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Design Of Internal Model Control Tuned PI Compensator for Two-Phase Hybrid Stepper Motor

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Abstract- This paper has presented design of Internal Model Control Tuned Proportional Integral (IMCT-PI) compensator for Two-Phase Hybrid Stepper Motor (TPHSM). The objective is to design a positioning control system for high-speed performance of TPHSM so as to meet performance criteria of Overshoot ≤ 5%, settling time < 0.16s, and rise time < 0.02 with 2% criterion. The transfer function that represents a TPHSM was obtained. Internal Model Control Tuning of Control and Estimation Tool Manager (CETM) of MATLAB was used to design a PI compensator. Simulation results indicated that the addition of IMCT-PI improved the transient response of the TPHSM while providing rise time of 0.002s, settling time of 0.02s, time to peak of 0.006s and overshoot of 5%.

Indexed Terms- Internal Model Control, Proportional Integral, Positioning control, TPHSM

I. INTRODUCTION

Stepper motors are a kind of electromechanical machines that are capable of transforming electric impulses in discrete time form, usually of square wave pulses, into linear or angular displacement [1]. As special type of synchronous motors, they are designed to rotate through fixed angle called a step for every electrical pulse received from control unit [2]. Stepper motors are commonly employed in control loop and measurement applications due to the advantage of easy open loop control and no error accumulation that they provide [1, 3]. They are ideal choice in applications with small power (less than 100 W), while ensuring fast and efficient positioning control such as in robotics, machine tools, servo, aerospace applications, printers, scanners [4].

The use of stepper motors comes with a lot of benefits because of small inertia, large output torque, and high frequency response they offer [1]. These characteristics have enabled their extensive usage in industry recently, especially in control applications and measurement [5]. Aside from the advantages earlier mentioned, there are other benefits offered by stepper motors such as compatibility with digital system and no feedback sensor requirement for position and speed sensing [2, 6] and these have made their application valuable in control systems. Despite the benefits provided by stepper motors, there are certain disadvantages associated with them such as: long settling time and overshoot for a given step response [1].

There are different types of stepper motors. One of which is the hybrid stepper motor (HSM). This type of stepper motor has permanent magnet and several teeth both on the rotor and the stator poles. An example of HSM is the two-phase hybrid stepper motor (TPHSM). These motors are usually used in industry because this guarantees that the power electronic circuits are relatively simple because of higher efficiencies over the variable reluctance permanent magnet stepper motors.

In this paper, the objective is to design linear quadratic tuned compensator control loop structure that will improve the performance response of a two-phase hybrid stepper motor. The system is expected to meet the following performance criteria. Overshoot ≤ 5%, settling time < 0.16s, and rise time < 0.02 with 2% criterion.

II. EMPIRICAL REVIEW

Several techniques have been proposed to enhance the step response performance of two-phase hybrid stepper motor based expected time domain characteristics: rise time, settling time, and overshoot. For instance, a fuzzy-proportional integral and derivative (Fuzzy-PID) algorithm for variable speed control of TPHSM in robotic grinding was implemented by Attiya et al. [1]. The study aimed to improve the speed control response performance of TPHSM, while considering six motor speed input conditions. Salis et al [7] examined learning position controls for hybrid step motors, from current fed to full order models. Experimental investigation of both adaptive and repetitive learning position control in literature for voltage-fed hybrid step motors was conducted. A stepper motor position control system based on digital signal processor (DSP) was designed by Liu and Li [8]. Incremental PID controller was considered. Experimental and simulation comparison of open-loop control and closed-loop with PID was carried out. With the PID closed-loop control, the response indicated that effective improvement of the precision and dynamic performance of the stepper motor can be realized. Emotional controller for position control of hybrid stepper motor derive called Brain Emotional Learning Based Intelligent Controller (BELBIC) was presented by Khalilian et al [9]. Direct torque control technique was adopted. Simulations were carried out to determine the effectiveness of the controller and the results obtained showed fast response, no overshoot and zero steady-state error. A bang-bang control technique was presented by [10] for two-phase hybrid stepper motor. Current tracking was conducted and the current was constantly kept within sustained limit in phase and desired speed obtained. Though, the control technique has fast switching limitation. Two-phase hybrid stepper motor control using Fuzzy-PID is presented by Zhang and Wang [6]. A comparison of the Fuzzy-PID with conventional PID showed that the former provided better performance than the later.

Remarkably, stepper motors have multiple "toothed" electromagnets arranged around a central gear-shaped piece of iron [1]. The general stepping motor main parts and a cross-section of two-phase hybrid motor are shown in Figures 1 and 2.

