Design and Analysis of Linear Reluctance Machine for Transportation

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ABSTRACT: This paper presents analysis and design optimization of linear reluctance motors for Metro applications. Synchronous reluctance machine is a suitable option for urban transportations due to the simple, robust, commercial and easy manufacturing of secondary. 2D finite element method is used for magnetic and electrical calculations. Propulsion force, power factor and efficiency of the proposed linear reluctance machines are investigated.

1 INTRODUCTION

Linear metro with linear machines propulsion and wheel on rail support has been used in many cities in Japan, Canada and France and has been developed and industrialized. Urban transportation systems are sought that reduce construction, maintenance, and operating costs that offer improved comfort and convenience, and that are environmentally friendly. Many users have expressed strong interest in the linear Metro for its compatibility with small cross section tunnels and its ability in some paths with steep gradients and sharp curves. Figure 1 shows two cases for transportation using linear motors.

Tehran, the capital of Iran is one of big cities with high population in the world that needs high capacity metro for transportation (Figure 2) that linear Metro with accessible technology can be used for this city. Usually linear induction machines with two layer secondary (iron and aluminum) are used for this application (Nozaki et al. 2005, Higuchi et al. 2001). Disadvantages of linear induction machine are first of all high end effects which reduces considerably thrust force of the linear motor machine specially in high speeds (>36 km/h) and non-constant force with speed and frequency and considerable eddy current loss in solid secondary that make low efficiency of linear motor.

(Photos: Tokyo Metropolitan Government)

(Photos: BCRT)

Figure 2. Examples for urban transportation using linear motor in Tokyo, Japan and British Colombia, Canada

Figure 1. Metro in Tehran, Iran

Synchronous type linear reluctance motors (LRMs) can be alternative for linear induction motors (LIMs) with less secondary loss and end effect and constant thrust force in different speeds (Edwards et al. 1978, Sanada et al. 2002). The secondary is only solid or laminated iron. Using laminated iron results minimum losses in secondary part relative to linear induction motor. In this paper, different configurations of LRMs are presented with distributed windings to get the required thrust force for Metro applications.

2 MODEL AND DESIGN DATA

Figure 3 shows 3D general model for LRMs with segmented secondary in two pole pitch.

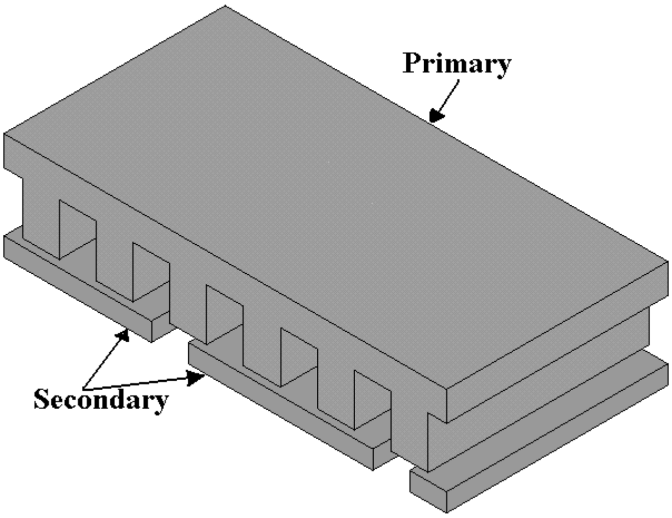

Figure 3. 3D Model of linear reluctance motor

The manufacturing of other configuration with multi-layer or axially laminated secondary is difficult and non-effective and expensive due to the limited dimension of secondary in vertical direction. Segmented reluctance type secondary could be a suitable structure of LRM for transport application.

The volume of the machine is one of the main restrictions in design procedure of the linear machine. Here we used the Japanese railway system for linear metro design. The design limitation data is listed in Table. 1 (Higuchi et al. 2001).

Table 1. Design limitations of linear motor [3]

Maximum length of machine	2.5 m
Maximum width of primary	0.4 m
Maximum length of primary overhang (pole pitch is equal 0.3 m)	0.18 m
Maximum width of primary with overhang	0.7 m
Maximum width of secondary	0.4 m
Maximum thickness of secondary	0.027 m
Minimum length of air gap	0.01 m
Maximum height of primary	0.124 m
Maximum line voltage of primary	1100 V

Higuchi et al. (2001) has changed the dimensions to get optimum structure. Figure 4 shows the force performance of Japanese linear metro which is used as a reference for design.

