles on translator is due to reduction of core loss and noise [2]. The winding areas related to one phase have been plotted in the FE model because excitation of one phase is required only for the analysis. It is noted that two separate areas are considered in the FE model for each coil because of doing 2D FE analysis. Two coils are connected in series to build one phase of the motor and consequently four general circuit element CIRCU124 should be used for each phase to link the electric circuit to the FE domain, as it is obvious from Fig. 1b.

The geometric structure of the LSRM is developed in the FE model as a parametric model using APDL, and therefore it can be applied easily to various designs of different conventional types of the LSRMs. Widths and heights of the poles, widths of the slots, depths of stator and translator cores, core stack thickness, air-gap length, number of poles and number of turns per phase are selected as the geometrical parameters in the developed electromagnetic simulation model. When using the simulation model for a typical LSRM, one only needs to identify the geometrical parameters and material properties such as B-H curve. At the simulation model output, some important electromagnetic characteristics of the LSRM are determined such as phase inductance, instantaneous phase current, thrust and normal force waveforms.

A time-stepping analysis should be carried out to determine the dynamic characteristics of the LSRM. The coupling equations between the stator and translator in the middle of the air gap are deleted at each time step, translator is moved by 0.5 mm, and then the coupling equations are rearranged and the analysis is restarted. More details about how to model the electric machine using ANSYS for doing the transient analysis are presented in [10].

3. New topologies for LSRM

The rotary SRM with segmental rotor has been already introduced in [11,12] in which the rotor consists of separate segments instead of a toothed rotor. In comparison with the conventional type of SRM, the magnetic flux passes shorter distance in the aligned position. This leads to higher aligned inductance and consequently larger torque for SRM with seg-

![Figure 1](image-url)  
**Figure 1**  Circuit-coupled FE model, (a) the developed FE model and (b) external circuit coupled to FE model for a phase.
mental rotor. Due to this significant capability, we have introduced the segmental translator linear switched reluctance motor (STLSRM) [13] and two different topologies of this motor are described at the following.

3.1. The fully-pitched STLSRM

The cross-section of a three-phase STLSRM with fully-pitched winding is illustrated in Fig. 2. Each slot is filled completely with a coil related to one phase and each coil encloses three stator poles. Translator is a series of separate laminated segments instead of a toothed translator. Unlike the conventional LSRM depicted in Fig. 1, there are only 4 segments on translator that makes it lighter. Fig. 3 shows the flux-lines representation of this motor for aligned and unaligned positions. In the aligned position, a slot is closed magnetically by a segment and consequently the magnetic flux path only encloses a stator slot. This leads to higher aligned inductance in comparison with the conventional LSRM in which flux path is half of the stator core length. As it is obvious from Fig. 3b, flux must flow between segments for the unaligned position which are magnetically insulated from each other.

As done for stator and translator of the conventional LSRM, stator and translator segments of the STLSRM are composed of high-grade sheet steel. The segment laminations are mounted on a steel translator. This translator must be constructed from nonmagnetic steel so that it did not produce a magnetic flux path between the segments. With regard to Fig. 3, dimensions of the translator segments are determined using below design criteria:

1. The length of overlap between each translator segment and stator pole should be equal to the stator pole width.
2. The segment height, stator core height and stator pole width are the same.
3. The gap between translator segments is equal to the slot opening length.

3.2. The short-pitched STLSRM

Another possibility for STLSRM is that created using the short-pitched winding as shown in Fig. 4 for the three-phase STLSRM. Similar to the full-pitched STLSRM, each slot is filled completely with conductors of a coil related to a phase but each coil is wrapped here around one stator pole. As it is obvious from Fig. 4, there are two different types for stator pole in the short-pitched STLSRM: double-width one having coil and the standard-width one without coil. The second type is required to provide a return path for flux when the related phase is excited as it is obviously illustrated from Fig. 5. Dimensions of translator segments are selected based on the rules similar to those for the full-pitched STLSRM.

4. Simulation results

Three types of LSRM described above which are conventional LSRM, full-pitched STLSRM and short-pitched STLSRM are considered here and their electromagnetic characteristics including static and dynamic characteristics are compared in this section. It is noted that all simulation results related to dynamic analyses are for the operating point: speed = 4 m/s, turn-on angle = 36° (el. degree), turn-off angle = 144° (el. degree) and the current regulation control mode when maximum current is 10 A. In this operating point, the produced output power is high and consequently an appropriate comparison between the three motors can be completed.

The three above-mentioned motors are introduced at the following. The core sheets of these motors and translator segments are assumed to be M800-50A with 0.5 mm thickness.

1. The first motor is a three-phase conventional LSRM with the specification given in Table 1, which is proposed based on the design procedure described in [7]. This motor which is called the proposed LSRM at the rest of the paper is considered here to present the simulation results for the electromagnetic simulation model developed in section II.
2. The second motor is a three-phase STLSRM with full-pitched winding. The stator dimensions, number of turns per phase, and air-gap length are chosen the same with those in the proposed LSRM. For the selected stator, translator is then designed using the rules given in Section 3.1. In the following, this motor whose specifications are given in Table 2 is called the discussed full-pitched STLSRM.
3. The third motor is a three-phase STLSRM with short-pitched winding in which its critical design parameters including stator pole width, air-gap length and number of turns per phase are selected the same with those obtained for the discussed full-pitched STLSRM. The other geometric parameters of this motor are then determined as explained in Section 3.2. In the remaining of paper, this motor whose specifications are given in Table 2 is called the discussed short-pitched STLSRM.

