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SLIDING MODE SIMPLIFIED VECTOR CONTROL STRATEGY FOR PM-HYBRID STEPPER MOTOR

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Abstract

This paper presents a robust control strategy for the two-phase PM-hybrid stepper motor. In order to eliminate the parameter and load variation influence, a position controller based on the sliding mode structure is investigated for high performance positioning applications. The field-oriented control is also applied to the hybrid stepper motor, with the purpose to improve the dynamic performance of the system drive. Detailed simulation and experimental results are presented to illustrate the good dynamic response of the motor.

1. INTRODUCTION

The two-phase PM-hybrid stepper motor is a widely used actuator in precision positioning applications such as industrial machinery, robotic systems or computer peripherals. The traditionally control systems of the stepper motor are based on a discrete sequence of current pulses. These open-loop schemes are characterized by poor dynamic performances, especially in case when strongly load torque variations occur. Applying the vector control strategy, the stepper motor can improve its stepper behavior with respect the precise motion control requirements. As results, the motor becomes a high dynamic AC servo drive, in such special cases without losing its stepper behavior [1]. The variable structure control strategy based on the sliding mode regime can offer a number of attractive properties, such as: insensitivity to the parameter variations and external disturbance, and also improvement of dynamic responses. 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 PM-hybrid stepper motor. Accurate simulation results are presented in order to prove the dynamic performances. The laboratory prototype digital control system used for the experiments and measurements are also indicated in the paper.

2. MATHEMATICAL MODELING OF THE PM-HYBRID STEPPER MOTOR DRIVE

If the PM-hybrid stepper motor phases are excited with quadrature sinusoidal currents, the motor can be regarded as a permanent magnet synchronous machine with uniform air-gap [2]. The adopted nonlinear state equations of the PM-hybrid stepper motor in the synchronous rotating reference frame can be expressed as follows [3]:

$$
\begin{aligned}
&\frac{d\theta_m}{dt} = \omega_m \\
&\frac{d\omega_m}{dt} = \frac{1}{J_m}(k_m(\Psi_m i_{sq\theta} + (L_{sd} - L_{sq}) i_{sd\theta} i_{sq\theta}) - B_m \omega_m - m_r) \\
&\frac{di_{sd\theta}}{dt} = \frac{1}{L_{sd}}(u_{sd\theta} - R i_{sd\theta} + \omega L_{sq} i_{sq\theta}) \\
&\frac{di_{s\theta}}{dt} = \frac{1}{L_{sq}}(u_{sq\theta} - R i_{sq\theta} - \omega L_{sd} i_{sd\theta} + \omega \Psi_M);
\end{aligned}
\tag{1}
$$

where $\omega = z_r \omega_m$. This stator model consists in the two electrical equations, one of each stator winding and one equation for the shaft mechanical dynamic. For the considered PM-hybrid stepper motor $L_{sd}=L_{sq}=L$ are the inductance of the stator phases, $i_{sd\theta}$ and $i_{sq\theta}$ are the currents of $d\theta$-$q\theta$ axis, Ψ_M is the permanent magnet flux, θ_m is the rotor position, ω_m is the rotor speed, z_r is number of rotor teeth, R is the phase resistance, J_m is the rotor inertia, B_m is the viscous friction, m_r is load torque.

To improve the dynamic performances of the stepper motor, the field-oriented principle is applied for the motor drive. This impose to keep the $d\theta$ axis current $i_{sd\theta}$ always to zero, to avoid the cross coupling effect in the dq model. In this reason, the torque equation becomes:

$$
m_e = k_m \cdot i_{sq\theta}, \tag{2}
$$

where $k_m = z_r \Psi_M$ is the motor constant.

The order of the model (1) can be reduced if the dq currents are considered as reference inputs for the system drive. Therefore, state space equations for the PM-hybrid stepper motor with field-oriented driven by a current controlled PWM inverter are given by the following equations [4]:

$$
\begin{aligned}
&i^*_{sd\theta} = 0 \\
&\frac{d}{dt}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} -\frac{B_m}{J_m} & 0 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} \frac{k_m}{J_m} \\ 0 \end{bmatrix} \cdot i^*_{sq\theta} + \begin{bmatrix} -\frac{1}{J_m} \\ 0 \end{bmatrix} \cdot m_r,
\end{aligned}
\tag{3}
$$

