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Design and some experimental results of the position control system of Bipolar Permanent Magnet Stepper Motors based on Adaptive Nonlinear Backstepping technique combining with Adaptive Fuzzy Logic

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Abstract— **Nowadays, stepper motors are widely used in industry in general and in CNC machines in particular because of their low price due to the large number of products manufactured and the ability to control velocity and position via open regulator circuits. However, due to the nonlinearity of this type of motor along with changes in its parameters during operation, the use of open regulator circuit for this motor type causes errors in speed adjustment as well as position adjustment of the motor. To overcome the above disadvantages, the paper offers a closed control circuit based on the Field oriented control for this type of motor, and uses Backstepping technique based non-linear adaptive control method combining with Adaptive Fuzzy logic technique to improve the position control quality of Bipolar Permanent Magnet Stepping Motor. The proposed position control system is experimented on the DSP based experimental system, which uses DSP TMS 320F2812. The experimental results show that, the performance of the proposed position control system has high accuracy, that meets the commands of the high precision CNC machines in industry.**

Index Terms— **Adaptive nonlinear Backstepping technique, Bipolar Permanent Magnet Stepping Motor, DSP TMS320F2812, Fuzzy Logic technique, Field Oriented Control Position control system.**

I. INTRODUCTION

The permanent magnet stepper motor has many permanent magnets mounted on the rotating part, with coils placed on the magnetic steel core at the fixed part forming a two-phase winding. The working principle of this type of motor is based on the working principle of the permanent magnet brushless motor, which has a large torque. The motor rotates at a given angle every time an input pulse is applied to the winding and therefore the motor rotation angle is proportional to the number of pulses fed to the windings, the motor rotation speed is proportional to the pulse frequency supplied to the motor. In addition, this type of motor usually has many poles, so the angle of rotation corresponding to a pulse supplied to a coil is very small so this type of motor is very suitable for precise position control systems [1] in the industry in general and in CNC machines in particular. One of the advantages of a permanent magnet stepper motor is that it is possible to control the position of the rotation angle through an open control circuit. However, the quality of position control of this motor type with open control circuit is not high, the overshoot of position is too high (up to 0.5 degree) and the settling time is too long, it causes position oscillation and loss of synchronism [3]. The reason is that, there are nonlinearities of this type of motor as well as variations of load and motor parameters during operation of the motor. Therefore, closed-loop control for permanent magnet stepper motors is necessary in precise position control systems as in CNC machines. Furthermore, in order to meet the increasing position control demands in CNC machines, advanced control techniques need to be applied. For that purpose, the field oriented control and backstepping combined fuzzy logic control technique are applied to design the permanent magnet stepper motor position control system.

There are two types of PMSM, that are Bipolar Permanent Magnet Stepper Motor and Unipolar Permanent Magnet Stepper Motor. In order to apply the Field Oriented Control, the BPMSM is used. In order to verify the performance of the proposed position control system, the proposed control system is experimented on the DSP based experimantal system, which uses DSP TMS320F2812. The expetimental results show that, the errors of positon is quite small, about 0.0015^0, these results prove that, the performance of the proposed position control system has high accuracy and meets the commands of the high precision CNC machines in industry.

II. MATHEMATICAL MODEL OF BIPOLAR PMSM

Acording to [1], [2], [4], by using a transformation method called: "Park Transformation" we have the mathemathical model of Bipolar PMSM on synchronous d-q coordinate fixed to the axis of the rotor magnetic field as shown in equation (1). Where I_d is the stator direct current (A); I_q is the stator quadrature current (A); V_d is the stator direct voltage(V); V_q is the stator quadrature voltage(V); V_a and V_b are stator voltages in phase a and phase b (V) respectively; i_a and i_b are stator currents in phase a and phase b (A) respectively; R is the resistance in each phase of motor (Ω); L is self inductance in each phase of motor (H); N_r is the number of rotor teeth of motor; Ψ_m is rotor flux linkage amplitude (Vs); ω_r is angular speed of the rotor (rad/Sec); θ_r is rotor position (rad); T_L is load torque (Nm). J is total inertial

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Moment of rotor (kg.m²); B_v is is the viscous friction coefficient (Nms/rad).

