DSP-BASED REAL-TIME CONTROL OF A TWO PHASE HYBRID STEPPING MOTOR

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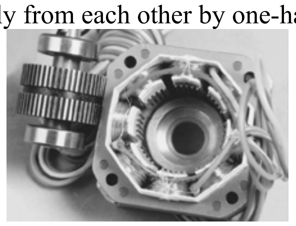
Abstract: The control of step motors has attracted much attention over the past few years, due to developments in control theory and low-cost digital hardware. Among various types of stepping motors, hybrid stepping motor is the most commonly used since it has the advantages of higher efficiency and torque capability. Stepping motors are widely used in precise motion control systems which require a high dynamic performance. However, an open loop speed control is insufficient, so closed loop control is essentially required. This paper presents a mathematical model by which the dynamic behavior of a hybrid stepping motor can be successfully predicted under different operating conditions. Hysteresis current control is used to produce the power converter gate drive pulses which enforce the phase currents follow their reference. The experimental results using DSP-DS1102 control board for hybrid stepping motor under different operating conditions have been presented. The criteria of high performance such as fast dynamic response, overshoot and undershoot of the proposed drive system are examined.

Key Words– Dynamic Analysis, DSP-Based Control, Hybrid Stepping Motor

I. INTRODUCTION

The Hybrid Stepping Motor (HSM) is a doubly salient machine which incorporates a permanent magnet in the rotor. It has a stator assembly similar to that of the variable reluctance stepper motor (VRSM), but the rotor consists of three sections. Two pieces are similar to the VRSM, but a magnet is placed between them, and they are offset circumferentially from each other by one-half tooth pitch



Hybrid stepping motor (HSM).

Hybrid stepper motor (HSM) is an electromechanical actuator which is widely used as a positioning device. It is a doubly salient machine which incorporates a permanent magnet in the rotor [4]. Its stator poles are provided with windings which are energized sequentially via a power electronic converter to produce the stepping motion. Compared with variable reluctance type, HSM has a small step length (typically 1.8 degrees) and possesses a higher torque/volume ratio. Because of its high precision in positioning, stepping motor is widely used in office and factory automation applications such as robotic systems, printers and consumer electronics [l].

The control of step motors has attracted much attention over the past few years, due to the developments in control theory and the availability of low-cost digital hardware. Hybrid stepping motor is generally operated in open loop due to its special structure. The motor develops its torque through mutual interaction between the electromagnetic excitation from the stator poles and the permanent magnet flux crossing the rotor teeth. Once a particular combination of phase currents is established and maintained in the stator, the rotor teeth will be attracted into an alignment with the stator poles in a particular position.

Stepping motors are mainly used for simple point-to-point positioning tasks in which they were open-loop controlled. In this way, they were driven by a pulse train with predetermined time interval between successive pulses applied to the power driver, and no information on the motor shaft position or speed was used.

The digital closed-loop principle was introduced to stepping motors in the 1970's in order to increase positioning accuracy and reduce their sensitivity to load disturbances [1], [2].

The closed-loop control is characterized by starting the motor with one pulse, and subsequent drive pulses are generated as a function of the motor shaft position and/or speed by the use of a feedback shaft encoder. Nowadays, due to advances made in both power electronics and data processing, stepping motors are more often closed-loop controlled, in particular, for machine tools and robotic manipulators in which they have to perform high-precision operations in spite of the mechanical configuration changes. Also, the use of classic closed-loop algorithms such as proportional–integral–derivative (PID) control is inadequate because these algorithms are often sensitive to mechanical configuration changes. This problem can be solved by applying advanced closed-loop control techniques such as self-tuning regulation (STR) where the controller is enforced to adapt itself to the motor operating conditions. Applied to the stepping motor, STR gives better performance than PID regulation because this technique is adaptive to system variations [3]. Nevertheless, this kind of control strategy is difficult to be implemented due to the large amount of floating-point computation, which means an increase in the sampling period.

In the open loop control the HSM often use about 50% of its nominal torque since a large torque reserve is required to overcome any load variation. In this classical control scheme there is no feedback of load position to the controller, however the motor must respond to each excitation change. This introduces large overshoot, resonance and torque ripple problems which degrade the operating performances. Besides, if fast excitation changes are applied, the stepper motor can lose steps and therefore it fails to move the rotor to the new demanded position. This would result a permanent error between the actual load position and the required position and consequently lose its stability and synchronization. For these limitations a closed loop controller is utmost importance for high performance applications [5].

