THE CONTROL STRATEGY OF A DRIVE SYSTEM WITH VARIABLE RELUCTANCE PERMANENT-MAGNET LINEAR MOTOR

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Abstract

The variable reluctance, permanent-magnet linear motor is one of the best choices for linear positioning systems. In the paper the control strategy of such a drive system is discussed considering two types of motors, with two and respectively four control coils, and two types of input voltages, sinusoidal and respectively square wave. The drive system is presented in two variants also, with position sensor and without it. The results obtained by computer modelling via a circuit-field model of the motor stand by to substantiate the conclusions that arise from the analysis done for the drive system control strategy.

1. Introduction

The variable reluctance permanent-magnet linear motor operates under combined principles of the permanent magnet excitation. The motor can operate in open-loop or in closed loop drive mode. In the open-loop drive mode the supplying control sequence is executed at a given frequency, existing a peril of losing the synchronism [6,7]. The control system must maintain the prescribed motor speed. The operating frequency is variable and depends on the motor capability to achieve an imposed displacement under given conditions as load and input source limits.

In the paper, based on a theoretical approach, under certain simplifying assumptions, the control strategy of a drive system with variable reluctance permanent-magnet linear motor is developed. Two types of motors were considered, with two, respectively four control coils. In the paper the control coils input voltage was take as sinusoidal and respectively square wave. The drive system under consideration is discussed in two variants with and without position sensor. The theoretical conclusions are substantiating with some results obtained by computer modelling via a circuit-field model of the motor.

2. The variable reluctance permanent-magnet linear motor

The variable reluctance permanent-magnet linear motor, known as linear stepper motor (LSM) also, consists basically of a moveable armature (the mover) placed over a fixed one (the platen). In figure 1 and 2 are given the variants of the motor under consideration, with two control coils and respectively four control coils.

