Design of Fuzzy-Like Position Controller for Permanent Magnet Stepper Motor

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Abstract – Permanent Magnet Stepper Motor (PMSM) is defined as a high nonlinear dynamics, MIMO electromechanical incremental actuator broadly applied as a position device. The closed loop control system is proposed to enhance the performance of PMSM from the load change, steady state error, and the parameters variation that appear in the open loop control. The proposed closed loop system is based on the Field Oriented Control (FOC). Fuzzy PID controller is proposed as an intelligent controller for the exact linearized system. The Feedback Linearization (FBL) technique is based on transforming the complex nonlinear model of PMSM into exact linearized model, unlike the Jacobian Linearization, which is based on linearizing the dynamics of the motor around operating point. The results of the proposed controller were compared with conventional PID on the exact linearized model and Fuzzy PID Controller on the nonlinear model of the PMSM. Robustness of the proposed controller was tested under parameters and load variation.

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Keywords – Stepper Motor, Feedback Linearization, Fuzzy PID Controller

1. Introduction:

The stepper motor is a brushless, synchronous motor, which is designed to rotate through a specific angle for each electrical pulse received from the driver unit. Stepper motors are low in cost because of their high volume use in industry. The stepper motor is a permanent magnet motor with many poles. They can produce high torque at a given motor winding currents. This makes the stepper motor ideal for precise motion control [1].

Three main types of Stepper Motor are:

1- Permanent Magnet Stepper Motor (PMSM).

2- Variable Reluctance Stepper Motor (VRSM).

3- Hybrid Stepper Motor (HSM).

Originally, stepper motors were designed to provide precise positioning control within an integer number of steps (e.g., 200 steps for a resolution of 1.8^o) without using sensors (open loop). That is, they are open-loop stable to any step position, and consequently no feedback is needed to control them.Stepper motor, due to their positional accuracies and fast response, is now finding applications in computer peripherals, process control, machine tools, robotics, medical application, and various surveillance systems. Especially in robotics and process control like silicon processing, Integrated Circuit Bonding and laser trimming applications [2].

The PMSM is normally operated in open loop with stable step response, but suffered from the low performance because of high overshoot (up to 0.5^o) and long settling time which may even lead to oscillatory response and loss of synchronism [3], as shown in Fig. 1.

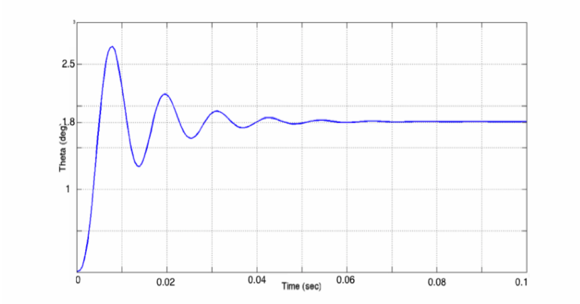

Figure 1. Open loop response for single step of PMSM

Hence, close loop control of stepper motor becomes essential to use the PMSM in the above applications duo to its ability to deal with the parameters uncertainties, disturbances on the system, and load torque variation on the motor.

The difficulty of applying the closed loop control on the PMSM shown in Fig. 2, is by dealing with the complex high nonlinear Multi inputs – Multi outputs (MIMO) model of the PMSM which requires an accurate sensors to feed the motor status to the controller, which needs a complex calculations to govern the PMSM toward the desired position or velocity trajectory with high performance response.

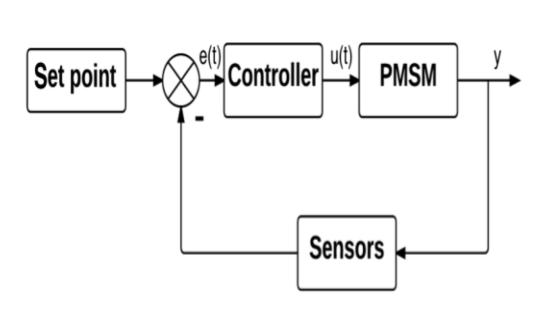

Figure 2. Closed loop control of PMSM

Two main approaches will be used to deal and control the motor model, they are:

- The MIMO nonlinear model of the PMSM.
- Exact Feedback Linearization of the PMSM.

