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Analysis and Design of the Frequency Response of a Brushless DC Motor (BLDCM) Servosystem Under Varying Conditions

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Abstract

A frequency response provides control engineers with the ability to analyze and design control systems in the frequency domain by describing the steady-state response of a system to sinusoidal inputs of varying frequencies. A system's frequency response is represented by two graphs: one that illustrates magnitude and the other that illustrates phase. The transfer function's phasor representation may be readily calculated at any frequency. The Electro-Mechanical Actuator (EMA) is a widely used position servo-system that is used extensively in several sectors. The control architecture of EMA typically employs a cascaded structure, where location, velocity, and current loops are incorporated, They are implemented using PID controllers.. The BLDCM is increasingly being used in EMA systems because to its compact size, superior efficiency, high power density, and less rotor inertia. This study introduces the development of a Position Servo-System for a Brushless DC Motor (PSSBLDCM) intended for use in an Electromechanical Actuator (EMA). Therefore, to fulfill the frequency response requirement of the position loop, the frequency responses of the velocity loop and current loop are established. A frequency domain approach is then used to construct the PID controllers. The system is simulated using SIMULINK, while the experimental system is created using the DSP TMS320VC33 and FPGA CYCLONEIIEP2C35. The results suggest that the PSSBLDCM is able to fulfill the requirements.

Keyword: Electromechanical Actuator (EMA), Position Servo-System of Brushless DC Motor (PSSBLDCM), Proportional Integral Derivative (PID)

1. INTRODUCTION

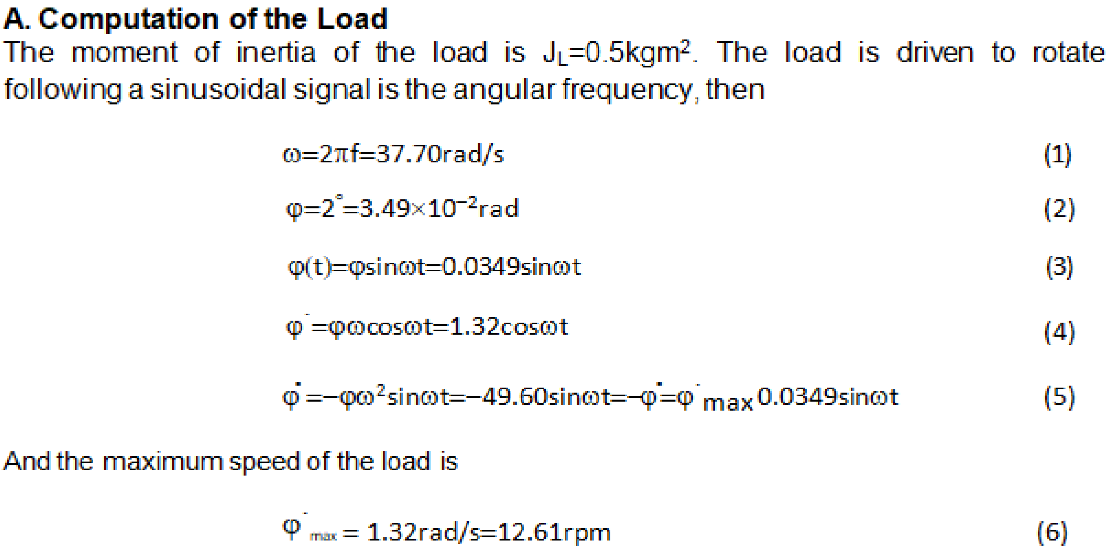
The Electro-Mechanical Actuator (EMA) is a commonly used position servo-system in many fields such as aeronautics, astronautics, military, traffic, and industrial and agricultural machinery. The weight is driven either directly or indirectly by an electrical motor or appliance, and the desired position may be achieved [1]. The control architecture of EMA typically utilizes a cascaded loop system, including position, velocity, and current control. The velocity loop enhances the damping of the system, hence improving its capacity to counteract disturbances.

The presence of the current loop leads to a reduction in torque ripple and eliminates the impact on DC bus voltage fluctuation. The BLDCM is increasingly used in EMA because to its compact size, superior efficiency, high power density, low rotor inertia, excellent dependability, and effective heat dissipation properties. The range is from 2 to 4 inclusive. This study presents the establishment of a position servo-system model employing the Brushless DC Motor (BLDCM) in an Electromechanical Actuator (EMA). The PID controllers are designed using a frequency domain approach to determine the frequency responses of the velocity loop and current loop, based on the frequency response requirement of the position loop. The system is simulated using SIMULINK, and the experiment is conducted using an experimental servo-system. The experimental servo-system's hardware platform is built using the DSP TMS320VC33 and FPGA CYCLONEIIEP2C35. The software platform used is μC/OS-II, a real-time operating system that has been adapted for usage on the DSP. The user's text is "[5]". A single current sensor is used to get the current feedback from the DC bus. The phase commutations are executed using the hall sensors to determine and compute the velocity of the BLDCM. The location of the BLDCM is acquired via an encoder. At any one moment, only two out of the three phases are conducting concurrently.

