Design of Electro Mechanical Actuator Control System Based on Frequency Domain

Kolli Naveen
Department of Electrical Engineering
Vit university, Tamilnadu, India

Abstract- *Electro Mechanical Actuator is a characteristic position servo system use in lots of fields. The control architecture of EMA is frequently implementing founded on cascaded position, velocity and current loop. The BLDCM is additional and more applied to EMA as of its tiny size, high effectiveness, high power density and low rotor inertia. A position servo system of BLDCM (PSSBLDCM) use in EMA is intended in this term paper and PID controllers are used in position loop, velocity loop and current loop. Because of the frequency response requirement of the position loop, the frequency results of the velocity loop and current loop can be obtain and a frequency domain method is used to implement the PID controllers .Simulation of the structure is done by by SIMULINK. The results explain the PSSBLDCM can assure the requirements.*

Keywords- Electro Mechanical Actuator, Position loop, Velocity loop, Current Loop

I. INTRODUCTION

The Electro-Mechanical Actuator (EMA) is a typical position servo-system, widely used in aeronautics, astronautics, military, traffic and mechanism for industry and agriculture. It drives the load directly or indirectly by electrical motor or appliance, and the position target can be realized. The control architecture of EMA is usually implemented based on cascaded position, velocity and current loop. Because of the velocity loop, the damp of the system is increased and the ability of anti-disturbance is improved. Because of the current loop, the torque ripple is reduced and the effect on DC bus voltage variation is eliminated. The BLDCM has been more and more used in EMA, because of its small size, high efficiency, high power density, low rotor inertia, high reliability and good heat dissipation characteristics. In this paper a position servo-system model is established using the BLDCM in EMA. According to the frequency response requirement of the position loop, the frequency responses of the velocity loop and current loop can be obtained and a frequency domain method is used to design the PID controllers. Simulation of the system is done by using the SIMULINK, and the experiment is implemented based on an experimental servo-system. One current sensor is used to obtain the current feedback from the DC bus. The phase commutations are implemented based on the hall sensors from which the velocity of the BLDCM is estimated and calculated. The position of the BLDCM is obtained from encoder. Only two of three phases are conducting simultaneously at any time.

II. THE SYSTEM STRUCTURE AND DESIGN REQUIREMENT

The Position Servo-System of BLDCM (PSSBLDCM) consists of Brush less DC motor, speed reducer, inverter, controller, signal detection unit, etc. The structure of the servo-system is shown in Fig 1.

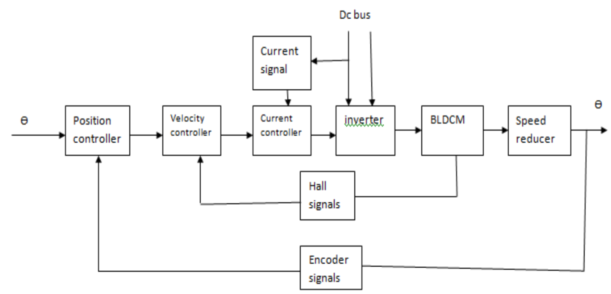

Fig.1.the structure of PSSBLDCM

The design requirements of the PSSBLDCM are below:

- The maximum rotation angle of the load is 40°.
- The frequency response of the PSSBLDCM should be 6Hz, when the rotation angle is 2°, which is the 5% of the maximum rotation angle.
- And the position error should be less than 0.1°.

