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DESIGN OF LINEAR SWITCHED RELUCTANCE MOTOR(LSRM) FOR RAILWAYS

Chunduri Indira Alekhya*, Dr. Abdul Ahad Shaik
*M.Tech, Power & Industrial Drives Department of EEE Nimra College of Engineering and Technology Vijayawada, Andhra Pradesh.
Professor, Head of the Department Department of EEE Nimra College of Engineering and Technology Vijayawada, Andhra Pradesh.

ABSTRACT

Switched-reluctance motors have gained attention in the variable-speed drive market. The savings in manufacturing cost of the motor due to its simplicity of construction and use of minimum number of switching devices in the drive circuit are two important factors in its favor compared to any other motor drive. Linear Switched Reluctance Motor (LSRM) is an SRM of unrolling stator and rotor into a plane. LSRMs are mostly used in the field of direct-drive linear motion systems. Differing from other linear motors, LSRM is simple in construction, less expensive, very suitable for high-speed travel over long distances, more robust and more fault tolerant. The presented concern is with some of the design aspects of the linear switched-reluctance motor with active stator and passive translator (mover) for railway applications. Towards this objective, a step-by-step procedure is developed for the design of linear switched-reluctance motors.

KEYWORDS: Linear Motion, Linear Switched Reluctance Motor, three phase, Stator, Translator.

INTRODUCTION

The invention of the steam engine was critical to the invention of the modern railroad and trains. In 1803, a man named Samuel Homfray decided to fund the development of a steam-powered vehicle to replace the horse-drawn carts on the tramways. Further research work in traction helped in developing electric traction which offered several benefits over the predominant steam traction, particularly in respect of its quick acceleration, suburban services and power (ideal for heavy freight trains through mountains/hilly sections).

Direct-current motors with series field windings were the oldest type of traction motors. These provided a speed-torque characteristic useful for propulsion, providing high torque at lower speeds for acceleration of the vehicle, and declining torque as speed increased. By arranging the field winding with multiple taps, the speed characteristic could be varied, allowing relatively smooth operator control of acceleration.

Apart from all these advantages, commutation became the major disadvantage of DC machine along with its high initial and maintenance cost. To eliminate this problem, further studies were carried and a variant of the DC system, AC Induction machines were introduced in the field of traction.

AC induction motors are simple and have low maintenance, but are awkward to apply for traction motors because of their fixed speed characteristics. An AC induction motor only generates useful amounts of power over a narrow speed range determined by its construction and the frequency of the AC power supply.

The advent of power semiconductors has made it possible to fit a variable frequency drive on a locomotive, allowing a wide range of speeds and rugged induction motors without wearing parts like brushes and commutators

Further research in the field of drives has introduced a novel kind of motor named Linear Switched Reluctance Motor, which can give an efficient speed control of the drive offering a very simple and robust design. Thus they are very suitable for highly reliable and fault tolerant applications. Hence this project aims at deign of LSRM for railway applications.

The name switched reluctance has now become the popular term in the technical literature. SRMs are alternatively known as variable reluctance motors (VRMs), reflecting the origins of the technology being derived from variable reluctance stepper motors. Variable reluctance machines are often referred to as SRMs to indicate the combination of a VRM and the switching inverter required to drive it. The SRM technology is now successfully penetrating into the industry with the promise of providing on efficient drive system at a lower cost. Switched Reluctance Machine has been under attention of researchers in the last few decades. The technological progress, particularly in the field of electronics and informatics, stimulate the development of new and better solutions to improve its performance. Its modeling presents important difficulties and its control is not yet a perfect art. However, SRM drives have been found competitive with traditional AC and DC drives due to the simple construction and fewer power converter requirements. In comparison to the other types of linear motor, linear SRM (LSRM) serves many advantages that other linear motors do not have. LSRM is simple in construction, less expensive, very suitable for high-speed travel over long distances, more robust and more fault tolerant. Since mechanical couplings, lead screws, magnets, and brushes are not required in LSRM, special mechanical adjustments and alignments are not necessary. Thus, LSRM is superior to other linear motors. The proposed LSRM has a much simpler structure and is less expensive. It is also more robust and more fault tolerant, and has less overheating problem. So it is a potential candidate for high performance linear motion drive.

