Minor Project ESL 263

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1 Objective:

Simulation of a four-quadrant chopper fed separately-excited DC motor running a constant-torque load in closed-loop control mode.

2 Procedure:

The following steps outline the process to simulate a four-quadrant chopper-fed separately-excited DC motor in closed-loop control mode:

2.1 Four-Quadrant DC Chopper:

- Use various libraries in Simulink and make four quadrant DC Chopper and use variables defined in m-file to input the parameters in the blocks. Make a control system to allow bi-directional voltage and current for the chopper to operate in all 4 modes.

2.2 Motor Dynamic Model:

- Implement the motor's dynamic model using the 3 equations:
  - Voltage equation: $V_a = \epsilon_b + I_a R_a + L_a \frac{d(I_a)}{dt}$
  - Torque equation: $T = K_e I_a$
  -Mechanical: $J\frac{d(\omega_m)}{dt} + B\omega = T - T_{Load}$ [In steady state,$\frac{d(\omega_m)}{dt} = 0$]

2.3 Closed-Loop Control System:

- Implementing a closed-loop control with speed and current control loops.
  - Using filter, PI controller and saturation to get $I_{reference}$ from ω and $\omega_{reference}$ (i.e. speed controller) as shown in the Figure 1
  -Use a current controller to get $V_{reference}$ from I_a and $I_{reference}$ by using PI controller, saturation and feed forward input as shown in Figure 2.

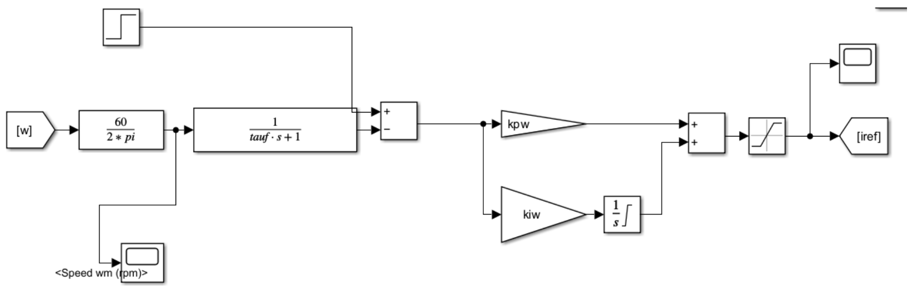

Figure 1: Speed Control

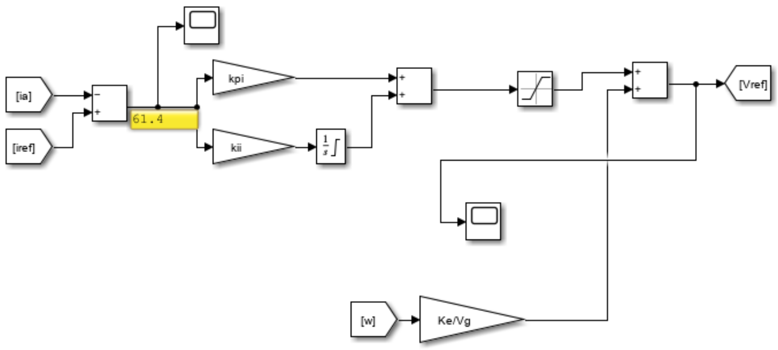

Figure 2: Current Control

2.4 Simulation in MATLAB/Simulink:

- Simulate the system under different operating modes (motoring and braking) and monitor performance metrics such as speed, torque, and current waveforms by connecting the speed, current control loops to the DC machine.