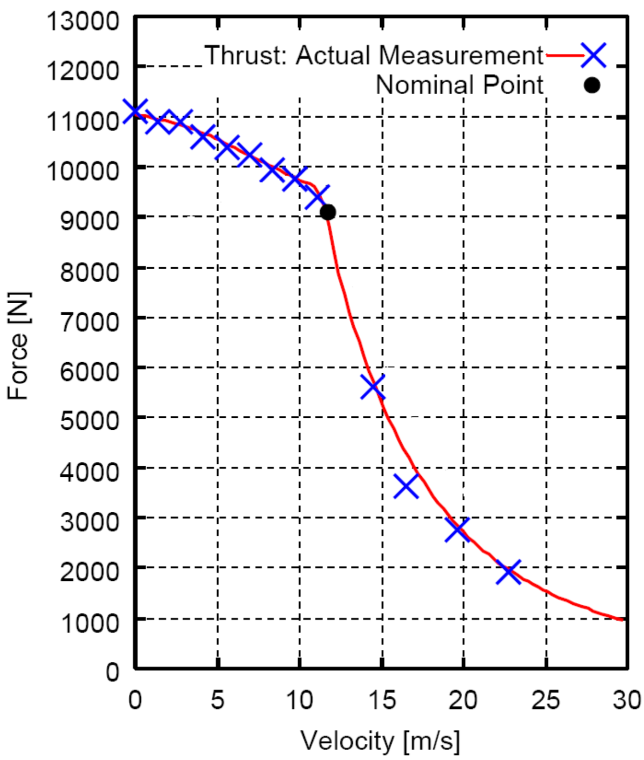

Figure 4. Force performance of Linear Metro-LIM

The nominal point is 12 m/s with required thrust force equals 9000 N. The starting thrust force is 11000 N.

3 PRIMARY DESIGN

First goal is to get the required thrust force for starting. Two parameters are important to get optimum performance:

1- Maximum power factor

$$Pf = \left| \frac{L_{\rm d} - L_{\rm q}}{L_{\rm d} + L_{\rm q}} \right| \tag{1}$$

2- Thrust force

$$F = \frac{3}{2}\frac{\pi}{\tau_{\rm p}}(L_{\rm d} - L_{\rm q}) I_d I_q \tag{2}$$

$$L_{\rm d} = c_{\rm d} L_{\rm m}$$
$$L_{\rm q} = c_{\rm q} L_{\rm m} \tag{3}$$
$$L_{\rm m} = \mu_0 (N k_{\rm W})^2 \frac{6}{\pi^2 p}\frac{L \tau_{\rm p}}{g}$$

where, $L_{\rm d}$, $L_{\rm q}$, $I_{\rm d}$, $I_{\rm q}$, p, $\tau_{\rm p}$, $c_{\rm d}$, $c_{\rm q}$, $L_{\rm m}$, N, $k_{\rm W}$, L and g are d axis inductance, q axis inductance, d axis current, q axis current, pole pair, pole pitch, saliency factor for d axis and saliency factor for q axis, magnetization inductance for smooth secondary (without segmentation), number of turns per phase in series, winding factor, primary transverse width, and magnetic air gap, respectively. With substitution of (3) in (1) and (2):

$$Pf = \left| \frac{c_{\rm d} - c_{\rm q}}{c_{\rm d} + c_{\rm q}} \right| \tag{4}$$

$$F = 9 \mu_0 (N k_{\rm W})^2 \frac{L}{\pi g p}(c_{\rm d} - c_{\rm q}) I_d I_q \tag{5}$$

Equations (2) and (3) show saliency factors are most important components to get maximum power factor and thrust force production. Magnetic air gap should be small as much as possible. These equations are valid for linear system without saturation. Taking into account saturation, the pole pitch become more important for thrust force production. Large pole pitch makes deep saturation in secondary yoke due to size limitation of secondary while small pole pitch needs more poles which needed for the same thrust force that causes high iron losses and needs higher frequency inverter. $c_{\rm d}$ is very sensitive to saturation and decreases considerably with saturation rate.