The digital closed-loop principle was introduced to stepper motors in the 1970's in order to increase positioning accuracy and reduce their sensitivity to load disturbances [1], [2]. Nowadays, due to advances made in both power electronics and data processing, stepper motors are more often closed-loop controlled, in particular, for machine tools and robotic manipulators in which they have to perform high-precision operations in spite of the mechanical configuration changes [3],[12].

The main contribution of this paper is to develop a closed loop control of hybrid stepping motor using DSP to realize a high dynamic system performance. The dynamic model of a two-phase hybrid stepping motor drive is presented. The development of a hysteresis current controller for a hybrid stepping motor is introduced. An experimental investigation study is conducted to evaluate the proposed drive system with closed loop control. The proposed hybrid stepping motor drive system is implemented in the laboratory using DSP-DS1102 control board. A high dynamic performance of the proposed drive system is assessed and tested during different operating conditions.

II. DYNAMIC MODELING OF HYBRID STEPPING MOTOR

The mathematical model of a stepper motor consists of electrical and mechanical parts. The electrical part is represented by the equivalent circuit, Fig. 1, which depends on the motor type.

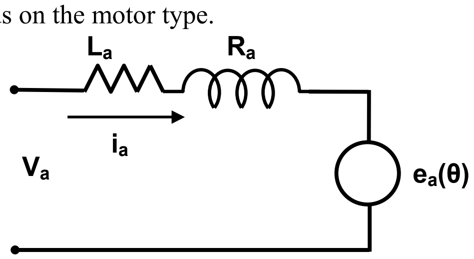


Fig. 1 Equivalent circuit of hybrid stepping motor

The present analysis assumes that the magnetic circuit is linear (no saturation) and the mutual inductance between phases is negligible. The mechanical part is represented by a state-space model based on inertia moment and viscous friction coefficient.

In this model, Ra and La represent respectively the resistance and inductance of A-phase winding. Due to the large value of the air gap introduced by the magnets, the winding inductance of the permanent-magnet or hybrid stepping motor can be considered to be independent of the rotor position. The voltage source ea(θ) represents the motor back EMF (electromotive force) which is a sinusoidal function of the rotor position:

$$e_a(\theta) = -\frac{d\psi}{dt} = -\frac{d\psi}{d\theta}\frac{d\theta}{dt} \quad (1)$$

$$e_a(\theta) = -N_r \psi_m \omega \sin(N_r \theta) \quad (2)$$

Where Nr is the number of rotor teeth and ψ_m is the motor maximum magnetic flux.

Note that at the reference position $\theta = 0$, the north pole on the rotor is fully aligned with A-axis pole so that the A-phase back EMF is then zero.

For phase B, the back EMF becomes

$$e_b(\theta) = -N_r \psi_m \omega \sin(N_r \theta - \pi/2) \quad (3)$$

The voltage equations of a two-phase hybrid stepper motors, can be obtained as,

$$V_a = r_s i_a + l_s \frac{di_a}{dt} - N_r \psi_m \omega \sin(N_r \theta) \quad (4)$$

$$(4) V_b = r_s i_b + l_s \frac{di_b}{dt} - N_r \psi_m \omega \sin(N_r \theta - \pi/2) \quad (5)$$

From the Eqns (2-3)

$$\frac{di_a}{dt} = -\frac{r_s}{l_s} i_a + \frac{N_r \psi_m}{l_s} \omega \sin(N_r \theta) + \frac{V_a}{l_s} \quad (6)$$

$$\frac{di_b}{dt} = -\frac{r_s}{l_s} i_b + \frac{N_r \psi_m}{l_s} \omega \sin(N_r \theta - \pi/2) + \frac{V_b}{l_s} \quad (7)$$

The electromagnetic torque produced by a two-phase hybrid stepper motor is equal to the sum of the torque resulting from the interaction of the phase currents and magnetic fluxes created by the magnets and the detent torque, which results from the saliency of the rotor:

The torque produced by a current i_a in winding A is given by

$$\tau_a = -N_r \psi_m i_a \sin(N_r \theta) \quad (8)$$

Similarly, the torque developed by current i_b is given by.