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. ω is the angular frequency, then:

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

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

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

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

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

And the maximum speed of the load is:

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

The maximum peak value of torque of the load is:

$M_{max} = J_L \ddot{\varphi}_{max} = 24.80$N-m (7)

If friction is considered, then:

$M_L = 1.2M_{max} = 29.76$N-m (8)

Where φ (t) is the sinusoidal signal that the load is following, M_L is the maximum output toque of speed reducer. The deceleration ratio and efficiency of speed reducer are:

i=100:1 (9)

η = 85% (10)

Then the required maximum speed of the motor shaft should be:

$n = i.\dot{\varphi}max = 1261$rpm (11)

And the required maximum torque of the motor shaft is:

$Mm = M\,L/(i.\eta) = 0.35$ N-m (12)

The three phase windings of the BLDCM are Y connected without neutral line. The detailed parameters of the BLDCM are shown in Table I

Nominal power	350W
Nominal torque	1.65Nm
Nominal speed	2022rpm
Phase resistance	17ohm
Phase Equivalent Inductance	20mH
Constant of Torque(K_T)	1.99Nm/A
Constant of Back-EMF(K_e)	0.208V/rpm
The moment of inertia(J_m)	$0.0002767kgm^2$

Table I Parameters of BLDC motor

The total inertia coupled to motor shaft can be computed:

$J = J_m + J/(i^2\eta) = 3.36\times10^{-4}kg.m^2$ (13)

b. Selection of the Position Sensor

The position sensor used is an incremental encoder. It generates a signal represented zero position and two orthogonal signals which are 2500 pulses per revolution each. The two orthogonal signals can generate a signal which has quadruple frequency and then increase the precision of the position detection. That is to say, 10000 states per revolution can be captured from the encoder. The resolution of the encoder is:

$360^0/10000 = 0.036^0 < 0.1^0$ (14)

The encoder selected satisfies the position error requirement

III. POSITION SERVO SYSTEM OF BLDC MOTOR MODELING

The model of the PSSBLDCM is given below. The model can be simplified because only two of three phases are conducting simultaneously at any time. Second, models of other parts of the PSSBLDCM are given. Finally the whole model of the PSSBLDCM is established.

3.1 Model of the Brushless DC Motor (BLDCM)

To simplify the analysis, the following assumptions are made:

1) The three phase windings are completely symmetric, and the waveform of air gap magnetic flux density is square
2) Effects of the teeth and slots, commutation and armature reaction are ignored
3) The magnetic circuits are unsaturated
4) The hysteresis loss and eddy current loss are ignored.

According to these assumptions, the electrical equation of BLDCM is written below:

$$\begin{pmatrix}u_A\\u_B\\u_C\end{pmatrix} = \begin{pmatrix}R&0&0\\0&R&0\\0&0&R\end{pmatrix}\begin{pmatrix}i_A\\i_B\\i_C\end{pmatrix} + \frac{d}{dt}\begin{pmatrix}L_A&M_{AB}&M_{AC}\\M_{BA}&L_B&M_{BC}\\M_{CA}&M_{CB}&L_C\end{pmatrix}\begin{pmatrix}i_A\\i_B\\i_C\end{pmatrix} + \begin{pmatrix}e_A\\e_B\\e_C\end{pmatrix} \quad (15)$$

Where

u_a, $u_b$and $u_c$are the stator winding phase voltages

i_a, $i_b$and i_c are the stator winding phase currents

e_a, e_b, and $e_c$are the Back-EMF

R is the winding resistance

L_A, L_B and L_C are winding self-inductances

M_{AB}, M_{BA}, M_{AC}, M_{CA}, M_{BC} and M_{CB} are the winding mutual inductances.

According to the assumptions, the inductances of the BLDCM don't vary with the change of rotor position and the three windings are completely symmetric, then:

$L_A = L_B = L_C = L_S$ (16)

$M_{AB} = M_{BA} = M_{AC} = M_{CA} = M_{BC} = M_{CB}$ (17)

Because of Y connection without neutral line, the following equation is obtained:

$I_A + I_B + I_C = 0$ (18)

And then:

$$\begin{pmatrix}u_A\\u_B\\u_C\end{pmatrix} = \begin{pmatrix}R&0&0\\0&R&0\\0&0&R\end{pmatrix}\begin{pmatrix}i_A\\i_B\\i_C\end{pmatrix} + \frac{d}{dt}\begin{pmatrix}L&0&0\\0&L&0\\0&0&L\end{pmatrix}\begin{pmatrix}i_A\\i_B\\i_C\end{pmatrix} + \begin{pmatrix}e_A\\e_B\\e_C\end{pmatrix} \quad (19)$$

Where $L=L_S-M$ is the phase equivalent inductance. The equivalent circuit of the BLDCM is shown in Figure b. This equivalent circuit can be simplified as Figure c, because only two of three phases are conducting simultaneously at any time.

