Application of Finite-Element Method to a PMLSM with Non-Sinusoidal Electromotive Force

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An accurate thrust control of permanent magnet linear synchronous motors (PMLSM) is more efficient with a fine knowledge of the harmonics value of the electromotive force (EMF). This is often difficult to obtain experimentally for a PMLSM. As a consequence, this paper deals with the study of the non-sinusoidal EMF of a PMLSM using the 3D Finite-Element Method (FEM). Two potential formulations are used to consider several cases. Afterwards, for the same accuracy, the computation times are examined. The results of the FEM are compared to those given by the measurements from a test bench composed of a Siemens LIMES400/120 linear motor and a dSPACE DS1005 real-time controller board. Finally, the advantages and the limitations of the FE Analysis will be discussed.

Keywords: PMLSM, non-sinusoidal electromotive force, finite-element analysis

1. Introduction

Nowadays, industrial applications such as machine-tools applications require high speed and high precision. To improve the performances of linear motion systems, classical solutions are to adapt more powerful linear motors, or to reduce the moving weight. But in the meantime, ripple forces induced by harmonics of Back-EMF are amplified as the power of the linear motor increases; consequently, the mechanical system is more and more perturbed by the force ripple and a high precision positioning becomes more difficult to reach. One solution is to improve the control strategy of such systems: to control permanent magnet linear synchronous motors (PMLSM) in an optimal way, the knowledge of the real waveform of different electrical characteristics is required. Thus, control strategies can be built on accurate values and yield reliable processes, notably on the thrust control. One of the electrical characteristics needed is the electromotive force (emf). This can be sinusoidal or not, which implies different control approaches. Furthermore, it is generally difficult to obtain this emf from measurements. Nowadays, the three-dimensional finite-element method (3D-FEM) is widely used to model PMLSMs. This approach takes into account the real geometry of the modelled electromechanical converter as well as the non-linear characteristic of the magnetic materials used. Thus, it leads to accurate results with regard to the real system. Then, it can be helpful to determine the electrical characteristics of a PMLSM when it is difficult to measure them. This can be used, in virtual prototypes, to quantify their electromagnetic variables in order to foresee the machine control or to modify the geometrical characteristics of the prototype to yield the desired results.

In this paper, we propose to use the finite-element method to study the non-sinusoidal emf of a PMLSM. In the first part, we introduce the 3D finite-element method; as there are several solutions to solve the Maxwell equations, two classical potential formulations are presented to express and solve the electromagnetic problem. We take into account the non-linear behaviour of the magnetic circuit. Then, the calculation principle of the linkage flux is explained.

The second part of the paper is devoted to the presentation of the studied system. We show the elementary part modelled and the geometrical characteristics, the effects of which are studied. The results obtained by both formulations are given in different cases. Comparisons are carried out on the accuracy and time calculations of both formulations. The advantages and the limits of the FE Analysis are discussed.

In the last part, the simulation results are compared to those obtained on an experimental bench. The studied system is
a prototype designed for high speed laser cutting (Fig. 1). To reach high acceleration and velocity, two linear motors from Siemens (LIMES400/120-P16) are used and controlled in parallel. A non steady-state technique necessary to identify the Back-EMF harmonics is presented. Then, different geometrical characteristics and their effects are studied by the 3D-FEM.

2. The Finite-Element Method

The finite-element method is used to solve the Maxwell equations related to two-or three-dimensional electromagnetic converter problems.

