Force Profile Comparison for Various Stator Teeth Configurations and Translator Material in Linear Switched Reluctance Motor (LSRM)

Rahul J. Modi, Dhruv U. Shah, P. N. Kapil

The objective of this paper is to improve force generated on the translator for given rating and translator design by simulating for various translator (moving assembly) materials as well as various stator teeth configurations in MagNet software. To verify the simulation results, testing is carried out on Linear Switched Reluctance Motor (LSRM) with 6/4 pole configuration having open slots, 3 phases, and 740 W. In the available motor, the magnetic parts are made up of soft pure iron. But, later in this paper the simulation results are shown proving that using easily available, low cost and relatively less permeable magnetic material (compared to soft pure iron) for translator, such as Stainless Steel (Grade 416), the force generated on translator (moving assembly) reduces only by a few newton. The similarity in force profile by using low cost material is highly desirable in industrial applications.

***Index Terms*—%Force ripple, Force profile, Open slots, Semi-enclosed slots, Winding pattern**

I. INTRODUCTION

Switched reluctance motor is a singly fed salient pole type DC motor, where DC supply is given to the stator whereas the rotor is simply a soft magnetic piece having protruding poles at the periphery. The rotation in this type of motor is achieved by switching the reluctance seen by the rotor in a systematic manner such that due to switching of reluctance the rotor being a soft magnetic material tries to attain a position with lowest reluctance and hence starts to follow the switching pattern finally producing rotation.

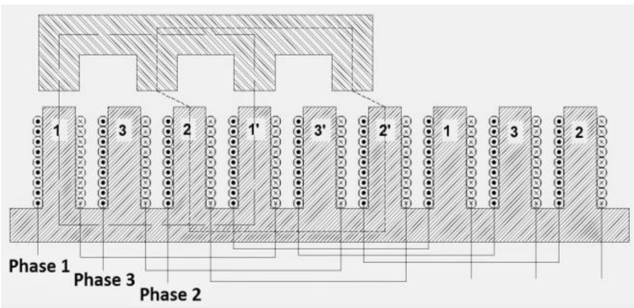

Fig. 1. Cross sectional view of Linear Switched Reluctance Motor

Now in a Linear Switched Reluctance Motor which can be imagined by slicing SRM from center up to the periphery and laying the cut section on a flat surface as shown in Fig. 1[1] [2], because this is a linear motor, the length of stator can be extended to the user's limit as a result there are more than 6 stator slots shown.

II. ELECTRICAL CIRCUIT

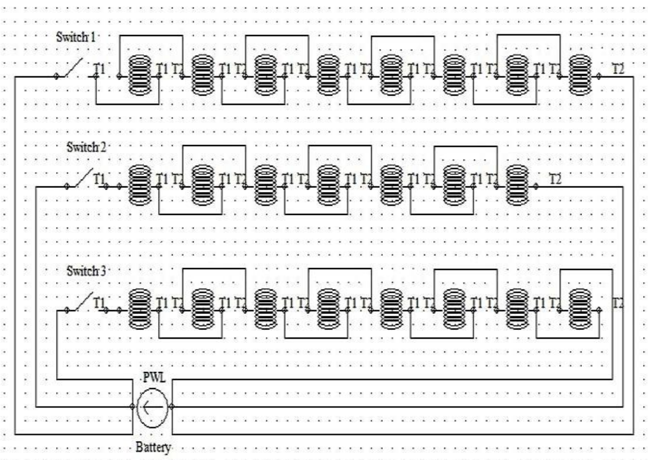

Fig. 2. Electrical circuit diagram

The power circuit of the system is shown in Fig. 2 that consists of winding coils, power supply and power electronic switches used to switch the phases. In Fig. 2 the power source used is a constant current source, i.e. Battery. The system being linearly distributed, there is one less coil in a phase due to its winding distribution. The coils are connected in series with alternate clockwise and counter-clockwise connection. This alternate coil connection allows the magnetic fields to produce forward force on the translator which causes linear motion. Winding coils are placed in the software circuit model having 27 numbers of turns and rated current of 10A.

