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Closed-Loop Stepping Motors Positioning System Using Variable-Structure Controllers

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Abstract

As it known, one of the most important disadvantages of the open-loop stepping motor-based positioning systems is the high sensitivity regarding the strongly load torque variations. The paper explores the feasibility for implementing a variable-structure position controller-based strategy for the hybrid stepping motors, in order to achieve insensivity and robustness for this actuator. This strategy can improve the dynamic response of the motor, and the insensivity regarding the motor parameters variation too. The block diagram of the proposed control structure and the variable-structure controller design methodology is discussed widely in the paper. Detailed numerical simulation results are indicated in order to prove the feasibility of the proposed control strategy.

Key words: *stepping motors, variable-structure position controller, dynamic response*

Introduction

The traditionally control systems of the stepper motor are based on a discrete sequence of current pulses. Dynamic performances of those open-loop control schemes could be strongly improved applying the vector control strategy. As a result the motor becomes a high dynamic AC servodrives, in such special cases without losing its stepper behavior [1]. The paper explores the feasibility for implementing a position controller based on the variable control structure using the sliding mode strategy for the vector controlled two-phase PM-hybrid stepping motor. Accurate simulation results are presented in order to prove the dynamic performances. Finally a robustness analysis of the closed-loop stepping motor positioning systems using variable structure controllers is efectuated, taking into account the conclusions regarding the numerical simulation results carried out in Matlab/Simulink environment.

The stepping motor variable-structure position control strategy

During the PM-hybrid stepping motor control process a lot of disturbance sources it is possible to be occur (measurement noises, mistakes in the system mathematical modeling, noise from the semiconductor devices switching). In case of this study the basic disturbance source is considered just only the load torque M_r. The reference magnitude of this control system is the imposed rotor position, and the input magnitude for the stepping motor is the "active current" $i_{sq\theta}$ [1]. The basic idea of this strategy is that the so-called "active current" $i_{sq\theta}$ in accordance with the necessities of the process will be generated, and the "reactive current" $i_{sd\theta}$ must be suppressed. As a result, the permanent magnet flux phasor will be perpendicularly to the “active current” phasor, and the developed electromagnetic torque is maximal [2].

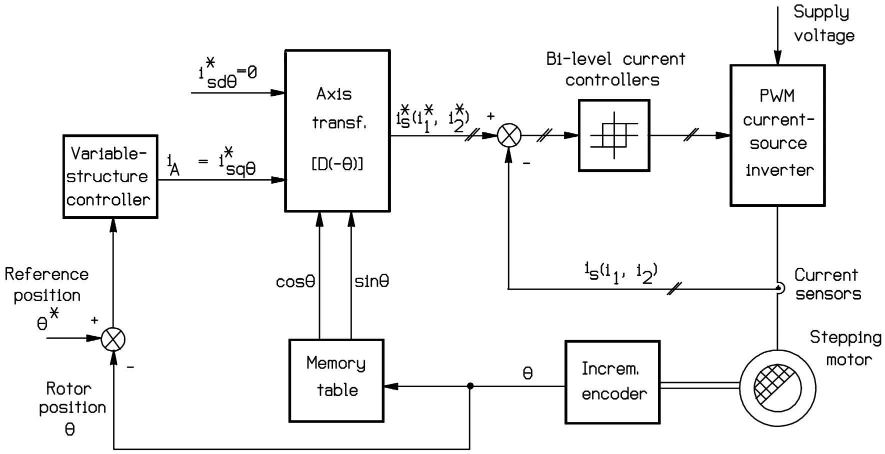

Fig. 1. The block diagram of the stepping motor position control system using variable-structure controller.

The block diagram of the control system running with the above-described strategy is indicated in figure 1. As shows, the input magnitude of the proposed variable-structure controller is the rotor position error, and the output magnitude the active component $i_{sq\theta}$ of the stator current. With help of the axis transformation unit, the reference currents for the power electronic converter inputs are applied, and in the motor phases through the PWM strategy will be reproduced.

