POSITION CONTROL OF LINEAR SYNCHRONOUS MOTOR DRIVES WITH EXPLOITATION OF FORCED DYNAMICS CONTROL PRINCIPLES

POLOHOVÉ RIADENIE POHONOV S LINEÁRNYM SYNCHRÓNNYM MOTOROM S VYUŽITÍM PRINCÍPOV RIADENIA S VNÚTENOU DYNAMIKOU

Jan Vittek[1)], **Peter Büchner**[2)], **Stephen J. Dodds**[3)]

1) Faculty of Electrical Engineering, University of Žilina, Veľký Diel, 010 26 Žilina, Slovak Republic
2) Elektrotechnisches Institut, Elektrische Antriebe und Grundlagen der Elektroenergietechnik, Technische Universität Dresden, Helmholtzstrasse 9, 010 62 Dresden, DE
3) School of Computing and Technology, University of East London, Dagenham, Longbridge Rd., RM8 2AS, United Kingdom

Summary Closed-loop position control of mechanisms directly driven by linear synchronous motors with permanent magnets is presented. The control strategy is based on forced dynamic control, which is a form of *feedback linearisation*, yielding a non-linear multivariable control law to obtain a prescribed linear speed dynamics together with the vector control condition of mutual orthogonality between the stator current and magnetic flux vectors (*assuming perfect estimates of the plant parameters*). Outer position control loop is closed via simple feedback with proportional gain. Simulations of the design control system, including the drive with power electronic switching, predict the intended drive performance.

Abstrakt V článku sa uvádza polohové riadenie mechanizmu priamo poháňaného lineárnym synchrónnym motorom s permanentnými magnetmi. Koncepcia riadenia je založená na riadení s vnútenou dynamikou, čo je forma linearizácie spätnej väzby, ktorá generuje taký viacpaprametrový nelineárny riadiaci algorismus, ktorý umožňuje dodržať predpísanú lineárnu dynamiku rýchlosti pohonu, spolu so vzájomnou kolmosťou vektorov statorového prúdu a magnetického toku motora, čo je podmienkou vektorového riadenia (*za predpokladu správneho odhadu parametrov systému*). Simulácie navrhnutého riadiaceho systému, ktoré obsahujú aj spínanie spínačov výkonovej elektroniky, potvrdzujú predpokladané vlastnosti pohonu.

1. INTRODUCTION

There is an increasing use of linear motors for industrial position control systems. The paper develops position control system for linear permanent magnet synchronous motor (*PMSM*) based on forced dynamics control principles. Forced dynamic control is a relatively new control method for controlling of a.c. electrical drives based on the principle of feedback linearisation [1], [2]. The reason for utilising this method is that it is possible to design the position control system to be linear and have a prescribed second order transfer function. In the linear synchronous motor, mutual orthogonality of the force producing stator current vector and magnetic flux vector is maintained, as in conventional vector control [3], [4]. The control system has an inner speed control loop utilising a speed estimate and a external force estimate from an observer [5], [6] and outer position control loop. Speed control loop has linear first order dynamics with an adjustable time constant. An outer position control loop with an adjustable proportional gain is then closed via a suitable position measurement.

2. CONTROL OF THE DRIVE WITH LINEAR PMSM

Forced dynamic control of electric drives prescribes linear speed response together with the vector control condition of mutual orthogonality between the stator current and rotor flux vectors. The control strategy for the linear synchronous motor exploits both principles. First, the model of linear synchronous motor is formulated in the d_q co-ordinate system, which is coupled with moving parts of the linear PMSM:

$$\frac{ds_{mp}}{dt} = v_{mp} , \tag{1}$$

$$\frac{dv_{mp}}{dt} = \frac{1}{M}\left[c\left(\Psi_d i_q - \Psi_q i_d\right) - F_{ext}\right], \tag{2}$$

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -R_s/L_d & -pv_{mp}L_q/(rL_d) \\ pv_{mp}L_d/(rL_q) & -R_s/L_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} - \frac{pv_{mp}}{rL_q}\begin{bmatrix} 0 \\ \Psi_{PM} \end{bmatrix} + \begin{bmatrix} 1/L_d & 0 \\ 0 & 1/L_q \end{bmatrix}\begin{bmatrix} u_d \\ u_q \end{bmatrix} \quad (3)$$