II. The Structure and Design Requirements of the System

The PSSBLDCM includes components such as the BLDCM, speed reducer, inverter, controller, and signal detection unit. Fig.1 illustrates the configuration of the servo-system. Here are the design requirements for the PSSBLDCM:

The load can rotate up to a maximum angle of 40°. The frequency response of the PSSBLDCM should be 6Hz, with a rotation angle of 2°, which corresponds to 5% of the maximum rotation angle. The position error must be kept below 0.1°. The maximum peak value of torque of the load is:



A. Computation of the Load

The moment of inertia of the load is $J_L=0.5kgm^2$. The load is driven to rotate following a sinusoidal signal is the angular frequency, then

$$\omega=2\pi f=37.70rad/s \tag{1}$$

$$\varphi=2^{\circ}=3.49\times10^{-2}rad \tag{2}$$

$$\varphi(t)=\varphi\sin\omega t=0.0349\sin\omega t \tag{3}$$

$$\dot{\varphi}=\varphi\omega\cos\omega t=1.32\cos\omega t \tag{4}$$

$$\ddot{\varphi}=-\varphi\omega^2\sin\omega t=-49.60\sin\omega t=-\ddot{\varphi}=\dot{\varphi}_{max}0.0349\sin\omega t \tag{5}$$

And the maximum speed of the load is

$$\dot{\varphi}_{max}=1.32rad/s=12.61rpm \tag{6}$$

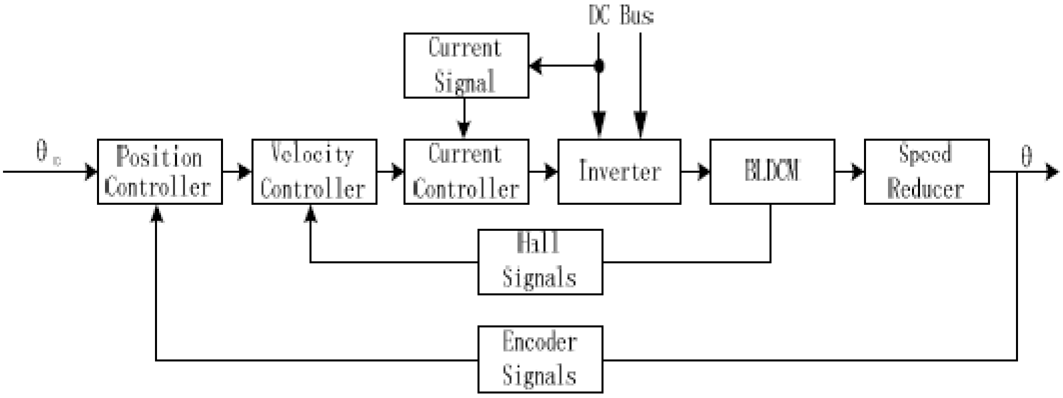


Fig.1. The structure of the PSSBLDCM

$$M_{max}=J_L\dot{\varphi}_{max}=24.80N\cdot m \tag{7}$$

If friction is consider, then:

$$M_L=1.2M_{max}=29.76N\cdot m \tag{8}$$

M_L is the maximum output toque of speed reducer.
The deceleration ratio and efficiency of speed reducer are

$$i=100:1 \tag{9}$$

$$\eta=85\% \tag{10}$$

The required maximum speed of the motor shaft Should be:

$$N=i\cdot\dot{\varphi}_{max}=1261rpm \tag{11}$$

And the required maximum torque of the motor shaft is:

$$M_m=M_L/(i.\varphi_{max}\cdot\eta)=0.35N\cdot m \tag{12}$$

The three phase windings of the BLDCM are Y connected without neutral line. The detailed parameters of the BLDCM used in this paper are shown in Table I. The total inertia coupled to motor shaft can be computed

$$J=3.36\times10^{-4}kg.m^2 \tag{13}$$

B. Selection of the Position Sensor

The process of selecting the position sensor

The position sensor used in this study is an incremental encoder. The system produces a signal that represents the zero position, as well as two orthogonal signals, each consisting of 2500 pulses per rotation. By combining two orthogonal signals, it is possible to create a signal with a frequency four times higher, hence enhancing the accuracy of location detection. Specifically, the encoder is capable of capturing 10,000 states every revolution. The encoder's resolution is

III. PSSBLDCM MODELING

The PSSBLDCM model is provided in this section. Initially, the three-phase model of a brushless DC motor (BLDCM) is presented. This model may be simplified since only two out of the three phases are conducting concurrently at any one moment. Furthermore, the PSSBLDCM is accompanied by models of several additional components. The complete model of the Permanent Magnet Synchronous Brushless Direct Current Motor (PSSBLDCM) has been successfully developed.

1. Model of the BLDCM

1) The three phase windings exhibit perfect symmetry, resulting in a square waveform for the air gap magnetic flux density.

2) The effects of teeth and slots, commutation, and armature response are disregarded.

3) The magnetic circuits are not saturated.

4) The hysteresis loss and eddy current loss are disregarded.

The electrical equation of a Brushless DC Motor (BLDCM) is expressed based on these assumptions:

For simplified analysis, assume:

TABLE I PARAMETERS OF BLDCM

Nominal power	350
Nominal torque	1.65Nm
Nominal speed	2022rpm
Phase resistance	17 ohm
Phase equivalent inductance	20mH
Constant Torque (KT)	1.99 Nm/A
Constant Torque- EMF	0.208V/rpm
The moment of inertia	0.002767kgm

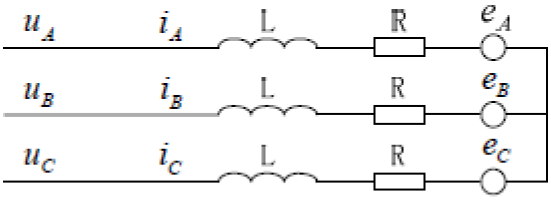


Fig.2. The equivalent circuit of the BLDCM

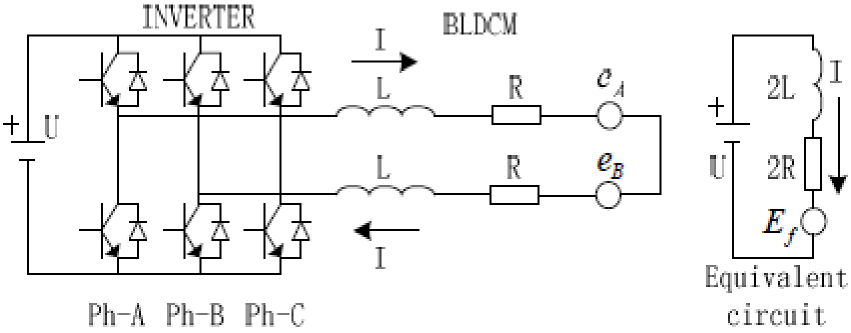


Fig.3. The simplified equivalent circuit of BLDCM

2. Model of other part of BLDCM

Current loop has frequency response ten times that of velocity loop.