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

3. THE SLIDING MODE SIMPLIFIED VECTOR CONTROL STRATEGY

In accordance with the vector control strategy, the so called “active current” $i^*_{sq\theta}$ must be controlled according to the necessities of the process, and simultaneously the so called “reactive current” $i^*_{sd\theta}$ must be suppressed, in order to avoid the magnetic flux changement in the air-gap. This control strategy offers satisfactory performances but more concrete implementation difficulties appear. The high complexity of the control algorithms needs important hardware and software implementing efforts and, as a result, is not appropriate for this little power servomotor. In order to avoid the mentioned problems, the "simplified vector control" strategy was developed for the PM-hybrid stepper motor [5]. The principle of this control strategy is indicated in figure 1.

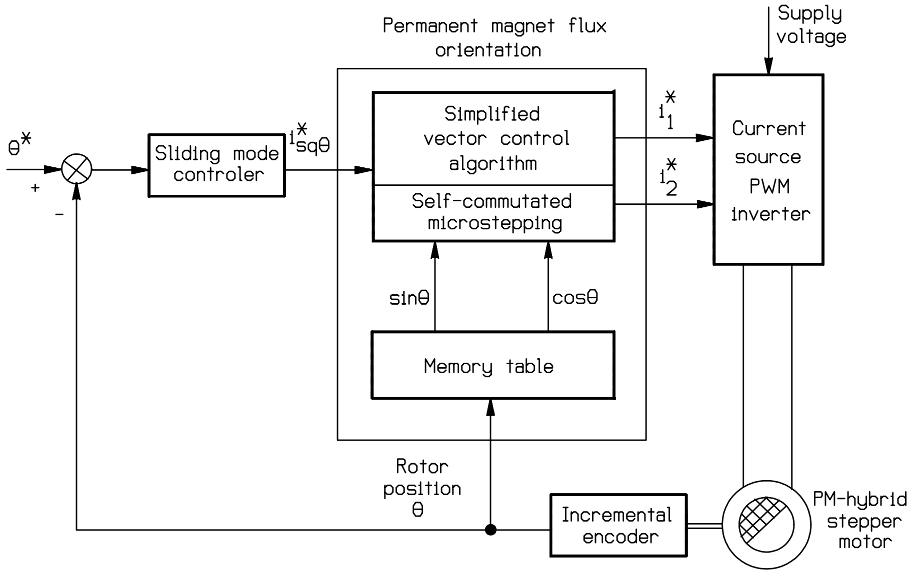

Fig.1. The sliding mode simplified vector control strategy.

This new control method is the combination of the two classical control strategies: the self-commutated and the microstepping operation mode [4], [6]. In the simplified vector control operation mode the stator current space-phasor is oriented according to the rotor position not only at the beginning of each mechanical step (self-commutated operation mode), but for each microstep, determined with a precision that depends only of the incremental encoder. For high number of microsteps, the errors in the current orienting that occurs during the microstep are possible to be neglected.

In figure 1 the active current $i^*_{sq\theta}$ is generated through by a variable structure sliding mode controller, in order to improve the dynamic response and insensitivity to the parameters and load variations of the PM-hybrid stepper motor. 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 [4], [7]. The position controller employs the q-axis, and the state space equation in the error coordinate can be derived from equation (3). The tracking error vector is defined as follow:

$$E = [\theta_{ref} - \theta_m \quad \omega_{ref} - \omega_m]^T = [e \quad \dot{e}]^T, \tag{4}$$

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

$$S = \ddot{e} - \lambda_1 \dot{e} - \lambda_2 e, \text{with } \lambda_1, \lambda_2 > 0. \tag{5}$$

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 [7], the sliding mode controller with a unified smooth control law can be obtained as follow:

$$i^{*}_{sq\theta} = i_{sq\theta-eq} + k \cdot s(t), \tag{6}$$

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) [8].