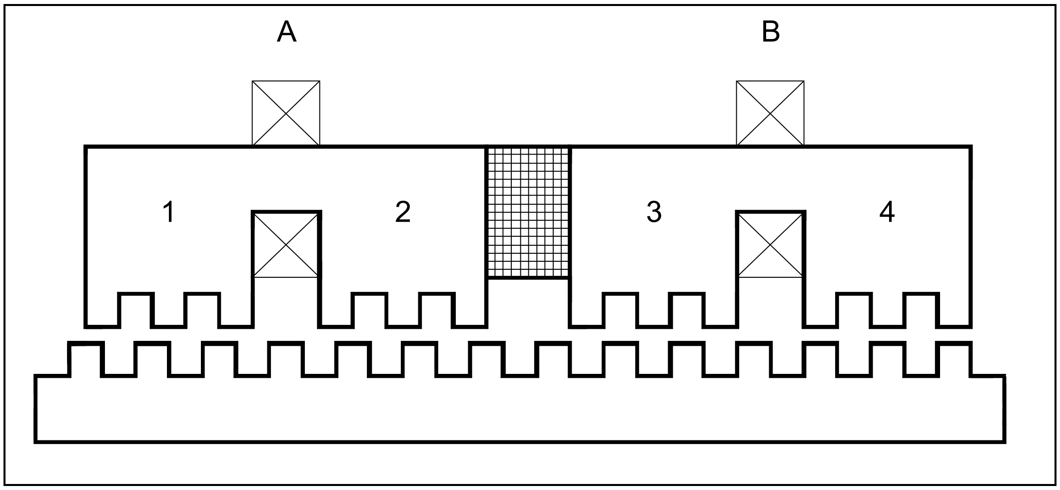

Figure 1

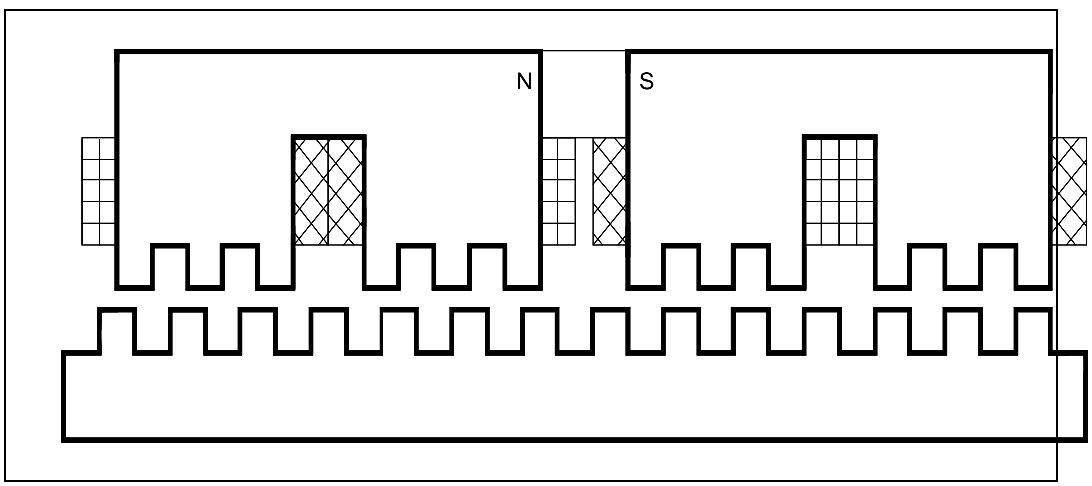

Figure 2

The fixed armature is an equidistantly toothed bar of any length fabricated from high-permeability cold-rolled steel. The mover consists of two electromagnets having command coils (two or four) and a permanent-magnet between them, which is the excitation source. Each electromagnet has two poles; all poles having the same number of teeth. The tooth pitch is the same on both armatures (mover and platen) Each of the two poles of one electromagnet are displaced with respect to the platen slotting by half of a tooth-pitch. The electromagnets are displaced by multiple of a quarter of tooth-pitch.

The permanent-magnet flux passes through the mover iron core, air-gap and platen. By commuting the permanent-magnet flux in a way to concentrate it into a single pole of one electromagnet is resulting in a tangential force. It will tend to align the teeth of that mover's pole with the platen teeth in a manner as to minimise the air-gap magnetic reluctance.

3. Theoretical approach

The circuit-field model [5,7], which takes fully into account all the nonlinearities, is based on an iterative procedure and can be solved only by means of a computer program. In order to obtain analytical results, which can offer important information for elaborating the control strategy all the calculus will lie basically on three assumptions:

• the air-gap reluctance are greater than all other reluctances, excepting of the permanent-magnet;

• the permanent-magnet reluctance is so great that no flux linkages produced by the currents which pass through the command coils will cross from one electromagnet to the other;

• the superposition principle can be applied because the core parts of the variable reluctance permanent-magnet linear motor are not affected by saturation and the permanent-magnet operating point does not change.

The equivalent magnetic circuit of the variable reluctance permanent-magnet linear motor with four command coils (Fig.2) is given in Fig.3.

The magnetic permeance of an electromagnet (one side of the magnetic circuit) is not dependent of the mover position,

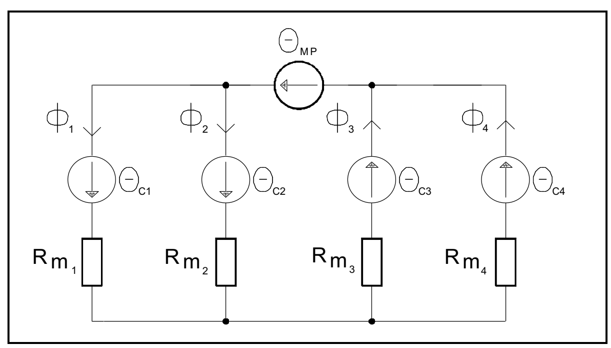

Figure 3

$$P_{me} = \frac{\mu_o A}{Z\delta'}(2Z + \lambda - 1) \tag{1}$$

The equivalent variable air-gap under the j pole is, [6],

$$\delta_{ej(x)} = \frac{2Z\delta'}{(2Z + \lambda - 1)(1 + a\cos\alpha_j)} \tag{2}$$

with the constant a,

$$a = \frac{\lambda[1+\lambda(2Z-1)]}{2(2Z+\lambda-1)} \tag{3}$$

and

$$\alpha = x\frac{2\pi}{t_d} \tag{4}$$

which means, for the booth variant of the motor,

$$\alpha_1 = \alpha, \alpha_2 = \alpha+\pi, \alpha_3 = \alpha+\frac{\pi}{2}, \alpha_4 = \alpha-\frac{\pi}{2}. \tag{5}$$

The tangential force is determined by the flux through each pole of the mover. This flux is a sum of two fluxes, one produced by the permanent-magnet; another produced by the command amperturns. The flux produced by the permanent-magnet is, [5,6],

$$\phi_{0j} = \frac{\Theta_{MP} P_{me}}{4}(1+a\cdot\cos\alpha_j), j = 1\div 4. \tag{6}$$

The flux produced by command amperturns, one command coil being excited once, is, for the left side electromagnet, [6],

$$\phi_{CA} = \frac{\Theta_{CA} P_{me}}{4}(1+a\cdot\cos\alpha_1)(1+a\cdot\cos\alpha_2), \tag{7}$$

Two cases will be considered, in the first the supplying control voltage will be sinusoidal and a square wave pulse sequence in the second.