$$\tau_b = -N_r \psi_m i_a \sin(N_r \theta - \pi/2) \quad (9)$$

The detent torque

$$\tau_d = -T_{dm} \sin(2N_r \theta) \quad (10)$$

The total torque equal

$$T_e = -N_r \psi_m i_a \sin(N_r \theta) - N_r \psi_m i_a \sin(N_r \theta - \pi/2) - T_{dm} \sin(2N_r \theta) \quad (11)$$

The mechanical equation

$$T_e - B_m\omega - T_L = J\frac{d^2\theta}{dt^2} \qquad (12)$$

That is, the following differential equations for the rotor angular velocity ω and displacement θ result

$$\frac{d\omega}{dt} = \frac{1}{J}(T_e - B_m\omega - T_L) \qquad (13)$$

$$\frac{d\theta}{dt} = \omega \qquad (14)$$

III. HYSTERESIS CURRENT CONTROL

The current control, which consists of two hysteresis controllers, is built with Simulink blocks. The motor currents are provided by measurement and compared to the reference currents. The current error is passed through hysteresis controller represented by relay block with band H to produce the inverter gate pulses as shown in Fig. 2. Square-wave current references are generated using the current amplitude and the step frequency parameters

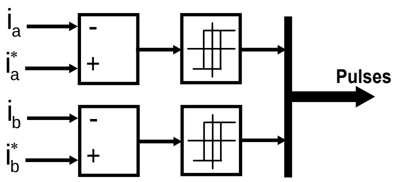


Fig. 2 Hysteresis current controllers for producing gate pulses.

The gate pulses are produced based on the following concepts taking phase a as an example,
In the positive half cycle,

$$\text{If } i_a > i_a^* + H \text{ then } Na = 0;$$

$$\text{If } i_a < i_a^* - H \text{ then } Na = 1;$$

In the negative half cycle,

$$\text{If } i_a > i_a^* + H \text{ then } Na = 1;$$

$$\text{If } i_a < i_a^* - H \text{ then } Na = 0;$$

IV. SYSTEM IMPLEMENTATION

The proposed current control algorithms have been realized and tested for feasibility in a motor drive containing a hybrid stepping motor with a power supply, inverter and gate circuit, and current controller.

The basic configuration of the experimental system is shown in Fig. 3. It consists of a HSM interfaced with a digital control board DS1102 based on a Texas Instruments TMS320C31 Digital Signal Processor for real-time control. Rating and parameters of the HSM are given in the appendix. Stator currents are measured and filtered using analogue circuitry. Hall-effect sensors are used for this purpose. The measured current signals are acquired by the A/D input ports of the DSP control board. This board is hosted by a personal computer on which mathematical algorithms are programmed and downloaded to the board for real-time control.

The motor phases are fed by H-bridge MOSFET PWM converters connected to a 4.5 V DC voltage source. The motor phase currents are independently controlled by two hysteresis-based controllers which generate the MOSFET drive signals by comparing the measured currents with their references. The output switching commands of the DSP control board are obtained via its digital ports and interfaced with the converter through opto-isolated gate drive circuits.

The Matlab/Simulink models can be implemented and tested in real time. The Real-Time Interface (RTI) contains a library of Blocks which connects the Simulink models to the real system. The Real-Time workshop (RTW) converts the model to C code. The C code is then automatically compiled to the assembly language of the target processors and downloaded to the controller board. Finally, ControlDesk, and Experimentation tools, are used to control, tune and monitor the running process. In real time it is available to capture the signals of the model and change parameters of the controller.

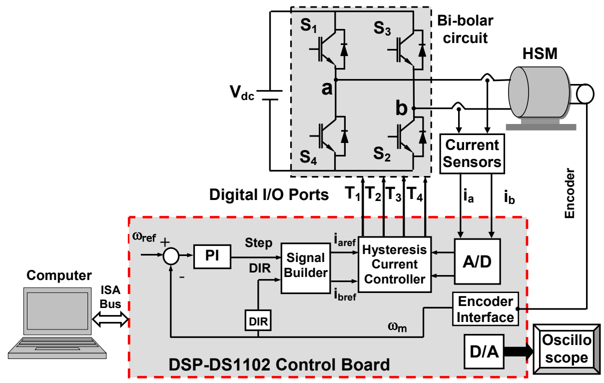
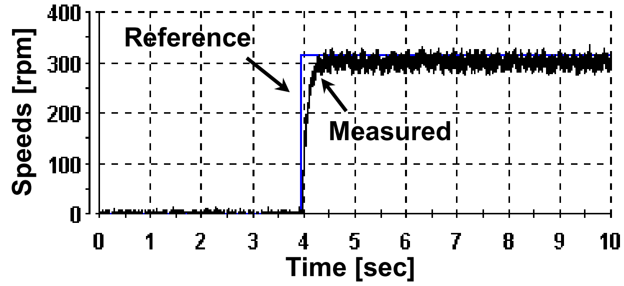