2. Feedback Linearization for PMSM

Feedback Linearization (FBL) is an approach to nonlinear design, which has attracted a great deal of research interest in recent years. The basic idea of this approach is to transform the nonlinear dynamics algebraically into full or partly linear one, so the linear control technique can be applied on the new system. This approach is differing entirely from the approximate linearization (i.e. Jacobain linearization), that the FBL is achieved by transformation and feedback rather than some approximation on the system dynamics as shown in Fig. 3.By using a transformation method called: "Park Transformation" or "dq – Transformation" [1], [4].

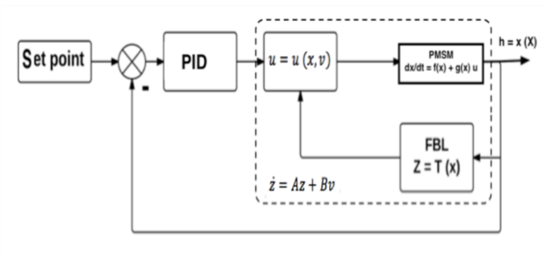

Figure 3. FBL for PMSM.

This method consists of choosing:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta) & \sin(N_r\theta) \\ -\sin(N_r\theta) & \cos(N_r\theta) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \qquad (1)$$

Where

i_d is the direct current correspond of the stator magnetic field along the axis of the rotor magnetic field.

i_q is the quadrature current corresponding to the orthogonal component.

Therefore, T matrix can be re-written in form of dq transformation as follows:

$$\begin{bmatrix} i_d \\ i_q \\ w \\ \theta \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta) & \sin(N_r\theta) & 0 & 0 \\ -\sin(N_r\theta) & \cos(N_r\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ w \\ \theta \end{bmatrix} \qquad (2)$$

By applying the above matrix on the PMSM model in (5) [4]:

$$\frac{di_a}{dt} = \frac{1}{L}\left[V_a - Ri_a + N_r K_m \frac{d\theta}{dt} \sin(N_r\theta)\right]$$

$$\frac{di_b}{dt} = \frac{1}{L}\left[V_b - Ri_b - N_r K_m \frac{d\theta}{dt} \cos(N_r\theta)\right]$$

$$\frac{d\omega}{dt} = \frac{1}{j}\left(-N_r K_m [i_a \sin(N_r\theta) - i_b \cos(N_r\theta)] - B_m\omega - T_L\right)$$

$$\frac{d\theta}{dt} = \omega \qquad (5)$$

yields:

$$\begin{bmatrix} \dot{i_d} \\ \dot{i_q} \\ \dot{w} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} (v_d - Ri_d + N_r L\omega i_q)/L \\ (v_q - Ri_q - N_r L\omega i_d - k_m\omega)/L \\ k_m i_q - B\omega/J \\ \omega \end{bmatrix} \qquad (6)$$

Where

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta) & \sin(N_r\theta) \\ -\sin(N_r\theta) & \cos(N_r\theta) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \end{bmatrix} \qquad (7)$$

v_d is the direct voltage.

v_q is the quadrature voltage.

The quadrature component i_q of the current produces torque, while the direct component i_d current doesn't produce any torque. However in order to attend a high speeds, it is necessary to apply a negative direct current to cancel effect of the back emf of the motor. Specially, note from the second row of (6) the term of $k_m\omega$.

By selecting a suitable v_d, v_q to cancel the nonlinear part as:

$$v_d = Ri_d - N_r L\omega i_q + Lu_d \qquad (8)$$

$$v_q = Ri_q + N_r L\omega i_d + k_m\omega + Lu_q \qquad (9)$$

The system becomes:

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{w} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} u_d \\ u_q \\ \frac{k_m}{J} i_q - B\omega / J \\ \omega \end{bmatrix} \quad (10)$$

Which represents a linear system that allows applying any linear or nonlinear controller on the control signals (u_d, u_q).

4. Fuzzy Logic Controller

Fuzzy control is based on the fuzzy logic, a logical system that is much closer in spirit to human thinking and natural language then traditional logical systems. The Fuzzy Logic Controller (FLC) based on fuzzy logic provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy [5] as shown in Figure 4.