$$\begin{bmatrix} \frac{dI_d}{dt} \\ \frac{dI_q}{dt} \\ \frac{d\omega_r}{dt} \\ \frac{d\theta_r}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{L}\left(V_d - RI_d + N_r L\omega_r I_q\right) \\ \frac{1}{L}\left(V_q - RI_q - N_r L\omega_r I_d - \psi_m\omega_r\right) \\ \frac{1}{J}\left(N_r\psi_m I_q - B_v\omega_r - T_L\right) \\ \omega_r \end{bmatrix} \tag{1}$$

III. CONSTRUCTION OF THE CLOSED LOOP CONTROL SYSTEM

The general construction of the closed loop control system of the Bipolar PMSM is depicted in figure 1. The closed loop control system has three closed control loop, that are position, speed and current control loop.

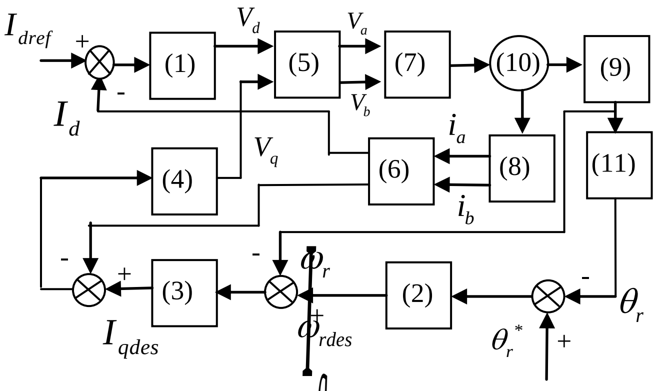

Fig. 1. The construction of the closed loop control system

In the figure 1, there are following basic blocks: 1- the nonlinear Backstepping direct current controller, that is designed by the Backstepping method; 2 - Fuzzy Logic Controller for the position loop; 3 - The nonlinear Backstepping speed controller;4 – the adaptive nonlinear Backstepping quadrature current controller; 5 - the Park transformation block transfoms (V_d , V_q) to (V_a , V_b) with the transfer function $e^{jN_r\theta_r}$; 6 - the reverse Park transformation block transfoms (i_a, i_b) to (I_d , I_q) with the transfer function $e^{-jN_r\theta_r}$; 7 - the DRIVER Block, which is MOFET transistors and Bipolar junction transistors; 8- the current senser Block is used to measure i_a , i_b; 9 - the Encoder block measures the angular speed of the rotor; 10 - the Bipolar PMSM; 11- the block, which caculates the real angle position of the bipolar PMSM.

IV. DESIGN THE CLOSE LOOP CONTROL SYSTEM

A. *Design of the nonlinear backstepping speed controller of bipolar PMSM*

The speed error is defined as

$$e_1 = \omega_r - \omega_{rdes} \tag{2}$$

Where ω_{rdes} is the desired reference value of the rotor angle. Derivate the speed tracking error, we have

$$\dot{e}_1 = \dot{\omega}_r - \dot{\omega}_{rdes} \tag{3}$$

Combine with (1), we have

$$\dot{e}_1 = \left(N_r\psi_m I_q - B_v\omega_r - T_L\right)/J - \dot{\omega}_{rdes} \tag{4}$$

Choose I_q as a control variable, choose the Lyapunov Function as

$$V_1 = \frac{1}{2}e_1^2 \tag{5}$$

Derivate V_1 and combine with (4), we have

$$\dot{V}_1 = e_1\dot{e}_1 = e_1\left[\left(N_r\psi_m I_q - B_v\omega_r - T_L\right)/J - \dot{\omega}_{rdes}\right] \tag{6}$$

To make $\dot{V}_1$ negative, we choose the desired control variable I_q as

$$I_q = \left(1/N_r\psi_m\right)\left(-k_1 Je_1 + J\dot{\omega}_{rdes} + B_v\omega_r + T_L\right) = I_{qdes} \tag{7}$$

Where, k_1 is positive constant.

