MODELING AND ANALYSIS OF DUAL-SIDED CORELESS LINEAR SYNCHRONOUS MOTOR

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Key words: linear synchronous motor, permanent magnets, concentrated windings, double-sided, without iron losses, FEM, coreless.

Accurate knowledge of magnetic field distribution, back-electromotive force and thrusting electromagnetic force in dual-sided coreless linear synchronous motor are essential for analyze and optimization of the motor. Further design is regarding the mechanical analysis of the stator yoke who should sustain the mechanical stress produced by the magnetically attraction force between the permanent magnets. Finite element analysis is used to determine the motor electromagnetic and mechanical parameters.

1. INTRODUCTION

Permanent magnet linear synchronous motors (PMLSMs) are used in a large variety of industrial applications due to elimination of an intermediate gears, screws or crank shafts. These types of motors have a high efficiency and are used in applications that need very good precision, low maintenance and high acceleration of the moving part. Despite these advantages, these motors often result in a significant cost increase due to a large amount of permanent magnet used ([1], [7]).

The PMLSM is composed of two rigid parts which are not in mechanical contact. The motor analyzed in this paper is a PMLSM doubled-sided, air cored without iron losses (Fig. 1). In this case, the stationary part of the motor is a balanced double-sided “U” shaped structure of iron within are mounted the permanent magnets with alternate polarities. The moving part is the three-phase windings without iron which moves with the load. The linear motor is supplied with sinusoidal three phase voltages. Because the moving part is without iron, the losses in iron are zero, the cogging force is zero and the attraction forces between the moving part and the stationary part is zero. This type of motor is widely used in applications that require high speed, high precision, fast response, zero backlash (due to simple mechanical transmission components) and maintenance free operation. The disadvantages of this type of motors are the high price of the rare
earth permanent magnets and lower force density due to large “air-gap” compared to an iron cored motor.

![Fig. 1 – Configuration of the double-sided PMLSM without iron losses.](image)

This work describes the design and tests of a double-sided linear synchronous motor without iron losses. The thrust and other motor characteristics are calculated analytical and the accurate predictions of the motor performances are made using a numerical method. The finite element method (FEM) has proved to be the most powerful and widely used numerical method in electric machine design and analysis. A FEM analysis can evaluate the motor final design but it is not time efficient during all design procedures, since it requires excessive computation time and resources. A prototype was constructed. The measured values of thrust and back electromotive force are compared with the calculated value.

2. MACHINE STRUCTURE

A sketch of the machine is presented in Fig. 1. The length of the stationary part can be extended stacking end-to-end more stationary parts, increasing in this way the linear motor traveling distance. The height of coils is greater compared with height of the permanent magnets, due to the end coil winding height. Two types of windings can be used in electrical machines: distributed coils and concentrated coils. In double-sided PMLSM without iron losses the two types of windings are shown in Fig. 2 [3]. The winding factor ($k_W$) for iron cored and without iron distributed windings are 1 respectively 0.955 and for concentrated windings the maximum $k_W$ can be 0.76. Though for concentrated windings the $k_W$ is 20% less than distributed windings, the copper fill factor is with 15 – 25% higher in
concentrated windings and the end windings will be shorter, as a result, the Joule losses will decrease. A three phase windings with concentrated coils was adopted due to advantages described before.

![Fig. 2 – PMLSM types of windings; (a) distributed coils; (b) concentrated coils.](image)

The global design parameters are defined in Fig. 3. The dimensions and material types are given in Table I in connection with Fig. 3.

**TABLE I**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_m )</td>
<td>Magnet height</td>
<td>7</td>
<td>mm</td>
</tr>
<tr>
<td>( T )</td>
<td>Pole pitch</td>
<td>30</td>
<td>mm</td>
</tr>
<tr>
<td>( w_{in} )</td>
<td>Magnet width</td>
<td>25</td>
<td>mm</td>
</tr>
<tr>
<td>( L )</td>
<td>Coil length</td>
<td>240</td>
<td>mm</td>
</tr>
<tr>
<td>( L_c )</td>
<td>Coil width</td>
<td>60</td>
<td>mm</td>
</tr>
<tr>
<td>( h_b )</td>
<td>Coil height</td>
<td>7</td>
<td>mm</td>
</tr>
<tr>
<td>( w_c )</td>
<td>End winding height</td>
<td>18</td>
<td>mm</td>
</tr>
<tr>
<td>( g_c )</td>
<td>Coil inner gap</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>( G )</td>
<td>Distance between magnets</td>
<td>9</td>
<td>mm</td>
</tr>
<tr>
<td>( l_{spin} )</td>
<td>Turn length</td>
<td>142</td>
<td>mm</td>
</tr>
<tr>
<td>( l_y )</td>
<td>Yoke height</td>
<td>9</td>
<td>mm</td>
</tr>
<tr>
<td>( p_c )</td>
<td>Coil pitch</td>
<td>40</td>
<td>mm</td>
</tr>
<tr>
<td>( d_c )</td>
<td>Coil air-gap depth</td>
<td>42</td>
<td>mm</td>
</tr>
<tr>
<td>( B_T )</td>
<td>Remanent flux density</td>
<td>1.2</td>
<td>T</td>
</tr>
<tr>
<td>( \mu_r )</td>
<td>Magnet relative permeability</td>
<td>1.05</td>
<td>-</td>
</tr>
<tr>
<td>( N_f )</td>
<td>Number of turns/phase</td>
<td>564</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>Yoke material</td>
<td>Magnetic steel</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. 3 – Global design parameters.