Here, $\mathbf{I}$ and $\mathbf{U}$ ($I^T = [i_d \ i_q]$ and $U^T = [u_d \ u_q]$) are, respectively, column vectors whose elements are the stator current and stator voltage components *(this notation being convenient for development of the control algorithm)*, s_{mp} and v_{mp} are the real moving part position and velocity, c=3p/2r where p is number of pole-pairs and r is a constant parameter dependent on the linear motor structure, having the dimensions of length, F_{ext} is the external force, R_s is the phase resistance, L_d and L_q are the direct and quadrature phase inductances, Ψ_{PM} is the permanent magnetic flux and M is the mass of the motor moving part plus the equivalent mass of the driven mechanism.

The moving part speed is controlled with a prescribed *closed-loop time constant,* T_v. The moving part speed is made to satisfy:

$$\dot{v}_{mp} = \frac{1}{T_v}\left(v_{dem} - v_{mp}\right). \quad (4)$$

The technique is to equate the right hand side of this equation with the right hand side of the corresponding motor equation (2). This *forces* the non-linear differential equation (2) to have the same response as the linear equation (4). Thus:

$$\frac{1}{M}\left[c\left(\Psi_d i_q - \Psi_q i_d\right) - F_{ext}\right] = \frac{1}{T_v}\left(v_{dem} - v_{mp}\right). \quad (5)$$

The second part of the control law is formulated on the basis of vector control, which requires mutual orthogonality between the rotor magnetic flux and stator current vectors. Inner current control loops implemented by switched power electronic circuits are assumed to follow the computed current demands from speed controller. Following conventional approach [3], current demand of the magnetic flux component in direct axis is set to:

$$i_d = 0. \quad (6)$$

Setting i_d=0 in (5) on the assumption that $i_d = i_{d\,dem}$ and solving (5) for torque producing component, i_q yields the following equation for the q-axis current demand:

$$i_{q\,dem} = \frac{1}{c\tilde{\Psi}_{PM}}\left[\frac{\tilde{M}}{T_v}\left(v_{dem} - \hat{v}_{mp}\right) + \hat{F}_{ext}\right], \quad (7)$$

where v_{mp} is replaced by its estimate from the observer of section 3 to avoid software differentiation of the measurement position, s_{mp} and the amplification of high frequency measurement noise. Permanent magnet flux, $\tilde{\Psi}_{PM}$ and mass of moving parts, $\tilde{M}$, are respectively, estimates of real values of Ψ_{PM} and M, because they cannot be known with infinite precision. Control law (7) yields a moving part speed response with linear, first order dynamics and unity dc gain:

$$\frac{v_{mp}(p)}{v_{dem}(p)} = \frac{1}{1 + pT_v}. \quad (8)$$

It remains to close a position control loop around already described first order speed control loop, as shown in Figure 1.

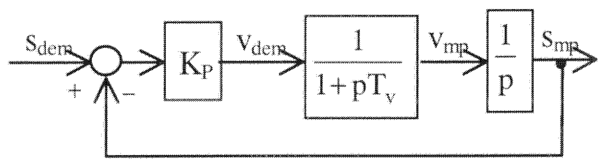


Figure 1. Drive position control loop

It is straightforward to show that the parameters, K_P and T_v can be adjusted to yield any desired second order closed-loop transfer function. For example a settling time, T_s, to 95% of the step position response, can be realised by coincident closed loop poles placed at p=-9/(2T_s). The closed-loop transfer function for polynomial with demanded behaviour being:

$$\left(p + \frac{9}{2T_s}\right)^2 = p^2 + \frac{9}{T_s}p + \frac{81}{4T_s^2}. \quad (9a)$$

Transfer function of the drive position control loop shown in Figure 1 is as follows:

$$F(p) = \frac{s_{mp}(p)}{s_{dem}(p)} = \frac{K_P/T_v}{p^2 + \frac{1}{T_v}p + \frac{K_P}{T_v}}. \quad (9b)$$

If corresponding coefficients are compared then the control loop gains are determined with respect to the chosen settling time T_s requiring:

$$T_v = \frac{T_s}{9} \text{ and } K_P = \frac{9}{4T_s} . \quad (10)$$

This way all the necessary gains for the position control system of the linear permanent magnet synchronous motor, which is shown in Figure 1, are designed. The drive is rendered robust performance with respect to the external force by incorporating external load force compensation in the control algorithm (7).