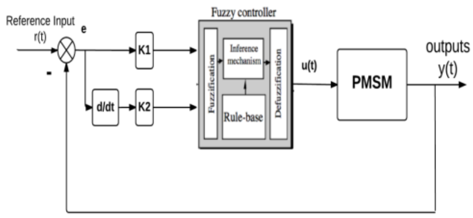

Figure 4. Fuzzy logic controller.

The Fuzzy PID controller is capable to reduce the steady-state error zero as well as maintaining the transient and stability requirements. Also, it is capable of producing nonlinear gains. Therefore, the undesirable effects of the integral and derivative being in constant proportion can be removed, since their effect changes with the output voltage and error signal. Figure 5 shows the Simulink model of the Fuzzy PID controller which has two inputs and one rule base. The inputs are the classical error (e) and the rate of the change of error (è).

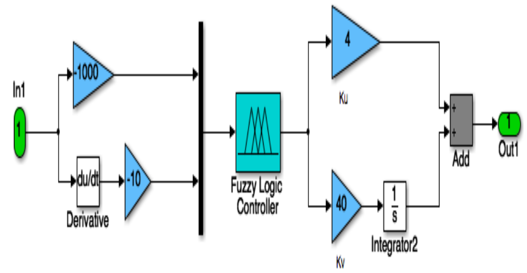

Figure 5. Fuzzy PID controller.

The rules govern the controller behavior use the AND operations as minimum. For the seven memberships in each input, the maximum generated rules are (49). Table1. Shows the rules used in the proposed FLC.

Table1. FLC rules.

è\ e	NA	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NVS	Z
NM	NB	NB	NM	NS	NVS	Z	PVS
NS	NB	NM	NS	NVS	Z	PVS	PS
Z	NM	NS	NVS	Z	PVS	PS	PM
PS	NS	NVS	Z	PVS	PS	PM	PB
PM	NVS	Z	PVS	PS	PM	PB	PB
PB	Z	PVS	PS	PM	PB	PB	PB

4. Simulation Results:

By using a nominal parameters listed in Table 2. For the PMSM model shown in (5). The overall positioning system of the Fuzzy PID controller for PMSM is shown in Figure 6.

Table 2.PMSM Nominal Parameters [31].

Parameter	Value	Units
R	30	Ω
L	32	mH
k_m	0.5	Nm/A
B_m	0.002	Nm/rad/sec
N_r	50	-
j	$5.4 * 10^{-5}$	kgm^2
T_L	2.6	kg/cm

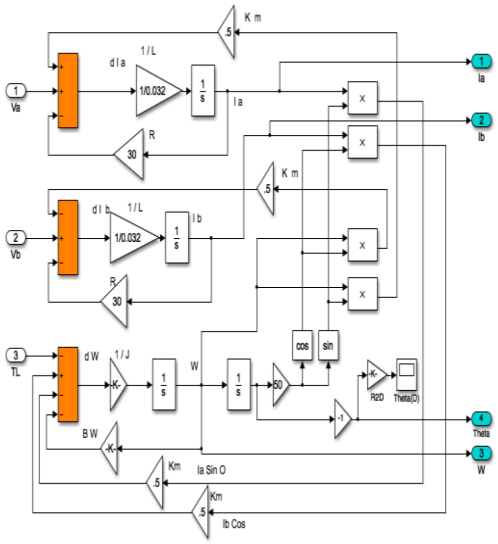

Figure 6a. PMSM Simulink model.

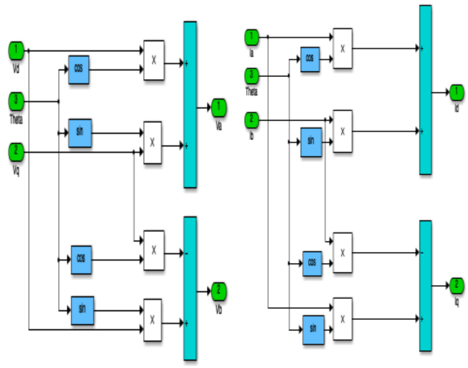

Figure 6b. Park transformation and inverse park transformation of PMSM.

The trajectory to the system is shown in Figure 7, while Figures 8 - 12 represent the PMSM response for the single steps trajectory.