B. *Design of the adaptive nonlinear backstepping quadrature current controller of bipolar PMSM*

The parameters B_v, T_L are changed in working of Bipolar PMSM, so we do not have their exact values. Their estimated values are $\hat{B}, \hat{T}_L$ and (7) becomes

$$\hat{I}_q = \left(1/N_r\psi_m\right)\left(-k_1 Je_1 + J\dot{\omega}_{rdes} + \hat{B}_v\omega_r + \hat{T}_L\right) = \hat{I}_{qdes} \tag{8}$$

However $\hat{I}_{qdes}$ is just a state variable and not the control, we implement to design the adaptive backstepping nonlinear current of Bipolar PMSM .

Define the difference between the real value and the estimated value of the quadrature current as

$$e_2 = I_q - \hat{I}_{qdes} \tag{9}$$

Define the difference between the real values B_v, T_L and the their estimated values are B_v , T_L , so we have

$$\hat{B}_v = B_v - \tilde{B}_v, \hat{T}_L = T_L - \tilde{T}_L \tag{10}$$

We also do the same as step 1 with an extended Lyapunov Funtion as

$$V_e = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{1}{\gamma_1}\tilde{B}_v^2 + \frac{1}{\gamma_2}\tilde{T}_L^2 \tag{11}$$

Where γ_1, γ_2 are positive constants.To combine with (1) and to make the derivation of V_e negative, we choose the adaptive laws as

$$\dot{\hat{B}}_v = \gamma_1\left(\frac{\dot{\omega}_r e_2}{N_r\psi_m} - \frac{e_1\omega_r}{J}\right) \tag{12}$$

$$\dot{\hat{T}}_L = -\gamma_2\frac{e_1}{J} \tag{13}$$

and the desired value of the control variable V_q as

$$V_q = \frac{L}{e_2}\Bigg(-\frac{N_r\psi_m}{J}e_1e_2 - e_1\dot{\omega}_{rdes} - \frac{B_v\omega_r}{J}e_1 - \frac{T_L}{J}e_1 + \frac{RI_q}{L}e_2 + N_r\omega_r I_d e_2 + \frac{\psi_m\omega_r}{L}e_2 - \frac{k_1 J}{N_r\psi_m}e_1e_2 + \frac{J\ddot{\omega}_{rdes}}{N_r\psi_m}e_2 + \frac{\dot{\hat{B}}_v\omega_r}{N_r\psi_m}e_2 + \frac{\dot{\omega}_r\hat{B}_v}{N_r\psi_m}e_2 + \frac{\dot{\hat{T}}_L}{N_r\psi_m}e_2 \Bigg) \tag{14}$$

C. Design of the nonlinear backstepping direct current controller of bipolar PMSM

Define the difference between the real value and the reference value of the direct current as

$$e_3 = I_d - I_{dref} \tag{15}$$

Where I_{dref} is the desired reference value of the direct current. Here, because there are permanent magnets in the Bipolar PMSM, we do not need the direct current to provide the magnetic field. Therefore, the desired reference value of the direct current equals zero. Derivate e_3, we have

$$\dot{e}_3 = \dot{I}_d - \dot{I}_{dref} \tag{16}$$

Combine with (1), we have

$$\dot{e}_3 = \left(V_d - RI_d + N_r L\omega_r I_q\right)/L - \dot{I}_{dref} \tag{17}$$

Choose V_d as a control variable, choose the Lyapunov Function as

$$V_3 = \frac{1}{2}e_3^2 \tag{18}$$

Derivate V_3 and combine with (16), we have

$$\dot{V}_3 = e_3\dot{e}_3 = e_3\left[\left(V_d - RI_d + N_r L\omega_r I_q\right)/L - \dot{I}_{dref}\right] \tag{19}$$

To make $\dot{V}_3$ negative, we choose the desired control variable V_d as

$$V_d = RI_d - N_r L\omega_r I_q + L\dot{I}_{qref} - k_3 L e_3 \tag{20}$$

Where, k_3 is positive constant.

D. Design of Adaptine Fuzzy Logic Controller for the position loop

The construction of the position controller based on Adaptive Fuzzy Logic of BPMSM is described in figure 2[5],[6].