The resulting tangential force developed by the motor when the input voltages are sinusoidal, is:

$$F_t = 4K_F[-k_{iA}\sin\alpha\sin(\omega t+\gamma_A)+k_{iB}\cos\alpha\sin(\omega t+\gamma_B) - \frac{a}{2}\sin 2\alpha[k_{iB}^2\sin^2(\omega t+\gamma_B)-k_{iA}^2\sin^2(\omega t+\gamma_A)]] \tag{8}$$

with the tangential force coefficient K_F,

$$k_F = \left(\frac{\theta_{MP}}{4}\right)^2 P_{me} a\frac{2\pi}{t_d} \tag{9}$$

In the ideal situation when sinα and sinωt have the same variation of time, [10], and the control coils m.m.f. are the same if θ_A=0 and θ_B=p/2, the total unitary tangential force is given by the expression:

$$f_{ti}^* = \frac{F_t}{4K_F} = k_i\cos 2\alpha(1-\frac{a}{2}k_i\sin 2\alpha) \tag{10}$$

If the control coils are supplied with a square wave pulse sequence, the total tangential force is given by the expression [8]:

$$F_t = 4\,K_F\left[k_{i2}C_2\sin\alpha + k_{i4}C_4\cos\alpha + \frac{a}{2}\sin 2\alpha(k_{i2}^2C_2 - k_{i4}^2C_4)\right] \tag{11}$$

where the control coils 2 and 4 m.m.f. are:

$$\theta_{C2} = \theta_{C2M}\,C_2 \quad \theta_{C4} = \theta_{C4M}\,C_4 \tag{12}$$

The unitary average tangential force in this case is:

$$f_{tm} = \frac{2}{\pi}[\sqrt{2}(C_4k_{i4}\cos\alpha_0 - C_2k_{i2}\sin\alpha_0) - \\ -\frac{a}{2}\sin 2\alpha_0(C_2k_{i2}^2 - C_4k_{i4}^2)] \tag{13}$$

and the optimum control angle is:

$$(\alpha_0)_{op} = asin\left[\sqrt{2}\,\frac{1-\sqrt{1+(2\,ak_{i4})^2}}{4\,ak_{i4}}\right] \tag{14}$$

For the same flux pattern as that one which conducted to the total tangential force, (12), the induced e.m.f. through the control coils are [7,8]:

$$e_1 = +N\,K_\phi\left[[asin\alpha(1+2\,ak_{i2}\cos\alpha)]\,\frac{d\alpha}{dt} + (1 - acos\alpha)\,\frac{dk_{i2}}{dt}\right] \tag{15}$$

$$e_3 = NK_\phi\left[a\cos\alpha(1 - 2ak_{i4}C_4\sin\alpha)\frac{d\alpha}{dt} + C_4\left(1 - a^2\sin^2\alpha\right)\frac{dk_{i4}}{dt}\right] \tag{16}$$

$$e_2 = e_1 \quad e_4 = e_3 \tag{17}$$

If there is no current through the number two coil, $k_{i2}=0$, in this coil the induced e.m..f. will be:

$$e_2 = -N\,K_\phi\,asin\alpha\,\frac{d\alpha}{dt} \tag{18}$$

where the flux coefficient K_F is:

$$K_\phi = \frac{1}{4}(\theta_{MP}\,P_{me}) \tag{19}$$

APPENDIX

The geometrical dimensions and parameters of the variable reluctance permanent-magnet linear motor under consideration:

- tooth width	1 mm
- slot width	1 mm
- tooth pitch (t_d)	2 mm
- nr. of teeth per pole (Z)	5
- airgap (d)	0.1 mm
- permanent-magnet type	VACOMAX-145
- residual flux density (B_r)	0.9 T
- coercive force	650 KA/m.
- nr. of coil turns	200
- coefficient of equivalent air-gap permeance (λ)	0.672
- motor's constant (a)	0.244

LIST OF MAIN SYMBOLS

a - motor constant
$\mathbf{e_1, e_2, e_3, e_4}$ - induced e.m.f. [V]
$\mathbf{F_t}$ - resultant tangential force [N]
j - pole number
$\mathbf{k_c}$ - Carter's factor
$\mathbf{k_F}$ - tangential force coefficient
$\mathbf{k_i}$ - m.m.f.'s factor (Q_c/Q_{MP})
N - coil turns
$\mathbf{P_{me}}$ - equivalent magnetic permeance [H]
t - time [s]
$\mathbf{t_d}$ - mover's tooth pitch [m]
v - mover's velocity [m/s]
Z - mover's pole teeth number
x - horizontal coordinate (displacement) [m]
$\mathbf{a_j}$ - angular displacement (j=1¸4) [rad]
$\mathbf{a_0}$ - optimum angular displacement [rad]
δ - motor air-gap [m]
- equivalent air-gap d'=k_cd [m]
λ - coefficient of equivalent air-gap permeance
Φ - flux linkages [Wb]
$\mathbf{m_0}$ - magnetic constant ($\mathbf{m_0}$=4p/10^7) [H/m]
$\mathbf{R_m}$ - magnetic reluctance [1/H]

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