K_{PWM}=240/3.3=72.73 (14)

The unit of velocity loop is delay unit which is reciprocal of sample frequency of velocity loop

G_d=1/1× $10^{-3}+1$ (15)

A. Model of PSSBLDCM

The frequency response of the current loop is 10 times that of the velocity loop, so the inverter can be considered as a proportional unit. The gain of the proportional unit is:

IV. DESIGN OF PSSBLDCM

Using the model acquired before, the design of PSSBLDCM may be completed to meet the frequency response design requirement of the position loop. PID controllers may be built utilizing a frequency domain approach for implementation in position, velocity, and current loops. The frequency response of the position loop adheres to the design criteria of the system.

The frequency response of position loop

f_p=6HZ

The frequency response of velocity loop

f_v=16.67f_p=100HZ

The frequency response of current loop

f_I=10f_V=1000HZ

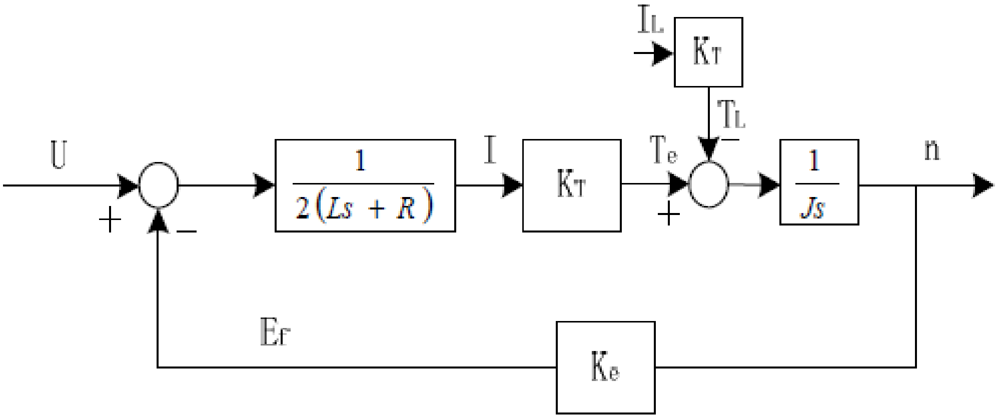


Fig.4. The block diagram of the model of the BLDCM

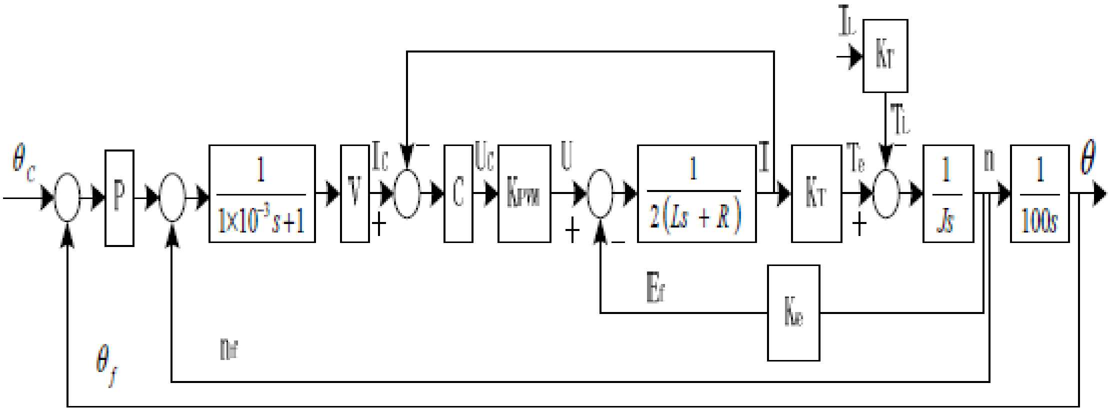


Fig.5. The model of the PSSBLDCM

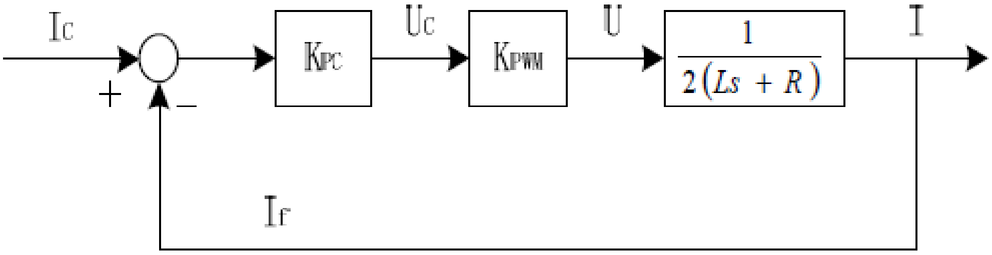


Fig.6. The block diagram of the current loop

IV. Design of the Current Loop

$$T_l = 1.18\times 10^{-3}\mathrm{s} \tag{16}$$

$$T_m = 2\mathrm{RJ}/((K_e K_T) = 2.76\times 10^{-2}\mathrm{s} \tag{17}$$

$$\emptyset_c = \frac{K_{PC}K_{PWM}}{2\mathrm{LS}+2\mathrm{R}+K_{PC}K_{PWM}} \tag{18}$$

