Finite Element Simulation of a Tubular Linear Induction Machine compared to Analytical Results and Measurements

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Abstract

An axisymmetric finite element model enables a more accurate description of a tubular linear induction machine compared to a pure analytical model. A time-harmonic solver combined with an enhanced force computation technique is applied to study the dependence of the force upon the exciting frequency. All simulations are compared to analytical models and measurement data.

1   Introduction

Linear induction machines (LIMs) are appropriate for drives requiring linear and jerk-free motion with high accelerations [1]. The LIM considered here consists of a translating aluminium tube inside a tubular stator and around an iron cylinder serving as yoke (Fig. 1 and Fig. 2) [2]. The tubular shape of the LIM prevents laminating the iron. As a consequence, both saturation and eddy currents are not negligible in the iron parts. The design of a highly dynamic control scheme requires accurate simulations for all operating conditions of the motor.

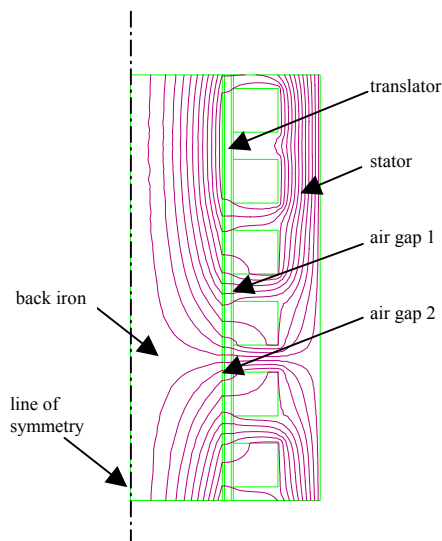Fig. 1: Tubular linear induction motor.

Fig. 2: Geometry and magnetic flux lines of the tubular linear induction motor.

2   Finite Element Model

As the geometry and the excitation is cylindrically symmetric, an axisymmetric model is applied. The governing differential equation

$$-\frac{\partial}{\partial r}\left(\frac{\nu}{r}\frac{\partial(rA_\theta)}{\partial r}\right)-\frac{\partial}{\partial z}\left(\nu\frac{\partial A_\theta}{\partial z}\right)+\sigma v_z\frac{\partial A_\theta}{\partial z}+j\omega\sigma A_\theta=-\sigma\nabla V$$

(1)

with $\mathbf{A}=(0,A_\theta,0)$ the magnetic vector potential, V the voltage, $\mathbf{v}=(0,0,v_z)$ the velocity, j the complex phasor, ω the electric pulsation, ν the reluctivity and σ the conductivity, is discretised by linear triangular elements.

The nonlinear permeability of the iron core is taken into account by providing an effective saturation characteristic to the nonlinear time-harmonic solver [3]. To enhance the accuracy of the simulation, especially in the neighbourhood of the axis of symmetry, adaptive mesh refinement is applied. The external electric circuit exciting the motor is incorporated in the overall matrix system [4].

3   Force computation

A choice is made to apply linear finite elements and to rely on adaptive mesh refinement to obtain a sufficient accuracy for the simulations. The piecewise linear approximation for the magnetic vector potential, however, yields a piecewise constant representation of the magnetic flux densities. This causes a severe discretisation error on the global force computed by the Maxwell stress tensor [5]. Here, out of the local field values evaluated along two lines in each air gap of the devices, local analytic solutions are constructed. The Maxwell stress tensor method relying on these local analytic field approximations, provides accurate forces while retaining small meshes with linear elements and thus acceptable computational times.