4. NUMERICAL SIMULATION AND EXPERIMENTAL RESULTS

The dynamic performances of the PM-hybrid stepper motor running with sliding mode simplified vector control strategy was carefully studied through Matlab simulations. It was taken into account a motor with the following characteristics: two-phase, 8 stator poles, 5 teeth/pole, 50 rotor teeth, 200 steps/revolution, 0.2 Nm, 12 V, 1 A/phase. The permanent magnet flux is Ψ_M =0.0044 Wb and the effective inertia is J_{EFF}=2.5x10^{-4} kg.m^2, ($J_{EFF} = J_M + J_L$). The position transducer was an incremental one, provided with 1000 pulses/revolution. As a result it was possible to investigate the motor operation with 5 microsteps/step. In the first step of the simulations the simplified vector control strategy was implemented. The resulted diagrams set shows similar dynamic performances for the simplified vector controlled PM-hybrid stepping motor with the DC motor ones.

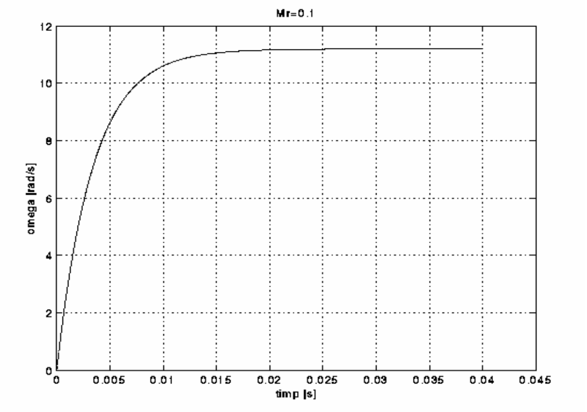

Fig.2. The angular speed.

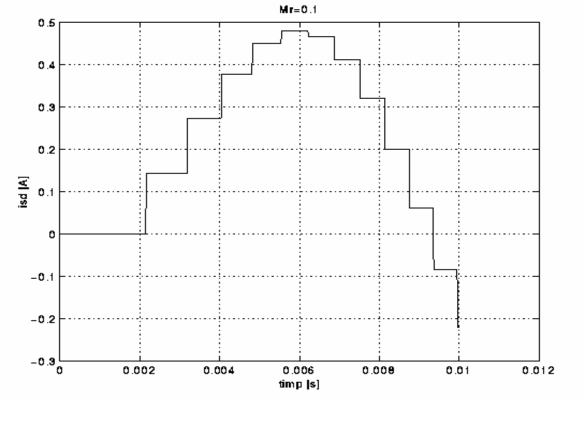

Fig.3. The phase current i_{sq}.

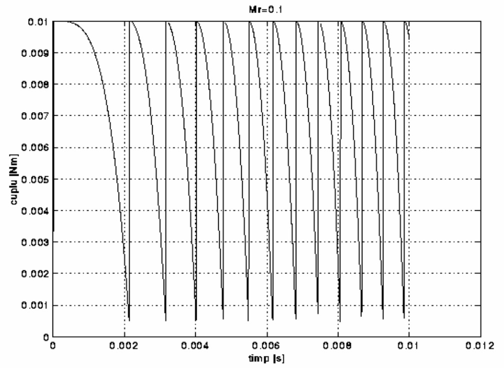

Fig.4. The electromagnetic torque.

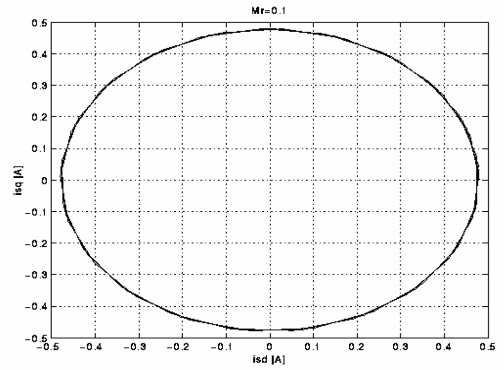

Fig.5. The phase current phasor.

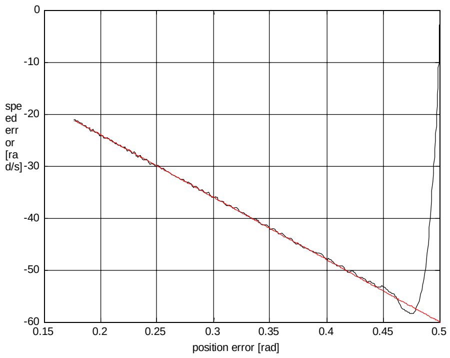

Fig.6. The state variables evolution.