To get more magnetization inductance and thrust force, it is better to use full pitch winding or fractional slot type ((3) and (5)) because winding factor in short pitch winding is less and reduces thrust force (Kamper et al. 2002).

Figure 5 shows magnetic flux distribution with and without segmentation. The stator winding is replaced with equivalent current sheet for simplification. It is shown due to reluctance change in secondary part, the flux distributions are different (pole pitch=0.3 m, machine width= 0.3 m, secondary thickness=27 mm and 8 poles). Using 2D FEM, magnetization inductance is calculated with and without saturation.

$$W_{\rm m} = \frac{3}{2} L_{\rm m} I^2{}_{\rm m} \tag{6}$$

where, $W_{\rm m}$ and $I_{\rm m}$ are magnetic energy, magnetizing current, respectively. Figure 6 shows B-H curve which used for calculations.

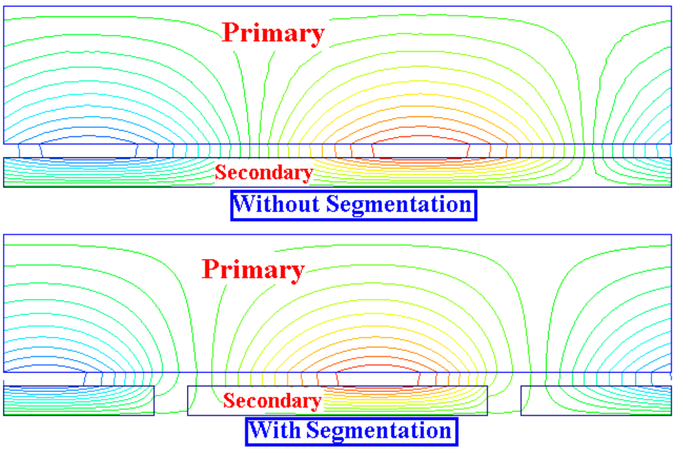

Figure 5. 2D magnetic flux distribution of simplified model with and without segmentation in longitudinal direction

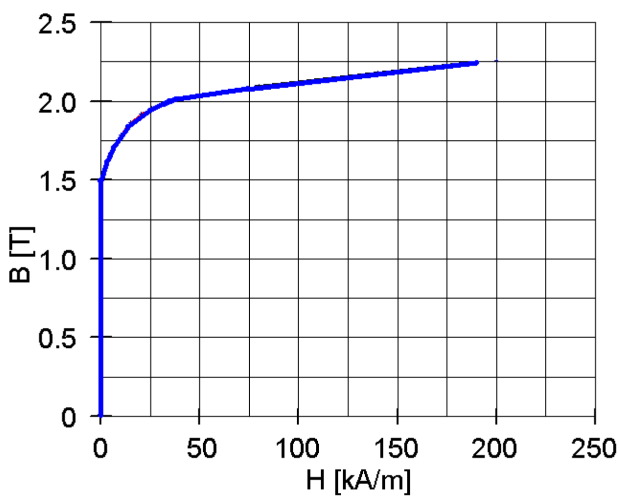

Figure 6. B-H curve – magnetic material used for primary and secondary

To get 11000 N from simplified model (figure 5), current loading equals 127000 A/m is needed with taking into account saturation. Without consideration of saturation, the thrust force is equals 18600 N when we consider infinite permeability for iron. This shows the high saturation of secondary.

With change of secondary structure to figure 7, the required current loading decreases to 112500 A/m due to the better saliency factors. In these cases, mechanical and magnetic air gap is equals to 12 mm. Reduction of air gap length to 10 mm; required current loading reduces to 109000 A/m. Reduction of pole pitch from 0.3 m to 0.2 m with air gap 10 mm decrease saturation in secondary but needs more current loading 112500 A/m to get 11000 Nm.