The parameters of this double-sided PMLSM without iron losses were calculated using an analytical method [8]. The field distribution in the linear motor is assumed to be known, for example, from a finite element model.

The back electromotive force per phase is:

\[ E_{ph} = \pi \cdot \sqrt{2} \cdot f \cdot N_f \cdot \Phi \cdot k_w \]  

(1)

where \( f \) is the frequency and \( N_f \) is the number of turns per phase. With \( B_g \) the amplitude of the first harmonic of the flux density in the air gap, the flux is:

\[ \Phi = B_g \cdot S_g \cdot \frac{2}{\pi} \]  

(2)

where \( S_g \) is the area of a pole.

In a PMLSM the velocity of the traveling magnetic field is:

\[ v = \frac{dx}{dt} = 2 \cdot \tau \cdot f \]  

(3)

where \( \tau \) is the polar pitch.

The voltage becomes:

\[ E_{ph} = \sqrt{2} \cdot v \cdot B_g \cdot L \cdot N_{ph} \cdot k_w \]  

(4)

The thrusting electromagnetic force of the linear three phases motor is:

\[ F = \frac{3 \cdot E_{ph} \cdot I}{v} \]  

(5)
where \( I \) is the RMS value of the sinusoidal current through the winding:

\[
I = J \cdot s
\]  

(6)

\( J \) is the current density and \( s \) is the section area of the conductor.

The copper fill factor is calculated as the total copper area divided by total available area:

\[
k_u = \frac{6 \cdot N_{ph} \cdot s}{L_c \cdot h_p}
\]  

(7)

The thrusting force of the dual-sided PMLSM with sinusoidal wave is:

\[
F = \frac{\sqrt{2}}{2} \cdot B_g \cdot L \cdot L_c \cdot h_b \cdot k_u \cdot k_w \cdot J
\]  

(8)

3. FINITE ELEMENT ANALYZE

For accurate prediction and for optimization of the performance of dual-sided, coreless PMLSM, finite element method is used. Also FEM is used to find out the magnetic field distribution in the linear motor ([2], [4]).

A. 2D Numerical Modeling

In order to obtain the magnetic flux density in the air-gap, the nonlinear 2D FEM analysis using Comsol Multiphysics [6] is employed. The magnetic flux lines in a 2D equivalent model are presented in Fig. 4.

![2D magnetic field distribution on no-load](image-url)
On the exterior air boundary is impose the Dirichlet condition \( A=0 \), where \( A \) is the magnetic vector potential.

The section plane passes through the middle of the coil length (\( L_c \)). On the outer boundary, the homogenous Dirichlet boundary condition \( A=0 \) is imposed in order to ensure the problem proper conditioning, where \( A \) is the magnetic vector potential ([5], [9]).

The average magnetic flux density in the air gap is 0.45 T. Supplying the linear motor windings with three-phase sinusoidal currents with a RMS value of 1.67 A, a thrusting electromagnetic force of 98.6 N results.

**B. 3D Numerical Modeling**

The linear motor was modeled in 3D with Comsol Multiphysics.

First, a static analysis of the stationary part of the linear motor was performed in order to find out the field distribution and for proper sizing of the yoke. In Fig. 5, the magnetic flux density distribution in the stationary part of the motor and air-gap flux density distribution in the middle of the air-gap are presented. Investigation of the magnetic field distribution in the yoke reveals that the distribution is predominant grouped for every two magnets. Due to magnetic field distribution, the yoke is heavily saturated and the flux density in the air-gap is irregularly distributed.