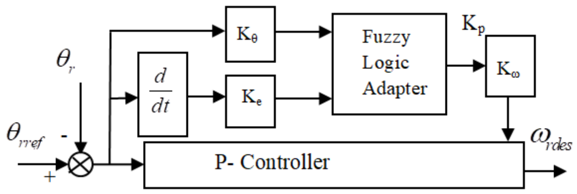

Fig.2. Construction of the Adaptive Fuzzy Logic Controller for the position loop of BPMSM

The two inputs of the Fuzzy Logic Adapter (FLA) are the error of position e = $\theta_{ref} - \theta_r$ and the derivative of the error of position de. These inputs are standardized by the coefficients K_θ and K_e so that they change in the range of -1 to 1. The output of FLA is the desired standardized proportional factor K_p^*, which changes in the range of 0 to 1. This output multiplied by the coefficient K_v makes the desired proportional factor K_p of the P-controler . The output of AFLC is the desired speed ω_{rdes}.

In or der to meet the main goal, that is the highest precision in angle position control, firstly, we design the simulation model of the control system by matlab/simulink. Secondly, we adjust the shapes of membership funtions for input and output variables to have the most appropriate shapes. We also do the same for the rules simultaneously. Finally, we have the membership Funtions (MFs) for the input and output variables , which are shown in figure 3, figure 4 and figure 5 and the basis of rules for the output K_p is expressed in table 1.

Table 1. Basis of rules for the out put K_p

e de	NB	NM	NS	ZE	PS	PM	PB
NB	B	B	B	B	B	B	B
NM	B	B	B	B	B	B	S
NS	S	S	B	B	B	S	S
ZE	S	S	S	B	S	S	S
PS	S	S	B	B	B	S	S
PM	S	B	B	B	B	B	S
PB	B	B	B	B	B	B	B

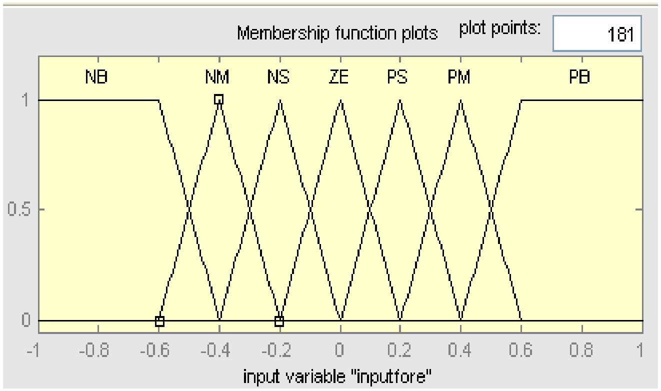

Fig.3. MFs for e

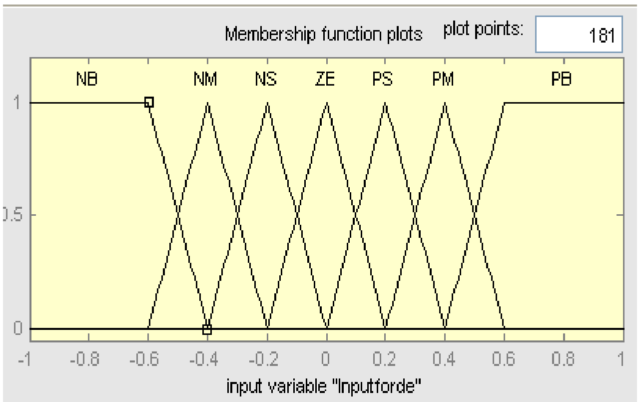

Fig.4. MFs for de

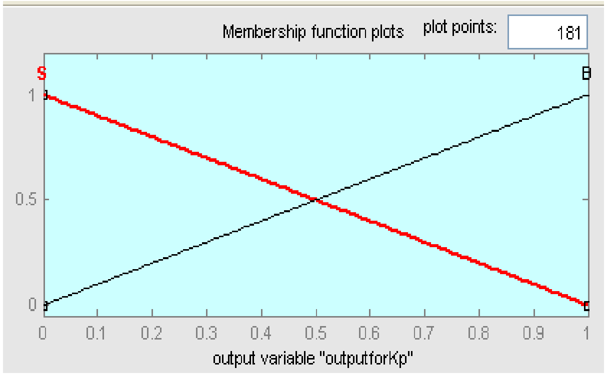

Fig.5. MFs for K_p

The diagram of the position control system of Bipolar Permanent Magnet Stepper Motors based on the Adaptive Nonlinear Backstepping technique combining with Fuzzy Logic is depicted in figure 4. In figure 4, we see the adaptive laws block, which is presented by equations (12) and (13). The inputs of the adaptive laws block are astimated values of the viscous friction coefficient and the load torque of the motor. These estimated values will be updated to the quadrature current control block, which is presented by the equation (14).