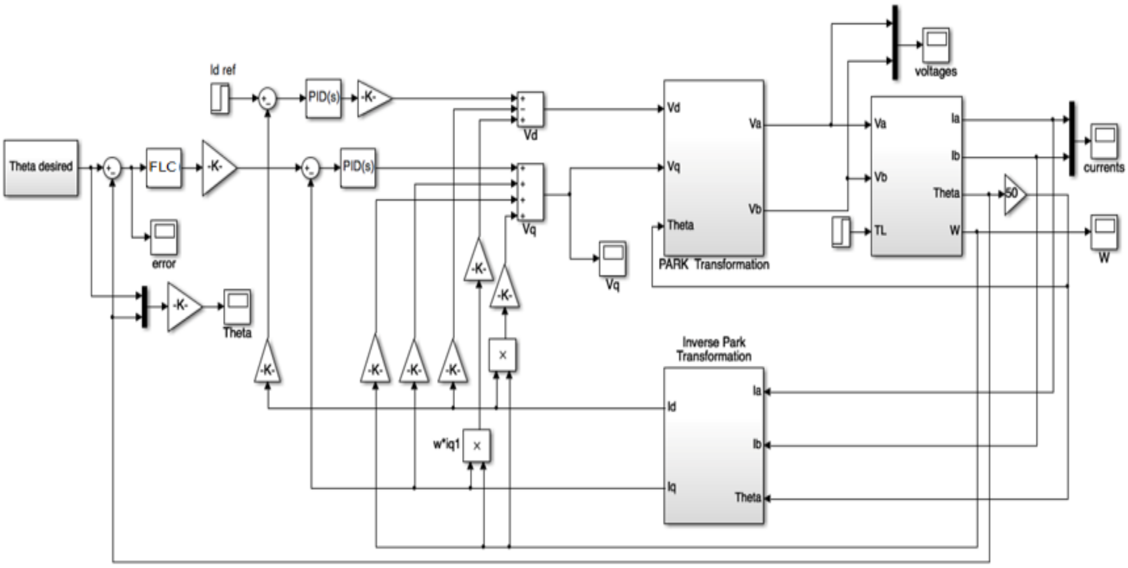

Figure 6 Fuzzy PID controller for PMSM

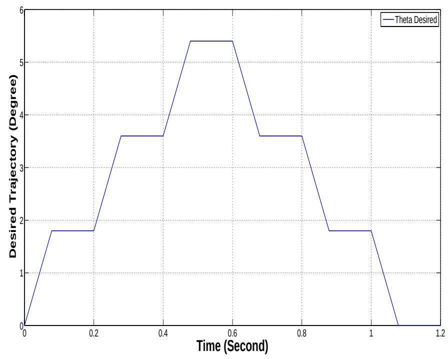

Figure. 7 Desired single steps trajectory for PMSM.

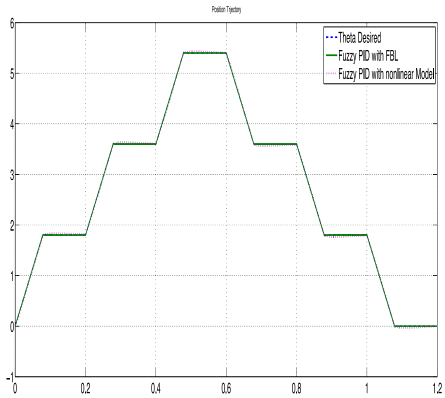

Figure 8. Angular Position for Fuzzy PID controller with FBL and with nonlinear model of PMSM

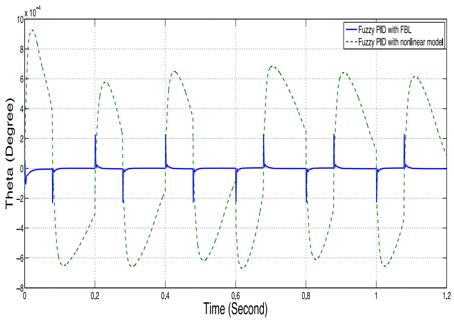

Figure 9. Position error of PMSM.