Reducing of 0.3 to 0.2 makes overhang length shorter and linear machine width can be bigger (increases from 0.3 to 0.42). In this case, the required current loading is 94500. With pole pitch equal 0.24, the current loading equal 91000 A/m is sufficient to produce 11000 N thrust force. Figures 8 to 10 show variations of tangential component of magnetic flux density in longitudinal direction. Big pole pitch (=0.3 m) depicts high saturation (>2 T). To decrease pole pitch to 0.2 m (12 poles), the magnetic saturation is removed but saliency ratio due to the large air gap and small pole pitch is not optimum.

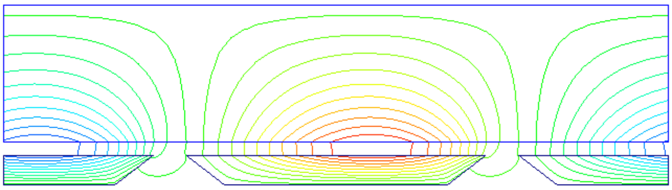

Figure 7. 2D magnetic flux distribution with segmentation in longitudinal direction –modified secondary

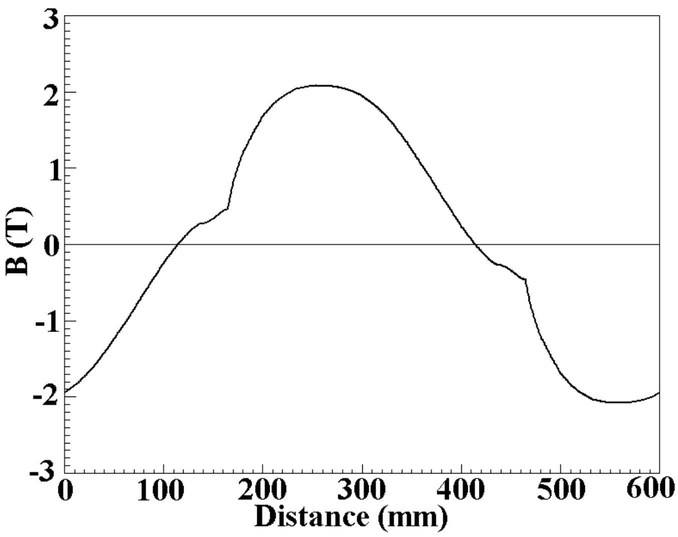

Figure 8. 2D magnetic flux density variation in middle of secondary (tangential component)- pole pitch=0.3 m

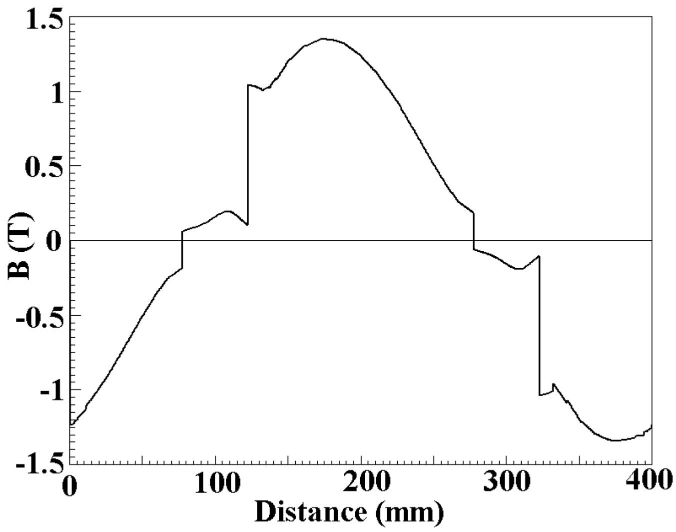

Figure 9. 2D magnetic flux density variation in middle of secondary (tangential component)–modified secondary- pole pitch=0.2 m

