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Modelling Polysolenoid Permanent Stimulation Linear Motors for Real Time Simulation Problem

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Abstract:* Nowadays, the creation of linear movements is mostly carried out indirectly by rotary motors, causing many disadvantages such as complex mechanical structures due to the existence of intermediate elements, low accuracy and performance due to the cumulative errors of the elements throughout the system. Using motors able to create directly linear movements can eliminates the above disadvantages. This paper introduces a special type of permanent stimulation tube-type linear motor powered by inverted two-phase voltage source and the method of building up mathematical description for this object based on simpower for real-time simulation problem. The results obtained significantly shorten the time when the controller is installed in the actual operating condition of the system.

***Keywords:* Polysolenoid Linear Motors, Space Vector Modulation, Two-Phase Inverter, SimPower, MatLab-Simulink.**

Symbol	Unit	Meaning
L_{sd}, L_{sq}	H	d-axis and q-axis inductance of stator
m	Kg	Mass of the primary part (stator)
u_s, i_s	V, A	Voltage and current vector
R_s	W	Stator resistance
v, v_e	m/s	Mechanical and electrical speed
F_m, F_c	N	Repulsive force, resisting force
i_{sd}, i_{sq}	A	d-axis and q-axis current
u_{sd}, u_{sq}	V	d-axis and q-axis voltage
t	mm	Pole pitch
p		Number of poles
y_p	Wb	Pole flux
w_e	Rad/s	Electric angular velocity
x_p	mm	Motor position

I. INTRODUCTION

Polysolenoid permanent stimulation linear motors belong to Short stator permanent stimulation synchronous motors and in tube form. The working principle of Polysolenoid permanent stimulation linear motors has been shown in [1, 2, 3, 4].

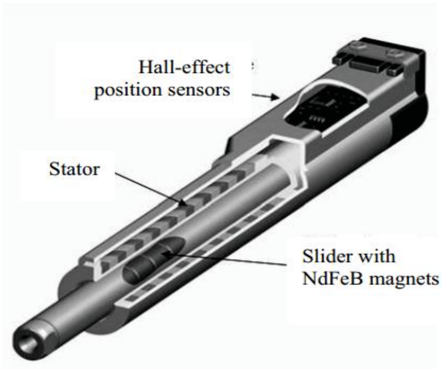

Fig. 1. A Polysolenoid Permanent Stimulation Synchronous Linear Motor [5]

In terms of the nature of linear motors, this motor creates directly linear movements. The working principle of linear motors is similar to that of common rotary motors based on the phenomenon of electromagnetic induction. In linear motors, the repulsive force acts on the dynamic part according to the forward direction instead of generating the rotation torque in a conventional rotating machine.

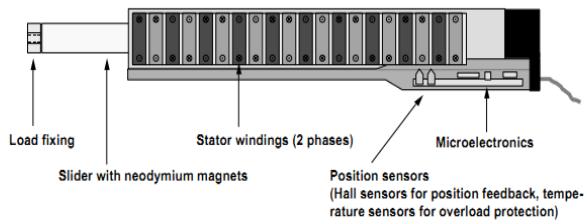

Fig. 2. Internal Structure of Polysolenoid Motors [5]

The internal structure of the engine consists of the following main parts:

Rotor is a permanent magnet made from NdFeB (neodymium) rare earth magnets:

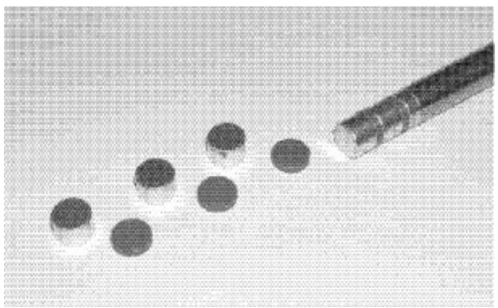

Fig 3. Rotor Structure (Secondary Part) [5]

