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Two-dimensional finite element analysis of steel-secondary linear induction motor under variable frequency and loading conditions

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SUMMARY

Short-primary sheet-secondary type linear induction motors (LIM) have been proposed for a number of applications [1] including high speed ground transportation [2-3]. In the literature, steady state performance characteristics of LIM have been determined using one, two and three-dimensional field analysis [4-7]. Furthermore, it has been shown that for steady-state analysis, a quasi-one-dimensional approach, which accounts for the three mentioned effects by superposition is adequate for practical reasons [8].

In this paper a doubled-sided linear induction motors (DLIM) with a steel-sheet secondary, which is generally used in high-speed ground transportation, is modeled. The model is obtained from the field analysis using finite elements in x-y plane. All fields are then assumed to be invariant in the z-direction with current restricted to the z-direction. Saturation in the stator is taken into account. The solution is found by iteration and adjustment of m for the elements until m, B and H coincide on the B-H curve. Thrust force is predicted. The flux pattern for a 4-pole machine is drawn. Computational results are verified by experimental measurements under variable frequency and loading conditions. In fact the analysis can be extended to three dimensional finite element modeling following the method outlined below.

Key words*: linear induction motor, steel-sheet secondary, thrust force, variable frequency excitation, finite element method.*

1. GOVERNING EQUATIONS

The magnetic field may be described using the magnetic vector potential *A(x,y)* which satisfies [9-13]:

$$\frac{\partial}{\partial x}\left[u\frac{\partial A}{\partial x}\right]+\frac{\partial}{\partial y}\left[u\frac{\partial A}{\partial y}\right]=-\left(J_s-jwsA-s\,U\frac{\partial A}{\partial x}\right) \qquad (1)$$

where, depending on rotor position, the current density takes the following values:

(i)	Stator slots:	$s=0$	(2a)
(ii)	Non-conducting regions:	$s=0,\ J_s=0$	(2b)
(iii)	Rotor sheet:	$J_s=0$	(2c)

The finite element method is adapted to analyse the motor. The region under consideration is divided into a set of linear triangle elements ensuring that material interfaces coincide with the edges. The unknown vector potential *A* within each element is approximated as a linear interpolation of its values at three vertices. Figure 1 shows the triangular element distribution.

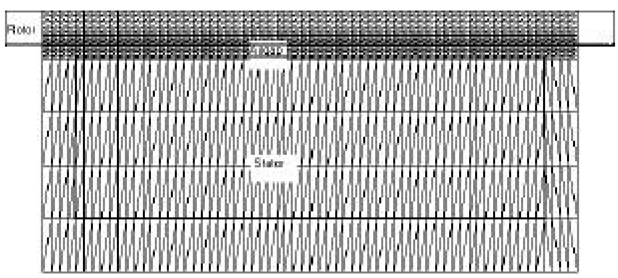

Fig. 1 Triangular element distribution

Galerkin method of weighted residuals is applied to Eq. (1) for each element. The summation of all elements is then performed which gives a system of equations in the following form:

$$\boldsymbol{K}\boldsymbol{A} = \boldsymbol{b} + \boldsymbol{g} \tag{3}$$

where $\boldsymbol{A}$ is a column vector listing the unknown potentials at all nodes, $\boldsymbol{K}$ is a square matrix; it is well banded and complex. Vector $\boldsymbol{b}$ is a column vector accounting for the stator excitation. The elements of vector $\boldsymbol{g}$ are found using a recursion technique to create a super element representing the exterior space [14-15].

It is found that the stator is not saturated. Therefore it is possible to represent the nonlinearity of the stator magnetization curve in its operating region using the reluctivity technique defined as:

$$u = \frac{a_1}{1 - b_1 B_d} \tag{4}$$

where a_1, b_1 and B_d are constants determined by the magnetization characteristic of the stator laminations.

2. PERFORMANCE CALCULATIONS

Having solved the system of equations (1) for the vector potential A, the motor performance can be found as follows:

$$B = \nabla \times A \tag{5}$$

$$B_y = \frac{\partial A}{\partial x} \tag{6}$$

$$B_x = \frac{\partial A}{\partial y} \tag{7}$$

$$F_t = Real\left(0.5 \int_0^L \int_{-a}^{a} J_s B_y^* \, dx \, dy \right) \tag{8}$$

3. RESULTS AND DISCUSSION

Figure 2 shows a sample of the flux density distribution for half the motor. It shows the equi-values contours of the real component of the x-component of flux density.