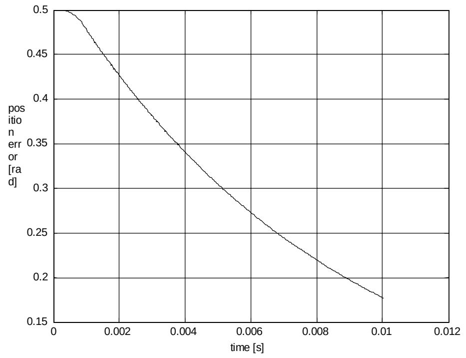

Fig.7. The position error x_1.

As we can observe from figure 2, the motor speed is set without oscillations, the dynamic response of the stepper motor is similar with the DC motor performances. Figure 3 shows the phase currents variation with the microsteps of the motor. For each microstep the stator current space phasor is oriented according to the rotor position, so for each microstep this phasor is perpendicular to the permanent magnet flux phasor. The electromagnetic torque developed by the stepper motor is nearly constant, like in the case of the DC motors. In a very small scale (Fig. 4) the electromagnetic torque has some oscillations, and this figure shows how the stator current space phasor is oriented, and the developed electromagnetic torque becomes maximal according for each microstep, similar with case of the compensated DC motor ones. Figure 5 shows the circle described by the stator current space phasor $\underline{i}_s$.

In figure 6 we can follow the state variables x_1 (position error) and x_2 (speed error) evolution according to the implemented sliding mode strategy. After reaching the sliding surface, the motor slides smoothly to the imposed reference rotor position $\theta_{ref}=0.5$ rad. The positioning error obtained during this process is indicated in figure 7.

The block diagram of the experimented sliding mode vector control system is presented in figure 8. The control system is based on an IBM PC computer. For the motor phase currents and the rotor angular position measurement a Keithley MetraByte DAS-1600 plug-in card data acquisition board is used [9]. The transistorised current source PWM inverter based on the L6203 bridges is able to generate in the motor windings alternative current wave-shapes according to the current reference signals generated through the above described digital control system. This is possible by the use of a voltage of 48V in the dc-link and operating with a high current chopping frequency. The power electronic module is equipped also with two current sensors (LEM-35) and the necessary interface circuits with the digital control system.

Figure 9 shows the transistorised current source asynchronous PWM inverter and the two-phase PM-hybrid stepper motor, together with the high resolution incremental encoder and the DC servomotor–based load. The general view of the whole digital control system based on the IBM-PC computer is presented in figure 10.

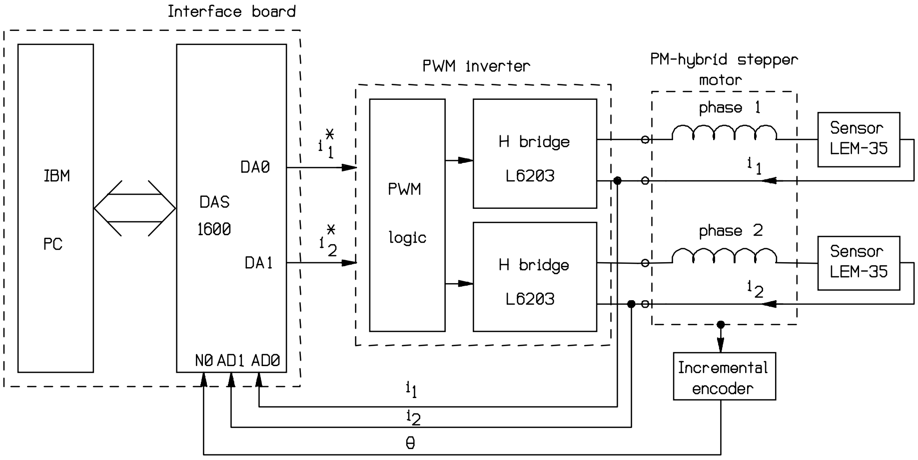

Fig.8. The block diagram of the digital control system.

The experimental results are focused upon the rotor position signal acquisition and processing and the current references estimation in the case of this vector control strategy. Figure 11 and 12 shows the recorded phase currents i_1 and i_2 and the rotor angular position of the stepping motor running in “simplified vector control“ operation mode.