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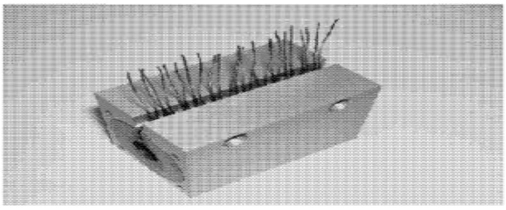

Fig. 4. Stator Structure (Primary Part) [5]

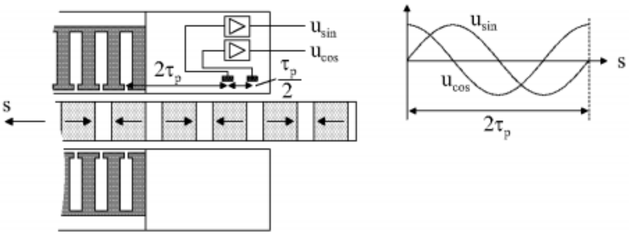

Fig. 5. Sine and Cosine Sensor of the Motor [5]

II. Build Up Mathematical Descriptions For Polysolenoid Motors

Two-phase Permanent Stimulation Synchronous Linear Motors work on electromagnetic induction phenomenon. When the coils are powered, the two-phase alternating current on the two coils will form a horizontal flow vector and its q-axis component will interact with the magnetic flux ψp of the permanent magnet, creating the compulsive force of the coils in the primary part of Permanent Stimulation Synchronous Linear Motors.

2.1. Continuous State Model:

Stator voltage equation:

$$\mathbf{u}_s = R_s.\mathbf{i}_s + \frac{d\boldsymbol{\psi}_s}{dt} \quad (1)$$

ψs includes ψsd and ψsq :

$$\begin{cases} \boldsymbol{\psi}_{sd} = L_{sd}.\mathbf{i}_{sd} + \psi_p \\ \boldsymbol{\psi}_{sq} = L_{sq}.\mathbf{i}_{sq} \end{cases} \quad (2)$$

Inferred :

$$\begin{cases} u_{sd} = R_s.i_{sd} + L_{sd}\dfrac{di_{sd}}{dt} - w_s.L_{sq}.i_{sq} \\ u_{sq} = R_s.i_{sq} + L_{sq}\dfrac{di_{sq}}{dt} + w_s.L_{sd}.i_{sd} + w_s.\psi_p \end{cases} \quad (3)$$

$$\Rightarrow \begin{cases} \dfrac{di_{sd}}{dt} = -\dfrac{R_s}{L_{sd}}.i_{sd} + \dfrac{1}{L_{sd}}.u_{sd} + \dfrac{2.\pi.v}{\tau}.\dfrac{L_{sq}}{L_{sd}}.i_{sq} \\ \dfrac{di_{sq}}{dt} = -\dfrac{R_s}{L_{sq}}.i_{sq} + \dfrac{1}{L_{sq}}.u_{sq} - \dfrac{2.\pi.v}{\tau}.\dfrac{L_{sd}}{L_{sq}}.i_{sd} - \dfrac{2.\pi.v}{\tau}.\dfrac{\psi_p}{L_{sq}} \end{cases} \quad (4)$$

Set the equation for the compulsive force of the motor

The energy input into two phases of the two stator coils:

$$p_{in} = u_A.i_A + u_B.i_B = u_{sd}.i_{sd} + u_{sq}.i_{sq}$$

$$\Rightarrow u_{sd}.i_{sd} + u_{sq}.i_{sq} = R_s.i_{sd}^2 + L_{sd}.i_{sd}\frac{di_{sd}}{dt} + R_s.i_{sq}^2 + L_{sq}.i_{sq}\frac{di_{sq}}{dt} + \frac{2.\pi.v}{\tau}i_{sq}[(L_{sd} - L_{sq})i_{sd} + \psi_p] \quad (5)$$

The final component of the electromagnetic energy enters the two phases of the motor.