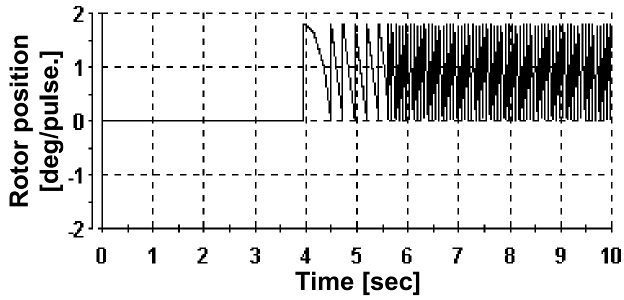
Fig. 3 Block diagram of the experimental system using DSP control board

V. EXPERIMENTAL RESULTS

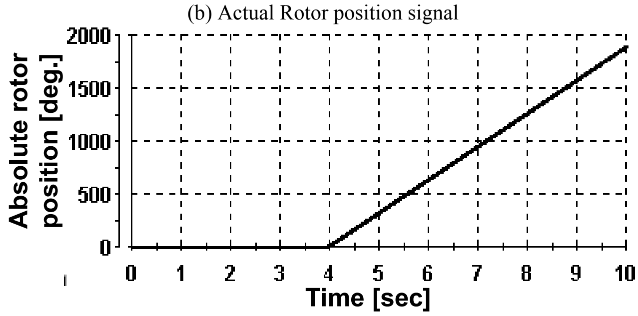
The experimental system of Fig. 3 is built in the laboratory to test the performance of the hybrid stepping motor drive system under different operation conditions. This includes step change of reference speed at different reference values 314, 125, and 65 rpm, respectively. Figs. 4 to 6 show the reference and actual speeds, rotor position signal and absolute rotor position under step speed change. It is obvious that the actual speed and consequently the rotor position reaches the steady state value smoothly without overshoot or undershoot. Moreover, the drive system has a fast dynamic response and takes a minimum rise time to reach the steady state value. However, the actual speed contains ripples which increase at low speeds. Experimental results are presented also during speed reversal, Fig.7. It is clear that the actual speed follows the reference speed smoothly. Moreover, experimental results are presented with repetitive operation to test the precise operation of the drive system and fast dynamic response, Fig.8. It is observed that the drive system preserves its stability and synchronization with fast start and stop operations. This proves the supremacy of the proposed closed loop control of hybrid stepping motor drive system.