2.1 Formulations in Term of Potentials  
In the magnetostatic case, the Maxwell equations are written on a domain “V” of boundary Γ, such as Γh ∪ Γb = Γ and Γh ∩ Γb = 0, under the following form:

\[ \text{curl} \mathbf{h} = \mathbf{j} \quad \text{with} \quad \mathbf{h} \times \mathbf{n} = 0 \quad \text{on} \quad \Gamma \]  
\[ \text{div} \mathbf{b} = 0 \quad \text{with} \quad \mathbf{b} \cdot \mathbf{n} = 0 \quad \text{on} \quad \Gamma \]

In these expressions, \( \mathbf{h} \) represents the magnetic field, \( \mathbf{b} \) the magnetic flux density and \( \mathbf{j} \), the current density. Vector fields \( \mathbf{b} \) and \( \mathbf{h} \) are linked by the constitutive relationship \( \mathbf{b} = \mu \mathbf{h} \). In the case of permanent magnets, the constitutive relationship takes the form:

\[ \mathbf{b} = \mu_s \mathbf{h} + \mathbf{h}_c \]

where \( \mathbf{h}_c \) is the coercitive field and \( \mu_s \) the permeability of the permanent magnets, which is close to the permeability of the air.

In our development, the studied domain “V” is considered as simply connected. To solve these equations, we can use a formulation in terms of scalar potential \( \varphi \) (called \( \varphi \)-formulation) with a source field \( \mathbf{h}_s \), or a formulation in terms of magnetic vector potential \( \mathbf{a} \) (called \( \mathbf{a} \)-formulation).

In the case of the \( \varphi \)-formulation, the current density is expressed from the curl of a magnetic field, as:

\[ \mathbf{h} = \mathbf{h}_s - \nabla \varphi \quad \text{with} \quad \mathbf{h}_s \times \mathbf{n} = 0 \quad \text{on} \quad \Gamma \]

The magnetic scalar potential \( \varphi \) is then the unknown and the source field \( \mathbf{h}_s \) is defined by:

\[ \text{curl} \mathbf{h}_s = \mathbf{j}_s \]

The formulation in terms of vector potential is obtained from equation (2) so that:

\[ \text{curl} \mathbf{a} = \mathbf{b} \]

To impose the uniqueness of \( \mathbf{a} \), it is necessary to add a gauge condition.

When an electromechanical system has to be studied, a choice has to be made between the two formulations. The results presented in the next part give some advice to make this choice.

To take into account the non-linear behaviour of the magnetic circuit, we have used an analytical approximation of the non-linear curve given by \( \mathbf{h}(b) \):

\[ \mathbf{h} = \frac{\mathbf{b} \varepsilon \tau + c b^{2\alpha}}{\mu_0 \tau + b^{2\beta}} \]

where \( \mu_0 \) is vacuum permeability and \( \mu_s \) is relative permeability. In the linear case: \( \mu_s = \text{cst} \). In the saturated case: \( \mu_s \) is deduced from the nonlinear magnetic curve \( \mathbf{b}(h) \) of the ferromagnetic sheets (Fig. 2).

This equation (7) is called the Marrocco equation. It needs four parameters \( \alpha, \varepsilon, \tau, \) and \( c \), which are obtained by fitting the Marrocco equation with the manufacturer values using an iteration procedure. Finally, we obtain: \( \alpha = 10.1126; \varepsilon = 1; \tau = 0.0002216 \) and \( c = 27005394 \).

The difference between the two curbs (Fig. 2) concerns the initial magnetizing curve. In fact, the Marrocco curb is closer to the representation of a magnetizing curve under an AC supply.

All the elements which compose the studied system are defined as explained and grouped under a matricial form. Then, the magnetic material non-linearity is considered using an iterative procedure (Newton-Raphson). The differential equation system is solved using an implicit Euler algorithm taking a constant time interval.