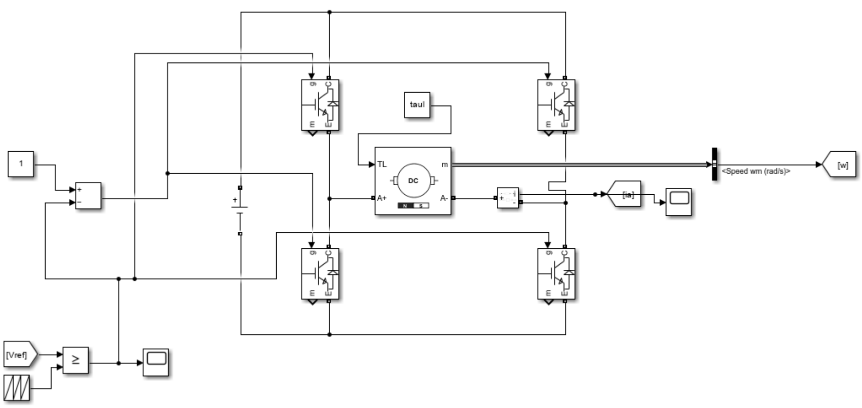

Figure 3: 4 Quadrant DC Chopper

2.5 Parameter Declaration:

- We define the following parameters: V_g =800, R_a= 0.052, L_a= 1e-3, f_{sw}= 2000, a= $\sqrt{2}$+1, P=250*745.7, K_e=3.65, J= 5, ω_{mr}=1250. We also declare the current and speed control variables k_p^i , k_s^i , k_p^w , k_s^w which we will give values as per the need. We also define $\tau_f = \frac{1}{2\pi 10}$, as it is generally used in filtering.

2.6 Simulation Results:

- We can see that the output in scope from the current control loop has faster response, around 10x(by comparing the ripple frequency of V_{ref} and ω) than the speed control loop because of current control being inside of the speed control loop. I_a ripple frequency will also be faster than ω ripple frequency because of the faster feedback.
- The response of the current control is 1^{st} order and the speed control is 3^{rd} order from the open loop transfer functions.
- At rated input, we get overshoot: ΔI_a= $0.3 I_a$, which can be reduced by increasing the value of inductance.

3 Simulation Exercise:

3.1 Question 1:

At steady state,

$$V_a = E_b + i_{avg} R$$

$$E_b = K_b \cdot \omega_{\text{rated}} = 3.65 \times 1250 \times \frac{2\pi}{60} = 477.8\,\text{V}$$

$$i_{avg} = \frac{T}{K_b} = \frac{P}{\omega_{\text{rated}} \cdot K_b} = \frac{P}{E_b} = 390.3\,\text{A} \quad \text{(assuming rated torque)}$$

$$i_{avg} R = 20.3\,\text{V}$$

$$V_a = 477.8 + 20.3 = 498.1\,\text{V}$$

$$V_a = V_{\text{ref}} \times V_g \quad \Rightarrow \quad V_a = (2d - 1) V_g$$

$$d = \frac{1}{2}\left(\frac{V_0}{V_g} + 1\right) = 0.811$$

We can verify this with the scope output of V_a to get duty cycle ≈ 0.81, here.

3.2 Question 2

At rated torque and speed conditions,

$$I_{avg} = \frac{\tau_{\text{rated}}}{K_b} = \frac{P}{\omega_{\text{rated}} \cdot K_b} = \frac{P}{\epsilon_b} = \frac{186500}{477.8} = 390.3\,\text{A}$$

3.3 Question 3

Current control parameters:

$$\text{We know:} \quad \frac{K_p^i}{K_i^i} = \frac{L_a}{R_a} \quad \text{and} \quad K_i^i = \left(\frac{2\pi f_{sw}}{10}\right) \cdot \frac{R_a}{V_g}$$

$$K_i^i = \frac{2\pi \times 2000 \times 0.052}{10 \times 800} = 0.082$$

$$K_p^i = \frac{0.082 \times 0.001}{0.052} = 0.0016$$

Speed control parameters ($K_i^\omega$and K_p^ω)

$$\omega_{BW} = \sqrt{\omega_p \omega_z} \quad , \quad \frac{\omega_p}{\omega_z} = \sqrt{2} + 1 \quad , \quad |G_{\text{ol}}|_{\omega=\omega_{\text{BW}}} = 1$$

$$\frac{K_i^\omega K_b}{J} \cdot \frac{\sqrt{1 + \frac{\omega_p^2}{\omega_z^2}}}{\sqrt{1 + \frac{\omega_{BW}^2}{\omega_z^2}}} \cdot \frac{1}{\omega_{BW}^2} = 1$$

$$K_i^\omega K_b \frac{(1+\sqrt{2})}{J} = \omega_{BW}^2$$

$$Also, \quad \omega_z = \frac{K_i^\omega}{K_p^\omega} \quad , \quad \omega_p = \frac{1}{\tau_i + \tau_f}$$

$$\tau_i = \frac{R}{K_i^i V_g} \quad \text{and} \quad \tau_f \text{ for filter circuit assuming to be} \quad \frac{1}{2\pi(10)}$$