According to the definition of Bandwidth, K_{PC} is:

$$K_{PC} = 2.99 \tag{19}$$

Then the closed-loop transfer function of the current loop

$$\emptyset_c = \frac{217.46}{0.04s+251.46} \approx \frac{1}{1.59\times 10^{-4}\ s+1} \tag{20}$$

Then the open-loop transfer function of the current loop

$$\emptyset_c = \frac{1}{1.59\times 10^{-4}\ s} \tag{21}$$

The cut-off frequency of current loop is:

$$\omega_{cc=} 6.29\times 10^3\ {}^{rad}/_{s} \tag{22}$$

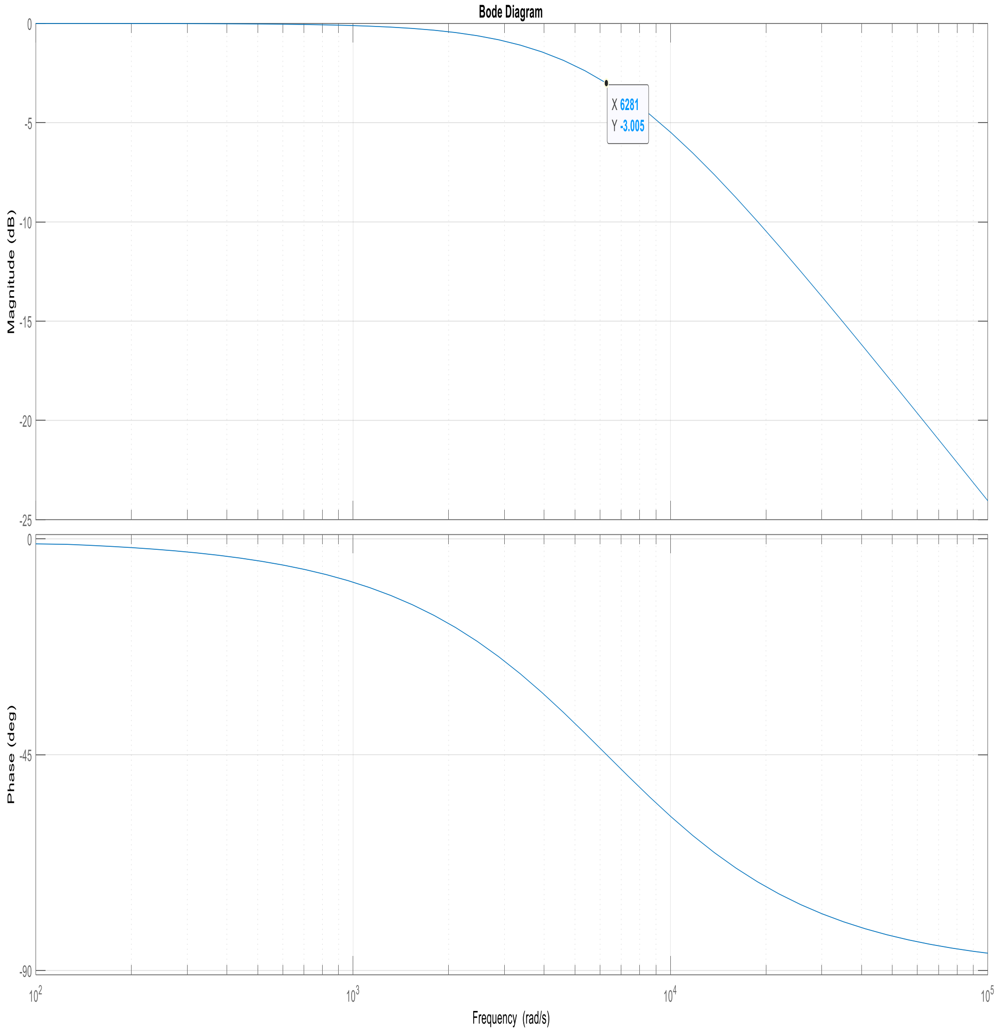


Fig.6. The closed-loop bode diagram of position loop

Design of the velocity Loop

$$T=0.001\pm0.000159=1.159\times 10^{\pm3}s \quad (23)$$

The equivalent inertia unit is:

$$G=\frac{1}{1.159\times10^{-3}\,s+1} \quad (24)$$

The closed-loop transfer function of the velocity loop is

$$\emptyset_v=\frac{5.11\times10^6\;K_{PV}}{S^2+8.63\times10^2\,S+5.11\times10^6\;K_{PV}} \quad (25)$$

According to the definition of bandwidth, K_{PV} is:

$$K_{PV}=7.50\times 10^{-2} \quad (26)$$

Finally the closed-loop transfer function of the velocity loop is

$$\emptyset_v=\frac{3.83\times10^5}{S^2+8.63\times10^2\,S+3.83\times10^5} \quad (27)$$

