Nonlinear Equivalent Magnetic Circuit Analysis for Linear Flux-Switching Permanent Magnet Machines

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Abstract —A Nonlinear Equivalent Magnetic Circuit (NEMC) modeling method is developed for Linear Flux-Switching Permanent Magnet (LFSPM) machines. The method is used to analyze the characteristics of linear FSPM machines by specific permeance calculations, in which the air gap nonlinear permeance is solved by FE analysis. Moreover, magnetic saturation as well as the field interaction is taken into account. A proposed LFSPM machine is used as example, the back-EMF, cogging force and thrust force are calculated. The NEMC method predicted results agree well with that deduced from FE analysis. Finally, the proposed method is verified by experimental testing of a prototype.

I. Introduction

Linear Flux-Switching Permanent Magnet (LFSPM) machine, which inherits all the merits of rotary FSPM machine [1][2] and Linear Permanent-Magnet machine (LPMM) is usually preferred for linear motor driven system which demand for high force, precision position control in numerical control machine tools. Although the Finite Element (FE) method is widely used for analyzing the electromagnetic performance of machines, the magnetic circuit method is usually preferred at the design stage due to it is convenient and time-saving for design and analysis [3]. In this paper, a novel LFSPM machine is proposed, and a Nonlinear Equivalent Magnetic Circuit (NEMC) model is developed for the static characteristics analysis of LFSPM machine.

II. NEMC Model of the Proposed LFSPM Machine

As shown in Fig. 1, the proposed LFSPM has 2 U-shaped mover cores with 4 teeth on each phase with a magnet between them. A flux barrier is sandwiched between 2 U-shaped cores in different phases, so the 3-phase concentrated windings essentially isolated physically [4].

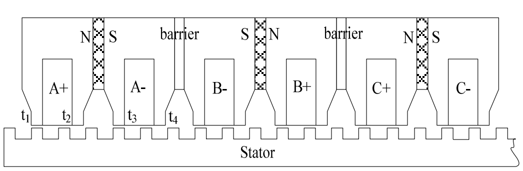

Fig. 1. Topology of the LFSPM machine

Fig. 2 shows the NEMC model of A-phase of the proposed LFSPM machine. In this model, P_{ti} and P_{yi} is the tooth and yoke permeance respectively, and P_{rui} is the equivalent permeance of Repetition-Unit (RU) detailed in section III [5]. While P_{li} and P_{mi} is the permeance of leakage flux and PM flux, which are of constant permeability.

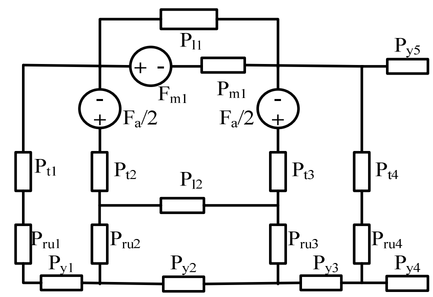

Fig. 2. NEMC model of A phase of the proposed machine

III. Specific Permeanence Calculaton

As shown in Fig. 3, the RU is the rectangle area "abcd" in which one mover tooth moves from one stator pole aligned position to the next one. The lines "ef" and "gh" may consider as different magnetic equipotential line respectively, and the magnetic potential difference between them and the flux through them can be calculated by FE analysis. Thus, the permeance of the RU in Fig. 3 can be solved as follows:

$$P_{RU}=\begin{cases}(F_{t1p1}/\phi_{p1})+(F_{t1p2}/\phi_{p2}) & \mathrm{x}\in(-\tau_{\mathrm{p}},0)\\ F_{t1p2}/\phi_{p2} & \mathrm{x}=0\\ (F_{t1p2}/\phi_{p2})+(F_{t1p3}/\phi_{p3}) & \mathrm{x}\in(0,\tau_{\mathrm{p}})\end{cases} \tag{1}$$

Where τ_p is the pole pitch of the stator, F_{tipj} is the magnetic potential difference between the equipotential lines on tooth t_i and pole p_j, Φ_{pi} is the flux through the magnetic equipotential surface on pole p_i.

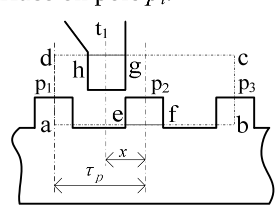

Fig. 3. Schematic of RU

Two look-up tables, which table-1 corresponds to the teeth of each phase which are adjacent to the PM (such as t_2, t_3), and table-2 corresponds to the other teeth of each phase (such as t_1, t_4), are created by FE analysis. In the tables, the values of position and current are known, and the value of magnetic potential difference is indexed from the current value. Thus, for A-phase, P_{t1} and P_{t2} can be obtained from table-1 and table-2 respectively, and obviously, P_{t3} equals to P_{t1} and P_{t4} equals to P_{t2}. For the other phases, the calculations are the same as A-phase.