So,

$$\tau_i = 0.008, \quad \tau_f = 0.016, \quad \omega_p = 59.85$$

$$K_b \frac{(1+\sqrt{2})}{J} = \frac{\omega_p}{K_p^\omega}$$

$$K_p^\omega = \frac{\omega_p J}{K_b(1+\sqrt{2})} = 33.96$$

$$\frac{\omega_p}{K_i^\omega} K_p^\omega = (1+\sqrt{2})^2 \quad \Rightarrow \quad K_i^\omega = \frac{\omega_p K_p^\omega}{(1+\sqrt{2})^2} = 348.72$$

3.4 Question 4

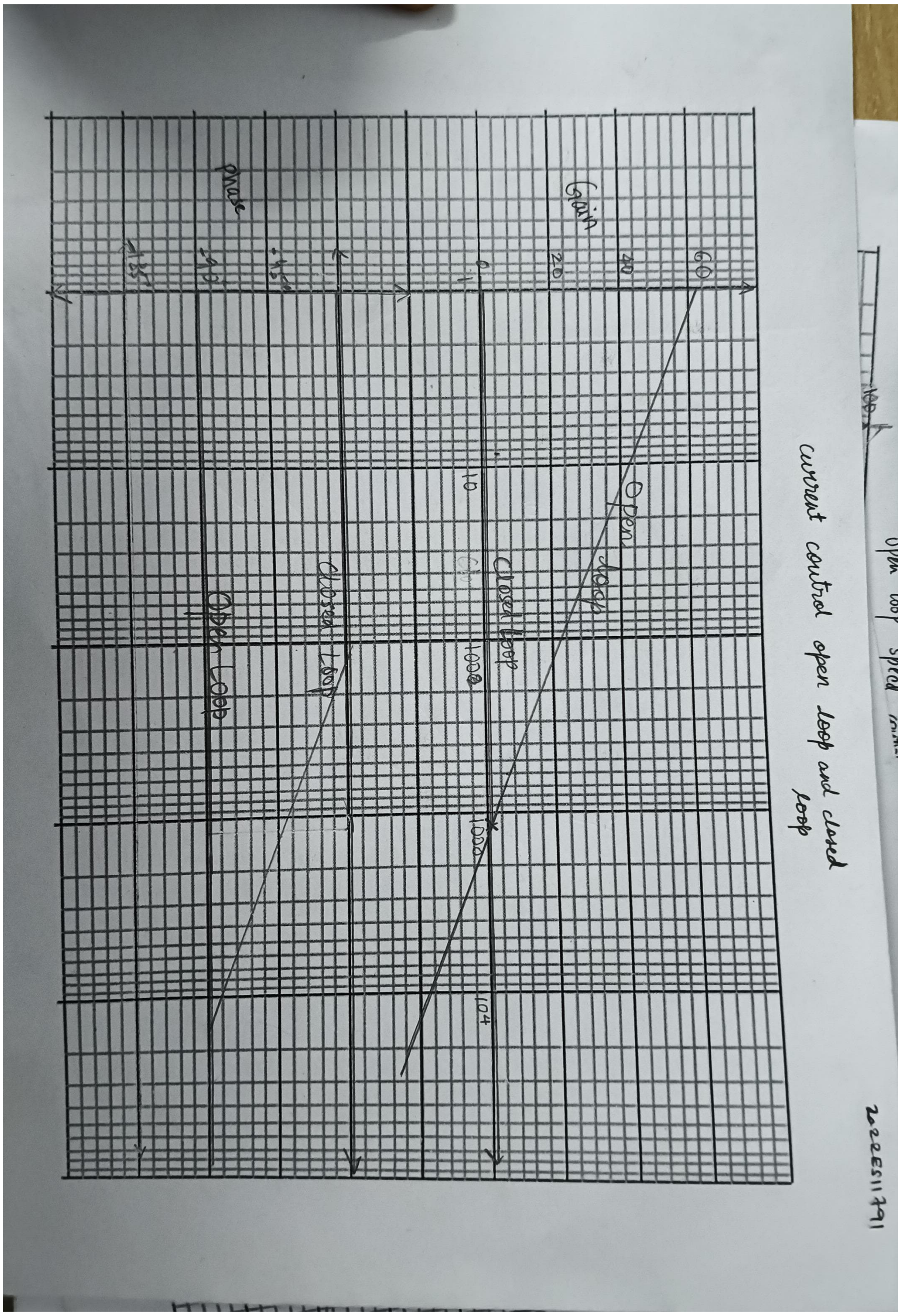

Figure 4: Current Control Open And Closed Loops

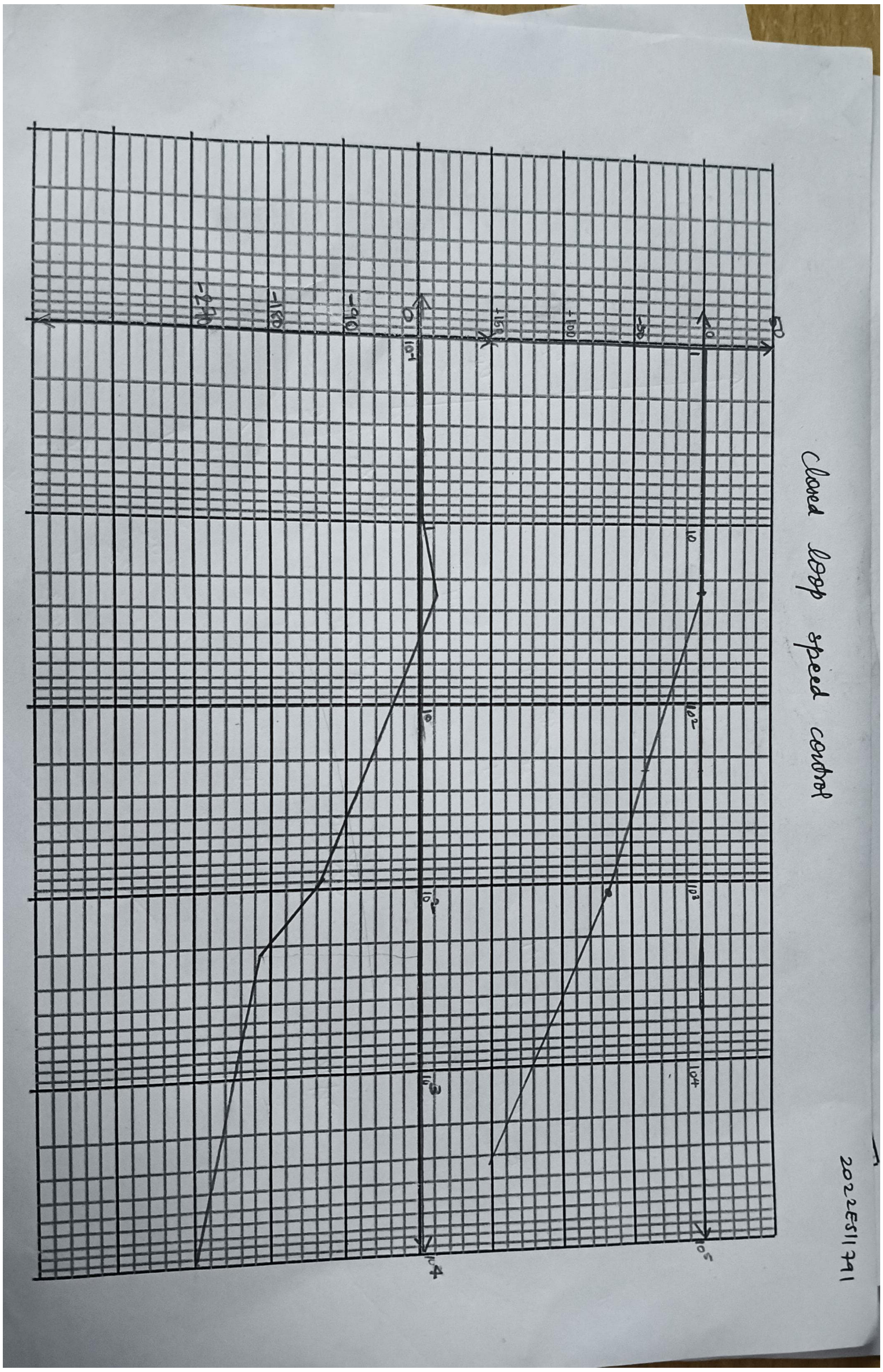

Figure 5: Closed Loop Speed Control

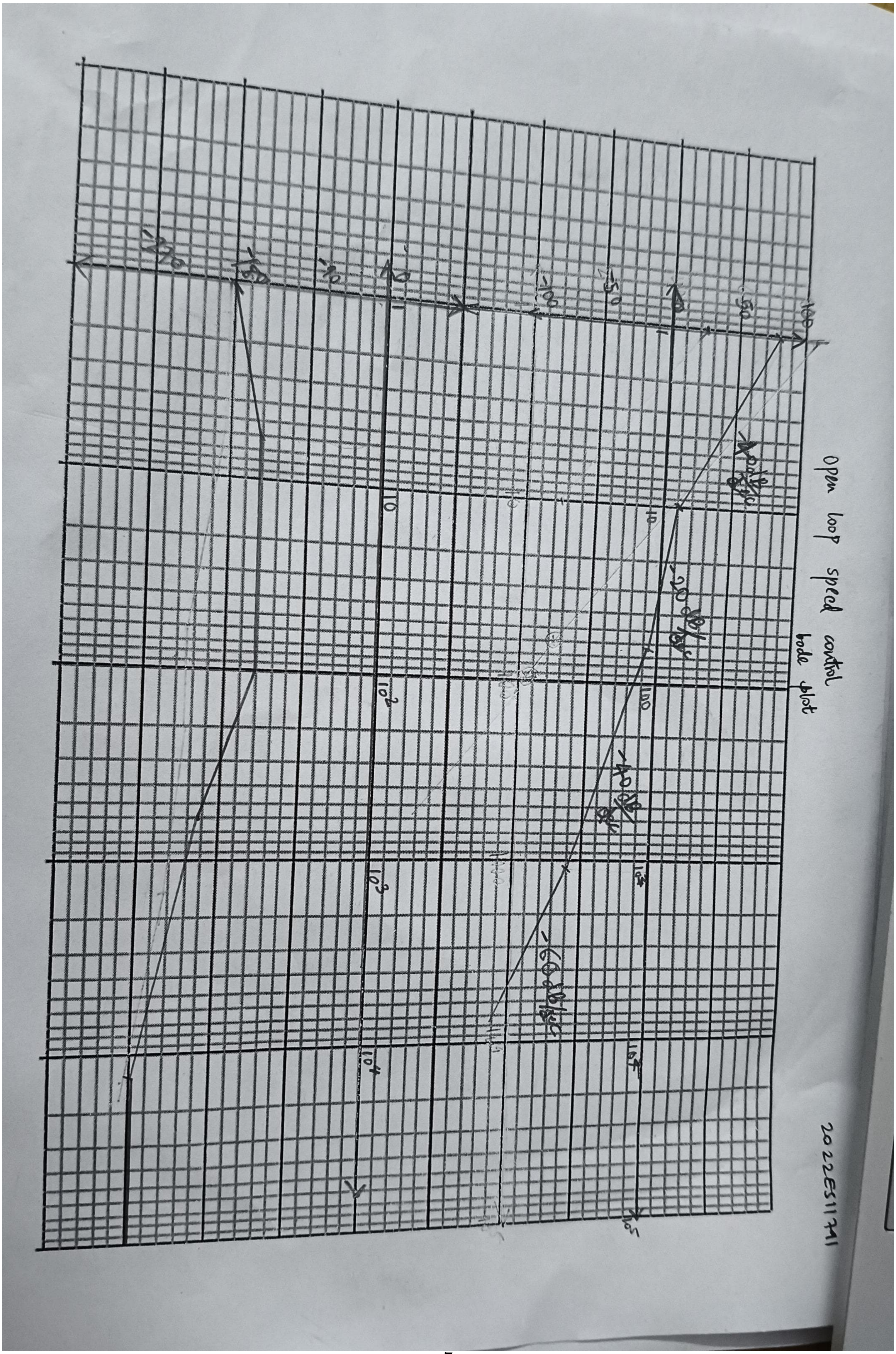

Figure 6: Open Loop Speed Control

3.5 Question 5

We know that the open loop transfer function of current control is:

$$G_{ol} = \left(\frac{K_i}{s}\right)\left(\frac{V_g}{R_a}\right)\left(1+\frac{sK_p}{K_i}\right)\left(\frac{1}{1+\frac{sL_a}{R_a}}\right)$$

and

$$\left(1+\frac{sK_p}{K_i}\right)\left(\frac{1}{1+\frac{sL_a}{R_a}}\right) = 1$$

so we get the open loop transfer function as

$$G_{ol} = \left(\frac{K_i}{s}\right)\left(\frac{V_g}{R_a}\right),$$

thus getting G_{cl} as:

$$G_{cl} = \frac{1}{1+\frac{sR_a}{K_iV_g}}$$

which can be multiplied with 1/s to get step response:

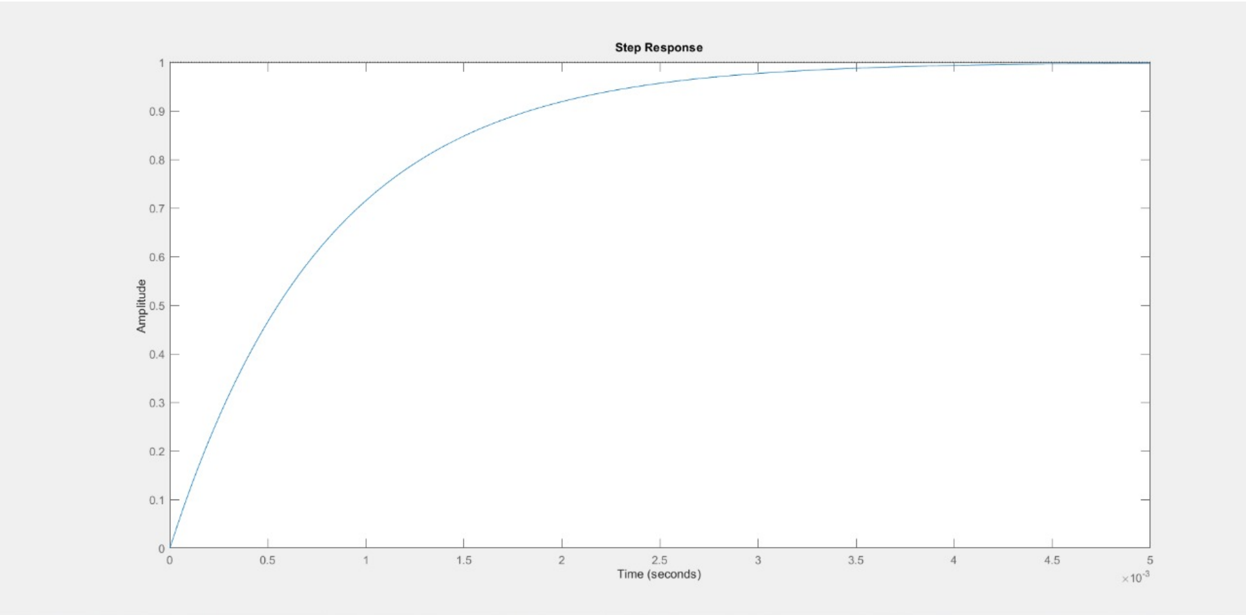

Figure 7: Current Loop Closed Step Response

For 1^{st} order response, we know overshoot is 0 and settling time is 5τ, which is $\frac{5R_a}{K_iV_g} = 3.97\text{x}10^-3$ which matches with the plot. For speed control, we have the following open loop transfer function:

$$G_{ol} = \left(\frac{K_i^\omega}{s^2}\right)\left(1+\frac{sK_p^\omega}{K_i^\omega}\right)\left(\frac{1}{1+sT_i}\right)\left(\frac{1}{1+sT_f}\right)\left(\frac{K_i}{J}\right)$$

and the corresponding closed loop transfer function:

$$G_{cl} = \left(\frac{K_b(sK_p^{\omega} + K_i^{\omega})}{J \cdot \tau_i \cdot \tau_f s^4 + J \cdot (\tau_i + \tau_f)s^3 + Js^2 + K_b(sK_p^{\omega} + K_i^{\omega})} \right)$$

which can be multiplied with 1/s to get step response:

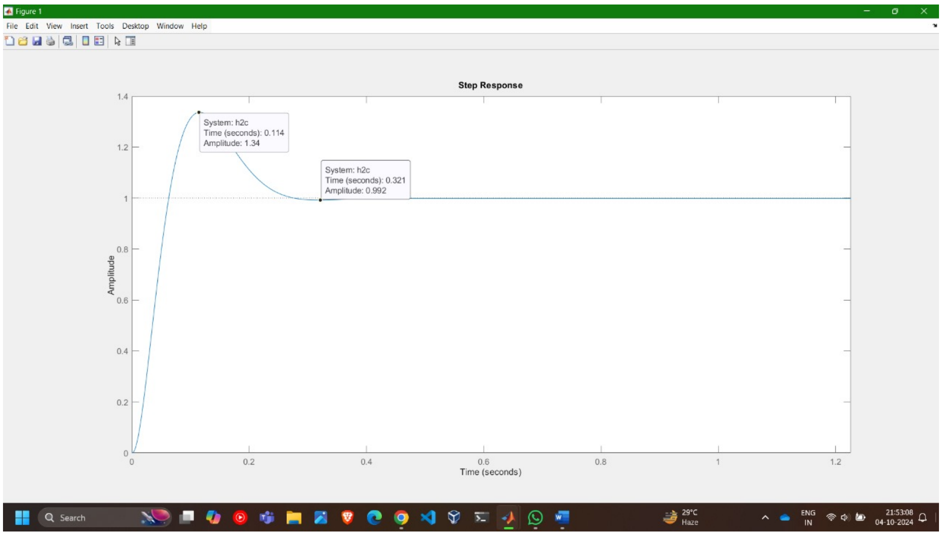

Figure 8: Speed Control Closed Loop Step Response

Here, we get the overshoot as 0.34 at t=0.114 seconds and settling time as 0.321 seconds.

3.6 Question 6

3.6.1 Forward Motoring

ω is kept at 500 rpm, and torque goes till 1800 Nm

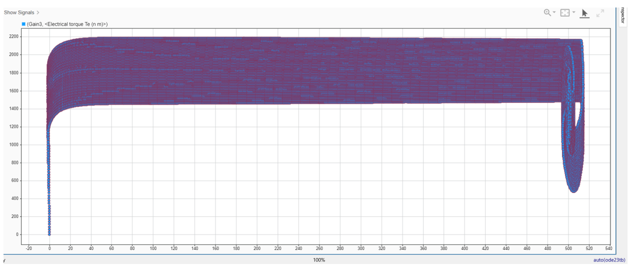

Figure 9: First Quadrant

Dynamic conditions: We observe positive rated torque increases till the value of ω_{mech} reaches 500rpm, then τ_{elec} decreases causing brakes and eventually decreases the speed and decreases it till torques value becomes less than 1200, then the graph spirals down to its steady state value.

Steady State: The steady state for the ω_{mech} is attained at around 1200Nm and the speed attains its steady state value of 500rpm.