4   Analytical Model

An analytical model is used for comparison. The travelling air gap field is approximately periodic in the z-direction. The governing equation (1) can be analytically solved inside the homogeneous layers of the device [6]. At the interfaces between two successive layers, appropriate boundary conditions for the electric and magnetic fields are applied. The three-phase current excitation is decomposed in the major harmonic components (Fig. 3) and added as a current sheet to the model. A linear superposition of the harmonic magnetic fields is

performed (Fig. 4). The conductive iron parts prevent penetration of the flux.
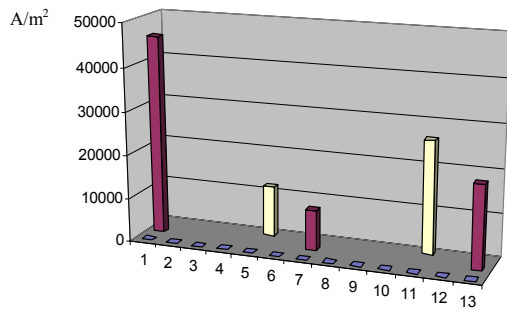

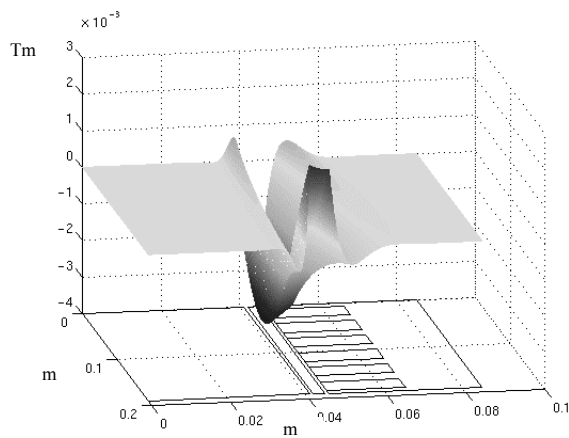Fig. 3: Harmonic components of the current excitation.

Fig. 4: Magnetic vector potential distribution simulated using the analytical model.

5 Finite Element Simulations

One pole pitch of the LIM is modelled. Nonlinear and conductive material properties are assigned to the appropriate regions. The LIM is excited by a 30 A current at different frequencies. The flux lines at 5 Hz are plotted in Fig. 2. The force operating upon the aluminium translator is measured and computed. Significant saturation of the iron at the rotor surface and the stator inner wall is observed. To study the reduction of the machine performance due to the eddy currents in the iron parts in the model, several fictitious models, each of them neglecting the eddy current effect in one or more iron parts, are simulated (Table I). The influence of the additional losses on the excited force is considerable. The force in terms of the frequency is compared to analytical results and measurements in Fig. 6. The analytical model provides too large forces. The reason can be the assumption of a linear ferromagnetic characteristic. The finite element model yields more reliable results.

Tabel I: Influence of eddy current effects on the force.

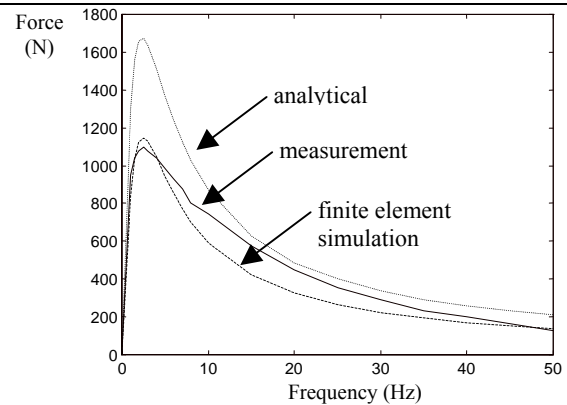| Conductive parts	Finite element	Analytical
Translator (TR)	362 N	365 N
TR+stator (TR+ST)	314 N	353 N
TR+back iron (TR+BI)	305 N	330 N
TR+ST+BI	267 N	319 N

Fig. 6: Dependence of the force on the applied frequency.

6 Conclusions

The axisymmetric simulation tools presented here, enable a full and accurate modellisation of the electromagnetic behaviour of the tubular linear induction machine. The adaptive mesh refinement strategy combined with the enhanced force computation module provides the opportunity to obtain a sufficient accuracy with relatively small finite element models. This enables the replacement of the analytical model in the design and optimisation procedure by more accurate and reliable finite element simulations.

Acknowledgement

References

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