



Improved Response Performance of Two-Phase Hybrid Stepping Motor Control Using PID Tuned Outer and Inner Loop Compensators

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Abstract. This paper has presented improved response performance of two-phase hybrid stepping motor control using proportional integral and derivative (PID) tuned outer and inner loop compensators. It is desired to improve the response performance tracking of a two-phase hybrid stepper motor to achieved overshoot less than 5 %, settling time less than 0.16 s, and rise time less than 0.02 with 2 % criterion. To achieve the objective of the study, a dynamic model of a two-phase hybrid stepper motor was obtained in the form of a transfer function. A robust PID tuning technique was adopted using the single input single output (SISO) Graphic User Interface (GUI) of the design task of the Control and Estimation Tool Manager (CETM) of MATLAB software in designing the compensators. A single compensator was designed and added to control loop of a two-phase hybrid stepping motor to improve the response performance. Simulation was performed in MATLAB and an overshoot of 8 % with the single loop compensator. However, the overshoot of the system requires further improvement. A new control loop was proposed using two-compensator loop structure. The outer loop and inner loop compensators were designed and added to the two-phase hybrid stepper motor control. Simulation was performed in MATLAB and the result obtained showed that with the two-compensator loop structure, the overshoot was greatly reduced to 2.6 % with rise time of 12 ms and settling time 11 ms. This indicates that the response tracking performance of the system has been improved by the combined outer and inner loop compensators.

Keywords: compensator, control loop, graphic user interface, proportional integral and derivative, PID tuning.

1 Introduction

Stepper motors are a kind of electromagnetic mechanical devices that can transform discrete electric impulses, typically of square wave pulses, into linear or angular displacement [1]. They are special type of synchronous motors designed to rotate through fixed angle called a step for each electrical pulse received from control unit [2]. They are usually employed in control and measurement applications because of the advantage of easy open loop control and no error accumulation which they offer [1, 3]. Stepping motors are perfect choice for applications with small power (less than 100 W) while maintaining fast and efficient positioning control such as in robotics, machine tools, servos, aerospace applications, printers, and scanners [1, 4].

There are various advantages offer by stepper motors such as small inertia, great output torque, and high frequency response [1]. These characteristics have made the

use of stepping motors to be wide in the industry currently, especially in control applications and measurement [1, 5]. Apart from the benefits mentioned above, such advantages like compatibility with digital system and no feedback sensor requirement for position and speed sensing [2, 6] have made their use worthwhile in control systems engineering. However, some drawbacks of stepping motor are its relatively long settling time and overshoot for a given step response [1]. There are different types of stepping motors. One of them is the hybrid stepping motor.

A stepping motor that contains the permanent magnet rotor and many teeth both on the rotor and stator poles is called the hybrid stepping motor. Two-phase hybrid stepper motor is stepper motor that contains the permanent magnet rotor and many teeth both on the rotor and the stator poles [1]. These devices are most commonly

employed in the industry as ensures that the power electronic circuits are relatively simple because of higher efficiencies over the variable reluctance permanent magnet stepping motors.

In this paper, the objective is to develop PID tuned two-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 is less than 5 %, settling time – 0.16 s, and rise time – 0.02 with 2 % criterion.

2 Literature Review

Attiya et al [1] designed a fuzzy-proportional integral and derivative (PID) controller for variable speed control of two-phase stepping motor in robotic grinding. It aimed to improve the speed control performance of two-phase hybrid stepping motor. Six motor speed input conditions were considered for simulations. Simulations were conducted in MATLAB. Salis et al [12] studied learning position controls for hybrid step motors, from current fed to full order models. Experimental study of both adaptive and repetitive learning position control presented in literature for voltage-fed hybrid step motors was carried out. Liu and Li [13] designed a stepper motor position control system based on digital signal processor (DSP). An incremental PID control algorithm was designed. Experimental and simulation comparison of open-loop control and closed-loop with PID effect was conducted. With the PID closed-loop control, the results indicated that effective improvement of the precision and dynamic performance of the stepper motor can be realized. An emotional controller for position control of hybrid stepper motor derives called Brain Emotional Learning Based Intelligent Controller (BELBIC) was proposed by Khalilian et al [14]. It adopted direct torque control technique. Simulations were conducted to ascertain the effectiveness of the controller and the results obtained indicated fast response, no overshoot and zero steady-state error. A bang-bang control strategy was proposed in [9] for two-phase hybrid stepper motor. Current tracking was performed and the current was continuously maintained within sustained limit in phase and desired speed obtained. However, 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 indicated that the former yielded better performance than the later.