$$p_{dt} = \frac{2.\pi.v}{\tau}i_{sq}[(L_{sd} - L_{sq})i_{sd} + \psi_p] \quad (6)$$

With the multiplex polarity two-phase linear motor, we have:

$$\mathrm{F} = p.\frac{p_{dt}}{v} = p.\frac{2.\pi.v}{\tau.v}i_{sq}[(L_{sd} - L_{sq})i_{sd} + \psi_p] \quad (7)$$

or

$$\mathrm{F} = p\frac{2.\pi}{\tau}i_{sq}[(L_{sd} - L_{sq})i_{sd} + \psi_p] \quad (8)$$

So we have the kinetic equation of the linear motor in dq system:

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\dfrac{R_s}{L_{sd}}.i_{sd} + \dfrac{1}{L_{sd}}.u_{sd} + \dfrac{2.\pi.v}{\tau}.\dfrac{L_{sq}}{L_{sd}}.i_{sq} \\ \dfrac{di_{sq}}{dt} = -\dfrac{R_s}{L_{sq}}.i_{sq} + \dfrac{1}{L_{sq}}.u_{sq} - \dfrac{2.\pi.v}{\tau}.\dfrac{L_{sd}}{L_{sq}}.i_{sd} - \dfrac{2.\pi.v}{\tau}.\dfrac{\psi_p}{L_{sq}} \\ m\ddot{x} = p\dfrac{2.\pi}{\tau}i_{sq}[(L_{sd} - L_{sq})i_{sd} + \psi_p] - F_c \\ \dfrac{dx}{dt} = v \end{cases} \quad (9)$$

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\dfrac{R_s}{L_{sd}}.i_{sd} + \dfrac{1}{L_{sd}}.u_{sd} + \dfrac{2.\pi.v}{\tau}.\dfrac{L_{sq}}{L_{sd}}.i_{sq} \\ \dfrac{di_{sq}}{dt} = -\dfrac{R_s}{L_{sq}}.i_{sq} + \dfrac{1}{L_{sq}}.u_{sq} - \dfrac{2.\pi.v}{\tau}.\dfrac{L_{sd}}{L_{sq}}.i_{sd} - \dfrac{2.\pi.v}{\tau}.\dfrac{\psi_p}{L_{sq}} \\ F = p\dfrac{2.\pi}{\tau}i_{sq}[(L_{sd} - L_{sq})i_{sd} + \psi_p] \end{cases} \quad (10)$$

From the above equations, we obtain a continuous state model:

$$\frac{d\mathbf{i}_s}{dt} = \mathbf{A}.\mathbf{i}_s + \mathbf{B}.\boldsymbol{u}_s + \mathbf{N}.\mathbf{i}_s.v + \mathbf{S}.\boldsymbol{\psi}_p.v$$

$$\mathbf{i}_s = \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}; \boldsymbol{u}_s = \begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} \quad (11)$$

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$$\mathbf{A}=\begin{pmatrix}-\frac{R_s}{L_{sd}} & 0\\ 0 & -\frac{R_s}{L_{sq}}\end{pmatrix};\mathbf{B}=\begin{pmatrix}\frac{1}{L_{sd}} & 0\\ 0 & \frac{1}{L_{sq}}\end{pmatrix}$$

$$\mathbf{N}=\begin{pmatrix}0 & \frac{2.\pi}{\tau}.\frac{L_{sq}}{L_{sd}}\\ -\frac{2.\pi}{\tau}.\frac{L_{sd}}{L_{sq}} & 0\end{pmatrix};\mathbf{S}=\begin{bmatrix}0\\ -\frac{2.\pi}{\tau}.\frac{1}{L_{sq}}\end{bmatrix} \quad (12)$$