The open-loop transfer function of the velocity loop is

$$\emptyset_v=\frac{3.83\times10^5}{S^2+8.63\times10^2\,S} \quad (28)$$

The cut-off frequency of the velocity loop is

$$\omega_{cv}=4.02\times10^2 rad/s \quad (29)$$

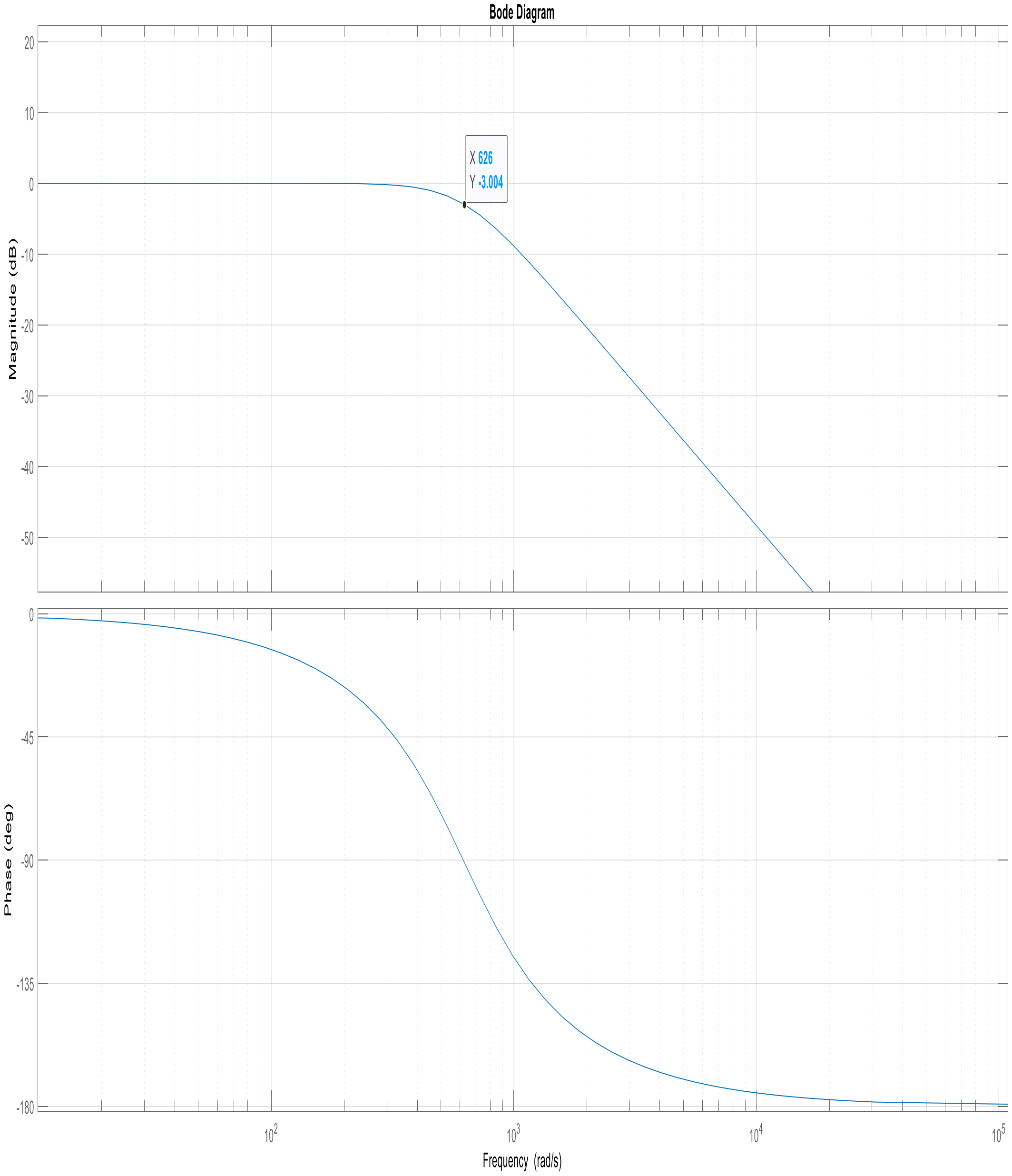


Fig.8.The closed-loop bode diagram of velocity loop

A. Design of the position Loop

The closed-loop transfer function of the position loop is:

$$\emptyset_P = \frac{K_{PP}S+K_{IP}}{2.25\times10^{-1}S^3+100\times S^2\ +K_{PP}S+K_{IP}} \tag{30}$$

$$K_{PP}=3505 \tag{31}$$

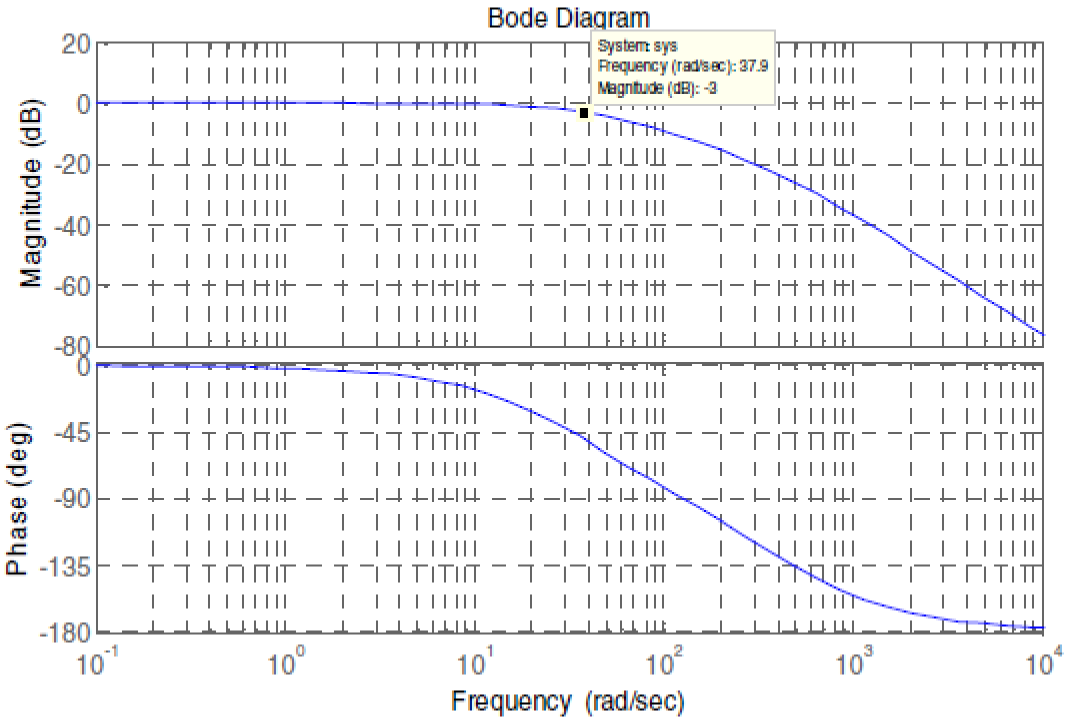
$$K_{IP}=200 \tag{32}$$

Then the transfer function of the position controller is:

$$P= 3505+200/S \tag{33}$$

Then the open-loop transfer function of the position loop

$$\emptyset_P = \frac{K_{PP}S+K_{IP}}{2.25\times10^{-1}S^3+100\times S^2\ +K_{PP}S+K_{IP}} \tag{34}$$