The variable-structure position controller design methodology

For the variable-structure position control system development the nonlinear state equations of the PM-hybrid stepper motor in the synchronous rotating reference frame are taking into account [2]. The state space equations for the stepper motor with field-oriented driven by a current controlled PWM inverter are given by the following equations [3], [4]:

$$\begin{aligned} & i^*_{sd\theta}=0 \\ & \frac{d}{dt}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} -\frac{B_m}{J_m} & 0 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} \frac{k_m}{J_m} \\ 0 \end{bmatrix} \cdot i^*_{sq\theta} + \begin{bmatrix} -\frac{1}{J_m} \\ 0 \end{bmatrix} \cdot m_r, \end{aligned} \tag{1}$$

where $i^*_{sd\theta}$ and $i^*_{sq\theta}$ are the imposed reference currents, and the new state vector is $x=[x_1(t)\ x_2(t)]^T=[\omega_m\ \theta_m]^T$ (the conventional notations are used).

The traditional sliding mode control law takes the form $u=u_{eq}+\beta \text{sat}(s/\Phi)$ where Φ is called the thickness of the boundary layer, and where the boundary layer corresponds to substituting of the function sgn(s) by a saturation function sat(s/Φ). If the system state is outside the boundary layer, than the control law becomes $u=u_{eq}+\beta \text{sgn}(s)$, which guarantee the sliding condition. The stepper motor response can be improved if the control law is modified as $u=u_{eq}+\alpha s+\beta \text{sgn}(s)$, where α is a positive constant and s is the switching function [3], [4]. The position controller employs the q-axis, and the state space equation in the error coordinate can be derived from equation (1). The tracking error vector is defined as follow:

$$E = \left[\theta_{ref} - \theta_m \quad \omega_{ref} - \omega_m\right]^T = \left[e \quad \dot{e}\right]^T, \tag{2}$$

where θ_{ref} specifies the reference position. The sliding surface for this design is considered as a function of both position and speed:

$$S = \ddot{e} - \lambda_1 \dot{e} - \lambda_2 e, \text{with} \lambda_1, \lambda_2 > 0. \tag{3}$$

With the definition of sliding surface as above, the design requirements from tracking θ_{ref} is reduced to being on the surface S(t)=0. Control law is designed to make the surface S(t)=0 attractive and reach the surface in a finite time.

Based on idea proposed by Wang and Lee [5], the sliding mode controller with a unified smooth control law can be obtained as follow:

$$i^*_{sq\theta} = i_{sq\theta-eq} + k \cdot s(t), \tag{4}$$

where $i_{sq\theta\text{-}eq}$ is the equivalent control term, s(t) the predefined sliding function, and k a positive constant. The proposed control law is smooth and continuous function, and the switching term ks(t) is always with the same sign as the saturation function sat(s/Φ) [6].

Numerical simulation results

The Simulink model of the whole PM-hybrid stepping motor variable-structure position control strategy is given in figure 2. In the first numerical simulation results set (figures 3, 5, 6, 7, and 11) carried out in Matlab/Simulink environment the following parameters are considered: θ_{ref} =1,5rad, K_v=50 and m_r =0.02Nm. In figure 3 the state variables (position error and speed error) evolution according to the implemented sliding mode strategy is shown. As it can be observed from the figure, after short time the motor reaches the sliding surface. In the first moment some oscillations occurs, but in the last part of the surface the motor slides smoothly to the imposed reference rotor position.