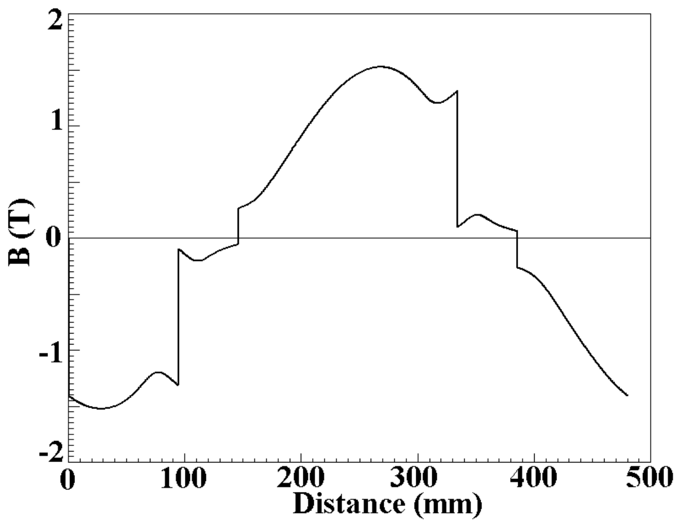

Figure 10. 2D magnetic flux density variation in middle of secondary (tangential component)–modified secondary – pole pitch=0.24

And also the magnetic flux density is less than 1.4 T (figure 9) that means the maximum capacity of secondary has not been used. To overcome the saturation problem and using the whole magnetic capacity of secondary iron, pole pitch is selected equal 0.24 m with 10 poles. The maximum flux density in this case is equal 1.55 T and is less than first model values with pole pitch=0.3 m.

In the following section, the detailed design of linear reluctance machine for metro application with consideration the preliminary design is presented. The first part is distributed winding with number of slot per pole per phase q=1 and second part is q=1.5 with fractional slot winding. The main goal of small q is to have simple winding manufacturing process and cheap one.

4 DETAILED DESIGN AND ANALYSIS

4.1 Magnetic analysis

In this part, detailed design of machine with distributed winding is presented. Formed winding is used due to better slot filling factor (=0.6) and high value line voltage (<1100 V). Small number of slots per pole per phase is used to have non expensive winding. Figure 11 shows full structure configuration of first proposed model full pitch winding.

The current shape is considered sinusoidal (figure 14) for simulation. The force ripple is generated due to the interaction of fifth and seventh harmonics of windings and slot and reluctance variation during secondary moving.

The big force ripple especially in train starting makes a go-back moving that is not comfortable from passenger viewpoint and also causes the lifetime of mechanical structures to be shorter and need more maintenance. Selecting q=1.5 is a method to decrease force ripple.

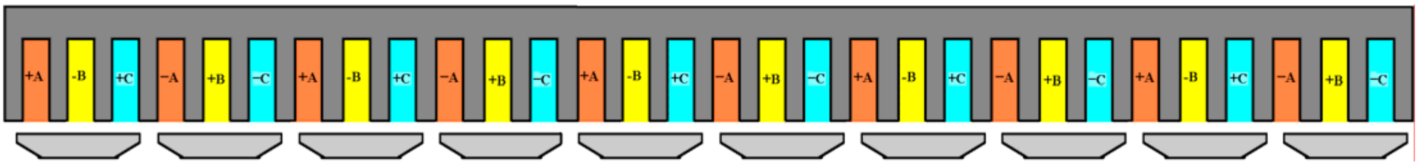

Figure 11. Full structure depiction of linear reluctance motor with 10 poles and q=1

Figures 12 and 13 show flux distribution and force curve at zero speed for 10 pole machine and pole pitch equal 0.25 m. It is shown that force curve has a big ripple around average value 11000 N (dashed line). The number of turns per coil is 30 and the current is 220 A.