Impressively, stepper motors have multiple “toothed” electromagnets arranged around a central gear-shaped piece of iron [1]. Figures 1 and 2 show the general stepping motor main parts and a cross-section of two-phase hybrid motor.

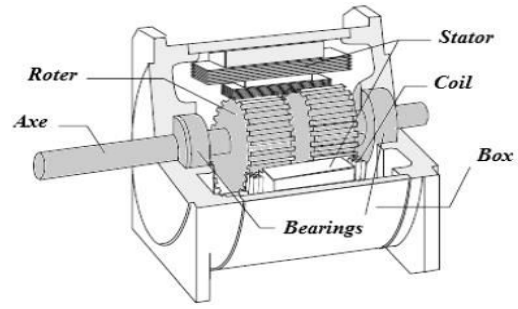


Figure 1 – General stepping motor with its main parts[1, 7]

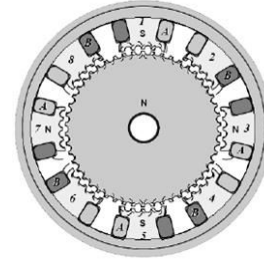


Figure 2 – Cross-section of two-phase hybrid stepping motor [1, 8]

3 Research Methodology

3.1 Mathematical modelling

3.1.1 General equations

Only A typical model of a two-phase hybrid stepping motor consists of the shaft mechanical dynamics together with the electrical dynamics of the stator coils [1, 9]. The electrical response is faster than the mechanical response [1, 9, 10] which makes it possible to consider the mathematical dynamics only [9], the model consists of electrical and mechanical equations [9]. The electrical dynamics are given by [9]:

$$\frac{dI_a}{dt} = \frac{1}{L} (V_a - RI_a + K_m \omega \sin N\theta); \quad (1)$$

$$\frac{dI_b}{dt} = \frac{1}{L} (V_b - RI_b + K_m \omega \cos N\theta). \quad (2)$$

Mechanical equations are [9]:

$$dI_a/dt = (K_m I_a \cos N\theta - K_m I_b \sin N\theta - B\omega - T_L - K_m \sin 4N\theta); \quad (3)$$

$$\frac{d\theta}{dt} = \omega \quad (4)$$

where I_a and I_b are the currents in phases A and B respectively, V_a and V_b are the voltages in phases A and B respectively, V ; ω is the rotor speed, rad/s; θ is rotor position, rad; R is the resistance of the phase winding Ω ; L is the self-inductance constant, H; B is the viscous friction constant (N·m·s/rad); J is the rotor inertia, kg·m²; T_L is the load torque, N·m.

3.1.2 Transfer function model

Figure 3 shows the model of a two-phase hybrid stepping motor [1]. The open loop transfer function of $G(s)$ of two-phase hybrid stepping motor is given by [1, 6, 11].

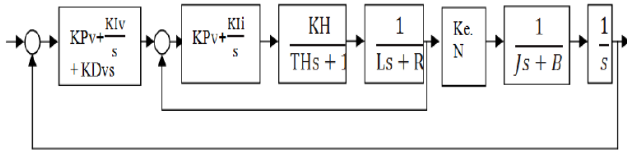


Figure 3 – Model of two-phase hybrid stepping motor [1]

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

Table 1 –Simulation parameters [8]

Parameter	Value	Unit
L	4.0	mH
R	1.2	Ω
J	260	kg·m ²
B	0	N·m·s/rad
β	1	–
K_{Dv}	100	–
K_e	0.2	N·m/A
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]:

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

3.1.3 State space model

The transfer function of a two-phase hybrid stepping motor presented in equation (5) is transformed into a state space model as follows:

$$\frac{Y(s)}{U(s)} = \frac{2.7 \cdot 10^6 (s+5)(s+100)}{s^4 + 19799s^3 + 6.5 \cdot 10^5 s^2 + 7500s}; \quad (6)$$

$$\frac{X(s)}{U(s)} \cdot \frac{Y(s)}{X(s)} = \frac{2.7 \cdot 10^6 (s+5)(s+100)}{s^4 + 19799s^3 + 6.5 \cdot 10^5 s^2 + 7500s}; \quad (7)$$

$$\frac{X(s)}{U(s)} = \frac{2.7 \cdot 10^6}{s^4 + 19799s^3 + 6.5 \cdot 10^5 s^2 + 7500s}; \quad (8)$$

$$X(s) \cdot [s^4 + 19799s^3 + 6.5 \cdot 10^5 s^2 + 7500s] = 2.7 \cdot 10^6 U(s). \quad (9)$$