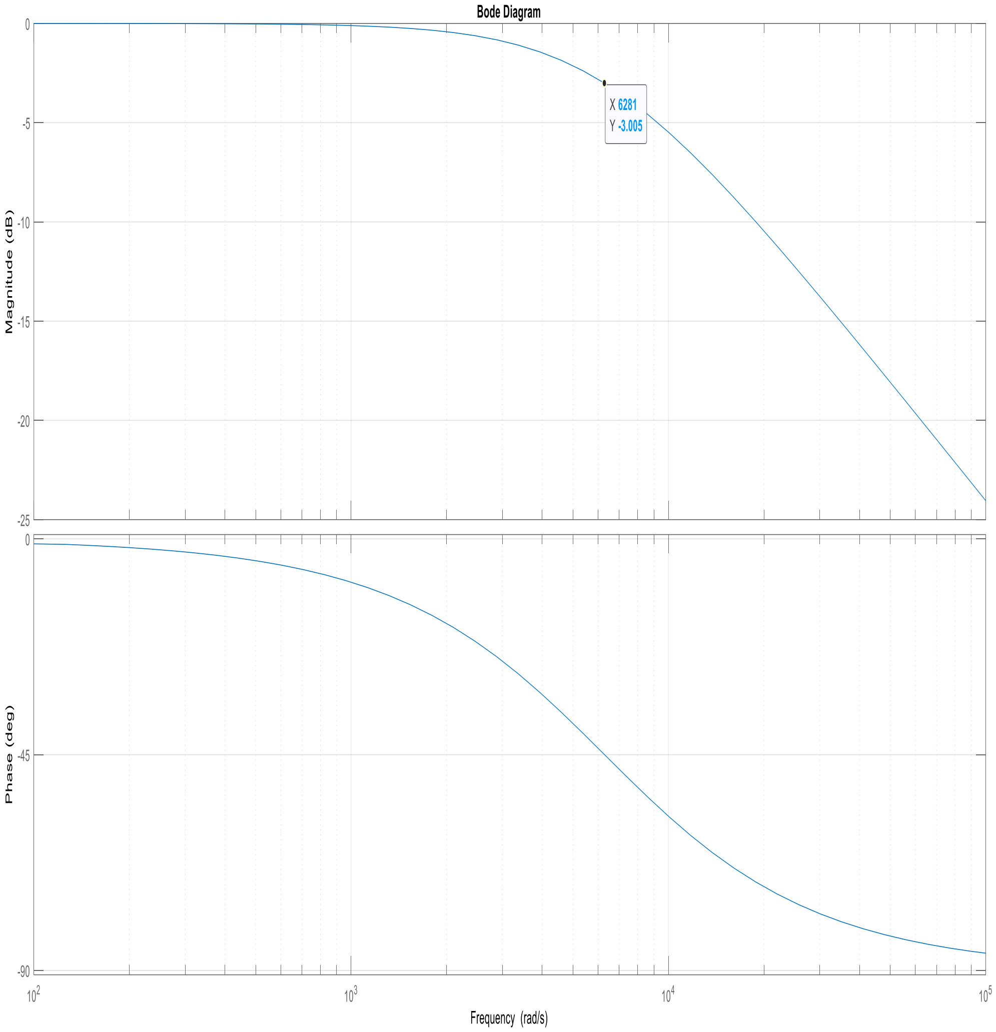


Fig.9. The closed-loop bode diagram of the position loop

V. The Outcomes of the Simulation

The PSSBLDCM is represented in section III, and the whole system is emulated using SIMULINK. Figure 12 displays the block diagram of the simulation. This study discusses the use of a position command as a signal to drive the load and induce rotation. Here, two position instructions are used. The first signal is a sinusoidal wave with an amplitude of 2° (0.0349 rad) and a frequency of 6 Hz. The second signal is a step signal with an amplitude of 40° (0.6981 rad). The simulated PSSBLDCM exhibits a sinusoidal response and a step response to the two signals, respectively.

The sinusoidal response of the system is shown in Figure 13, where it is compared to the initial position instruction. It is evident that the amplitude difference between the two curves is less than 3dB and the phase lag is less than 90°, which meets the design requirement.

The figure labelled as Fig.14 displays the step response of the system. It depicts a comparison between the step response and the second position instruction. The reaction exhibits little overshoot. The positional discrepancy may be calculated using the information provided in Figure 14, which is below 0.1°and meets the design criteria.

Experimental Results

The experimental Permanent Magnet Synchronous Brushless DC Motor (PSSBLDCM) is developed using the DSP TMS320VC33 and FPGA CYCLONEIIEP2C35 as the controller's hardware platform.

The controller utilizes the real-time operating system μC/OS-II, which has been adapted for use on the DSP, as its software platform.

The tasks in μC/OS-II are split and assigned priority. The velocity command is a discrete signal that transitions from 200rpm to 300rpm. At a DC bus voltage of 110v, the step response of the velocity of the experimental PSSBLDCM is shown in Figure 15. The top curve represents the velocity command, while the bottom curve represents the step response.