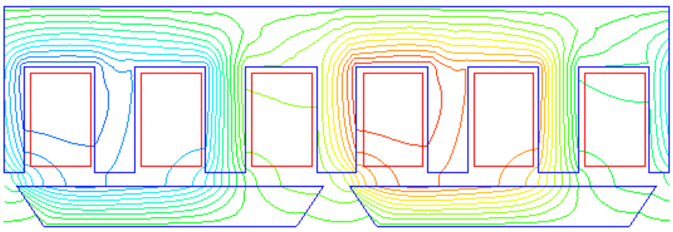

Figure 12. 2D magnetic flux distribution for first design with q=1

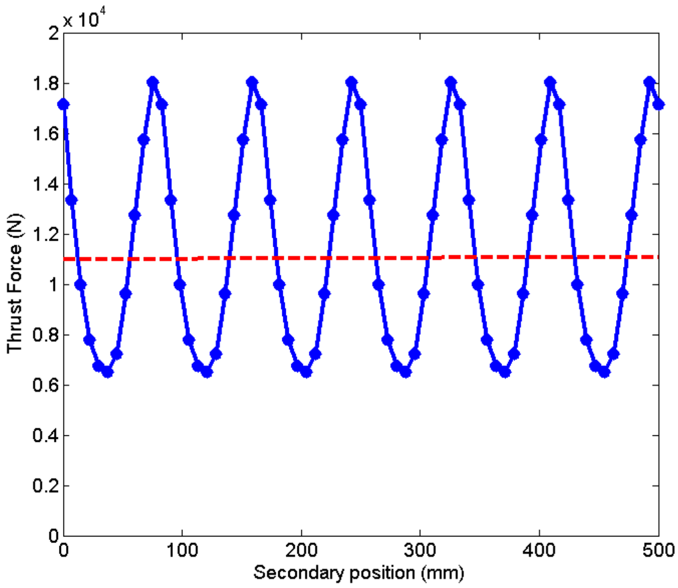

Figure 13. Thrust force variation versus secondary position – q=1

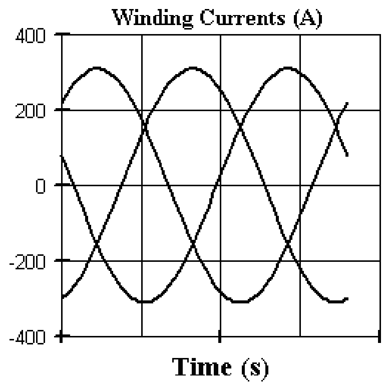

Figure 14. The applied sinusoidal current to primary

Figure 15 shows full structure configuration of second proposed model with short pitch winding and fractional slot structure. Winding pitch to pole pitch ratio is 8/9. The produced thrust force at zero speed with 220 A per phase is shown in figure 16. The force ripple has been reduced considerably in comparison with last model with q=1.

Figures 17 to 20 show the produced force and line voltage curve at nominal speed and maximum speed according to figure 4. The force ripple in all speeds is in acceptable region. The applied currents are 194.5 A and 65.5 A for nominal and maximum speeds, respectively. The required line voltages are 856 V (rms value) at nominal speed and 724 V at maximum speed that are less than 1100 V in both cases.

The pole pitch is 0.23 m with consideration 2.5 m for maximum iron length of linear machine. The number of turn per coil is 10 and slot pitch and tooth width are 51 mm and 18 mm, respectively. The machine width is 0.38 m. The number of slots is 49 and half-filled end slots winding is used to have more sinusoidal *mmf* in air gap.

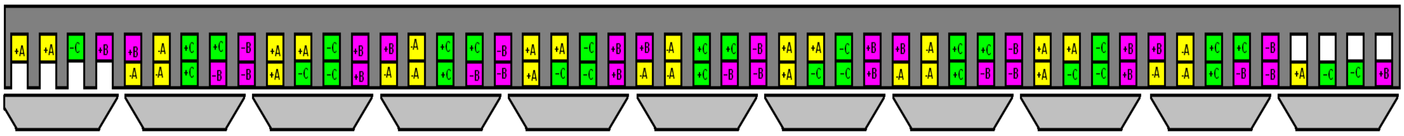

Figure 15. Full structure depiction of linear reluctance motor with 10 poles and q=1.5

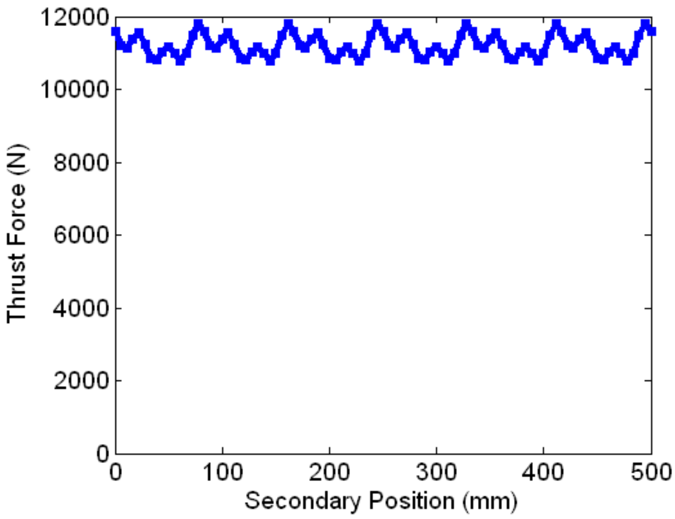

Figure 16. Thrust force variation versus secondary position – q=1.5 and at zero speed