Assuming zero initial conditions:

$$s^4 X(s) + 19799s^3 X(s) + 6.5 \cdot 10^5 s^2 X(s) + 7500s X(s) = 2.7 \cdot 10^6 U(s). \quad (10)$$

The expression in s-domain is converted into time domain as follows:

$$x = x_1; \quad (11)$$

$$\frac{dx_1}{dt} = x_2; \quad (12)$$

$$\frac{dx_2}{dt} = x_3; \quad (13)$$

$$\frac{dx_3}{dt} = x_4; \quad (14)$$

$$\dot{x}_4 = -7500x_2 - 6.5 \cdot 10^5 x_3 - 19799x_4 + 2.7 \cdot 10^6 u(t). \quad (15)$$

Transforming equations (11)–(15) into state space form gives:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -7500 & -6.5 \cdot 10^5 & -19799 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 2.7 \cdot 10^6 \end{bmatrix} u(t); \quad (16)$$

$$\frac{Y(s)}{X(s)} = s^2 + 105s + 500; \quad (17)$$

$$Y(s) = (s^2 + 105s + 500)X(s). \quad (18)$$

Solving equation (18) and transforming it into state space form gives:

$$y = [500 \ 105 \ 1 \ 0] \cdot [x_1 \ x_2 \ x_3 \ x_4]^T. \quad (19)$$

Equations (16) and (19) match the general, linear state space form:

$$\dot{x} = Ax + Bu; \quad (20)$$

$$y = Cx + Du, \quad (21)$$

where $D = 0$ for simulation in this paper.

3.2 System Configuration and Compensator Design

3.2.1 System configuration

Two closed-loop structures of the two-phase hybrid stepper motor control system were considered in this paper as shown in Figures 4 and 5. The structures conform to single-input single-out feedback loop of the MATLAB control tool. The loop has two compensators, two summing points, and a unit feedback gain.

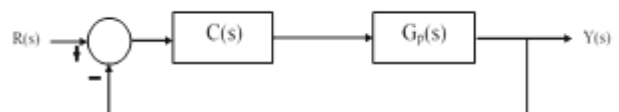


Figure 4 – Initial system configuration

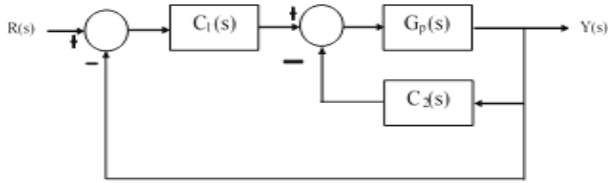


Figure 5 – Final system configuration

3.2.2 Compensator design

In this paper, three compensators were designed using proportional integrating and derivative (PID) tuning method. Automatic (balanced performance and robustness) design mode was adopted. This was achieved using the SISO graphic user interface (GUI) design task of the Control and Estimation Tool Manager (CETM) of MATLAB software. The first compensator, $C(s)$ was designed and added to the control loop and simulation performed as shown in Figure 4. In a bid to further improve the response performance of the plant, two-compensator control technique was developed, with outer loop compensator, $C_1(s)$ and inner loop compensator, $C_2(s)$ as shown in Figure 5. Tables 2–4 show parameters of the developed compensators.

Table 2 – Parameters of compensator, $C(s)$

Type	Location	Damping	Frequency
Real Pole	-175.40	1	175.4
Integrator	0.0	-1	0.0
Real Zero	-83.3	1	83.3

Table 3 – Parameters of compensator, $C_1(s)$

Type	Location	Damping	Frequency
Real Pole	-2.38	1	2.38
Integrator	0.00	-1	0.00
Real Zero	-1.18	1	1.18

Table 4 – Parameters of compensator, $C_2(s)$

Type	Location	Damping	Frequency
Real Pole	-1.00	1	1.00
Real Pole	-5.88	1	5.88
Real Zero	-1.00	1	1.00
Real Zero	-1.00	1	1.00

The gain of the compensator is equal to 0.6, 944.1 and 3.0 for data presented in Tables 2, 3, 4 correspondently.