An important feature of the overall position control system is the representation of the driven mechanical load, which is shown in Figure 2.

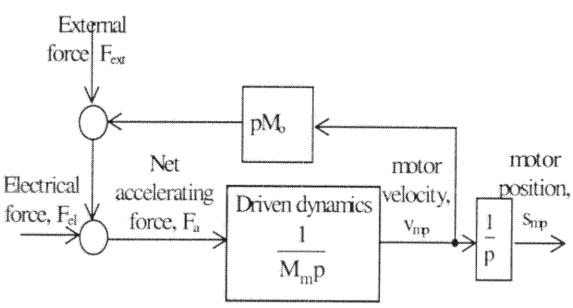


Figure 2. Representation of driven mechanical load.

Thus the forward path is a rigid body of mass, M_m, moving *without external force and friction*. External force and friction are modelled in the feedback path, as shown. The justification for this is that the friction forces for high precision machine tool axes are dominated [9].

3. EXTERNAL FORCE AND MOTOR SPEED OBSERVER

Estimates of the external disturbing force and motor speed, which are parts of control algorithm, are provided here by a standard full-state observer having a similar structure to a Kalman filter, whose real time model is based on the motor force equation (1) and (2), augmented by the third state equation, $F_{ext}=0$, of the piecewise constant external force, F_{ext}. The error between real motor position and estimated position of observer, $e_s = s_r - \hat{s}_r$ is added with corresponding gain into every differential equation:

$$\frac{d\hat{s}_{mp}}{dt} = \hat{v}_{mp} + K_s e_s , \quad (11)$$

$$\frac{d\hat{v}_{mp}}{dt} = \frac{1}{\tilde{M}}\left[c\left(\Psi_d i_q - \Psi_q i_d\right) - \hat{F}_{ext}\right] + K_v e_s , \quad (12)$$

$$\frac{d\hat{F}_{ext}}{dt} = 0 + K_F e_s . \quad (13)$$

Block diagram of observer for external force and speed of the moving part is shown in Figure 3.

The observer gains may be chosen to yield a non-oscillatory state estimation error transient with settling time, T_{so}, (*to 5% of an initial error*). The transfer function of observer is given as:

$$F(p) = \frac{\hat{s}_{mp}(p)}{s_{mp}(p)} = \frac{p^2 K_s + pK_v + K_F / M}{p^3 + p^2 K_s + pK_v + K_F / M} . \quad (14a)$$

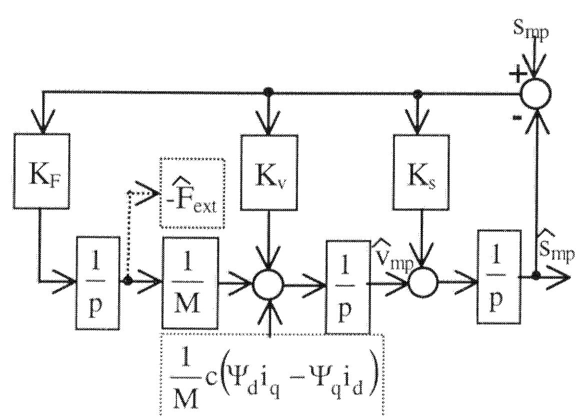


Figure 3. Moving part speed and external force observer.

If observer poles are chosen as coincident and placed at $p=-6/T_{so}$ to yield prescribed settling time, T_{so}, (*95% of the step position response*), then the desired polynomial is:

$$\left(p + \frac{6}{T_{so}}\right)^3 = p^3 + \frac{18}{T_{so}}p^2 + \frac{108}{T_{so}^2}p + \frac{216}{T_{so}^3} . \quad (14b)$$

Equating the denominator of the correction loop characteristic polynomial (14a) to the desired one (14b) then yields:

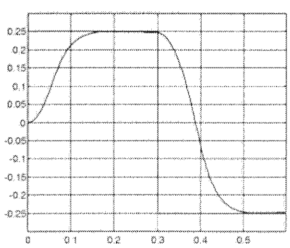
$$K_s = \frac{18}{T_{so}}, \quad K_v = \frac{108}{T_{so}^2} \quad \text{and} \quad K_F = \frac{216M}{T_{so}^3}. \tag{15}$$

Since the error in the value of mass, M_m used, can be represented as a dynamic load force and this together with any external force acts at the same point as F_{ext}, then the estimate, $\hat{F}_{ext}$, from the observer will include both these forces and so both of them will be compensated as well as the external force.