III. WINDING PATTERN

The winding pattern as shown in Fig. 3 is quite easy configuration and easy to place in the slots as the slot pitch remains the same as well as overhang for all three phases' remains the same. Also, this winding pattern uses all the slots efficiently for winding. Due to double layer winding the overall length of the stator can be reduced. In double layer winding each slot has two coil sides of different phases.

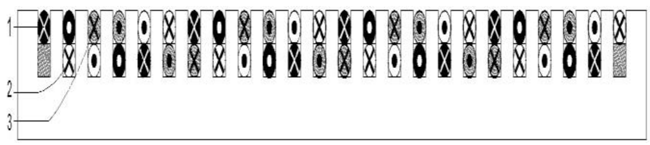

Fig. 3. Winding pattern

The simulations are carried out for exact dimension of

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available motor as designed in MagNet shown in Fig. 4. Material used in available motor is represented in Table 1[3].

TABLE I
MATERIALS

Stator	Soft pure Iron
Channel	Fiber Reinforced Plastic (FRP)
Channel support	Fiber Reinforced Plastic (FRP)
Translator	Soft pure Iron
Translator Frame	Aluminum

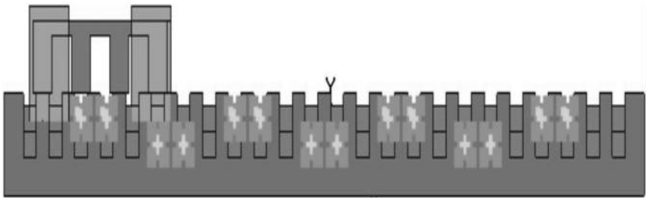

Fig. 4. Linear switched reluctance motor design for MagNet simulation

In the winding pattern shown in Fig. 3, each phase is distributed in such a way that first coil is wound around first teeth clockwise and the next coil of same phase is placed at third teeth counter clockwise as a result there is only one flux path formed as shown in Fig. 5[4].

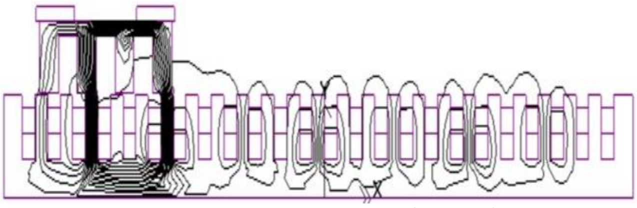

Fig. 5. Flux lines when translator is under influence of excited coils

Because of the coils wound and placement of them, the clockwise coil will always form a South pole whereas the counter clockwise coil will always form a North pole due to this reason and from the MagNet simulation it can be seen that flux path is getting completed from coil to airgap between stator and translator to magnetic piece and back to next coil.

IV. STATOR SLOT DESIGNS

A. Open slot design

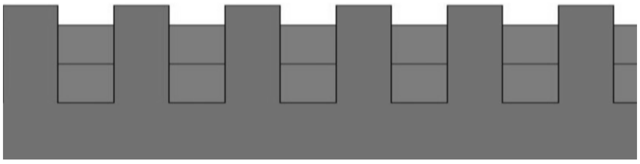

Fig. 6(a). Stator design with open slots using MagNet Software

In the stator design with open slots the stator poles and translator poles are rectangular bars protruding out from the stator back iron and translator back iron as shown in Fig. 6(a). As a result of this design the airgap between two consecutive stator teeth opening has increased, because of this reason, pulling the translator into aligned condition demands more flux at the teeth opening and thus the current drawn is increased. Also due to this design, the flux exiting from translator teeth has to go through airgap at the near alignment condition, hence force produced due to flux reduces as there is higher airgap reluctance acting upon the flux path.