In the actual calculation, an actual position or current value can be obtained by interpolation [6][7]. For example, the method of obtaining a RU's flux value $\phi(F_0, x_0)$ by the linear interpolation scheme is described as follows. When $F_0 \in [F_1, F_2], x_0 \in [x_1, x_2]$, the two intermediate values can be obtained:

$$\phi(F_0, x_1) = \phi(F_1, x_1) + \frac{F_0 - F_1}{F_2 - F_1}[\phi(F_2, x_1) - \phi(F_1, x_1)] \tag{2}$$

$$\phi(F_0, x_2) = \phi(F_1, x_2) + \frac{F_0 - F_1}{F_2 - F_1}[\phi(F_2, x_2) - \phi(F_1, x_2)] \tag{3}$$

Finally, the RU's flux value is given by

$$\phi(F_0, x_0) = \phi(F_0, x_1) + \frac{F_0 - F_1}{F_2 - F_1}[\phi(F_0, x_2) - \phi(F_0, x_1)] \tag{4}$$

On the other hand, the specific permeance of core in the magnetic circuit is determined by iterative calculation due to its permeability is nonconstant.

IV. NONLINEAR MAGNETIC CIRCUIT EQUATION

In this paper, nodal analysis method is employed to solve the proposed magnetic circuit. The nonlinear magnetic circuit equation can be established as follows:

$$\mathrm{G}(\mu_\mathrm{i})\mathrm{F} = \Phi_\mathrm{s}(\mu_\mathrm{i}) \tag{5}$$

Where μ_i is permeability of branch *i*, $\mathrm{G}(\mu_\mathrm{i})$ is node permeance matrix, F is vector of the node magnetic potential and $\Phi_s(\mu_\mathrm{i})$ is vector of magnetic flux source.

It should be noted that, in the matrix $\mathrm{G}(\mu_\mathrm{i})$, the permeance of RU is obtained from look-up tables by interpolation. On the other hand, the other permeance of core in main flux is determined by iterative step by step.

V. ANALYSIS OF STATIC CHARACTERISTICS

The phase flux linkage can be calculated directly from the NEMC model, and the phase back-EMF determined from

$$\mathrm{EMF} = \frac{\mathrm{d}\psi_\mathrm{m}}{\mathrm{dt}} = \frac{\mathrm{d}\psi_\mathrm{m}}{x} v \tag{6}$$

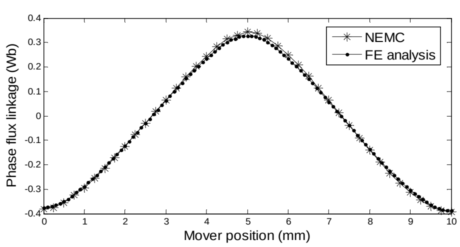

Fig. 4. Phase flux linkage comparison between NEMC and FE

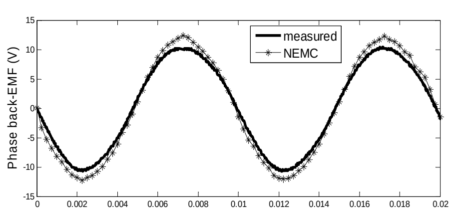

Fig. 5. Phase back-EMF from NEMC and test (0.5m/s)

The waveforms of phase flux linkage and phase back-EMF are shown in Fig. 4 and Fig. 5.

Since the reluctance force in LFSPM machine can be neglected, the electromagnetic force can be predicted from

$$F_e = 3\frac{2\pi}{\tau_\mathrm{p}}\psi_m I_m + F_{cog} \tag{7}$$

Fig. 6 is shown the comparison of cogging force by NEMC and FE model. Fig. 7 is shown thrust force when the proposed machine is fed by a 3-phase AC current resource operating on self-control model.

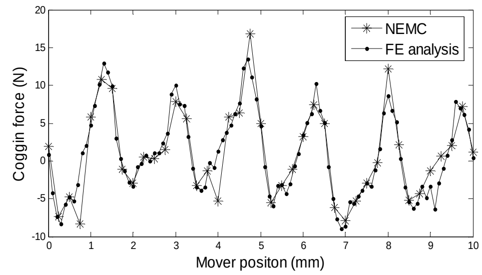

Fig. 6. Cogging force comparison between NEMC and FE

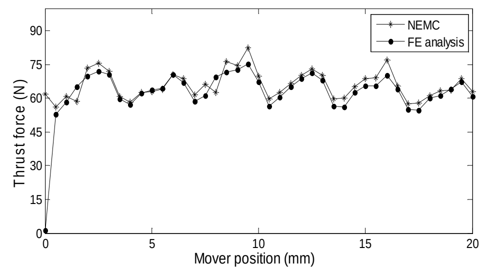

Fig. 7. Thrust force comparison between NEMC and FE (2A, 50HZ, 0.5m/s)

VI. CONCLUSION

A nonlinear equivalent circuit model embedded the data of FE analysis has been proposed, and the predicted results are validated by the FE analysis and test.

VII. REFERENCES

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