2.2 Flux Linkage Expressions  
We assume that the domain “V” has one inductor and we denote “I” the current. We also note that the current density distribution is assumed to be uniform in each cross section. Consequently, \( \mathbf{j}_s \), in the inductor can be written as:

\[ \mathbf{j}_s = N \mathbf{i} \]

where \( \mathbf{N} \) is the vector of turn density. Its magnitude is given by the ratio of the number of turns to the winding section and its direction by its spatial orientation. The flux linkage in a winding can be obtained by integrating, on the whole domain, the projection of the magnetic vector potential on the vector of turn density. Thus, we can write:

\[ \Phi = \int_{\Gamma} \mathbf{a} \cdot \mathbf{N} \, dv \]

To determine flux linkage in the case of the \( \varphi \)-formulation, as the current density vector \( \mathbf{N} \) is divergence free, a vector \( \mathbf{K} \) is introduced under the form: \( \text{curl} \mathbf{K} = \mathbf{N}^{\text{in}} \). Then, from equation (9), permuting \( \mathbf{N} \) with its expression in function of \( \mathbf{K} \) and using Green’s formula, we can write:

\[ \Phi_w = \int_{\gamma} \mathbf{K} \cdot \text{curl} \mathbf{a} \, dv \]

From equations (10) and (6) and considering the constitutive relationship and the expression of the magnetic field (3),...
we can write the flux in function of \( \mathbf{K} \) and \( \phi \) under the form:

\[
\Phi_w = \int_V \mu \mathbf{K} \cdot (\mathbf{K} - \text{grad} \phi) \, dv \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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cases. The results obtained from the calculations with both formulations are compared in Table 1.

Classically, the a-formulation always gives greater values than the ϕ-formulation for the magnetic energy and the flux. This is not always true in the case of the emf, because it is a derivative variable. However, it can be noticed that whatever the formulation used, the coefficients are greater with the pole shoes.

4.2 Comparison Linear/Saturated In Table 2, we present a comparison of the emf coefficient harmonics given by both formulations in linear and non-linear cases.

In both formulations, the emf values are very close: about 5%. Indeed, the air-gap is about 2.2 mm and the magnet induction used in calculations is about 1.2 Tesla. This induces a low level of saturation in the magnetic circuit of the primary, which implies that emf values obtained in this case are lower than those obtained with a linear ferromagnetic circuit.

Fig. 5 shows the emf in different cases.

4.3 Computation Time The Maxwell equations have been solved on a Cluster PC XEON microprocessor with 2.8 GHz frequency and 512 Mb RAMBUS PC1066 (533 MHz). The required degree of accuracy for both formulations is fixed to $10^{-12}$ in the numerical resolution of magnetic flux density. ϕ-formulation and a-formulation computation times are compared in Table 3:

For the analysis of the linear ferromagnetic material, the a-formulation needs more computation time than the ϕ-formulation. Hence, the computation time ratio between the two formulations is very close to the matrix size ratio of about 1.5.

For the analysis of the saturated ferromagnetic material, the ϕ-formulation needs more computation time than the a-formulation. Indeed, the iteration procedure of the a-formulation is based on the Newton-Raphson algorithm, whereas the ϕ-formulation is based on the substitution algorithm. Classically, the ϕ-formulation needs three times more iteration for a similar position analysis.

4.4 Conclusion of the FEM Results Regarding to results in Table 1, Table 2 and Table 3, in studied cases, the a-formulation requires too much computation time compared to the ϕ-formulation. Furthermore, the emf values reached with each formulation are very close. Finally, the level of saturation in the system is not enough to justify the computation time required in the saturated case.

The emf analysis of the PMLSM in the linear case, with pole shoes and in the ϕ-formulation, requires an acceptable computation time, and gives precise enough results on the emf values (less than 10% difference with other results) regarding all the hypotheses taken. Finally, the values of the emf harmonics obtained by FEM are shown in Table 4.

Lastly, regarding the results of Table 4, looking at the rank harmonics of EMF higher than the 5th is not necessary:

- the ratio H7/H1 is insignificant between the other ratios, and the thrust ripple induced for the upper rank harmonics is also negligible.
- the magnetic circuit tooth size shows dispersion, so it’s impossible to guarantee a precision that allows to find the same value of the high harmonics in the real primary.
- the magnet disposition on the yoke is most of the time made by pieces of yoke put together, which changes magnetic circulation of the magnets flux and consequently the harmonics value of the Back-EMF.