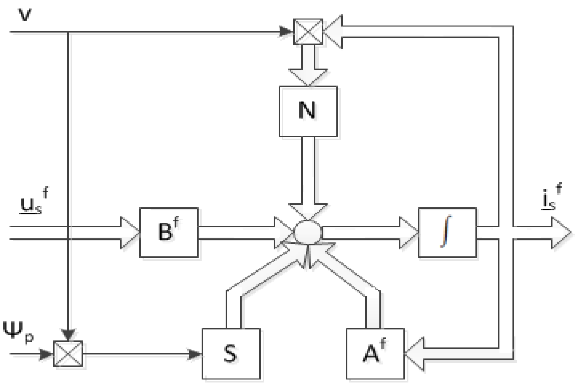

Fig. 6. The State Model of the Permanent Stimulation Synchronous Linear Motor in the dq System

Looking at the model, we see that the input signals of the system include not only voltage vector $\mathbf{u}_s$ but also speed $\mathbf{v}$. Therefore the current state variable depends not only on the voltage values u_{sd}, u_{sq} but also on the motor speed. The nonlinear property of the permanent stimulation synchronous linear motor is shown by the multiplication between the state variable is and the input variable $\mathbf{v}$ through $\mathbf{N}.\boldsymbol{i}_s.\mathbf{v}$ with the determining factor of matrix N.

In addition to the nonlinear characteristics bearing the above structure, the nonlinearity of the permanent stimulation synchronous linear motor is also shown in the following two main characteristics:

The parameters depend on the state variable in the saturation relationship (L(i),…). This makes the motor model nonlinear, stacking.

Some other nonlinear phenomena can be removed after systematic analysis such as surface phenomenon, nonlinear resistance, Foucault eddy current…

2.2. Intermittent State Model:

To interrupt the model, we temporarily consider ψ_p as the system parameter (due to the constant nature of ψ_p)

$$\frac{d\boldsymbol{i}_s}{dt}=\mathbf{A}.\boldsymbol{i}_s+\mathbf{B}^*.\boldsymbol{v}^f+\mathbf{N}.\boldsymbol{i}_s.\mathbf{v} \quad (13)$$

with :

$$\mathbf{v}^f=\left[u_{sd},u_{sq},v\right];\mathbf{B}^*=\left[B,S.\psi_p\right] \quad (14)$$

The intermittent model of the synchronous motor on state space after repeating integral of the model:

$$\boldsymbol{i}_s(k+1)=\phi.\boldsymbol{i}_s(k)+\mathbf{H}^*\mathbf{v}^f(k) \quad (15)$$

with:

$$\phi=e^{|A+N.v(k)|T}=\sum_{v=0}^{\infty}[A+N.v(k)]^v\frac{T^v}{v!} \quad (16)$$

$$\mathbf{H}^*=\int_{kT}^{(k+1)T}e^{|A+N.v(k)|\tau}d\tau B^*=\sum_{v=1}^{\infty}[A+N.v(k)]^{v-1}\frac{T^v}{v!}B^* \quad (17)$$

The first approximation result of the transition matrix and the input matrix is as follows:

$$\mathbf{\Phi}=\begin{pmatrix}1-\frac{T}{T_{sd}} & v.T.\frac{2.\pi}{\tau}.\frac{L_{sq}}{L_{sd}}\\ -v.T.\frac{2.\pi}{\tau}.\frac{L_{sd}}{L_{sq}} & 1-\frac{T}{T_{sq}}\end{pmatrix};\mathbf{H}^*=[H,h];$$

$$\mathbf{H}=\begin{pmatrix}\frac{T}{L_{sd}} & 0\\ 0 & \frac{T}{L_{sq}}\end{pmatrix};\mathbf{h}=\begin{bmatrix}0\\ -\frac{2.\pi}{\tau}.\frac{v.T}{L_{sq}}\end{bmatrix} \quad (18)$$