Carrying out the 2D FE transient analysis of the proposed LSRM for the considered operating point using the developed electromagnetic model, the instantaneous phase current and thrust force waveforms are predicted and shown in Fig. 6. The calculated average thrust force is 23.7 N (4042 N/m³) and the computation time is about 15 min on a 2.27 GHz Intel Core 2 with 4 GB RAM. For the considered operating point, the flux-line representation and flux density distribution in an intermediate translator position are depicted in Fig. 7. Since the air-gap length is relatively large here in comparison with the rotary SRM, stator pole flux density is not so high.

In order to predict the dynamic characteristics of the discussed full-pitched and short-pitched STLSRMs, their simula-
tion models are developed in a similar manner done for LSRM described in section II. Using the developed simulation models, 2D FE transient analysis of the discussed full-pitched STLSRM is carried out for the considered operating point and instantaneous current and thrust force waveforms are predicted and given in Fig. 8. Having the predicted thrust force waveform, it is possible to calculate the average thrust force which is 170.8 N (103515 N/m³). For the considered operating point, the flux-line representation and flux density distribution related to the discussed full-pitched STLSRM in an intermediate translator position are obtained and illustrated in Fig. 9. Comparing Figs. 7 and 9, it is seen that flux density in the discussed full-pitched STLSRM is higher than that for the pro-

<table>
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<th>Table 1 Specifications of the proposed LSRM.</th>
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<td>Stator pole width (mm)</td>
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<td>Stator slot width (mm)</td>
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<td>Stator pole height (mm)</td>
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<td>Stator core depth (mm)</td>
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<td>Air-gap length (mm)</td>
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<td>Translator pole width (mm)</td>
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<td>Translator slot width (mm)</td>
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<td>Translator core depth (mm)</td>
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<td>Core stack thickness (mm)</td>
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Figure 3 Flux-lines representation for full-pitched STLSRM: (a) unaligned position and (b) aligned position.

Figure 4 Cross section of the discussed short-pitched STLSRM.

Figure 5 Flux-lines representation for short-pitched STLSRM: (a) unaligned position and (b) aligned position.
posed LSRM. This results in producing a larger thrust force for the full-pitched STLSRM as it is clear from Figs. 6 (b) and 8(b).

<table>
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<th>Table 2 Specifications of the discussed STLSRMs.</th>
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<td><strong>Full-pitch</strong></td>
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<td>Width of stator pole tip (mm)</td>
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<tr>
<td>Stator slot width (mm)</td>
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<tr>
<td>Stator core depth (mm)</td>
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<td>Air-gap length (mm)</td>
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<td>Segment height (mm)</td>
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<td>Segment width (mm)</td>
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<tr>
<td>Gap between segments (mm)</td>
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<td>Core stack thickness (mm)</td>
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For the considered operating point, the 2D FE transient analysis of the discussed short-pitched STLSRM is carried out and the predicted instantaneous current and thrust force waveforms are shown in Fig. 10. The average force derived from the predicted thrust force waveform is 87.5 N (21341 N/m³). For the considered operating point, the flux-line representation and flux density distribution are predicted in an intermediate translator position and they are shown in Fig. 11.

Using the developed electromagnetic simulation models, static analyses of the three above-mentioned motors are also done when phase current is 10 A and the obtained simulation results are compared in Fig. 12. In these figures, 0 indicates to the unaligned position and 0.07 is related to the aligned position. As discussed in Section 3 and it is obviously seen from Fig. 12(a), the phase inductance of the discussed full-pitched STLSRM is much larger than that for the proposed LSRM because its magnetic flux path is shorter. As it is clear from Fig. 12, the discussed full-pitched STLSRM has capability to produce much larger values of both thrust and normal forces in comparison with the proposed LSRM.

![Figure 6](image)

**Figure 6** The dynamic characteristics predicted for the proposed LSRM: (a) phase current and (b) thrust force.

![Figure 7](image)

**Figure 7** The FE calculations related to the proposed LSRM for an intermediate position: (a) flux-lines representation and (b) flux density distribution.
Figure 8  The dynamic characteristics for the discussed full-pitched STLSRM: (a) phase current and (b) thrust force.

Figure 9  The FE calculations related to the discussed full-pitched STLSRM for an intermediate position: (a) flux-lines representation and (b) flux density distribution.

Figure 10  The dynamic characteristics predicted for the discussed short-pitched STLSRM: (a) phase current and (b) thrust force.
5. Conclusion

An electromagnetic simulation model was introduced for the conventional linear switched reluctance motor in which some important electromagnetic characteristics could be determined accurately with 2D finite element transient analysis using ANSYS FE package. The simulation model was created totally as a parametric model in ANSYS parametric design language and it can be utilized easily for various designs to predict the dynamic characteristics including instantaneous phase current and thrust force. Applying the electromagnetic simulation model to a proposed three-phase linear switched reluctance motor, the simulation results are presented.

Introducing linear switched reluctance motor with segmental translator, two different topologies for this motor titled the full-pitched STLSRM and the short-pitched STLSRM were described. The simulation results were presented for these two motors and they are compared to those for the proposed conventional linear switched reluctance motor. Carrying out 2D FE transient analysis for the considered operating point,
the discussed full-pitched STLSRM showed the best performance and its thrust force/weight ratio was 25.6 times larger than that of the proposed conventional linear switched reluctance motor. Based on simulation results derived from static analysis, it was also seen that the normal force produced by the discussed full-pitched STLSRM was much higher. Due to smaller translator and higher force/weight ratio, the full-pitched STLSRM could be considered appropriately in some special applications.

References