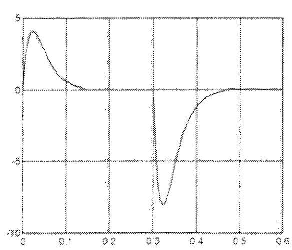
4. SIMULATION RESULTS

The simulations were performed with the following linear permanent magnet synchronous motor parameters: P_n=800 W, p=3, r=0.056 m, R_s=0,59 Ω, L_d=3,7 mH, L_q=3.5 mH and Ψ_{PM}=0,3 Vs. The total load mass and external force are M=5 kg and F_{ext}=20 N. Settling time of the drive position loop was set to T_s=0,1 s and the observer settling time was chosen as to T_{so}=10 ms. A sampling frequency of 10 kHz was assumed for the power electronics switching.

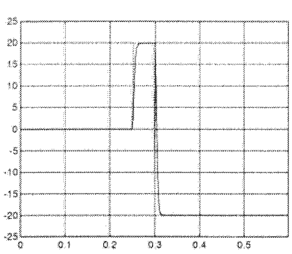
The first set of the system response to a step position demand of s_{dem}=0,25 m applied for time interval $t \in (0, 0{,}3]$ s with zero initial states of all state variables followed immediately by step position demand s_{dem}=-0,25 m applied for time interval $t \in [0{,}3\ 0{,}6)$ s is shown in Figure 4. The external force F_{ext}=20 N is applied at t=0,25 s. There is change of sign for external force when step position demand changes sign at t=0,3 s.



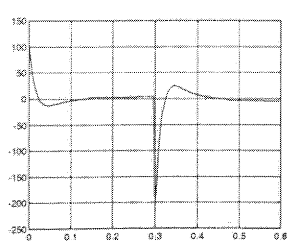
a) $s_{mp}=f(t)$



b) $\hat{v}_{mp}=f(t)$



c) $F_{ext}=f(t)$

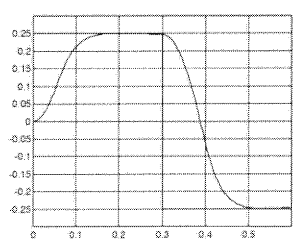


d) $i_{q\ dem}=f(t)$

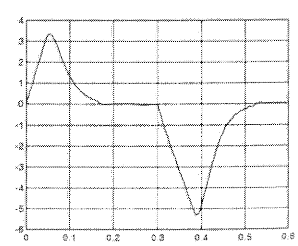
Figure 4. Simulation results for position controlled linear PMSM drive.

From Figure 4a can be clearly seen that prescribed settling time of the position control system is equal to the prescribed one (*95% of the demanded position s_{dem}=0,25 m is achieved at t=0,1 s*). Figure 4b shows observed motor speed, v_{mp} as the output of observer. Figure 4c shows applied external force to the drive. In this plot the prescribed settling time for observer, T_{so}=0,01 s can be followed. Demanded i_q torque producing component of stator current is shown in Figure 4d. The magnitudes of this current component are high, therefore more realistic simulation results are shown in Figure 5,where current limits were imposed.

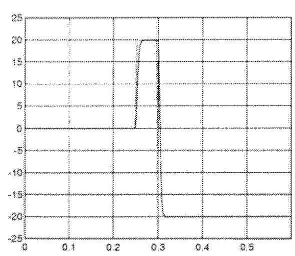
The second set of the simulation results to a step position demand, when current limit was imposed to the torque component, is shown in Figure 5. The position demands including application of the external force are identical with the previous Figure 4. The coefficients for position controller were computed for prescribed settling time T_s=0,1 s. In this case the motor speed is controlled with a prescribed *closed-loop time constant*, T_v=0,0111 s and observer settling time was chosen again as T_{so}=0,01 s. For comparison the individual plots correspond to the subplots of Figure 4. As can be seen from Figure 4a the settling time of the system is longer than prescribed one (T_s=0,1 s), which is clear due to impose current limit for torque component. Corresponding observed motor speed is shown in Figure 5b.