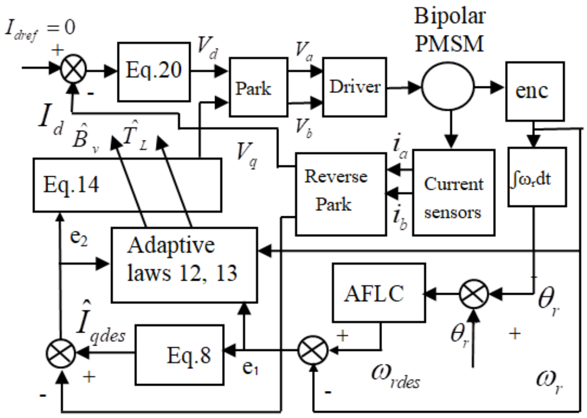

Fig.6. The diagram of the proposed position control system

V. EXPERIMENTAL SYSTEM AND RESULTS

A. Experimental system

For the purpose of experiment, we use the Bipolar PMSM that has following values of the parameters: R=0.7 Ω, L= 0.0014H. Ψ_m=0.005Vs, N_r=50, J=0.0000057kgm2, B_v=0.002Nms/rad, the load torque T_L= 2Nm. The controllers are implemented by using TMS320F2812 DSP of Texas Instruments. We use Matlab/Simulink to build the control system, then connect with Code Composer Studio software of Texas instruments to make and load the code of controllers to the TMS320F2812 DSP. The DSP based Bipolar PMSM driving system is described in Figure 7 and the DSP based experimental system for Bipolar PMSM drive is shown in Figure 8.

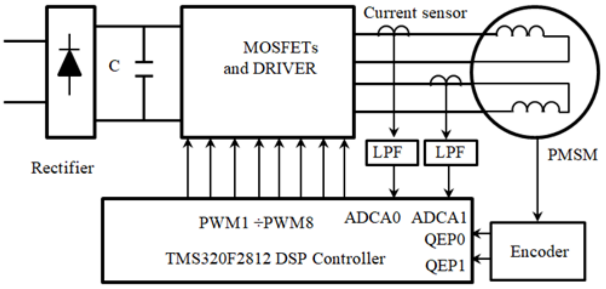

Fig.7. DSP based Bipolar PMSM driving system (LFP- Low Pass Filter)

In figure 5, we supply the one phase AC votage with frequency of 50 Hz to the rectifier with four diodes. The output DC votage of the rectifier is filtrated by filter capacitor, then it is supplied to two phase inverter. The two phase inverter has two H-Bridge circuits. Each H-Bridge circuit has four MOSFETs and is connected to one phase coil of the Bipolar PMSM. The eight PWM ouputs (from PWM1 to PWM8) of DSP TMS320F2812 supply eight MOSFETs of two H-Bridge circuits with pulses through the driver circuit. The Encoder is used to measure the angle speed of the motor's rotor. Two outputs of the encoder are connected to specifically applied inputs of QEP0 and QEP1of DSP TMS320F2812. The DSP TMS320F2812 kit is connected to personal computer.