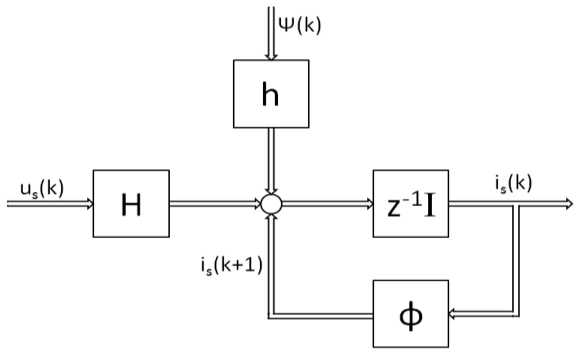

Fig. 7. The Intermittent State Model of the Permanent Stimulation Synchronous Linear Motor

Finally, we have the intermittent state model of the synchronous motor as follows:

$\mathbf{i}_s(k+1) = \Phi.\mathbf{i}_s(k) + \mathbf{H}.\mathbf{u}_s(k) + \mathbf{h}.\psi_p(k)$ (19)

On image domain z

$z\mathbf{i}_s(z) = \Phi.\mathbf{i}_s(z) + \mathbf{H}.\mathbf{u}_s(z) + \mathbf{h}.\psi_p(z)$ (20)

Suppose y is the real output quantity of the adjustment stage, then we set the function under the following form:

$\mathbf{u}_s(k) = \mathbf{H}^{-1}[y(k-1) - \mathbf{h}.\psi(k)]$ (21)

or $\mathbf{u}_s(k+1) = \mathbf{H}^{-1}[y(k) - \mathbf{h}.\psi(k+1)]$ (22)

The expression containing $\mathbf{y}(k-1)$ shows that when calculating the voltage $\mathbf{u}_s(k)$ of the current cycle, we use the output quantity $\mathbf{y}(k-1)$ of the previous cycle,

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including hardware delay which delays a beat in the adjustment sewing function. -h.ψ(k) has a duty to compensate the component dependent from the rotor flux. The effect of the compensation will be obvious when replacing into the equation above:

$$\mathbf{i}_s(k+1) = \Phi.\mathbf{i}_s(k) + \mathbf{y}(k-1) \quad (23)$$

On the z domain, the model takes the form

$$[z\mathbf{I}-\mathbf{\Phi}]\mathbf{i}_s(z) = z^{-1}\mathbf{y}(z) \quad (24)$$

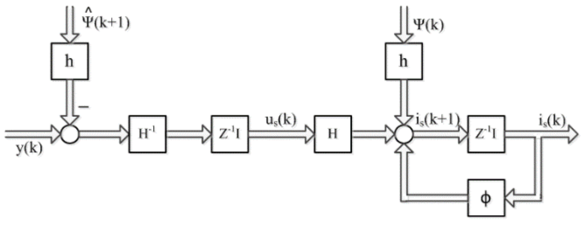

Fig. 8. Magnetically Compensated Model of the Stator Object of the Synchronous Motor

III. MODELLING THE POLYSOLENOID MOTOR ON MATLAB-SIMULINK-SIMPOWER PLATFORM

This simulation model consists the following main components: the model of the permanent stimulation synchronous linear motor, inverter circuit. The model of the permanent stimulation synchronous linear motor is built on mathematical model and the parameters taken from LinMot P01-23X80/80X140 motor.

The models of the inverter circuit and motor are built using the Simpower toolbox in Mathlab-Simulink. Simpower allows describing electrical circuits and electronic components in the form of principle diagrams, in which components and devices are visually connected as in reality. These models which are built by a Simulink toolbox and work within this environment could be paired with other systems also built on Simulink platform.

