Laboratory Five - Advanced Control Systems

Objectives

The objectives of this simulation study are to learn how to design and analyze cascaded PI control systems for a permanent magnet synchronous machine (PMSM) electrical system whose model we built in Lab 4. The simulation skills acquired in this lab can be extended to design power converter control, induction motor control and control of other electrical systems.

Lab Requirements

1. A maximum of three students are allowed per group. The groups must be fixed between Labs 4−5 and all group members must attend the same lab session. No exceptions will be made to these rules.
2. Due to the work required to complete the lab, students who do not attend a lab with their group will not receive a mark for the report. Remember to sign the attendance sheet.
3. Labs 4−5 will be combined into a single report worth 15% of your ACS grade. Please submit the report on Canvas. Only one submission is required per group.
4. Please ensure that the content included in your report is your own intellectual property. RMIT's policies on Academic Integrity will be observed while marking.

In the control system design, a cascade feedback and feedforward control system is configured for angular speed control. Figure 0.1 shows the speed control system configuration of a typical industrial PMSM drive.

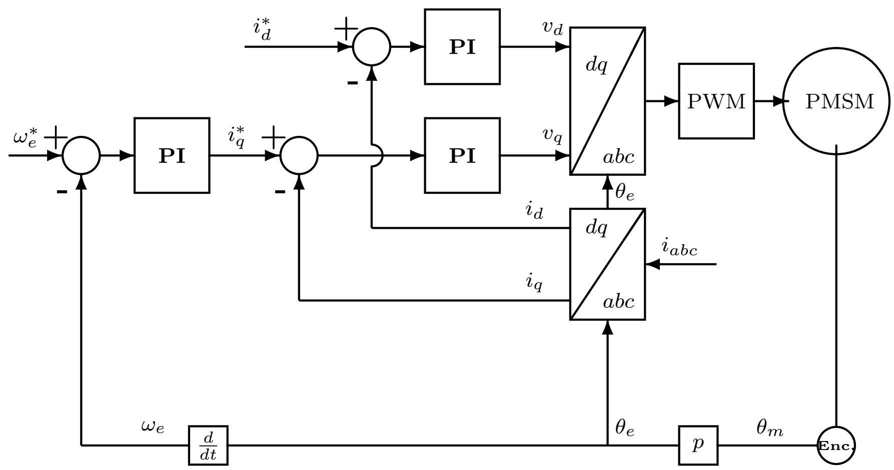

Fig. 0.1 Schematic diagram for cascade control of PMSM angular velocity

Model of PMSM

In the drive control systems, there are two PI controllers to control the d-axis and q-axis currents (i_d and i_q) and one PI controller in the outer-loop to achieve the primary control objective of regulating the speed, ω_e(see Figure 0.1). To design the PI controllers, we need to know the mathematical model of the AC machine, which is given by the differential equations in the $d-q$ frame of reference as:

$$\frac{di_d(t)}{dt} = \frac{1}{L_d}(v_d(t) - R_s i_d(t) + \omega_e(t) L_q i_q(t)) \tag{0.1}$$

$$\frac{di_q(t)}{dt} = \frac{1}{L_q}(v_q(t) - R_s i_q(t) - \omega_e(t) L_d i_d(t) - \omega_e(t)\phi_{mg}) \tag{0.2}$$

$$\frac{d\omega_e(t)}{dt} = \frac{p}{J_m}(T_e - \frac{B_v}{p}\omega_e(t) - T_L) \tag{0.3}$$

$$T_e = \frac{3}{2}p[\phi_{mg} i_q + (L_d - L_q) i_d(t) i_q(t)] \tag{0.4}$$

where the parameters in the mathematical model are given as

1. ω_e is the electrical speed and is related to the rotor speed by $\omega_e = p\omega_m$ with p denoting the number of pole pairs, v_d and v_q represent the stator voltages in the $d-q$ frame, i_d and i_q represent the stator currents in

this frame, and T_L is load torque that is assumed to be zero if no load is attached to the motor. The electromagnetic torque T_e in (0.3) consists of two parts: the one produced by the flux of the permanent magnet ϕ_{mg} and the other by i_d and i_q, respectively. The complete expression of T_e is given by (0.4).

2. Physical parameters used in the simulation are the same as Lab 4 and are given here for reference. $\phi_{mg} = 0.125\ Wb$, $L_d = 7 \times 10^{-3}\ H$, $L_q = 7 \times 10^{-3}\ H$, $R_s = 2.98\ \Omega$, $B_v = 11 \times 10^{-5}\ Nm \cdot s$, $p = 2$, $J_m = 0.47 \times 10^{-4}\ kg \cdot m^2$.