Hence, the mathematical expressions of the compensators are given by equations (22)–(24). The closed loop control structure for the simulation in MATLAB environment is shown in Figure 5:

$$C(s) = 0.6 \frac{1 + 0.012s}{s(1 + 0.0057s)}; \quad (22)$$

$$C_1(s) = 944.1 \frac{1 + 0.85s}{s(1 + 0.42s)}; \quad (23)$$

$$C_2(s) = 3.0 \frac{(1 + s)(1 + s)}{(1 + s)(1 + 0.17s)}. \quad (24)$$

4 Results

This section presents the simulation results obtained in MATLAB. Figure 6 is simulation results for control loop simulation of the plant (uncompensated). With first feedback compensator added to the forward path of the closed-loop, simulation was conducted and result obtained is shown in Figure 7. Figure 8 is the simulation result of the final proposed closed control system for two-phase hybrid stepping motor with two-compensator control algorithm. Figure 9 is the Bode stability plot of the proposed two-compensator closed loop control. The performance comparison of the system for various simulation cases considered is presented in Table 5.

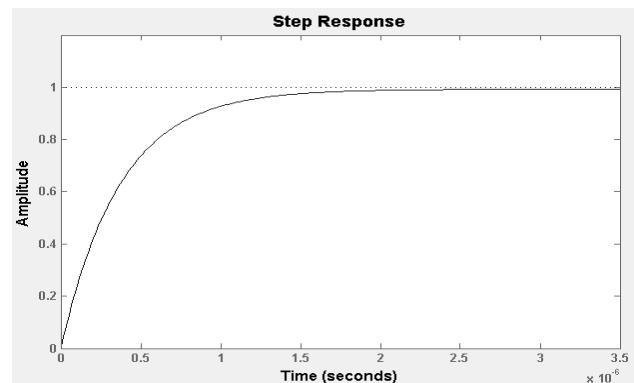


Figure 6 – Step response plot for uncompensated system

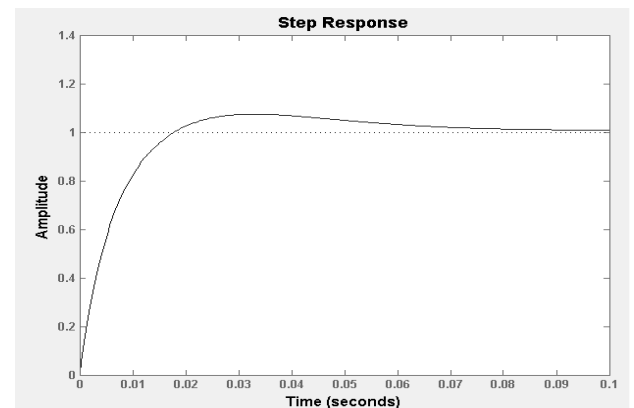


Figure 7 – Closed loop step response with compensator $C(s)$

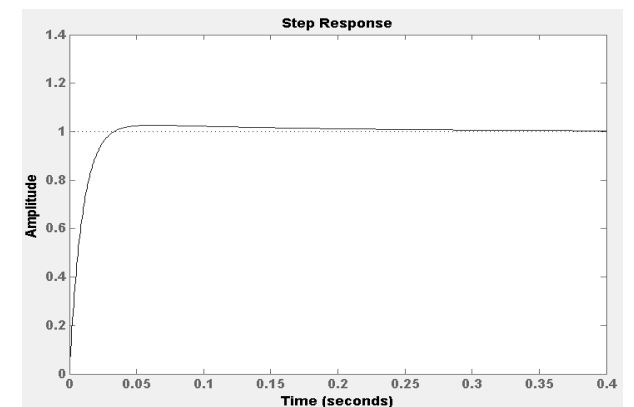


Figure 8 – Closed loop step response with two-compensator

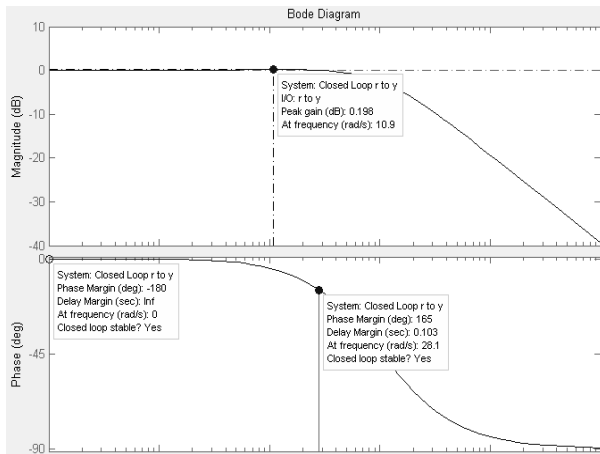


Figure 9 – Bode plot of the final simulation closed-loop system

Table 5 – Characteristics performance comparison

Characteristics	uncompensated	$C(s)$	$C_1(s)$ and $C_2(s)$
Rise time (s)	$8.3 \cdot 10^{-7}$	0.01	0.02
Settling time (s)	$1.6 \cdot 10^{-6}$	0.07	0.11
Overshoot (%)	0.0	8.01	2.56

5 Discussion

The step response performances of the various cases considered are presented in Table 5. It can be seen that the result of the uncompensated two-phase hybrid stepping motor control loop shown in Fig. 6 is quite promising. However, the response performance gives 0 % overshoot and below the setpoint value. This indicates that the

system is sluggish and requires that the response being improved to enhance the setpoint tracking performance. With the first compensator $C_1(s)$ added to the forward path of the closed loop control structure, the step response curve (Figure 7) shows that system characteristics performance is enhanced with a better tracking performance. However, the system overshoot is higher than the desired overshoot (less than 5 %). In Figure 8, the step response performance of the system is well improved by the proposed two-compensator control network for two-phase hybrid stepper. A more preferred stable control loop is achieved with better tracking performance than the single loop compensator control system. Figure 9 shows the stability plot of the proposed control loop structure for a two-phase hybrid stepper motor. The plot shows that the system is stable