(a) reference and actual speeds

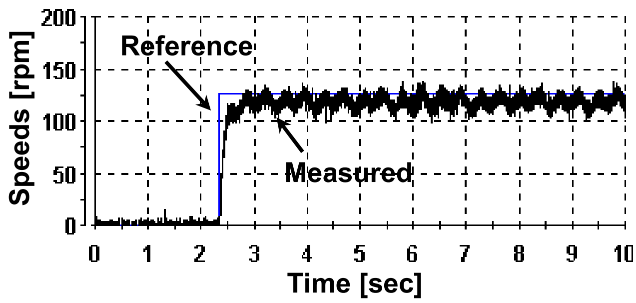


(b) Actual Rotor position signal

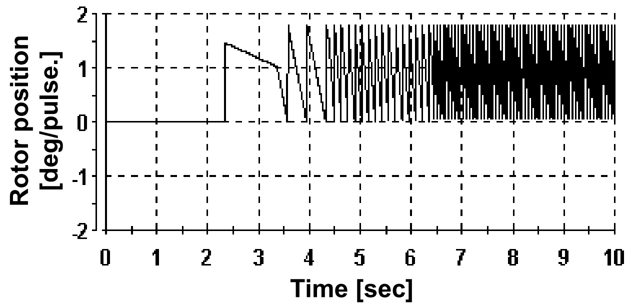


(c) Absolute rotor position(actual

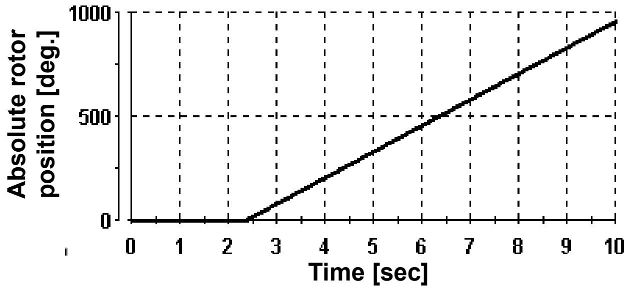
Fig. 4 Experimental results at step change of speed reference at 314 rpm.



(a) reference and actual speeds

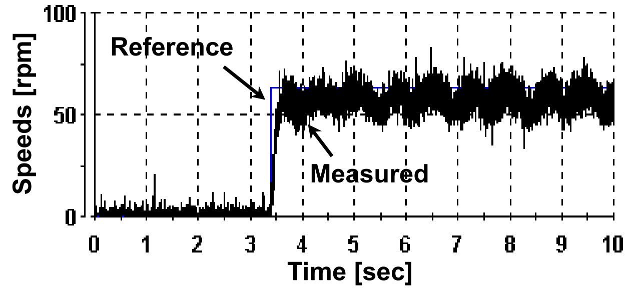


(b)) Actual Rotor position signal

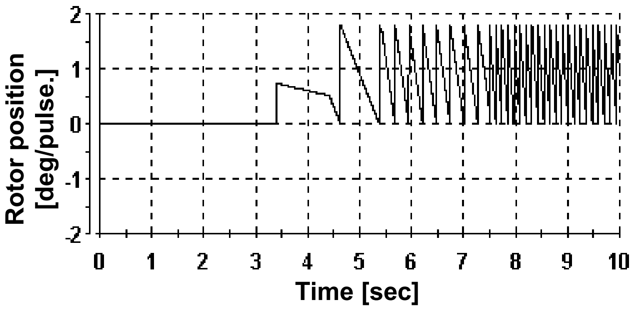


(c) Absolute rotor position

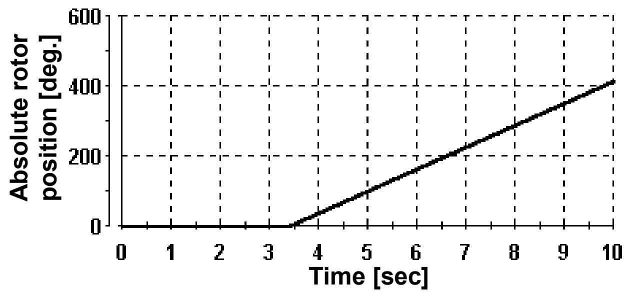
Fig. 5 Experimental results at step change of speed reference at 125 rpm.