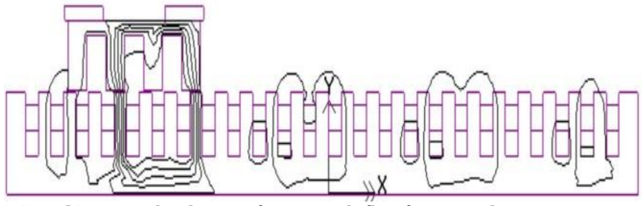

Fig. 6(b). Open slot design of stator with flux function plot using MagNet software

Fig. 6(b) shows the flux function graph of stator design with open slots and concentration of flux lines at certain position of translator [4], from this figure it can be seen that the force exerted on translator is only available when translator teeth starts to align with stator teeth, thereby reducing average force. Because the translator aligns only after passing full teeth length of airgap the force generated during that portion is also less as there is no magnetic path for flux to complete therefore during that portion the instantaneous force becomes nearly equal to zero.

B. Force generated for Stainless Steel as translator material with open slots

Here, the force generated is for translator made up of Stainless Steel grade 416. Stainless Steel grade 416 is having relative permeability of 1200.

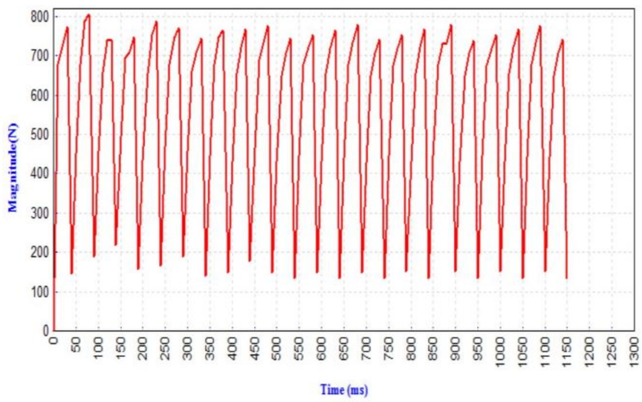

Fig. 7. Force generated on translator made up of Stainless Steel with open slots

The maximum force (F_{max}) generated in open slot configuration with translator made up of stainless steel is 804 N whereas the minimum force (F_{min}) generated on the translator is 134 N as seen from Fig. 7[5]. According to force ripple formula,

$$\%Force\ ripple = \left(\frac{Fmax - Fmin}{Favg} * 100\right) \quad (1)$$

Where,

F_{avg} = Average force (value from Table II, which was calculated using MagNet software)

The %force ripple in this type is 122.20%. On account of large ripples, smooth translator motion is not achieved which is highly undesirable.

C. Force generated for Soft pure Iron as translator material with open slots

The soft pure iron material used here has relative permeability of 6000.

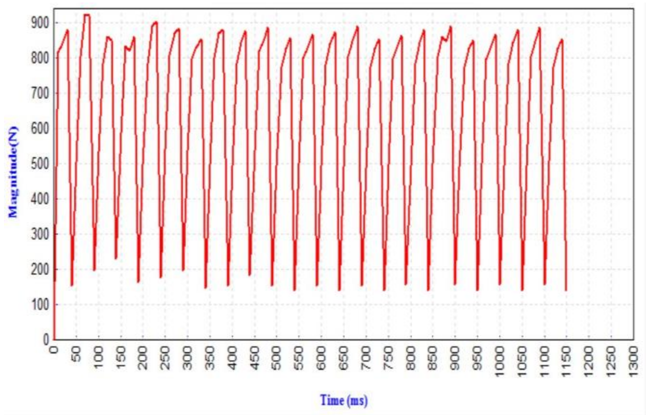

Fig. 8. Force generated on translator made up of soft pure Iron with open slots

Here due to high relative permeability (as compared to Stainless steel) of the translator material the maximum force generated increases by a few hundred newton as a result the %force ripple increases by small amount.

The maximum force in this type is 922 N but minimum force remains approximately same i.e. 134 N as seen from Fig. 8[5]. Using (1) and average force value from Table II the calculated %force ripple is 123.60% which is slightly higher compared to previous type.

D. Prototype of Linear Switched Reluctance Motor

In Fig. 9 all the parts of prototype model are clearly marked on which tests were performed in order to verify the FEA results achieved from MagNet software for open slot configuration. The translator frame was made up of aluminium structure in order to reduce the overall weight of translator system. In order to mitigate effects of other forces such as guiding force and levitating force, translator is placed on a guide made up of Fibre Reinforced Plastic (FRP) as a result current requirement of the system can be reduced.