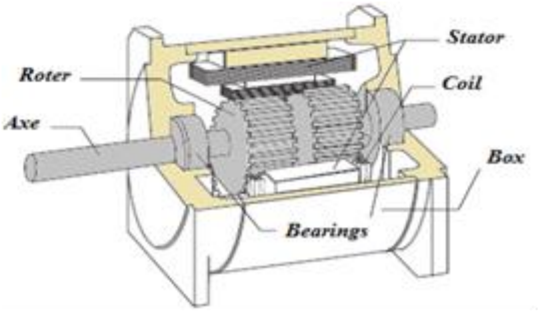


Figure 1 Main parts of stepper motor [11]

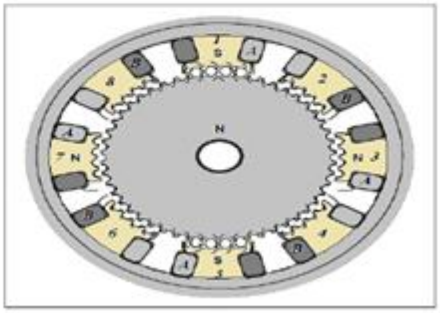


Figure 2 Cross-section of TPHSM [12]

III. MATHEMATICAL MODELING AND SYSTEM DESIGN

A. Dynamic Model

A typical TPHSM comprises shaft mechanical dynamics and electrical dynamics of the stator coils [1, 10]. The mathematical equations of the mechanical and electrical components of the motor are given:
Mechanical equations are [10]:

$$\frac{dI_a}{dt} = \frac{\left[-KmI_a\sin\left(N\theta\right) + K_mI_a\cos\left(N\theta\right) - B\omega - T_L - K_d\sin\left(4N\theta\right)\right]}{J}$$

……. (1)

$$\frac{d\theta}{dt} = \omega \tag{2}$$

$$\frac{dI_a}{dt} = \frac{\left[V_a - RI_a + K_m\omega\sin(N\theta)\right]}{L} \tag{3}$$

$$\frac{dI_b}{dt} = \frac{\left[V_b - RI_b + K_m\omega\cos(N\theta)\right]}{L} \tag{4}$$

where I_a and I_b are the currents in phases A and B respectively in ampere (A). V_a and V_b are the voltages in phases A and Bin volt (V) respectively. ω is the rotor speed (rads^{-1}), θ is rotor position (rad), R is the resistance of the phase winding in (Ω), L is the self-inductance constant (Nm/A), B is the viscous friction constant (Nms^2/rad), J is the rotor inertia (kgm^2), T_L is the load torque (N/m).

A model of two-phase hybrid stepping motor is shown in Figure 3. The open loop transfer function of G(s) of two-phase hybrid stepping motor is given by [1, 6, and 13].

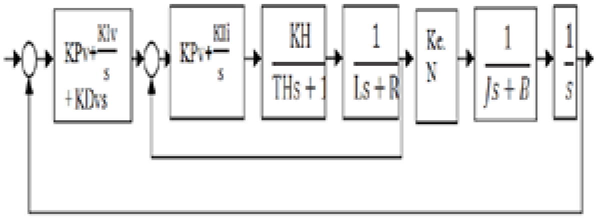


Fig.3 Model of two-phase hybrid stepping motor [1]

The values of the parameters of selected stepping motor for MATLAB simulation are presented in Table 1.

Table 1 –Simulation parameters [12]

Parameter	Value	Unit
L	4.0	mH
R	1.2	Ω
J	260	kgm^2
B	0	Nmsrad^{-1}
β	1	-
K_{Dv}	100	-
K_e	0.2	NmA^{-1}
N	180	-
K_{iv}	0	-
K_H	15	-
K_{li}	500	-
K_{pi}	5	-
K_{pv}	500	-

The open-loop transfer function of two-phase hybrid stepping motor considered in this paper given by [6]:

$$G(s) = \frac{2700000(s+5)(s+100)}{s^4 + 19799s^3 + 650000s^2 + 7500s} \tag{5}$$

B. Compensator Design and System Configuration

The approach to designing the compensator is based on Internal Model Control (IMC) tuning using the single input single output (SISO) graphical User Interface (GUI) design task of the Control and Estimation Tools Manager (CETM) of MATLAB. The designed compensator is given by:

$$C(s) = 0.074074\,\frac{(86s+1)}{s} \tag{6}$$

The developed compensator is a Proportional Integral (PI) controller such that the proportional gain $k_p = 6.4$, and the integral gain $k_i = 0.074074$. The dynamics of the compensator are shown in Fig. 4.

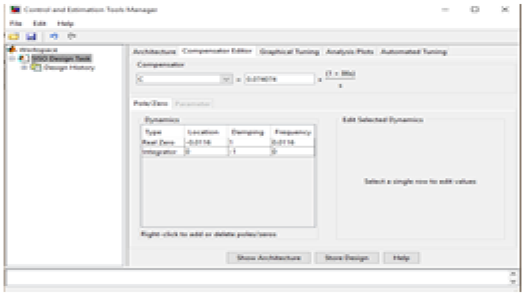


Fig. 4 Designed compensator dynamics

The structure of the designed TPHSM control system is a SISO arrangement shown in Fig. 5.