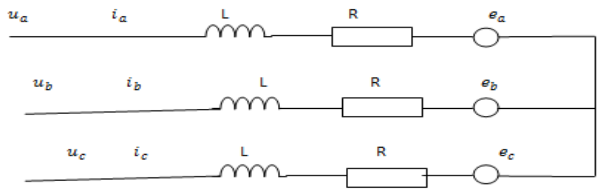

Figure b. the equivalent circuit of the BLDCM

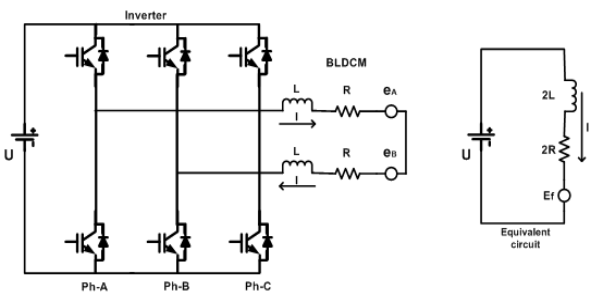

Figure c. The simplified equivalent circuit of BLDCM

When phase A and phase B are conducting, the electrical equation can be written as:

$U_{AB}=E_f+2RI+2LdI/dt$ (20)

The torque equation of BLDCM is:

$T_e = (e_a i_a+e_b i_b+e_c i_c)/\omega$ (21)

$\omega=2\pi n/60$ (22)

The mechanical equation of BLDCM is:

$T_e-T_L=J\ d\omega/dT$ (23)

Where,

T_e= motor torque

T_L= load torque

J = total inertia of rotor and load.

Suppose

$K_e=E_f/n$ (24)

$K_T=T/I$ (25)

Then the transfer function of BLDCM can be obtained as below:

$$\frac{n}{u}=\frac{Km}{2(Ls+R)Js+KeKm} \quad (26)$$

The block diagram of the BLDCM model is shown in Figure d.

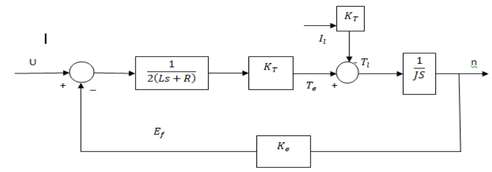

Figure d. Block diagram of the model of the BLDCM

3.2 Model of Other Parts of the BLDCM

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:

K_{PWM}= 240/3.3 =72.73 (27)

The sample unit of the velocity loop is considered as delay unit. The delay time is the reciprocal of the sample frequency of velocity loop.

$$G_d=\frac{1}{1\times10^{-3}s+1} \quad (28)$$

3.3 Model of the PSSBLDCM

With the models of BLDCM and other parts of the PSSBLDCM, the whole model of the PSSBLDCM can be obtained as shown in Figure 5.5. P, V and C are the position, velocity and current controllers respectively in Figure e.

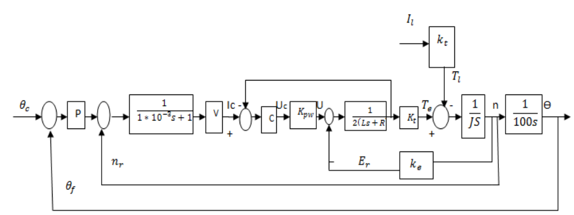

Figure e. The model of the PSSBLDCM

3.4 DESIGN OF THE PSSBLDCM

With the model obtained above, the design of PSSBLDCM can be accomplished to satisfy the frequency response design requirement of the position loop. PID controllers which are implemented in position loop, velocity loop and current loop can be designed using a frequency domain method. According to the design requirements of the system, the frequency response of position loop is:

$f_p=6H_Z$ (29)

Then the frequency response of velocity loop can be obtained:

$f_v=16.67f_P=100H_Z$ (30)

Then the frequency response of current loop is obtained:

$$f_i = 10f_V = 100H_Z \quad (31)$$

To design a PSSBLDCM is to design the three loops in turn. The order of the design is:

First - the current loop,
Second - the velocity loop and
Last - the position loop.