5. Experimental Validation

5.1 EMF Identification Experimentally, a special technique is required to identify the harmonic components of the emf (Fig. 6). Indeed, steady state at a rated speed is difficult to reach because of the finite-length of the PMLSM. Furthermore, the PMLSM coils are star connected, which eliminates the 3rd harmonics of the line-to-line emf. The induced voltage is divided by the instantaneous speed to obtain the emf. The quality of the results depends on the high precision of the position measurement. Here, we have used a Heidenhain exposed linear encoder with a grating period of 40 μm.

As we can notice in Fig. 6, the emf measures are noisy; from about 5%, it becomes a problem at low speed, so the identification procedure has to be made with a sufficient speed to maximise the accuracy of the measures.

![Experimental results of emf](image)
5.2 Comparison FEM/Experimental Results

We obtain from the FEM a simple emf Ean and a line-to-line emf Eab (Fig. 7). With a star-connected primary, we confirm that the 3rd harmonic has disappeared.

With the symmetry of the PMLSM primary, we can recombine the complete signal of the back-EMF from the FEM. More precisely, as we only mesh one pole using the FEM, results only present a half period of back-emf.

As explained previously, we have 96 nodes for a pole, which are separated from each other by a mesh size of 0.375 mm as in Fig. 4. Thus, we create a step by step movement by swapping the state of each node for the state of its adjacent node. The time step used to calculate the back electromotive force with the FEM is defined to represent the movement of a mesh size at a virtual speed of 1 m/s. It gives a time step of 0.375 ms.

Next, we estimate the back electromotive force from the position and the speed, and we compare it with the value of the voltage probe. Measure and estimation of Back-emf are made in real-time with a dSPACE 1005 card.

The comparison between FEM and experimental measurement of line-to-line emf is presented in Fig. 8.

The FEM results use the a-formulation with pole shoes. We can notice that the FEM results overrate the emf values.

Influence of Pole Shoes

The results on emf coefficient calculations with the φ-formulation and the a-formulation are compared in Table 1 and Table 2. Between the PMLSM without pole shoes and the PMLSM with pole shoes, we notice that emf values increase by about 5%.

Indeed, the pole shoes increase the surface of steel in front of the air-gap. Here, the air-gap surface increases from 50% to 75% of the maximum air-gap surface. Thus, the magnetic flux induced in a phase is increased. The main interest of pole shoes PMLSM is that 5 extra percent of emf values results in more generated electromagnetic thrust, but reduces power factor. But, at the same time, the pole shoes increase the value of emf harmonics, which generates ripple force.

6. Conclusion

In this paper, we have presented the finite-element analysis of non-sinusoidal electromotive force of a permanent magnet linear synchronous motor. We have verified on the emf rms value that FEM and experimental results are close (the maximal error is about 5% of the emf fundamental values). That allows us to validate the approach and to understand the effects of geometrical characteristics. Then, a notable advantage of the FEM analysis is to obtain the third harmonics of emf, whereas experimental results cannot give this result because the PMLSM phases are star-connected, with an inaccessible neutral wire. As we have neglected the coils end effects and the longitudinal end effects, we cannot determine precisely the fifth and upper level harmonics by FEM. On the other hand, experimental results give harmonic values of emf up to the 7th rank with a variance of less than 10% (out of more than thirty analyses).

Several cases have been studied and analysed: with or without pole shoes, in linear or saturated ferromagnetic material, with φ-formulation or a-formulation.

For high-precision applications, the optimal control of the position for a system is firstly based on the control of the PMLSM. Non-sinusoidal electromotive forces generate ripple force on the electromagnetic thrust of up to 15% of the rated thrust. Resonant controllers allow us to compensate harmonics of emf, and so to generate a non-oscillating electromagnetic thrust.

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References

(3) I. Boldea and S.A. Nasar: Linear Motion Electromagnetic Devices, Taylor & Francis (2001-12)


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