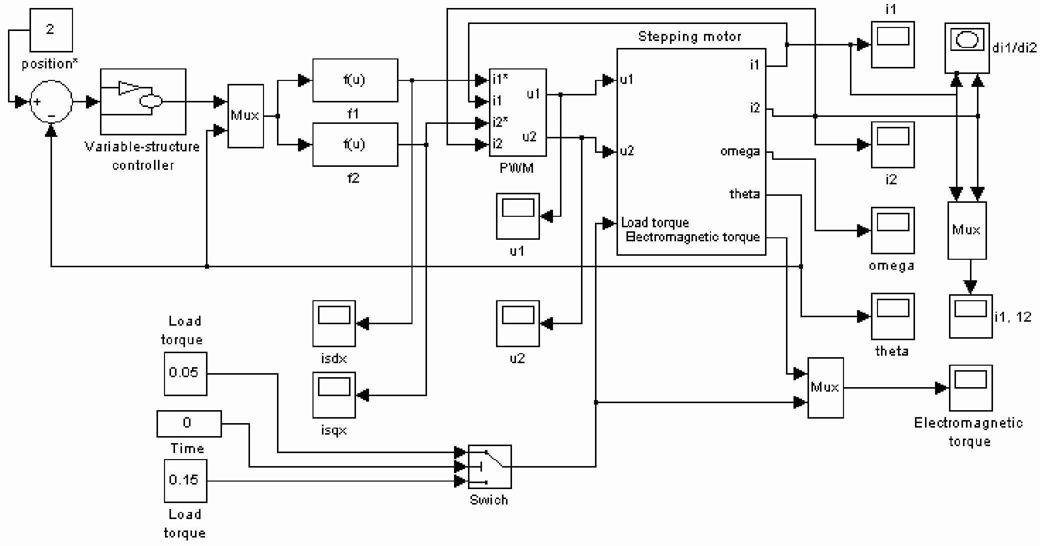

Fig. 2. The Simulink model of the stepping motor position control system.

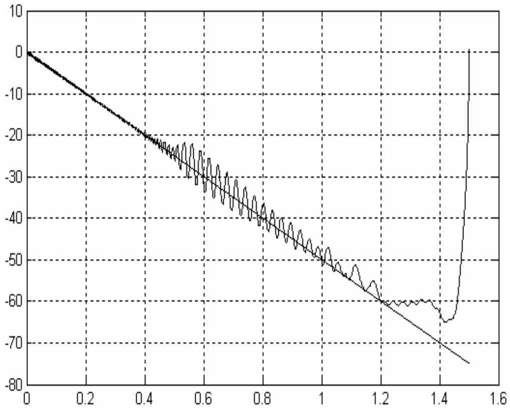

Fig. 3. The state variables evolution.

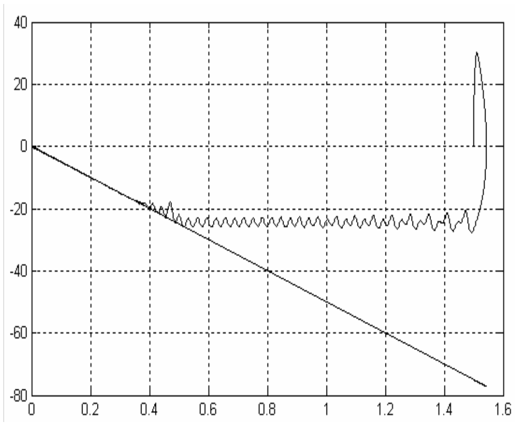

Fig. 4. The state variables evolution.

The rotor position evolution and the rotor speed waveform are given in figure 5 and 6. As we can observe from figure 5, the stepping motor has a good dynamic response, without stationary positioning error. This response is similar with dynamic performances of the compensated DC motor ones. It is important to mention also that the rotor position evolution is without any oscillations and perturbations. The stepping motor velocity is indicated in figure 6. After a quickly increasing wave-shape the rotor speed is decreased shortly to zero, in accordance with the imposed positioning strategy. In figure 11 the two-phase currents (i_1 and i_2) wave-shapes during this process are presented. The second simulation results set is obtained for θ_{ref} =1,5rad, K_v=50, and for load torque m_r =0.2Nm.

Figure 4, 8, 9, 10 and 12 shows also the very good dynamic performances of the whole control system. This simulations set it was obtained for case when the load torque is increased very strong (m_r =0.2Nm). Now the motor reaches the sliding surface not so early that in the in first case, but with very small oscillations too. The rotor position is set also quickly and without oscillations to the imposed reference position θ_{ref} =1,5rad (figure 8). The developed electromagnetic torque waveform given in figure 12 is nearly constant, just with small oscillations around the imposed load torque.