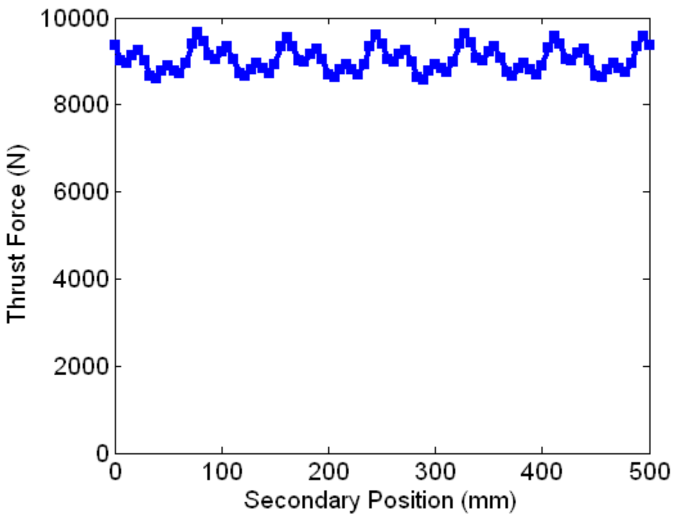

Figure 17. Thrust force variation versus secondary position – q=1.5 and at 12 m/s (Nominal speed)

4.2 Electrical analysis

The maximum power factor (1) for second design with q=1.5 at nominal speed:

$$Pf = \left| \frac{20.3(\mathrm{mH}) - 8.7(\mathrm{mH})}{20.3(\mathrm{mH}) + 8.7(\mathrm{mH})} \right| = 0.469$$

The computed value for maximum power factor is good for linear machine. The efficiency for this machine is calculated as follows:

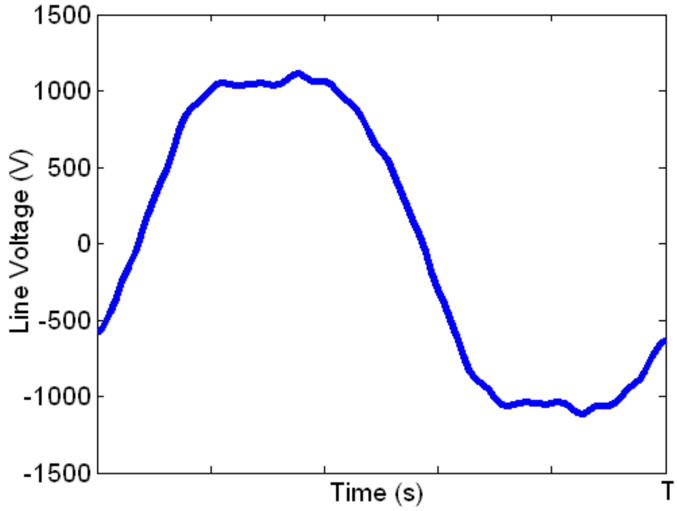

Figure 18. Line voltage at nominal speed (12 m/s)

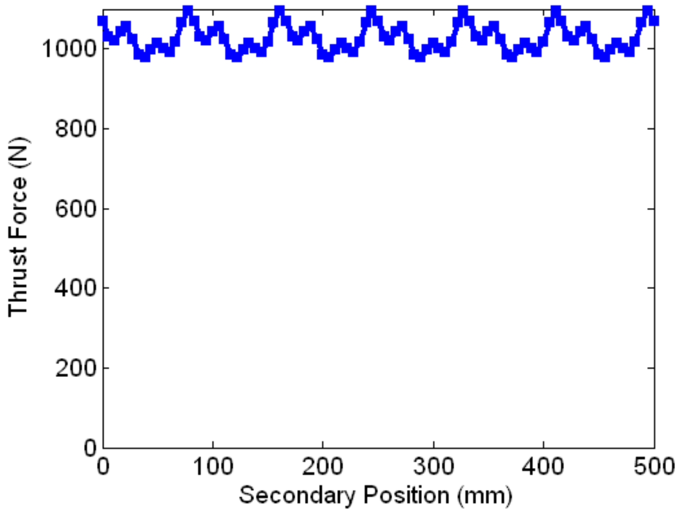

Figure 19. Thrust force variation versus secondary position – q=1.5 and at 30 m/s (Maximum speed)