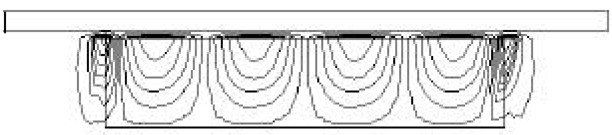

Fig. 2 Flux density contours

Figure 3 shows comparison between the measured thrust-speed curves and the predicted results from the FE model for *50 Hz* and *30 Hz* excitation. Predicted and experimental data are in reasonable agreement. Discrepancy between the two sets of results is mainly caused by neglecting both end effects and the non-linear variation of rotor reluctivity with flux density. These effects are under investigation.

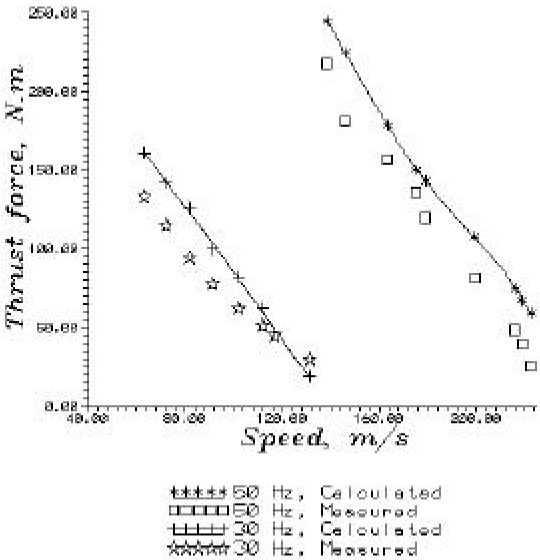

Fig. 3 Thrust at various frequencies vs. speed

4. CONCLUSIONS

The paper presents theoretical and experimental results of the variation of the thrust force with speed for a double-sided linear induction motor (DLIM) with a steel-sheet secondary under variable frequency excitation. The main discrepancy between experimental and predicted values is caused by neglecting end effects, leakage flux and nonlinear variation of rotor reluctivity with flux density. It is hoped such discrepancy will vanish by including these effects.

5. NOMENCLATURE

x, y, z	cartesian coordinates; the subscripts also denote components in the x, y, and z directions respectively.
A	magnetic vector potential in the z direction, *T/m*
B	flux density, *Tesla*
F_t	thrust force, *N*
J	current density in the z direction, *A/m*
J_s	stator excitation, *A/m*
U	rotor velocity in the x-direction, *m/s*
u	stator reluctivity, *H/m*
s	rotor conductivity, *S/m*
w	supply frequency, *rad/s*
a	half the secondary thickness

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DVODIMENZIONALNA ANALIZA ÈELIÈNOG SEKUNDARNOG LINEARNOG INDUCIJSKOG MOTORA METODOM KONAÈNIH ELEMENATA POD PROMJENJIVOM FREKVENCIJOM I OPTEREÆENJEM

SAŽETAK

Kratko primarni i plosnato sekundarni tip linearno indukcijskih motora (LIM) preporuèuje se za razne primjene [1] što ukljuèuje i prijevoz velikim brzinama na kopnu [2-3]. Radne karakteristike stacionarnog stanja LIM motora opisane su u literaturi pomoæu jednodimenzionalne, dvodimenzionalne i trodimenzionalne analize [4-7]. Nadalje, pokazuje se da je s praktiènog gledišta za analizu stacionarnog stanja prikladan nazovi jednodimenzionalni pristup koji pomoæu superpozicije ukljuèuje sva tri efekta [8].

U ovom se radu modelira dvostrani linearni indukcijski motor (DLIM) s èelliènim plosnatim sekundarnim tipom koji se najèešæe rabi u prijevozu velikim brzinama na kopnu. Model se dobiva iz analize polja pomoæu konaènih elemenata u ravnini x-y. Pretpostavlja se da su sva polja nepromjenljiva u z-smjeru sa strujom ogranièenom u z-smjeru. Uzima se u obzir i zasiæenje u statoru. Rješenje je pronađeno iteracijom i podešavanjem m za elemente dok se m, B i H ne sastanu na B-H krivulji. Predviđa se i sila potiska. Nacrtan je uzorak toka za stroj s 4 pola. Izraèunati rezultati potvrđuju eksperimentalna mjerenja pod promjenjivom frekvencijom i uvjetima optereæenja. Analiza se može proširiti na modeliranje trodimenzionalnim konaènim elementima slijedeæi ovdje navedeni model.

***Kljuène rijeèi**: linearni indukcijski motor, èelièni-plosnati-sekundarni tip, potisak, promjenjiva frekvencijska pobuda, metoda konaènih elemenata.*