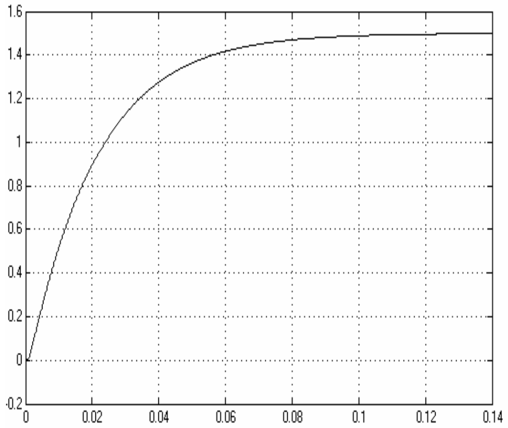

Fig. 5. The rotor position.

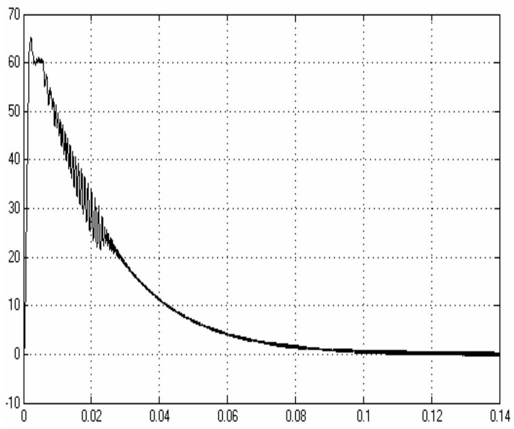

Fig. 6. The rotor speed.

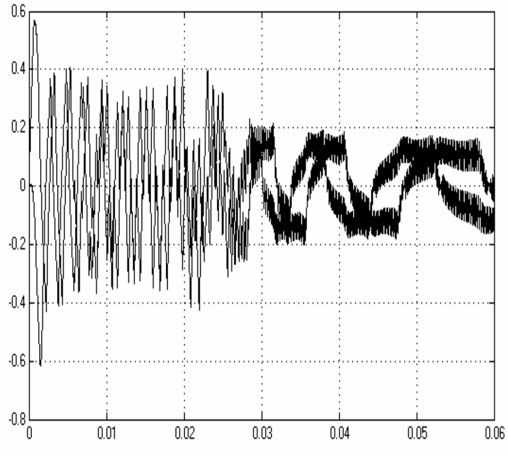

Fig. 7. The phase currents waveforms.

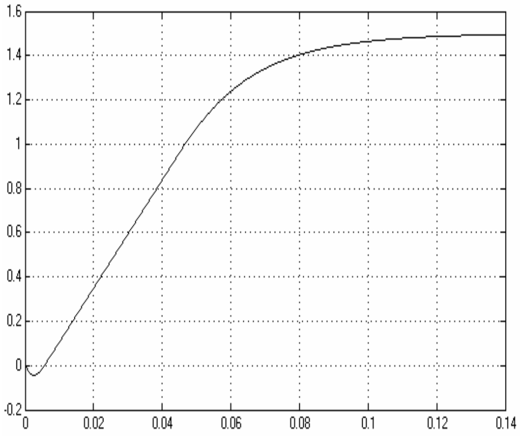

Fig. 8. The rotor position.

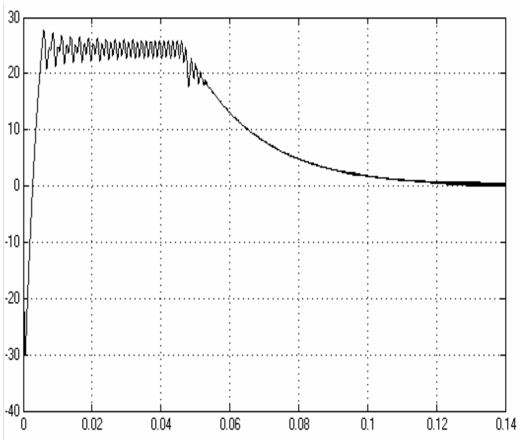

Fig. 9. The rotor speed.