$$\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{out}} + P_{\mathrm{copper}} + P_{\mathrm{Fe,S}} + P_{\mathrm{Fe,R}}} = \frac{9000 \times 12}{9000 \times 12 + 658 + 709 + 20} = 98.74\% \qquad (7)$$

To calculate efficiency, additional losses have been considered but the efficiency value shows the good performance of machine. The input VA of machine is:

$$P = \frac{P_{\mathrm{out}}}{\eta Pf} = 233\ k\mathrm{VA}$$

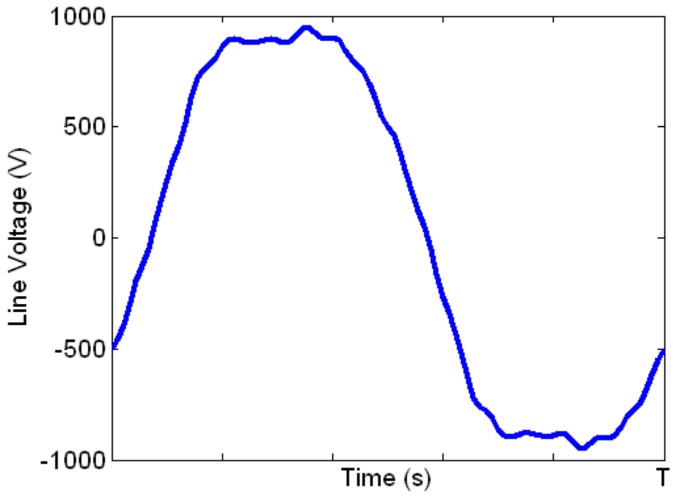

Figure 20. Line voltage at maximum speed (30 m/s)

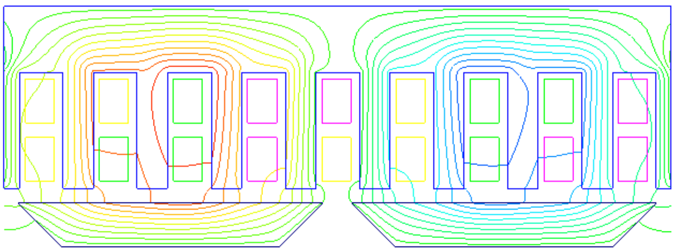
Figure 21. 2D magnetic flux distribution for first design with q=1.5

The magnetic flux distribution for q=1.5 is shown in figure 21 with 9 slots for two poles.

In comparison with linear induction machine, linear reluctance motors can be an alternative for Metro application. The main advantage of this synchronous motor is less losses in secondary and better efficiency relative to linear induction machine with solid secondary. And also the longitudinal and transverse end effects are negligible and these effects don't disturb the performance of linear reluctance machine as much as in linear induction motors. Another advantage of this machine especially in last design is constant force and independent of speed.

The inverter part has not been discussed here and just constant current case has been simulated. The constant voltage and constant flux will be analyzed in the future. The control system is very important to switching of switches according to the position of secondary poles. Here we offer a constant current or square-wave constant voltage inverter to make system to be cheap as much as possible.

5 CONCLUSIONS

Here in this paper, linear reluctance motors have been introduced for linear Metro application. Two configurations with distributed winding have been analyzed and the results have been shown. With q=1, the machine force ripple is very high and is not suitable for passenger transportations. But with fractional slot winding, the linear motor shows better performance especially force ripple is considerably small. The main disadvantage of linear reluctance machine is poor power factor (>0.5) due to the large magnetic air gap with consideration carter factor (minimum mechanical air gap=10 mm)

6 REFERENCES

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