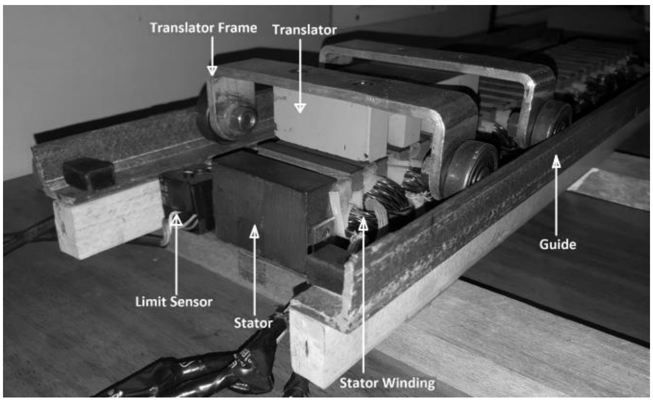

Fig. 9. Prototype of LSRM

E. Semi-enclosed slot design

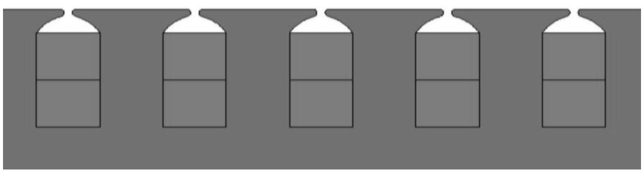

Fig. 10(a). Stator design with semi-enclosed slots using MagNet Software

Fig. 10(a) shows a small change in the stator teeth opening where the opening of teeth is changed from open slots to semi enclosed slots with 2 mm opening between two consecutive teeth and arc with radius 5 mm, having centre at midpoint of slot width. In this design the airgap between successive stator teeth is effectively reduced to only 2 mm as a result the flux will start to flow through the teeth as soon as it reaches near to the teeth opening such that it will start before the projected teeth opening appears. Because of the increase in area of stator teeth opening the translator and stator teeth align for more time and as a result the force produced on the translator increases as well as the negative force value also reduces. Now as there is large reduction in airgap between two successive teeth the flux requirement through the semi-enclosed teeth as reduces causing reduction in current as reluctance offered to flux has reduced. The flux function graph for the semi-enclosed stator slot is shown in Fig. 10(b).

In Fig. 10(b), it is evident that the flux lines are emitted from one teeth through the semi enclosed slot edge and enters into translator and through translator it is completed by semi enclosed slot opening. Also there is minor interaction of flux between unexcited and excited phase teeth causing small amount of flux to pass through unexcited teeth through the tip of the slot opening.

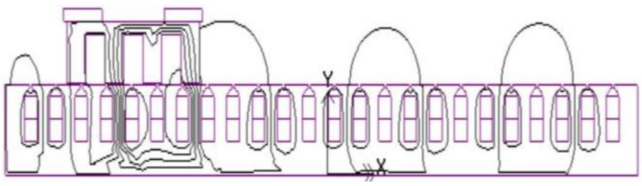

Fig. 10(b): Semi-enclosed slot design of stator with flux function plot using MagNet software

This problem can be mitigated by replacing the tip of slot opening by semi-circular shaped edges and widening the stem of the stator teeth as a result cross sectional area of teeth increases and Flux density reduces. Another point to be considered for this design is the instantaneous force being applied by stator on the translator, here due to widening of the stator teeth opening there is very small length where the flux path will not be completed through translator, due to this reason the instantaneous force never reaches to near zero values thereby always pulling the translator towards the stator. As a result of semi enclosed slot design there is more path for flux lines to pass. Hence, the minimum value does not drop much, resulting in higher average force and lower %force ripple compared to open slot design.