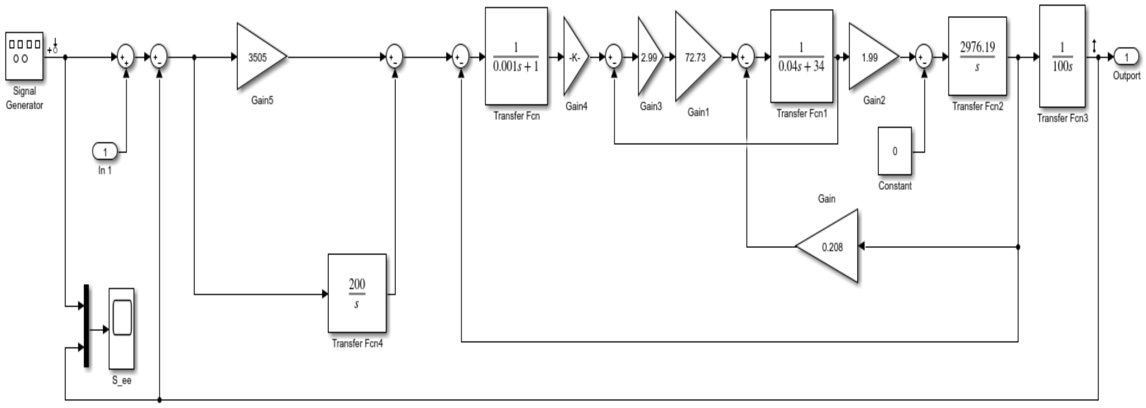
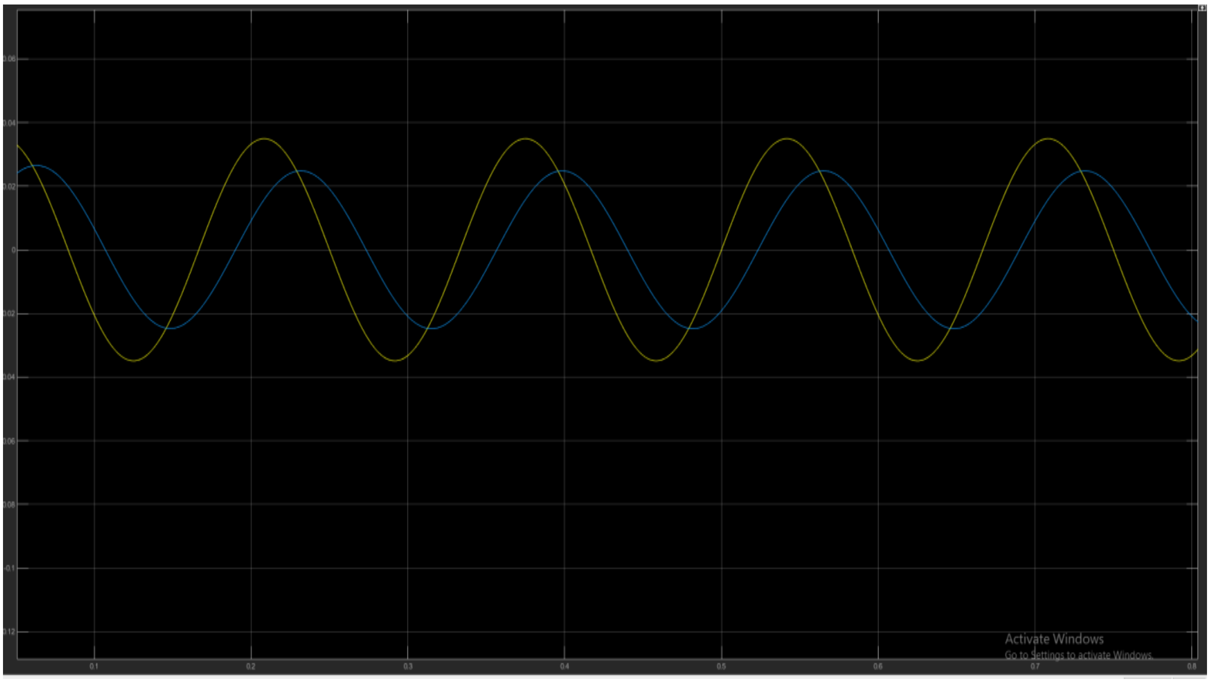