This is because the former loop is one part of the latter loop.

3.4.1 Design of the Current Loop

A proportional controller is applied in the current loop, and KPC is the gain of the controller. In the real system, the electromagnetic time constant is far less than the mechanical time constant. In this paper, the two time constants of BLDCM are:

$$T_i = L/R = 1.18X10^{-3}\,s \quad (32)$$
$$T_m = 2RJ / (K_e K_T) = 2.76 X 10^{-2} s \quad (33)$$

Because the effect of the Back-EMF on current loop is ignored, the block diagram of the current loop is shown in Figure f.

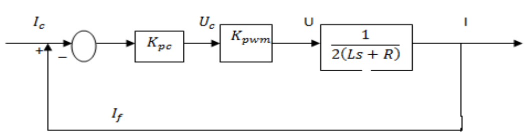

Figure f. The block diagram of the current loop

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

$$\Phi_c = \frac{Kpc\,Kpwm}{2Ls+2R+Kpc\,Kpwm} \quad (34)$$

According to the definition of the bandwidth, KPC is:

$$K_{PC} = (4L\pi f_I - 2R)/ K_{PWM} = 2.99 \quad (35)$$

Then the closed-loop transfer function of the current loop is:

$$\Phi_c = \frac{217.46}{0.046s+251.46} \approx \frac{1}{1.59\times10^{-4}s+1} \quad (36)$$

The open-loop transfer function of the current loop is:

$$\Phi_C = \frac{1}{1.59\times10^{-4}s} \quad (37)$$

The cut-off frequency of the current loop is:

$$\Omega_{CC} = 6.29X10^3 \text{ r ad /s} \quad (38)$$

The closed-loop bode diagram of the current loop is shown in Fig.g.

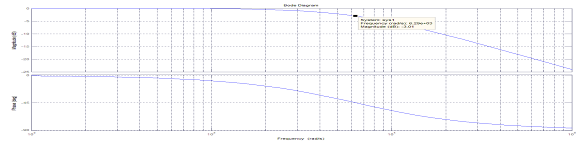

Fig.g. The closed-loop bode diagram of the current loop

3.4.2 Design of the Velocity Loop

A proportional controller is applied in the velocity loop, and K_{PV} is the gain of the controller. The block diagram of the velocity loop is shown in Figure h.

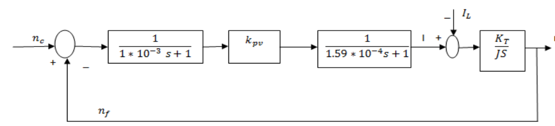

Figure h. The block diagram of the velocity loop

As both the delay unit and the current loop are low-inertia units, which mean the time constant of them are far less than the mechanical time constant, the two units in series are equivalent to one low inertia unit. And the equivalent time constant is:

$$T = 0.001 + 0.000159 = 1.159X\,10^{-3}s \quad (39)$$

The equivalent inertia unit is:

$$G = \frac{1}{1.159X10^{-3}s+1} \quad (40)$$

$$\Phi_V = \frac{5.11X10^6 K_{P\upsilon}}{s^2+8.63\times10^2 s+5.11\times10^6 K_{P\upsilon}} \quad (41)$$

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

$$K_{PV} = 7.50\times10^{-2} \quad (42)$$

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

$$\Phi_V = \frac{3.83X10^5 K_{P\upsilon}}{s^2+8.63\times10^2 s+5.11\times10^5 K_{P\upsilon}} \quad (43)$$

The open-loop transfer function of the velocity loop is:

$$\Phi_V = \frac{3.83X10^5}{s^2+8.63\times10^2 s} \quad (44)$$

The cut-off frequency of the velocity loop is:

$$\Omega_{CV} = 4.02\times10^2 \text{ r ad / s}$$

5.45

The closed-loop bode diagram of the velocity loop is shown in Figure i.