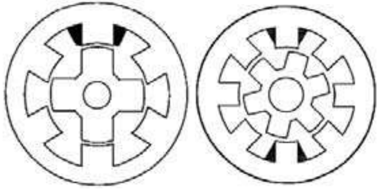
SWITCHED RELUCTANCE MOTOR

Switched Reluctance Motor (SRM) was used in 1838in Scotland for the first time as a locomotive motor. Although this motor's basic working principle, variable reluctance motor theory had been known before, it was started to be used for variable and adjustable speed applications merely after 1980's. In recent years, through the technological progress of power electronic materials, appropriate opportunities have been supplied for the use of this motor.

Switched reluctance motors have saliency in both stator and rotor and so they are the simplest electric motors in construction. The stator and rotor are usually both made of laminated silicon steel in order to diminish eddy currents. The stator has independent windings with excitation field coils on its poles whereas the rotor is solid laminated and has no coils or permanent magnets on it. Hence the SRM is denoted as a doubly-salient, singly-excited machine. A typical switched reluctance motor is shown in Fig. 1.

Fig. 1 A typical switched reluctance machine

The stator windings on diametrically opposite poles are connected in series or parallel to form one face of motor. Generally, the number of stator poles is greater than that of rotor poles. Some possible combinations are 6/4 (six stator poles and four rotor poles), 8/4, 8/6, 10/6, 12/10, etc. The larger the number of stator and rotor poles, the less the torque ripple. By choosing a combination where there are two more stator poles than rotor poles, high torque and low switching frequency of the power converter can be achieved. The three phase 6/4 SRM and the four-phase 8/6 SRM are typically used. Stator and rotor configurations of the SRMs are shown in Fig 2.



(a) ***(b)***

Three-phase 6/4 SRM ***Four phase-8/6 SRM***

Fig. 2 Stator and rotor configurations of an SRM

LINEAR SWITCHED RELUCTANCE MOTOR

Operation of the LSRM is based on the inductance profile of the machine. The inductance of the machine is related to machine dimensions such as the stator and translator pole and slot widths, excitation currents, and rotor position. Assuming the magnetic circuit is linear and therefore the inductance characteristics are independent of stator current excitation.

A. *Development of Linear Switched Reluctance Motor:*

A three-phase LSRM with active stator and passive translator (mover) structure is designed and calculated in this paper. The LSRM model has 1m long stator and 75 W rated power for one stator sector. It is considered on the high speed of 1.5 m/s for the application of railways.

- Firstly, the desired specifications of LSRM are changed into equivalent rotary SRM specifications.
- Secondly, the rotary SRM is designed.
- Thirdly, the LSRM dimensions and design variables are obtained by inverse translation.
- Finally, the design is satisfied with the fact that the length of one sector of the stator must be equal that of the translator.

The proposed linear switched reluctance motor will be designed and the complete dimension will be constructed using ANSYS Maxwell software.

B. *Theoretical calculation of design parameters of LSRM:*

The proposed design procedure utilizes the rotating switched reluctance machine (rotary SRM) design by converting the specifications of the linear machine into those of an equivalent rotating machine. The machine design is carried out in the rotary section, which then is transformed back into the linear section. A standard or classical design procedure begins with the power output equation relating the machine dimensions such as bore diameter, lamination, stack length, speed, magnetic loading, and electric loading.

