II-2. CALCULATION OF LINEAR MOTOR PERFORMANCE USING FINITE ELEMENT METHOD

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Abstract – The paper presents calculation of linear induction motor and linear synchronous motor steady-state characteristics using finite element method. 2D non-linear magnetostatic and eddy-current solver were used for magnetic field and force calculation. A detailed insight in magnetic field distribution and produced output force is a basic step for evaluation of motor performance. Calculations were performed for different excitation currents and different air gap lengths for both types of linear motor. The results obtained from the magnetic field calculations could also be used for determination of motor parameters (e.g. inductance) useful for mathematical modelling and control system simulations.

Introduction

Linear motors are widely used in machine tools, linear tables, textile tools, saws, separators, transportation systems and many others [1]. This paper focuses on permanent magnet linear synchronous motor (PMLSM) and linear induction motor (LIM) applied as servo motor for machine tools. For optimal operation of the motor a detailed insight into a steady-state and dynamic performance characteristics is very important [2,3,4].

Both types of linear motors are installed in our laboratory and a lot of measurements have already been performed. In spite of that there is a problem of analysing steady-state operating conditions since the available moving range is short, the system is highly dynamic and during operation there are almost no steady states. Furthermore all measurements of electrical and mechanical quantities are very demanding. In Table 1 basic parameters of the linear motors are stated.

Table 1. Basic constructional and rated parameters of the motors

<table>
<thead>
<tr>
<th></th>
<th>Number of pole pairs</th>
<th>Length of primary part (mm)</th>
<th>Length of secondary part (mm)</th>
<th>Rated force (N)</th>
<th>Rated current (A)</th>
<th>Rated speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIM</td>
<td>2</td>
<td>390</td>
<td>3000</td>
<td>1000</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>PMLSM</td>
<td>4</td>
<td>390</td>
<td>3000</td>
<td>1500</td>
<td>17</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Analyses of Motors Using FEM

For analyses of both motors a 2D FEM software was used. The force produced by the motor was calculated using a method of virtual work. For linear induction motor analyses the eddy current solver was used. Magnetic field was described by equation (1)

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times \vec{A} \right) = \sigma \cdot \nabla \phi - \sigma \cdot \frac{\partial \vec{A}}{\partial t}
\]

where \( \mu \) is permeability, \( \vec{A} \) is magnetic vector potential, \( \sigma \) is conductivity and \( \phi \) is electric scalar potential.

The fluxes in primary and secondary part have different frequencies for all operating states except for a locked primary condition. Equation (1) describes electromagnetic conditions only at one frequency. To solve that problem the frequency of primary excitation current corresponds to instantaneous slip
value at chosen steady-state operating point [5]. With sweeping the excitation frequency from rated value down to zero the complete steady-state force characteristic can be obtained.

For analyses of linear synchronous motor a magnetostatic field solver was used and the result was derived from equation (2)

$$\bar{\nabla} \times \left( \frac{1}{\mu} \bar{\nabla} \times \bar{A} \right) = \bar{J}$$

(2)

where $\bar{J}$ is current density which consists of exciting current and equivalent magnetizing current of permanent magnets. Force was calculated for different displacement of primary part and different air gap lengths.

Magnetic Field Distribution

Figure 1 shows the magnetic field distribution at maximal force of (a) linear induction motor at slip 0.12 and (b) linear synchronous motor at displacement of 12.5 mm. The primary part has a two-layer winding with half-filled end slots, which is typical topology for linear motors [1]. Because of this constructional particularity the number of poles is odd. Contrary to the magnetic field in rotational motors, which is always symmetrically distributed along air gap the magnetic conditions in linear motors are regularly asymmetrical. Besides that the holes of the water-cooling system are placed in the yoke of the linear synchronous motor primary core (Fig. 1b). They obviously have an additional influence to asymmetrical magnetic flux distribution. The linear induction motor also has a water-cooling system but the aluminium unit is mounted above the primary part and has no influence on the magnetic field.

Fig.1. Magnetic field distribution of (a) linear induction motor and (b) linear synchronous motor