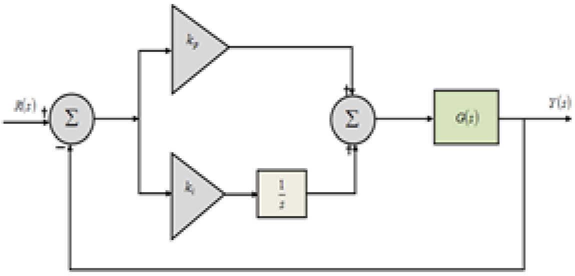


Fig. 5 System configuration

IV. RESULT S AND DISCUSION

The results obtained from the simulation of the designed control system in MATLAB are presented in this section. Figure 6 shows the step response plots of the closed loop system when the designed compensator has not been introduced. The response of the system with the addition of the Internal Model Control Tuned Proportional Integral (IMCT-PI) compensator is shown in Fig. 7. The performance comparison plot of the uncompensated and compensated systems is shown in Fig. 8. The Bode stability plot of the system is shown in Fig. 9. Table 2 shows the numerical analysis of the response of the system to unit forcing step input for uncompensated and compensated conditions

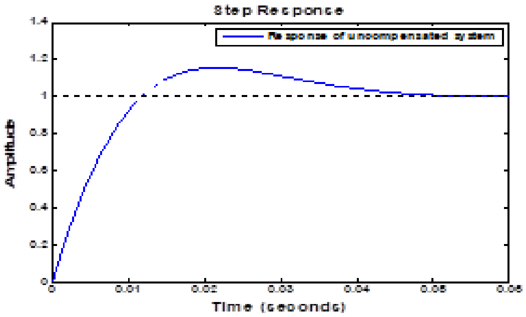


Fig. 6 Step response of system (uncompensated)

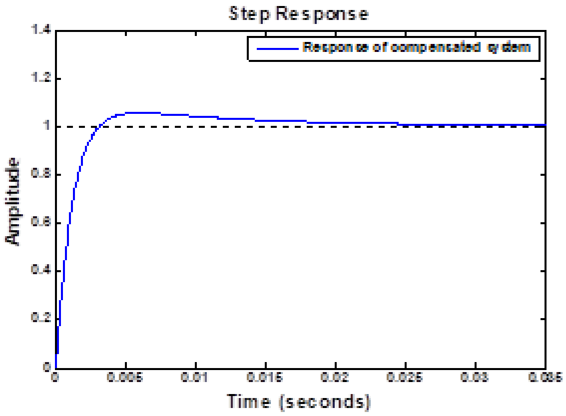


Fig. 7 Step response of system (compensated)

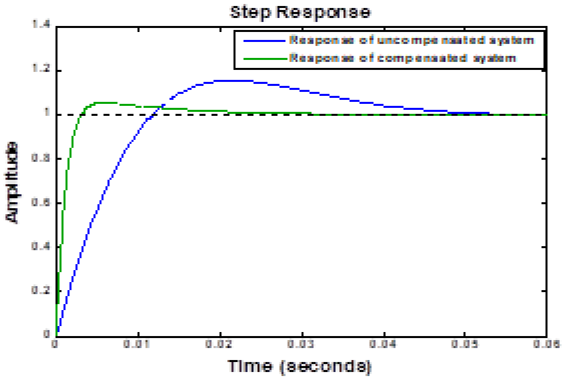
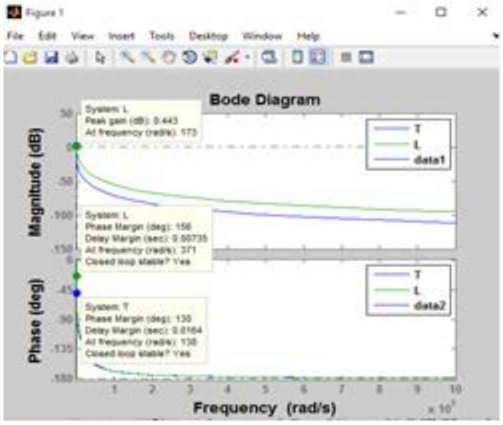


Fig. 8 Performance comparison



System: L
Peak gain (dB): 0.443
At frequency (rad/s): 173

System: L
Phase Margin (deg): 156
Delay Margin (sec): 0.00735
At frequency (rad/s): 371
Closed loop stable? Yes

System: T
Phase Margin (deg): 130
Delay Margin (sec): 0.0164
At frequency (rad/s): 138
Closed loop stable? Yes

Fig. 9 Stability plot (Bode diagram)

Table 2 Time domain performance comparison

Parameter	Uncompensated (T)	Compensated (L)
Rise time (s)	0.009	0.002
Settling time (s)	0.051	0.02
Time to peak (s)	0.02	0.006
Overshoot (%)	15.0	5.0

The response performances of the system in uncompensated and compensated cases to unit step forcing input are presented in Table 2 in terms of time domain parameters: rise time, settling time, peak time and percentage overshoot. It can be seen that the response of the system in was largely enhanced by the addition of IMCT-PI compensator more especially the overshoot.

CONCLUSION

This paper has presented a new control technique to improve the positioning performance of Two-Phase Hybrid Stepper Motor (TPHSM). The developed IMCT-PI compensator provided improved the transient response performance of the TPHSM in terms of rise time, settling time, peak time and overshoot. Hence, using the IMCT-PI compensator will result to faster speed of operation.

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