(a) Reference and actual speeds

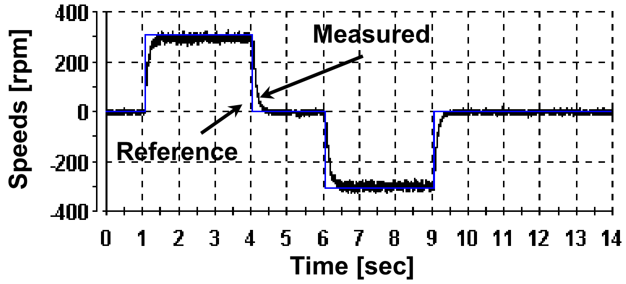


(b)) Actual Rotor position signal

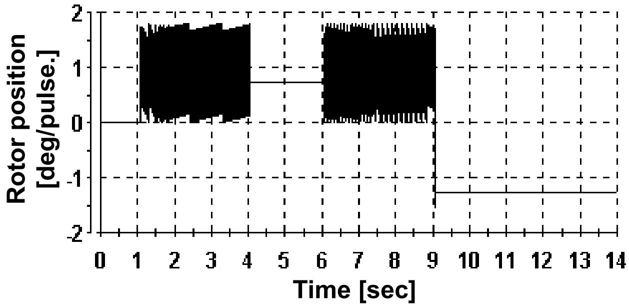


(c) Absolute rotor position

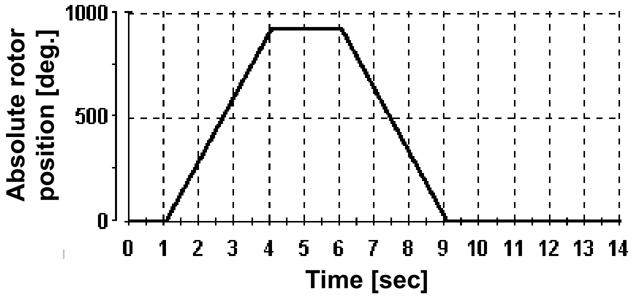
Fig. 6 Experimental results at step change of speed reference at 65 rpm.



(a) Reference and actual speeds

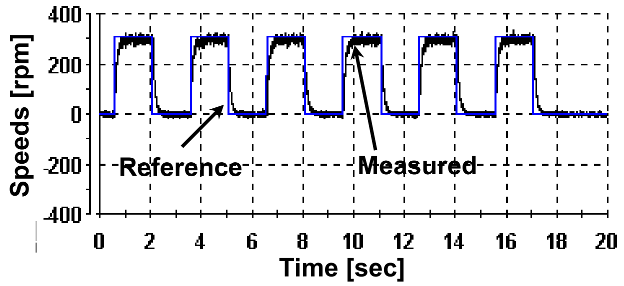


(b)) Actual Rotor position signal

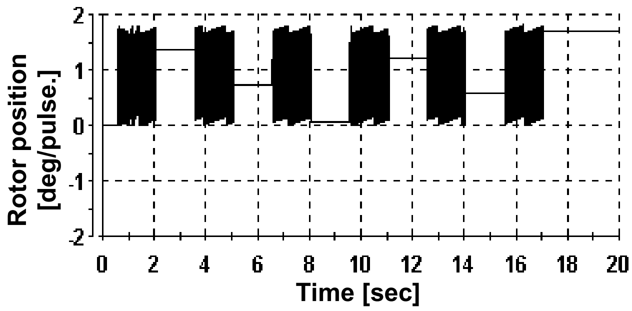


(c) Absolute rotor position

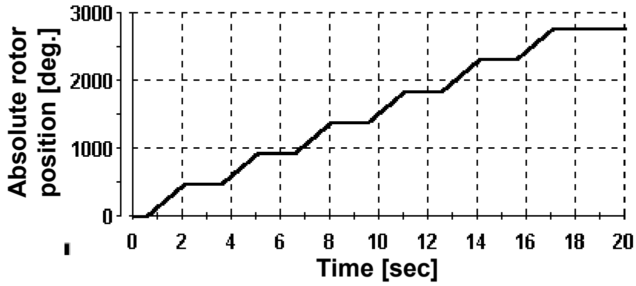
Fig. 7 Experimental results during speed reversal.



(a) Reference and actual speeds



(b)) Actual Rotor position signal



(c) Absolute rotor position

Fig. 8 Experimental results during repetitive operation.

VI. CONCLUSION

This paper has presented a mathematical model with which the dynamic behavior of a hybrid stepping motor could be successfully predicted. This model has been used to illustrate the dynamic operation as well as steady state operation of hybrid stepping motor with hysteresis current control. The experimental results using DSP-DS1102 control board for a hybrid stepping motor under different operating conditions has been presented. Experimental results have been presented during step change of speed reference, speed reversal and repetitive operation. It has been obvious that the actual speed and consequently the rotor position reaches the steady state value smoothly without overshoot or undershoot. Moreover, the drive system is fast dynamic response and takes a minimum rise time to reach the steady state value. In addition, it has been observed that the drive system can not lose its stability or synchronization with speed reversal and fast start and stop operations. This proves the supremacy of the proposed closed loop control of hybrid stepping motor drive system. With the high performance DSP and advanced control techniques, attempts are done to overcome speed ripples.

APPENDIX

Table I Hybrid Stepping Motor Parameters

Number of Phases	2	Detent torque	0.002 N.m
Winding inductance	0.0014 H	The total inertia	1.2e-7
Winding resistance	0.7 Ω	The total friction	0.0001
The step angle	1.8º	Initial Speed(rad/sec)	0
Maximum flux linkage	0.005	Initial Position (degree)	0

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