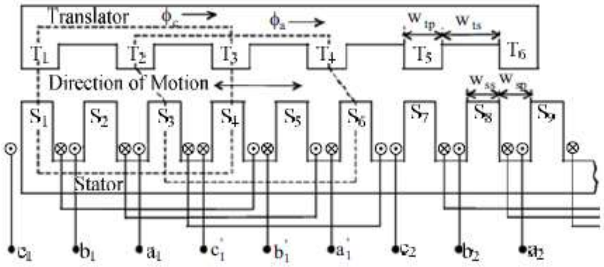


Fig. 3 Three-phase LSRM with active stator and six translator poles

Transformation of desired specifications of LSRM to equivalent rotary SRM specifications:

The figure shows the three-phase LSRM structure and its winding diagram with an active stator, a passive translator, and a longitudinal flux configuration. The LSRM consists of six translator poles and n stator poles. This corresponds to the six stator and four rotor pole rotary SRM. One stator sector is composed of six stator poles, and the number of stator sectors N_{sc} is given by:

$$N_{sc} = \frac{n}{6}$$

Specifications of LSRM

- Length of LSRM = 1 m
- Maximum linear velocity = 1.5 m/s
- Acceleration time = 0.6 s
- Maximum mass of translator assembly = 20 kg
- The acceleration is

$$a_a = \frac{v_m}{t_a} = \frac{1.5}{0.6} = 2.5\ m/s^2$$

- The force for initial acceleration is calculated as:

$$F_a = M_t a_a = 20 \times 2.5 = 50\ N$$

- Deceleration, $a_d = -a_a = -2.5\ m/s^2$
- Deceleration force, $F_d = -F_a = -50\ N$
- Power capacity of the LSRM, P= $F_a v_m = 50 \times 1.5 = 75\ W$

a) Design in Rotary Domain:

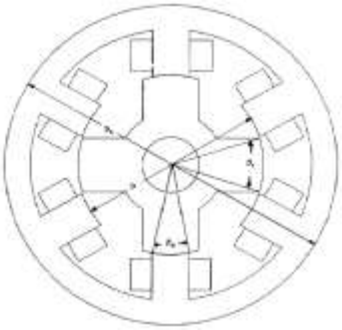


Fig.4. Schematic of Rotary Switched Reluctance Motor

Output Equation:

The output equation relates the bore diameter, length, speed, and magnetic and electric loading to the output of a machine. In general, the conventional machines are designed starting from the output equation. A similar development of the output equation for the switched-reluctance motor will make its design systematic.

The output equation of rotary SRM is

$$P = K_e K_d \left(\frac{\pi^2}{120}\right)\left(1 - \frac{1}{\sigma\lambda_u}\right) B A_{sp} D^2 L N_r$$

The above equation can be rearranged to resemble that of the conventional output equation of ac machines and is given as

$$P = K_e K_d K_1 K_2 B A_{sp} D^2 L N_r$$

Where,

N_r is the rotor speed in r/min
D is the bore diameter,
L is the axial length of the stator pole,
B is the flux density at the aligned position,
A_{sp} is the specific electric loading
K_e is the efficiency.
K_d is the duty cycle given as

$$K_d = \frac{\theta_i q P_r}{360}$$

θ_i Is the current conduction angle for each raising inductance profile,
qis the number of phases = $P_s/2$,
P_r is the number of rotor poles.
$K_1 = \frac{\pi^2}{120}$, $K_2 = 1 - \frac{1}{\sigma\lambda_u} = 1 - \frac{L_u}{L_a^s}$

For continuous starting torque, the minimum stator pole arc is chosen. Therefore, it can be calculated as follows.

$min[\beta_s] = \frac{4\pi}{6\times 4} = 30° = 0.5236\, rad$

Since$\beta_r > \beta_s$, the value of β_r is chosen as 36°.

Therefore,

Stator pole angle of rotary SRM, $\beta_s = 30° = 0.5239\, rad$
Rotor pole angle of rotary SRM, $\beta_r = 36° = 0.6283\, rad$

Then to get the maximum power developed, current conduction angleθ_i, must be equal to stator pole arcβ_s.

$$k_d = \frac{\theta_i \times qP_r}{360} = \frac{30 \times 3 \times 4}{360} = 1$$

$$k_2 = 1 - \frac{L_u}{L_a^s}$$

For the constant, k_2, it needs to be calculated maximum stator current to extract the maximum output power. For that matter, the magnetic characteristics of the steel core material gives the ratio of L_u toL_a^s, 0.3. Therefore

$k_2 = 1 - 0.3 = 0.7$

For steel core lamination, B = 1.13 T and A_s = 24400
For non-servo application, k is chosen as 0.65.