6 Conclusions

This paper has successfully simulated a two-compensator control loop network for two-phase hybrid stepper motor. Though many control techniques using bang–bang control, conventional PID, Fuzzy-PID, and other form of controllers have been widely implemented in Literature. However, in this paper, a new approach has been proposed which combines two-compensator in a two-phase hybrid stepper motor control loop to improve tracking response performance. The result obtained shows that the developed control system meets the required performance criteria in terms of rise time, settling time, and % overshoot.

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Покращення характеристики керування двофазним гібридним кроковим двигуном із застосуванням PID-налаштованих компенсаторів зовнішнього та внутрішнього контурів

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Анотація. У статті наведено поліпшену характеристику керування двофазним гібридним кроковим двигуном із використанням PID-налаштованих компенсаторів зовнішнього та внутрішнього контурів. Підвищено ефективність відгуку двофазного гібридного крокового двигуна до досягнутого пере регулювання нижче 5 % і часу регулювання 0,16 с. Для досягнення мети дослідження створено динамічну модель двофазного гібридного крокового двигуна за допомогою передаточної функції. Обрано надійну методику PID-налаштування, яка використовує єдиний вхідний сигнал із застосуванням графічного інтерфейсу користувача, а також диспетчера інструментів контролю та оцінки програми MATLAB для проектування компенсаторів. Для підвищення ефективності відгуку один компенсатор спроектовано і вбудовано до керуючого контуру двофазного гібридного крокового двигуна. Числове моделювання виконувалось у програмі MATLAB, а коефіцієнт перерегулювання становив 8 % для одноланкового компенсатора. Однак наявне перерегулювання системи вимагає подальшого її удосконалення. У зв'язку із цим, було запропоновано новий контур керування із використанням структури з двокомпенсаторним контуром. У результаті розроблено компенсатори зовнішнього і внутрішнього контуру, які застосовані при керуванні двофазним гібридним кроковим двигуном. Числове моделювання здійснювалось із застосуванням MATLAB, а отриманий результат показав, що для двокомпенсаторної структури перерегулювання було значно скорочено до 2,6 % з часом регулювання 12 мс. Цей результат свідчить про покращення ефективності системи відстеження відгуків шляхом застосування комбінованих зовнішніх і внутрішніх контурів компенсаторів.

Ключові слова: компенсатор, контур керування, графічний інтерфейс користувача, пропорційні інтеграл і похідна, PID-налаштування.