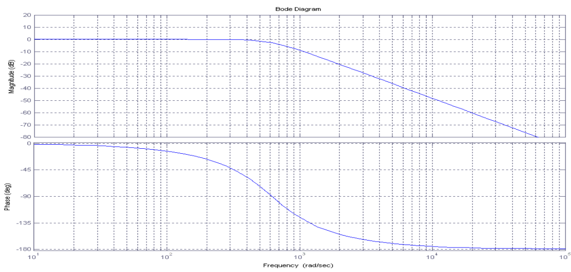

Fig.i. the closed-loop bode diagram of the velocity loop

3.4.3 Design of the Position Loop

A PI controller is applied in the position loop to eliminate the static error. K_{PP} is the gain of the PI controller, and K_{IP} is the integral coefficient. Ignoring the high order terms, the reduced order closed-loop transfer function of the velocity loop can be obtained as below:

$$\frac{n}{nc} = \frac{3.83X10^5}{8.63\times10^2 s+3.83X10^5} = \frac{1}{2.25\times10^{-3}s+1} \qquad (46)$$

The block diagram of the position loop is shown in Figure 5.10.

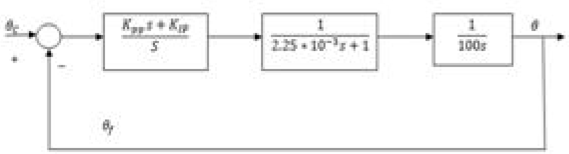

Fig.j. the block diagram of the position loop

The closed loop transfer function of the position loop is:

$$\phi_P = \frac{K_{PP}S+K_{IP}}{2.25\times10^{-1}s^3+100\,S^2+K_{PP}S+K_{IP}} \qquad (47)$$

According to the definition of bandwidth, the following is obtained:

$$\frac{\sqrt{K^2_{PP}\omega_b^2+K^2_{IP}}}{\sqrt{(K_{IP}-100\omega_b^2)^2+(K_{PP}\omega_b-2.25\times10^{-1}\omega_b^3)^2}} = \frac{1}{\sqrt{2}} \qquad (48)$$

Where ω_b = 2×6×3.14 = 37.70 r ad / s.

The open-loop transfer function of the Position loop is:

$$\Phi_P = \frac{K_{PP}S+K_{IP}}{100s^2(2.25\times10^{-3}s+1)} \qquad (49)$$

The phase margin is greater than π /4, then:

$$\frac{\sqrt{K^2_{PP}\omega^2_{CP}+K^2_{IP}}}{100\omega^2_{CP}\sqrt{\left(5.34\times^{-4}\right)^2\omega^2_{CP}+1}} = 1 \qquad (50)$$

$$Arc\ t\ g\frac{K_{PP}\omega_{CP}}{K_{IP}} - arctg2.25\times10^{-3}\omega_{CP} > \frac{\pi}{2} \qquad (51)$$

Where w_{cp} is the cut-off frequency of the position loop

From 48, 50 and 51, we can get:

K_{PP} =3505 (52)

K_{IP} = 200 (53)

Than the transfer function of the position controller is:

$$P = 3505 + \frac{200}{s} \qquad (54)$$

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

$$\phi_P = \frac{1.56\times10^4 s+8.89\times10^2}{s^3+4.44\times10^2 s^2+1.56\times10^4 s+8.89\times10^2} \qquad (55)$$

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

$$\Phi P = \frac{1.56\times10^4 s+8.89\times10^2}{s^3+4.44\times10^2 s^2} \qquad (56)$$

The cut-off frequency of the position loop is:

w_{cp} =35 r a d / s (57)

The closed-loop bode diagram of the position loop is shown in Fig.k.