After fine-tuning the parameters, the constants are as follows:
$k_c = 0.4,\ k_d = 1,\ k_1 = \frac{\pi^2}{120},\ k_2 = 0.7$, B = 1.13T,
$A_s = 24400$ and k = 0.65

Then, the bore diameter is evaluated as

$$D = \sqrt{\frac{P\pi}{60 \times K_e K_d K_1 K_2 K B A_s v_m}} = \sqrt{\frac{75\pi}{60 \times 0.4 \times 1 \times \frac{\pi^2}{120} \times 0.7 \times 0.65 \times 1.13 \times 24400 \times 1.5}}$$
$$= 0.0796444\text{m} \approx 80\text{mm}$$

Speed of the rotary SRM is

$$N_r = \frac{v_m}{D/2} \times \frac{60}{2\pi} = \frac{1.5 \times 10^3}{40} \times \frac{60}{2\pi} = 358.1 \approx 360 rpm$$

Switching frequency in phase winding for LSRM is

$$f_{sw} = 2P_r \frac{N_r}{60} = 2 \times 4 \times \frac{360}{60} = 48 \approx 50Hz$$

The pole pitch of LSRM is

$$\tau = \frac{v}{f_{sw}} = \frac{1.5}{50} = 30mm$$

The stack length of the rotary SRM is

$$L = kD = 0.65 \times 80 = 52mm$$

The stator yoke thickness is calculated as

$$b_{sy} = \frac{D\beta_s}{2} = \frac{80 \times 0.5236}{2} = 20.944 \approx 21mm$$

Assuming the stator outer diameter$D_0 = 200mm$, the height of the stator pole, h_s can be calculated.

$$h_s = \frac{D_0}{2} - \frac{D}{2} - b_{sy} = \frac{200}{2} - \frac{80}{2} - 21 = 39mm$$

The rotor back iron width,b_{ry}, and the height of the rotor pole (translator pole), h_r are calculated as:

$$b_{ry} = \left(\frac{D}{2}\right)\beta_r = \left(\frac{80}{2}\right) \times 0.6283 = 25.132 \approx 25mm$$
$$h_r = \frac{D}{2} - \lambda_g - b_{ry} = \frac{80}{2} - 1 - 25 = 14mm$$

The magnetic field intensity in the airgap is calculated as:

$$H_g = \frac{B}{\mu_0} = \frac{1.13}{4\pi \times 10^{-7}} = 899{,}225.43\ A/m \qquad = 899.2254\, A/mm$$

For a peak phase current of $I_p = 9A$ allowable in the machine, the number of turns per phase is

$$T_{ph} = \frac{H_g(2\lambda_g)}{I_p} = \frac{899.2254 \times (2 \times 1)}{9} = 199.83 \approx 200\ turns/phase$$

Assuming a current density of J=6.4 A/mm^2, the area of the conductor is

$$a_c = \frac{I_p}{J\sqrt{q}} = \frac{9}{6.4\sqrt{3}} = 0.812mm^2$$

Therefore, the closest wire size chosen from Table II (APPENDIX) for this cross sectional area of the conductor is SWG 19. It has an area of 0.8171 mm^2 and is selected for the phase windings. The calculation of the winding turns complete the rotary SRM design.

Now, the conversion from the rotary to the linear domain is calculated as follow.

The number of sectors of the LSRM and the resultant total number of stator poles are

$$N_{sc} = \frac{L_t}{\pi D} = \frac{1}{\pi \times 80 \times 10^{-3}} = 3.98 \approx 4$$

$n = P_s N_{sc} = 6 \times 20 = 120$

In the active stator and passive translator structure of LSRM, the stator and rotor of the rotary SRM correspond to the stator and translator of LSRM respectively.