Task-1: Current Controller Design

1. Find two Laplace transfer functions for the design of the current PI controllers for i_d and i_q. By looking at the system block diagram Fig. 0.1, we are interested in transfer functions $G_1(s) = \frac{I_d(s)}{V_d(s)}$ and $G_2(s) = \frac{I_q(s)}{V_q(s)}$. Refer to the book '*PID and Predictive Control of Electrical Drives using MATLAB/Simulink*' (soft copy free to download from RMIT library).
2. Check the order of the open loop transfer functions $G_1(s)$ and $G_2(s)$ and if they can be expressed in the form of $\frac{b}{s+a}$. Moreover, assess if PI control is the right type of controller for this.
3. Design the current PI controllers with the following closed-loop performance specifications: the damping coefficient $\xi = 0.707$ and the closed-loop bandwidth
$$w_n = \left(\frac{1}{1-\gamma_1}\right)\frac{R_s}{L_q} \tag{0.5}$$
where γ_1 is chosen between 0.8 and 0.95. Recall that a standard second order control system expression is given by $s^2 + 2\xi\omega_n s + {\omega_n}^2$.
4. Compare the coefficients of your closed-loop system denominator (given by $1 + C_x(s)G_x(s)$) with the standard second order polynomial and find out equations for the controller parameters K_{cd}, τ_{id} and K_{cq}, τ_{iq} for d and q axis control loops, respectively.
5. Make a copy of MATLAB m-file that was generated to define parameters in Lab 04 and save it with another suitable name such as *Lab5Parameters.m*.
6. Open this file and below the previously written instructions, define $\xi = 0.707$, and γ_1 and ω_n as given above. Note: the bandwidth for both d and q axis controllers is ω_n.
7. Proceed to type the equations that you formulated for PI control parameters in the step-4. Save this file by clicking 'Save' icon.

Task-2: Speed/Velocity Controller Design

1. Find the transfer function model for the speed controller design. We are interested in the transfer function $G_3(s) = \frac{\Omega_e(s)}{I_q^*(s)}$. Refer to the book '*PID and Predictive Control of Electrical Drives using MATLAB/Simulink*' (soft copy free to download from RMIT library).
2. Check the order of the transfer function $G_3(s)$ and if it can be expressed in the form of $\frac{b}{s+a}$. Moreover, assess if PI control is the right type of controller for this.

3. Design the speed PI controller with the following closed-loop performance specifications: the damping coefficient $\xi = 0.707$ and the closed-loop bandwidth
$$w_{nv} = \left(\frac{1}{1-\gamma_2}\right)\frac{B_v}{J_m} \tag{0.6}$$
where the parameter γ_2 is selected in the range between 0.8 and 0.95.
4. Compare the coefficients of your closed-loop system denominator (given by $1 + C_x(s)G_x(s)$) with the standard second order polynomial and find out equations for the controller parameters K_{cv}, τ_{iv} for speed/velocity control loop.
5. Open the *Lab5Parameters.m* m-file and below the previously written instructions, define γ_2 and ω_{nv} as given above.
6. Proceed to type the equations that you formulated for K_{cv}, τ_{iv} control parameters in the step-4. Save and run this file so that all the controller parameters appear in the workspace.

Task-3: Simulation of Closed-loop Control of Speed/Velocity

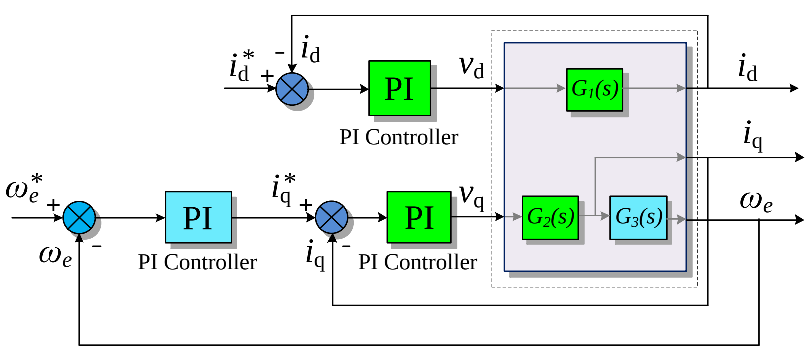

Fig. 0.2 Block diagram for closed-loop control of PMSM

1. Make a copy of the *PMSMModel.slx* file from Lab 04 and save it with a suitable name such as '*PMSMModel_Control.slx*'.
2. Open this new file and identify the inputs (v_d, v_q) and outputs (i_d, i_q, ω_e) of your Simulink model of PMSM.
3. Now by holding the left-click on mouse, select the whole Simulink model, leaving only the inputs and output terminals. Press right-click anywhere on the selected area and choose 'Create Subsytem from Selection'. This will enclose the whole Simulink model in a subsystem box with inputs on the left and outputs on the right.

4. Using your knowledge from Lab 02, find 'PID' block from Library Browser and change it to 'PI'. Make three copies of the 'PI' control block and close the control loops on i_d, i_q and ω_e. Use Fig. 0.2 as a reference for doing this.
5. Configure the three PI controllers with their respective parameters. Here, make sure to use the same spellings for parameters as you did in the m-file. Otherwise, Simulink will generate an error.
6. Find and connect 'Constant' blocks to i_d^* and ω_e^* terminals. The reference signal for i_d is zero, and the reference signal for ω_e is 300. Configure the 'Constant' blocks to reflect these reference values.
7. Choose the simulation time as 1 seconds. At half of your simulation time, add a step disturbance in the form of load torque T_L. Do this by replacing the 'Constant' block on 'Tm' terminal of the 'Permanent Magnet Synchronous Machine' block in the subsystem with a 'Step' block. Choose its step time as half of your simulation time and the final value as `TL`.
8. Save this Simulink file and simulate it. Tuning a cascade control system is related to the closed-loop performance specifications of both inner-loop and outer-loop systems. Try the following combinations of γ_1 and γ_2.

   a. $\gamma_1 = \gamma_2 = 0.8$;
   b. $\gamma_1 = \gamma_2 = 0.93$;
   c. $\gamma_1 = 0.93$; $\gamma_2 = 0.8$;
   d. $\gamma_1 = 0.8$; $\gamma_2 = 0.93$.

9. Record and observe the sum of squared errors for i_d and ω_e to find any performance differences.