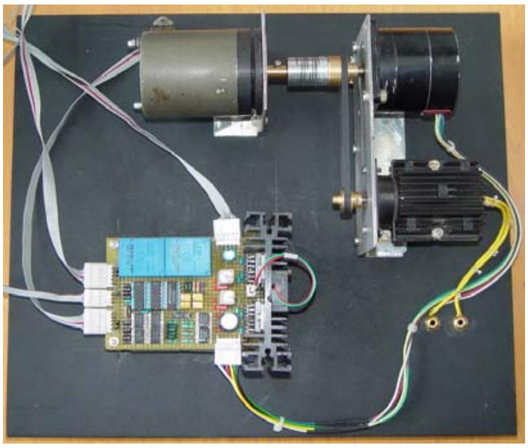

Fig.9. The PWM inverter and the PM-hybrid stepping motor with the adequate incremental encoder and DC motor-based load.

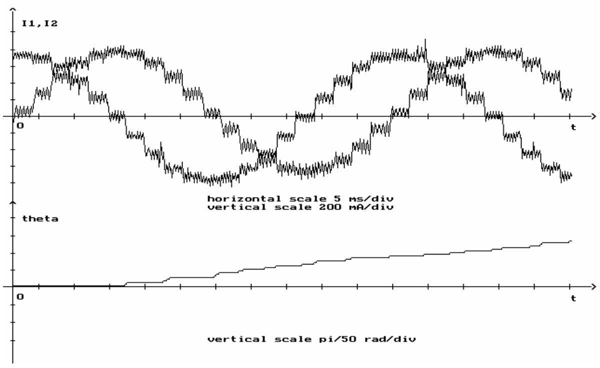

Fig.11. The phase currents and the rotor angular position, (load torque 0.1 Nm).

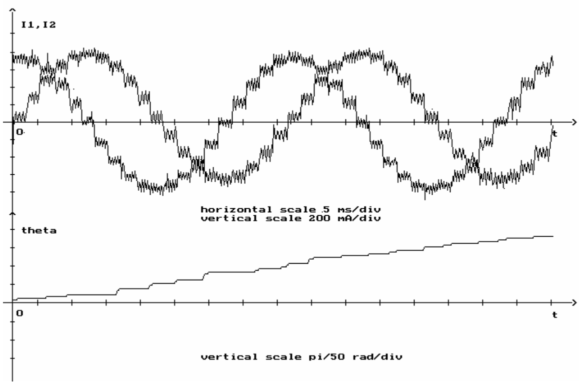

Fig.12. The phase currents and the rotor angular position, (load torque 0.08 Nm).

Fig.10. The laboratory prototype digital control system.

A current amplitude of 0.75 A was taken into account. In can be seen in figure 11 that the motor operates with 75 steps/s, that means 375 microsteps/s. In new running conditions, when the load torque is decreased from 0.1Nm to 0.08 Nm(Fig. 12), the stepping motor operates with 100 steps/s, that means exactly 500 microsteps/s. As it was expected, reducing of the load torque implies higher rotor speed. The experimental results presented in figure 11 and 12 could be compared with the current waveforms obtained through Matlab simulations in figure 3. In booth case we can observe the microsteps of the PM-hybrid stepper motor in "simplified vector control operation mode".

5. CONCLUSIONS AND OUTLOOK

It is well known that using the vector control strategy the stepper motor becomes a high dynamic AC servodrive. In order to get the robustness of this actuator, the variable structure control using sliding mode strategy is proposed. The operation in sliding regime can improve the dynamic responses and offer advantages as insensitive to the parameter variations and external disturbance.

In the first step of the experiments the simplified vector control strategy was investigated trough carefully Matlab simulations. The diagram set (Fig. 2-5) resulted from the numerical simulation shows for this actuator similar dynamic performances with the DC motor ones. The motor speed is set quickly and without oscillations, the developed electromagnetic torque is nearly constant. The detected small oscillations of the electromagnetic torque show how the stator current space phasor is oriented, and the developed electromagnetic torque becomes maximal according for each microstep, similar with case of the compensated DC motor ones. Figure 6 and 7 shows the dynamic performances of the positioning system based on the designed sliding mode controller. The recorded phase currents i_1 and i_2 presented in figure 11 and 12 indicate clearly the microsteps of the stepper motor in "simplified vector control" operation mode.

The conclusions of the experiments indicate that the PM-hybrid stepper motor provided with this efficient and not expensive sliding mode vector control strategy presents promising dynamic performances, and could be a future alternative to the classical PM-hybrid stepper motor position control methods.

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