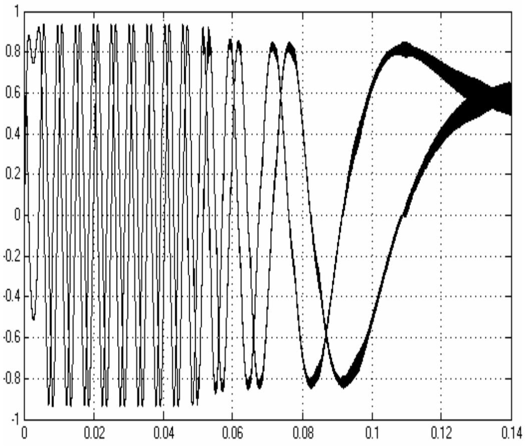

Fig. 10. The phase currents waveforms.

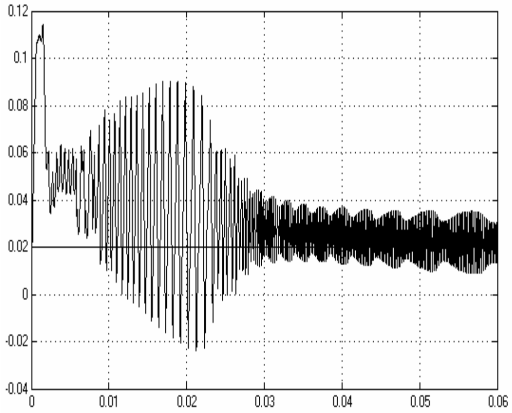

Fig. 11. The electromagnetic torque.

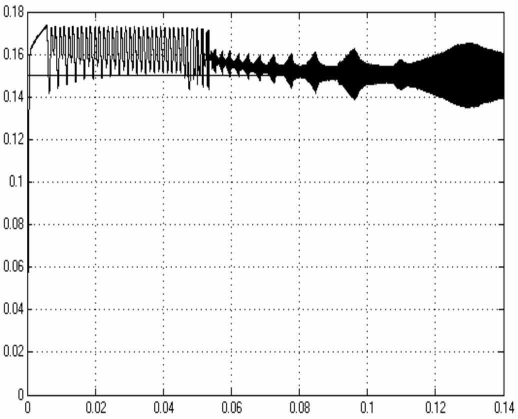

Fig. 12. The electromagnetic torque.

Conclusions

The operation of the stepping motor in variable-structure control regime can improve the dynamic responses and offer advantages as insensitive to the parameter variations and external disturbance. The diagram set resulted from the numerical simulation shows for this actuator high dynamic performance, similar with case of DC motor ones. The indicated strategy could be a promising solution for the future stepping motor robust control systems approach.

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Sistem de poziționare a motoarelor pas cu pas folosind regulatoare cu structură variabilă

Rezumat

Se cunoaşte că una dintre cele mai importante dezavantaje ale sistemelor de poziționare în circuit deschis a motoarelor pas cu pas o constituie sensibilitatea deosebită la variația cuplului rezistent la arbore. Lucrarea studiază posibilitatea implementării unui sistem de poziționare în circuit închis a motorului pas cu pas hibrid folosind regulatoare cu structură variabilă. Această strategie de reglare poate înbunătății răspunsul dinamic al motorului şi poate asigura insensivitatea acestuia față de variațiile cuplului rezistent la arbore. Este prezentată pe larg în lucrare schema bloc de principiu a strategiei de reglare precum şi modul de proiectare a regulatorului cu structură variabilă. Se analizează detaliat rezultatele simulărilor numerice pentru a demonstra avantajele sistemului de reglare propus.