The width of the stator pole and the width of the stator slot are obtained as:

$$w_{sp} = b_{sy} = \frac{D\beta_s}{2} = \frac{80 \times 0.5236}{2} = 20.944 \approx 21mm$$

$$w_{ss} = \frac{(\pi D - P_s w_{sp})}{P_s} = \frac{(\pi \times 80 - 6 \times 21)}{6} = 20.889 \approx 21mm$$

The width of the translator pole and width of the translator slot are calculated as:

$w_{tp} = b_{ry} = 25mm$

$$w_{ts} = \frac{(\pi D - P_r w_{tp})}{P_r} = \frac{(\pi \times 80 - 4 \times 25)}{4} = 37.8319 \approx 38mm$$

Since the LSRM designed has six translator poles, the total length of the translator is

$L_{tr} = 6w_{tp} + 5w_{ts} = 6 \times 25 + 5 \times 38 = 340mm$

The core stack width of the LSRM is obtained from the stator stack length of the rotary SRM as:

$L_w = L = kD = 0.65 \times 80 = 52mm$

The fill factor of the winding must be calculated to verify that the slot size is sufficient to hold the windings.

The diameter of the conductor is

$$d_c = \sqrt{\frac{4a_c}{\pi}} = \sqrt{\frac{4 \times 0.8171}{\pi}} = 1.02mm$$

Assuming the width of wedges w=3 and packing factor P_f=0.8, the number of vertical layers of the winding is

$$N_v = P_f \frac{(h_s - w)}{d_c} = 0.8 \times \frac{(39 - 3)}{1.02} = 28.2353 \approx 28$$

and the number of horizontal layers of the winding is

$$N_h = \frac{T_{ph}}{2 \times N_v} = \frac{200}{2 \times 28} = 3.5714 \approx 4$$

The winding area is given by

$$Stator\ winding\ area = 2\frac{a_c N_v N_h}{P_f}$$

$$= 2 \times \frac{0.8171 \times 28 \times 4}{0.8} = 228.788\ mm^2$$

$$Stator\ slot\ window\ area = w_{ss}(h_s - w) = 21 \times (39 - 3) = 756\ mm^2$$

The fill factor is calculated as:

$$F_f = \frac{Stator\ winding\ area}{Stator\ slot\ window\ area} = \frac{228.788}{756} = 0.30263$$

It is in the normal range of $0.2 \le F_f \le 0.7$

Then it has to be proved that the following two equations are equal.

$$P_s(w_{sp} + w_{ss}) = 6 \times (21 + 21) = 252$$

$$P_r(w_{tp} + w_{ts}) = 4 \times (25 + 38) = 252$$

Finally, it is observed that the above equation is satisfied with the LSRM design. The dimensions of the designed three-phase LSRM is shown in the Fig 10.

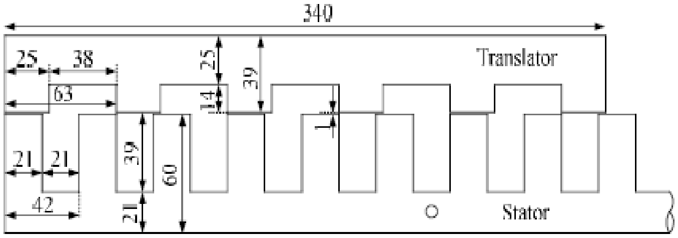


Fig.5: Dimension of the designed three-phase LSRM
Unit of Dimension: mm
Stack width: 52mm

FEM SIMULATED MODEL OF LSRM

To validate the initial motor design based on the simplified modelling approach of Section III, complete FEM analysis have been performed for linear motors using the commercial Maxwell FEM tool (by Ansoft).