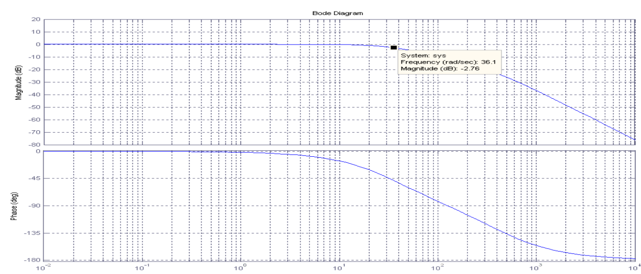

Fig.k. the closed-loop bode diagram of the position loop

Therefore the design of the current, velocity and position loops is completed, and all parameters of these controllers are given according to the design requirement of frequency response

3.5 Simulation Results

The PSSBLDCM is modeled in the section III, and the whole system is simulated in SIMULINK. The block diagram of the simulation is shown in Figure l.

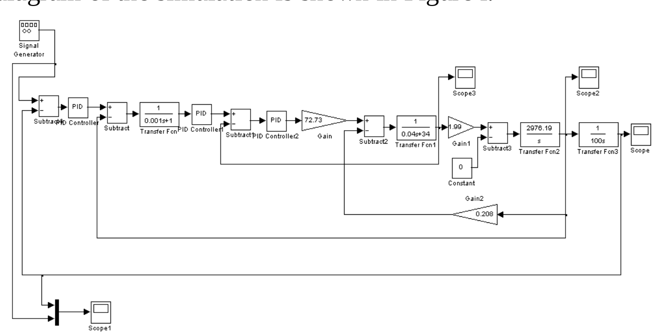

Figure l. The block diagram of the simulation

In this paper, the position command is a signal which the load is driven to rotate following. Two position commands are used here. First is a sinusoidal signal whose amplitude is set to be 2°(0.0349rad) and frequency is 6Hz. Second is a step signal whose amplitude is set to be 40°(0.6981rad). And the responses of the simulated PSSBLDCM to the two signals are sinusoidal response and step response respectively. The sinusoidal response of the system is shown in Figure m, in which the sinusoidal response is compared with the first position command.

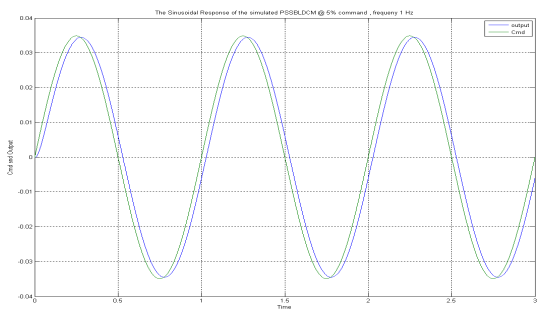

Figure m. The sinusoidal response of the simulated PSSBLDCM

The step response of the system is shown in Figure m, in which the step response is compared with the second position command. It can be seen that the overshoot of response is very small. The position error can be computed from the data of Figure m which is less than 0.1° and satisfies the design requirement.

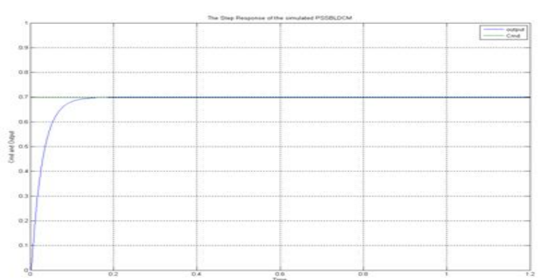

Figure .m. The step response of the simulated PSSBLDCM

3.6 CONCLUSION

In this a frequency domain design method of PSSBLDCM is represented which is to determine the frequency responses of the velocity and current loop according to the design requirement of the position loop. A design method of the controllers applied in the three loops is also discussed. The results prove the feasibility of the frequency domain design method. It is shown that this method is a general method which has the reference value in other position servo-system using BLDCM.

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