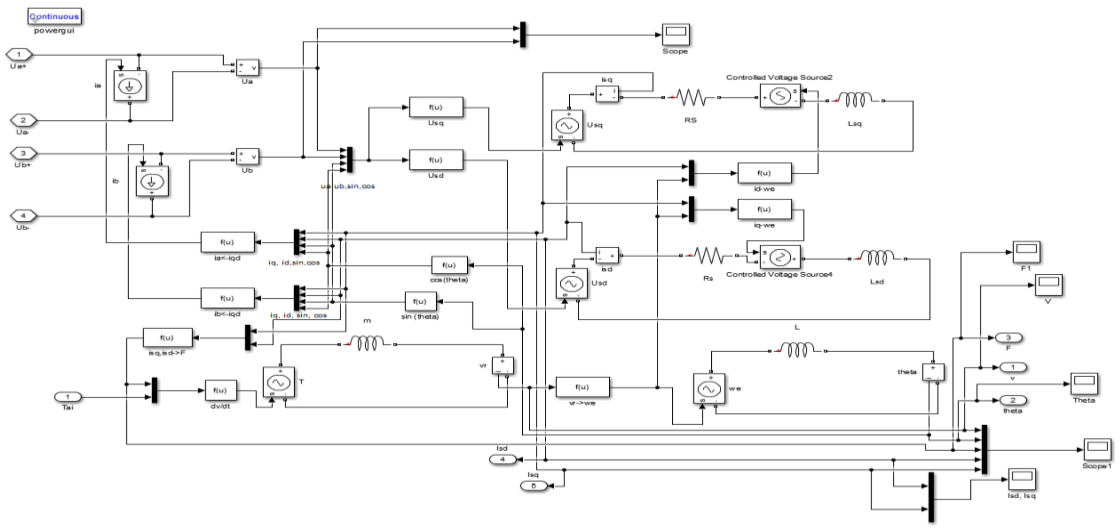

Fig. 9. The Model of the Polysolenoid Motor Built on Simpower

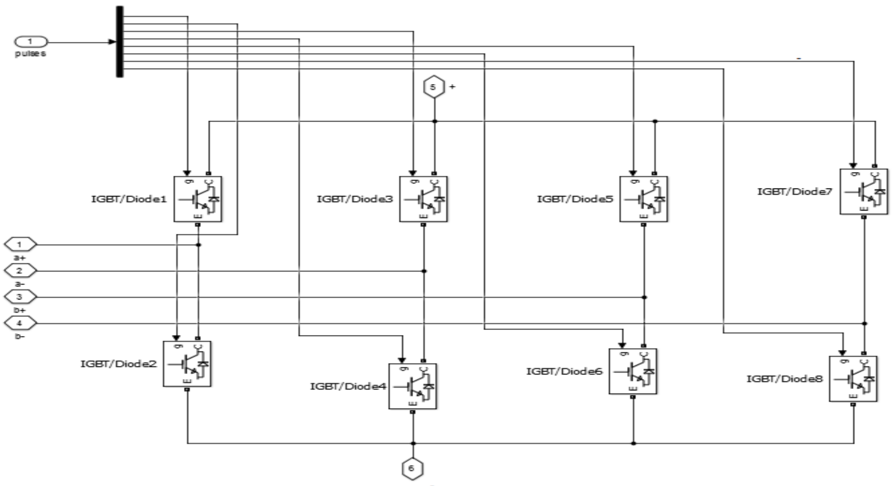

Fig. 10. The Inverter Model Supplying 2 Phases 4 Branches

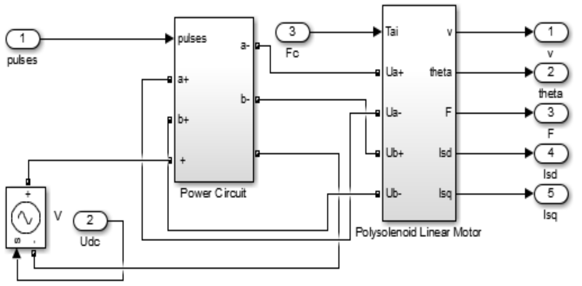

Fig. 11. Pairing Between the Inverter and the Polysolenoid Motor

IV. CONCLUSIONS

This paper presents the method of building up mathematical description for the Polysolenoid linear motors in continuous and intermittent domains, modelling the object on Matlab-Simulink-SimPower platform. This provides the basis for testing control algorithms for objects that is an important premise for performing simulations before implementing the experiment on real devices.

ACKNOWLEDGMENT

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