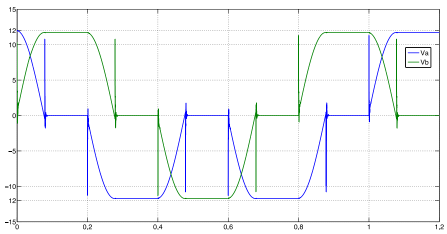

Figure 10. Input voltages for the winding of PMSM.

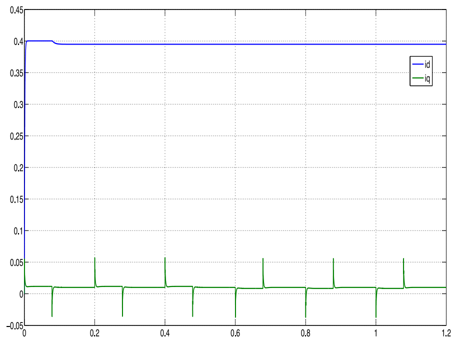

Figure 11. Direct and quadrature currents for PMSM.

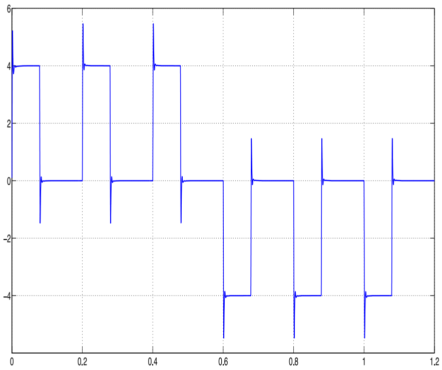

Figure 12. Angular velocity of PMSM.

In real implementation the PMSM parameters may suffer from small variation around the nominal value, therefore the proposed controller was tested under parameter variation in the motor constant (k_m) by from its nominal value. Figures 13 - 15 show the response toward this variation.

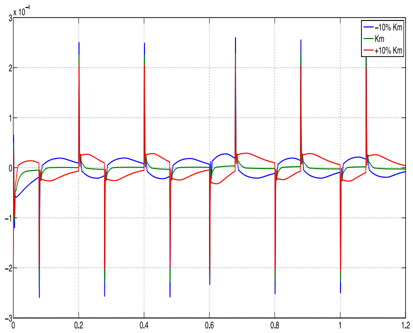

Figure 13. Position error (rad) due to parameter variation in the motor constant.

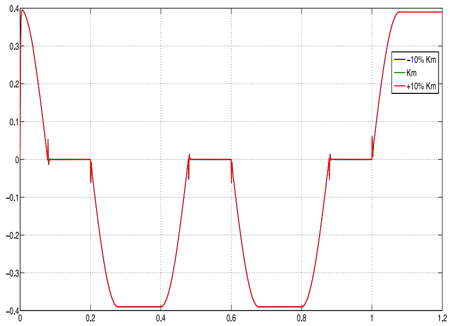

Figure 14. Winding current due to parameter variation in the motor constant.

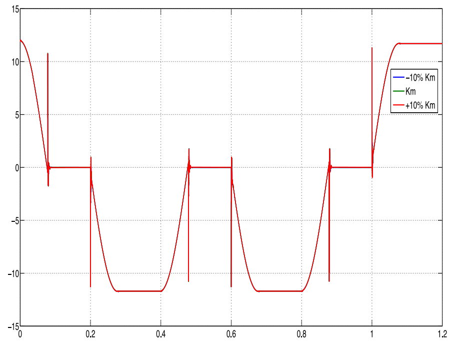

Figure 15. Stator winding voltage due to parameter variation in the motor constant.

5. Conclusion:

The Fuzzy Logic controller as a nonlinear and intelligent controller can perform a better performance using the FBL as a platform(position error = 1 $*10^{-5}$ degree, and maximum overshoot = 0.015^{0})than the other proposed controllers in position control (position error = 7 $*10^{-4}$ rad, and maximum overshoot = 0.04^{0} in Fuzzy PID controller on the nonlinear model), because the FBL by transforming the nonlinear model to linear one, so there is no need to deal with the model nonlinearities and focused the controller effort on the tracking problem and overcome the parameters variations to make the PMSM less effect, which is proved that the FBL has the ability to work as a platform for applying the linear and nonlinear control techniques on nonlinear MIMO systems.

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