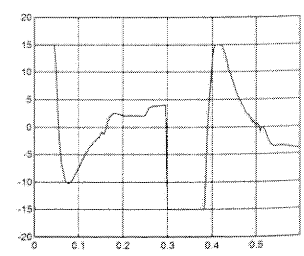
a) $s_{mp}=f(t)$



b) $\hat{v}_{mp}=f(t)$



c) $F_{ext}=f(t)$



d) $i_{q\ dem}=f(t)$

Figure 5. Simulation results for position controlled linear PMSM drive with imposed current limits.

Observer settling time, T_{so}=0,01 s can be checked with positive results from Figure 5c where the applied external force and observed one are compared. Based on simulations it can be also observed that all three outputs of observer have non-oscillatory character as it was assumed. Figure 5d shows that imposed current limit of i_{q_max}=15 A was justified. Simulations of the both design control systems therefore predict the intended drive performance.

5. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

The presented simulation results indicate that the designed control system operates properly. It can be clearly observed from Figure 4 and also from Figure 5 with imposed current limits. The observer estimates the external force correctly according to both figures. The corresponding changes of magnitude of the stator current torque component are as expected.

The aforementioned simulation results of this new position control system for electric drives employing linear permanent magnet synchronous motor indicates possibility that the prescribed second order closed loop position dynamics and first order speed dynamics with counteraction of external forces is attainable with realistic errors in the assumed motor parameters.

Experimental verification will therefore be sought as a continuation of this work.

REFERENCES

[1] Isidori, A.: *'Nonlinear Control Systems'*, 2nd edition, Springer-Verlag, 1989.

[2] Krstic, M., Kanellakopoulos, I., Kokotovic, P.: *'Nonlinear and Adaptive Control Design'*, John Wiley and Sons, 1995.

[3] Boldea, I., Nasar, A. S.: *'Vector Control of AC Drives'*, 2nd edition, CRC Press, 1992.

[4] Leonhard, W.: *'Control of Electrical Drives'*, Springer Verlag, 1997.

[5] Dodds, S. J., Vittek, J., Perryman, R. and Altus, J.: *'Preliminary Experimental Results for Synchronous Motor Drives with Forced Dynamics'*, Proceedings of IASTED ***CA'98*** Conference on 'Control and Applications', Honolulu, USA, 1998, pp. 219–223.

[6] Dodds, S. J. and Vittek, J.: *'Robust Cascade Forced Dynamics Control of Shaft Sensorless Synchronous Motor Drives'*, Proceedings of the Third International Symposium on ***ELECTROMOTION'99***, July 1999, Patras, Greece, Vol.1, pp. 447-452.

[7] Brock, S., Deskur, J. and Zawirski, K.: *'A Modified Approach to the Design of Robust Speed and Position Control of Servo-Drives'*, Proceedings of ***EPE'PEMC 2002*** Conference, Cavtat, Croatia, 2002, CD Rom.

[8] Utkin, V. I., Loukianov, A. G., Canedo, J., Ramirez, J. and Cabreva-Vazquez, J.: *'Observer Based Sliding Mode Control of Synchronous Generator'*, Proceedings of ***8th IEEE MED'00*** Conference, Patras, Greece, July 2000, CD-Rom.

[9] Wild, H. and Dodds, S. J, *'Real-time Identification of the Friction Coefficient of a Rolling Guided High Dynamic Linear Motor'*, Proceedings of ***Control'98***, Conference, United Kingdom.

[10] Hamada, D., Uchida, K., Yusivar, F., Haratsu, H., Wakao, S. and Onuki, T.: *'Sensorless Control of PMSM using Linear Reduced Order Observer including Disturbance Torque Estimation'*, Proceedings of ***EPE'99*** Conference, Lausanne, Switzerland, 1999, pp. 312-317.

Acknowledgements The authors wish to thank to "*Slovak – German Commission*" for funding bilateral DAAD scientific project No. 4/2003 "R&D of a Sensorless Micro-processor Controlled AC Drives Employing Synchronous Rotating- and Linear Motors" together with "*Czech and Slovak Joined Commission*" for funding bilateral research projects No. 017/2003, 'Analysis & Development of the Modern Controlled Drive', in the frame of which this contribution was created.

CONTACTS

Jan Vittek
tel: +421 41 513 2151, fax: +421 89 513 1515,
e-mail: jan.vittek@fel.utc.sk

Peter Büchner
tel.: +32 351 463 32916, fax: 0351 463 37111,
e-mail: buechner@eti.et.tu-dresden.de