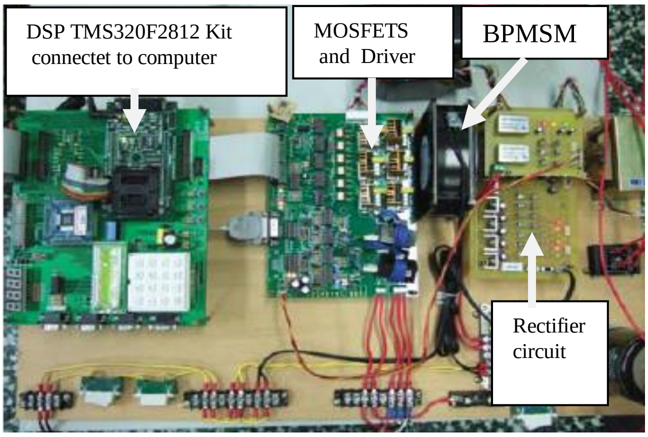

Fig. 8. The DSP based experimental system for Bipolar PMSM drive

B. Results of experiments

The desired reference trajectory of the rotor angle is depicted in figure 9. In figure 9, the position trajectory of rotor angle is commanded to track the linear line in the forward directon to 300 in the time of 0.75s, then the motor stops at this position. After that, at the time of 0.25s, the motor changes the direction and rotates according to the linear line in the reverse direction to the original position and stops at this position.

The real trajectory of the rotor angle is shown in fig.10, and the position error is shown in figure 11.

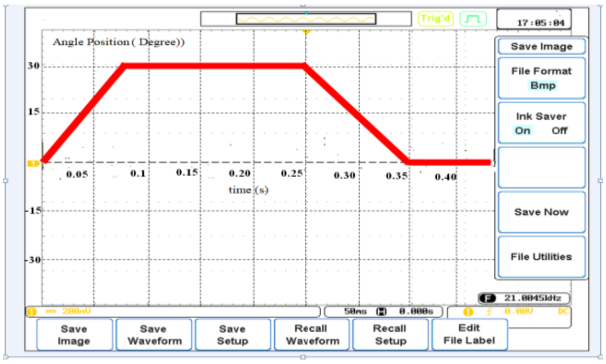

Fig. 9. The desired reference trajectory of the rotor angle

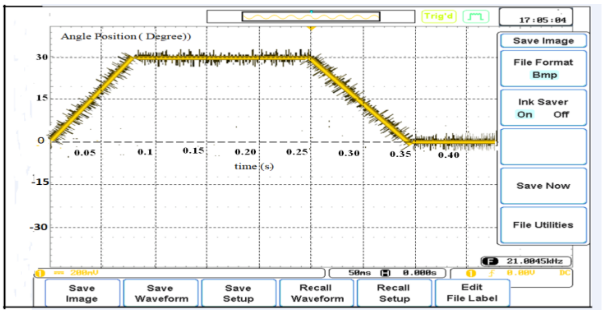

Fig.10. The real trajectory of the rotor angle

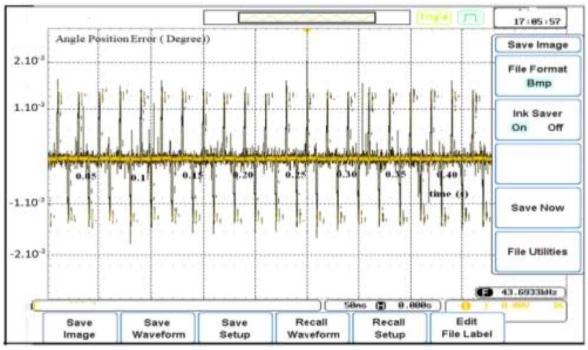

Fig.11. The position error

The results of experiments show that, the position control system of Bipolar Permanent Magnet Stepper Motors based on the Adaptive Nonlinear Backstepping technique combining with Fuzzy Logic makes the real trajectory of rotor angle to reach the desired reference trajectory with the quite small error of position, it is about 0.0015^0. This error is much smaller than the error of open loop system (it is about 0.5^0).

VI. CONCLUSIONS

This paper presents the design of the closed loop position control system of Bipolar Permanent Magnet Stepper Motors based on the Adaptive Nonlinear Backstepping technique combining with Fuzzy and experiments of the proposed position control system, which is based on DSP TMS320F2812. The experiments are implemented with different speeds and different direction. The experimental results show that, the performance of the proposed closed position control system is quite good, the position error of the proposed position contrl system is qiute small comparing with the open loop position control system.

In conclusion, the quality of the closed loop position control system of Bipolar Permanent Magnet Stepper Motors based on the Adaptive Nonlinear Backstepping technique combining with Fuzzy meets the requirements of position control of CNC machines in industry.

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