Fig.11. The block diagram of simulation



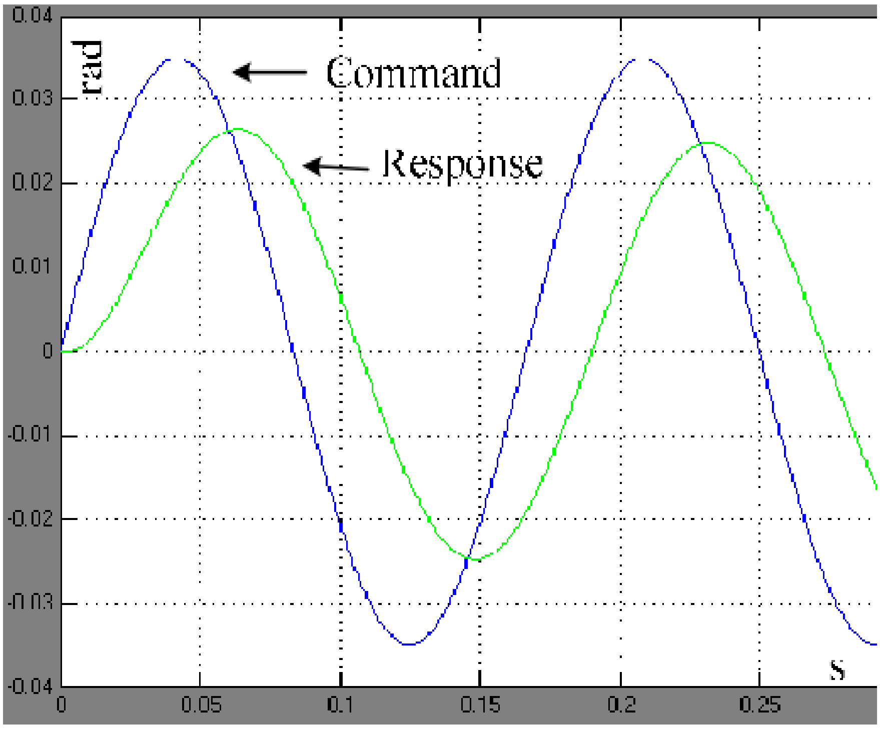
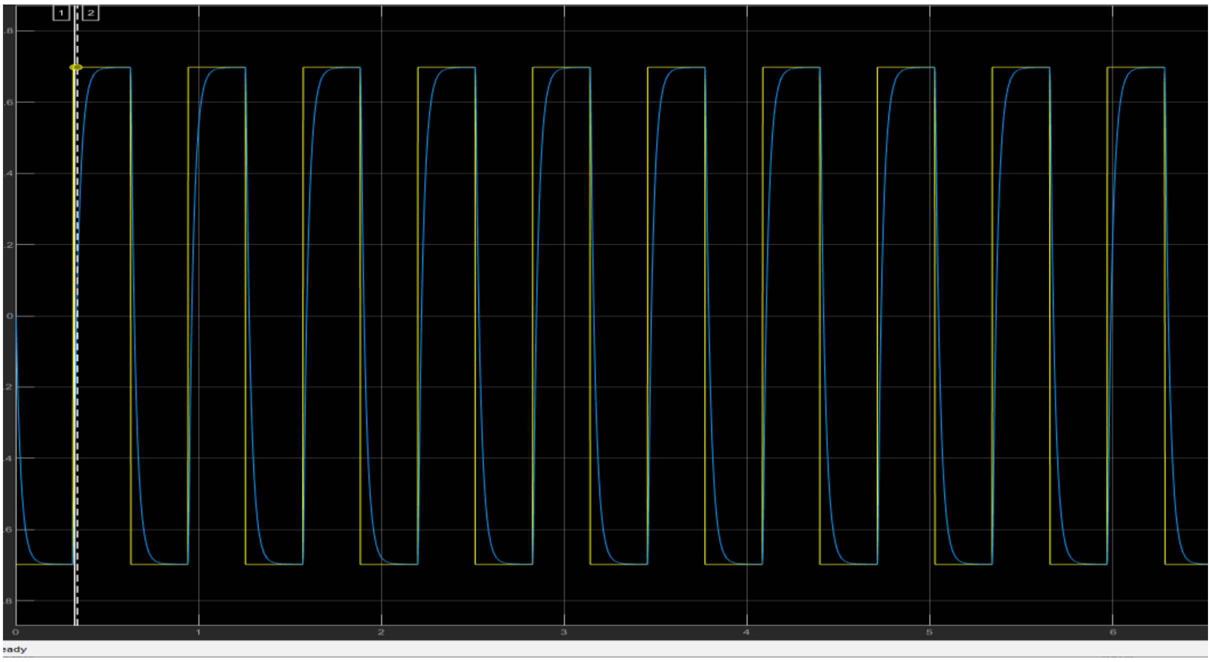


FIG.12. The sinusoidal response of simulated PSSBLDCM



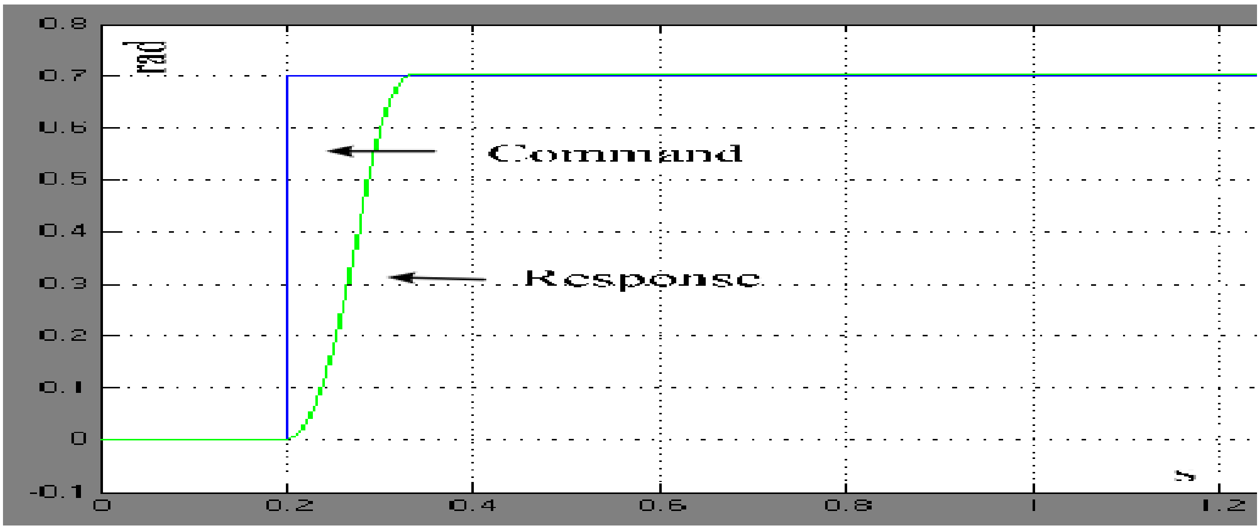


FIG. 13. The Step response of simulated PSSBLDCM

CONCLUSION

This study presents a frequency domain design technique for PSSBLDCM. The method aims to calculate the frequency responses of the velocity and current loop based on the design requirement of the position loop. The paper also discusses a design strategy for the controllers used in the three loops. The findings demonstrate the practicability of the frequency domain design approach. This approach demonstrates its generality and reference value in various position servo-systems using BLDCM.

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