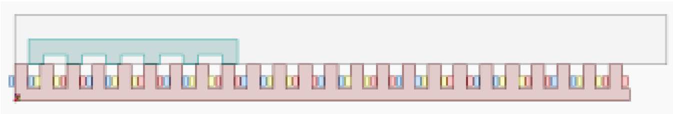


Fig.6: FEM Simulated Model of LSRM

Due to additional stray flux and edge effects, the propulsion force of the linear motor is a bit lower in comparison with the rotational motor with the same excitation However, the difference is marginal, so both motor concepts can be considered as nearly identical with respect to energy consumption and electromagnetic force or torque. Based on this assumption the control algorithms can be conveniently developed and tested on the rotational motor in the lab before porting it onto a real vehicle with the linear SRM.

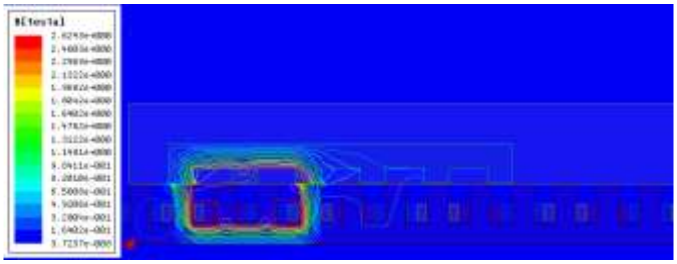
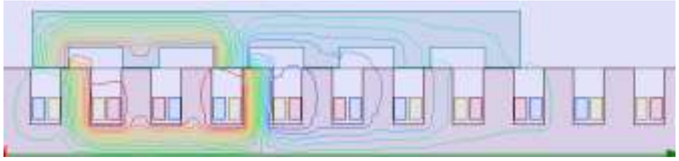
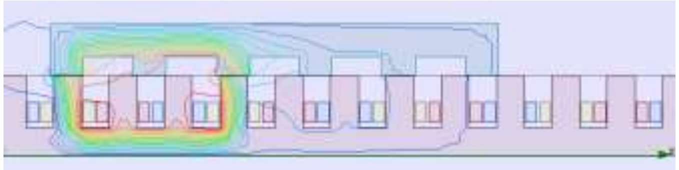


Fig.7: Magnetic flux density and flux lines for the linear SRM with a single excited phase.



(a) Unaligned position of linear SRM



(b) Aligned position of linear SRM
Figure.8: Magnetic flux density and magnetic flux lines for (a) unaligned and (b) aligned positions of linear SRM

The position of the translator with respect to time when a single phase is excited is shown in the below graph

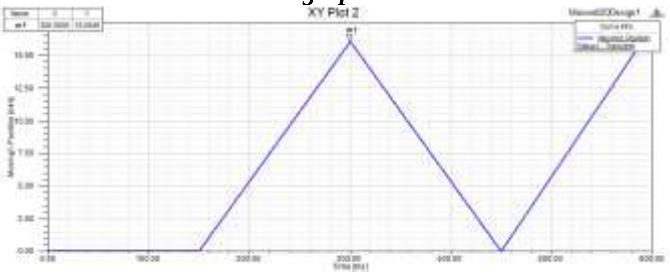


Fig.9: Static FEM results, position of LSRM with respect to time when a single phase is excited

CONCLUSION

The paper presents a study on model-based developing of linear switched-reluctance motors. The models presented are validated with FEM analysis. The characteristics of the linear and of the rotational motor are almost identical. Nowadays, all over the world, the linear SRM is emerging for many applications. Since many movements in production and transportation systems are translatory, LSRMs are useful in these fields. In such motors linear movements are generated directly, so that the lead screws, gear units such as spindle/bolt, gear rack/pinion, belt/chain systems are unnecessary. Hence LSRMs are used to reduce the cost of the system and to make the system compact and highly reliable. This paper is mainly intended for knowing design consideration and calculation for linear SRM. The increasing demand for linear design of SRMs has made the circle of electrical engineering extremely important and has result in the new, modern and developed nation leading to extend other advanced design technologies in new areas of applications. The initial design tasks have been solved, therefore the linear SR motor can be supposed as a good candidate for use in an autonomous railway system.

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