![Fig. 5 – Magnetic flux density distribution; (a) Magnetic flux density distribution in stationary part; (b) Air-gap flux density norm in the air-gap, on the middle of the magnets.](image)

On the exterior air boundary the magnetic flux component in the normal direction is impose to be zero \( B_n=0 \).

In Fig. 6 is shown the magnetic flux density distribution and air-gap flux density distribution in the air-gap, after increasing of the yoke height (\( l_b \)) with 3.5 mm. With the optimized yoke, the magnetic flux density in the air-gap is regularly
distributed and the average flux density in the air gap is 0.5 T with 11% higher compared with 2D predicted value.

Second, a transient magnetic simulation was performed in order to accurate predict the linear motor performances. In order to reduce the computation time, the sliding mesh technique was used, which moves node data of tetrahedral mesh above a sliding surface. The machine has a longitudinal symmetry plane on the middle of the coils, where the magnetic field intensity component in the tangential direction is impose to be zero $H_t = 0$. Partial mesh of the 3D problem is presented in Fig. 7. In Fig. 8 is presented the 3D finite element predicted phase back electromotive force waveforms for all the phases.

When the linear motor running at constant speed is driven with three-phase sinusoidal currents with a RMS value of 1.67 A, the numerical computed thrusting electromagnetic force is 124.4 N.
A mechanical analysis of the stationary part of the linear motor was also performed in order to find out the von Mises stress distribution (Fig. 9), the yoke total displacement (Fig. 10) and the magnetically attraction force developed by the permanent magnets. As a result of the numerical evaluation, the attraction force between the two sides of the yoke is 1160 N. The total displacement of the yoke sides was numerical computed having a value of only $5.9 \cdot 10^{-6}$ mm, resulting that the air gap dimension is not affected.

4. EXPERIMENTAL VALIDATION

Fig. 11 shows the component parts of the linear machine. The machine windings are presented in Fig. 11 a. The coils are fixed in a nonmagnetic support. For a better mechanical fixation and better cooling the windings were potted into high thermal conductive resin. In Fig. 11 c, the stationary part of the linear machine is shown. The dual-sided U shaped inductor is made of magnetic steel. The yoke (including the connecting part between the two plates on which are fitted the permanent magnets) was mechanically and magnetically modeled using 3D FEM, in order to sustain the force between magnets and for regular distribution of the magnetic flux density in the air-gap.
Fig. 11 – Parts of the dual-sided, coreless PMLSM; (a) Coils fixed in a nonmagnetic support; (b) Moving part of the linear motor; (c) U shaped stationary part of the linear motor; (d) Linear machine on a test bench.

The windings parameters, back-electromotive force and electromagnetic force were measured. The phase back-electromotive force waveforms were compared with the 2D and 3D numerical computed waveforms (Fig. 12).

The 3D numerical predicted voltage coincides very well with the measured voltage. As expected, the 2D numerical predicted voltage differs from the measured value. The amplitude is lower due to the neglected flux fringing. In this type of motor, the 3D numeric model is more appropriate since the motor geometry and the magnetic field have 3D behavior.
Fig. 12 – Phase back electromotive force at 1 m/s. Measurement: continuous green line. Calculated by: 2D FEM blue line, 3D FEM orange dashed line.

With the winding connected in star and the terminals 2 and 3 connected, the motor was supplied with a continuous current of 2.34 A. Using a dynamometer, a constant force of 72 N/A was measured, resulting in a continuous thrusting electromagnetic force of 120 N. The 3D numerical predicted thrusting force where the running path friction was neglected coincides fairly well with the measured value. The 2D numerical predicted force is much lower than measured force due to the neglected end winding of the coils and due to the neglected real axial length of the stator yoke (the height of the yoke is greater compared to the height of permanent magnets or coils).

5. CONCLUSIONS

In this paper, we have been described the design, development and experimental evaluation of a dual-sided coreless permanent magnet linear synchronous motor. The configuration of the studied machine requires 3D finite element analyses for accurate performance prediction and sizing of the machine component parts. 3D FEM investigation of the magnetic field distribution in the yoke reveals that the distribution is predominant grouped for every two magnets. The hard saturation of the magnetic circuit causes the irregular magnetic flux density distribution in the air-gap.
Due to the air cored moving part, the iron losses are zero, the parasite cogging forces between the magnets and iron teeth are zero and the magnetic attraction forces between the stationary part and moving part are zero in comparison with other permanent magnets motors.

The magnetically attraction force between the permanent magnets generate a mechanical stress in the double-sided stator yoke. For dual-sided coreless permanent magnet linear synchronous motor an accurate stress prediction (employing finite element analyses) is required to assure that the stator yoke can sustain the mechanical stress and the double air gap dimension is not major affected.

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