3.6.2 Reverse Motoring

ω is kept at 500 rpm, and torque goes till 1800 Nm

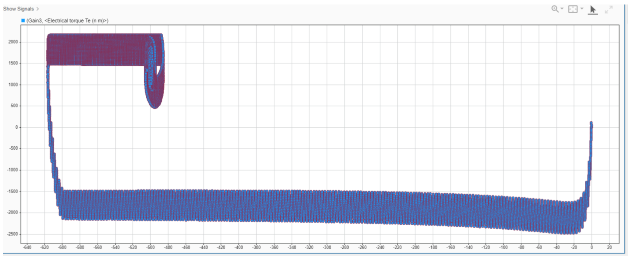

Figure 10: Third Quadrant

Dynamic conditions: We observe negative torque is in motoring mode till the value of ω_{mech} reaches -620rpm, then the graph spirals up to its steady state value.

Steady State: The steady state for the ω_{mech} is attained at around -1200Nm and the speed attains its steady state value of -500rpm.

3.6.3 Reverse Braking

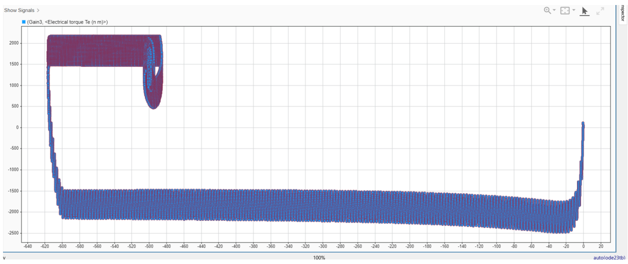

Figure 11: Second Quadrant

Dynamic conditions: We observe positive rated torque increases till the value of ω_{mech} reaches -620rpm, it is seen that the motor rotates in the negative direction, then the graph spirals down to its steady state value.

Steady State: The steady state for the ω_{mech} is attained at around 1200Nm and the speed attains its steady state value of -500rpm.

3.6.4 Forward Braking

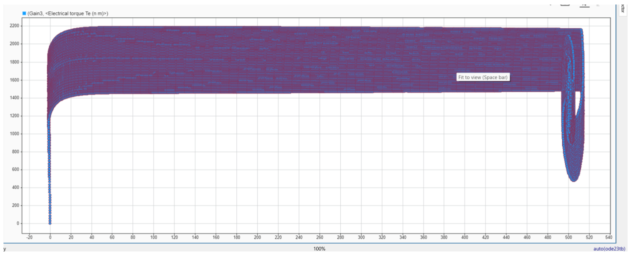

Figure 12: Fourth Quadrant

Dynamic conditions: We observe positive rated torque acts on the motor, which increase ω_{mech} till 515rpm, and the torque increases till 1800Nm, then the graph spirals down to its steady state value.

Steady State: The steady state for the ω_{mech} is attained at around 1200Nm and the speed attains its steady state value of 500rpm.

3.7 Question 7

We first run the motor at 0 load torque until it reaches steady state, at which the motor rotates at a constant speed of 1200rpm (which was set as rated). At t=3s, when the steady state is reached, load torque of 1424Nm(rated) is applied. The following effects are observed:

3.7.1 Speed Change:

The speed is initially constant at 1200rpm, then after 3 seconds, there is an immediate reduction in the motor speed, but then eventually settles at 1200 rpm. This is because the closed loop system compensates for the increased load and helps the speed to settle back to its desired value, ensuring the motor is able to bear wide range of torque while maintaining its speed.

3.7.2 Armature Current Change:

Initially, the graph for armature current is oscillating with mean value 0, so at no load torque, the armature current is almost 0. After we apply load torque at t=3s, there is an increase in current and oscillates for some time to settle at a higher value, which we get as we know τ is proportional to I_a.

3.8 Question 8

For peak to peak current ripple within 10%

$$E_b = 477.8\,\mathrm{V}, \quad I_{avg} = 390.3\,\mathrm{A}$$

$$V_g = I_{avg}R_a + L\frac{di}{dt} + E_b$$

$$\Delta I = \frac{(V_g - I_{avg}R_a - E_b)\cdot dT_s}{L} = 0.1224 \quad \leq \quad \frac{I_{avg}}{10}$$

$$\therefore L \geq \frac{10 \times 0.1224}{\frac{390.3}{10}} = 3.14\,\mathrm{mH} \quad \text{, more inductor needed} \Rightarrow 2.14\,\mathrm{mH}$$