F. Force generated for Stainless Steel with semi-enclosed slots

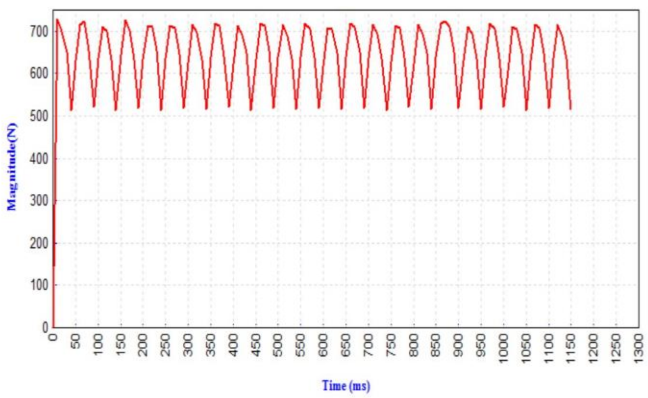

Fig. 11. Force generated on translator made up of Stainless Steel with semi-enclosed slots

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The maximum force generated on translator is 730 N and minimum force is 510 N with same design parameters used in open slot design as seen from Fig. 11[5]. Using (1) and average force value from Table II, the calculated %force ripple is 34.10%. This value is quite less compared to open slot design with stainless steel as translator material. Even though maximum force (F_{max}) is less compared to open slot design, the average force obtained is higher.

G. Force generated for Soft pure Iron with semi-enclosed slots

Here, the maximum force is 764 N and minimum force is 540 N as seen from Fig. 12[5]. From Table II and (1), the %force ripple is 33.36%. It can observed that for semi-enclosed slot design, the change in translator material yields almost same maximum force, minimum force, average force and %force ripple. Thus, stainless steel can be employed as a substitute of soft pure iron for its low cost and easy availability.

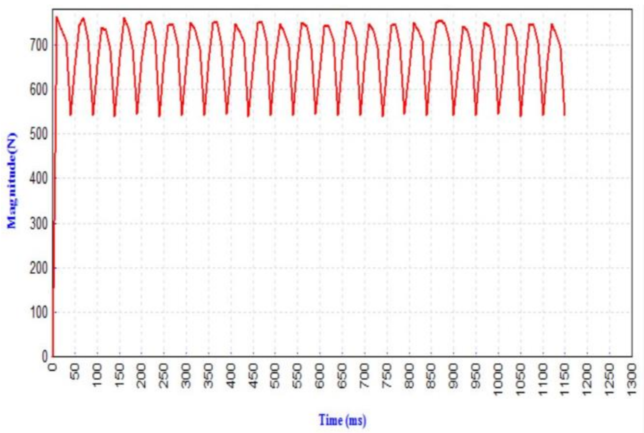

Fig. 12. Force generated on translator made up of soft pure Iron with semi-enclosed slots

V. FORCE COMPARISON FOR DIFFERENT TRANSLATOR MATERIALS AND SLOT DESIGNS

On account of significant difference in relative permeability of different materials, the instantaneous force generated on translator varies which is shown in Table II.

TABLE II
COMPARISON OF FORCE GENERATED

Stator material: Soft pure Iron				
Translator material	Stainless Steel (Grade 416)		Soft pure Iron	
Relative permeability	1200		6000	
	Open	Semi-enclosed	Open	Semi-enclosed
Average Instantaneous force	550 N	640 N	630 N	675 N
%Force ripple	122.20%	34.07%	123.60%	33.36%

VI. CONCLUSION

In this paper, the force generated is calculated using force profile for open slot and semi-enclosed slot design. Further, in both designs, force generated is calculated for a couple of translator materials. When the design is changed from open slot to semi-enclosed slot, the average force increases by a few newton. Using stainless steel (grade 416) in place of soft pure iron, the average force reduces only by a few newton for both designs. Additionally, for semi-enclosed slot design the %force ripple reduces drastically which is quite desirable for smooth motion of translator. Hence, from the results obtained, it can be concluded that for a semi-enclosed slot design with stainless steel (grade 416) as translator material, average force remains almost same and %force ripple is very less. So, for industrial applications considering low cost and relatively unobstructed motion, the said combination is an optimum solution.

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