In this assignment you will develop a drive system for the 500-hp Induction Motor (book page 244). Assume a mechanical load with inertia \( J_{\text{load}} = 3.5 \text{kg} \cdot \text{m}^2 \) and the torque-speed characteristic
\[
T_m = 0.2 \text{sgn}(\omega_m)T_b + 0.8T_b \frac{P^2}{4\omega_b} \omega_m^2.
\]
Assume \( \omega_b \approx 377 \text{ rad/sec} \) (\( f_b = 60 \text{ Hz} \) base frequency).

### Part 1. Scalar Volts/Hertz Controller

Calculate the dc voltage that will be required to operate this motor up to 120% of the nominal voltage and speed assuming Voltage Source Inverter (VSI) with modulation: a) Sine Triangle PWM; b) Sine Triangle PWM with 3\(^{rd}\) Harmonic Injection; and c) Space-Vector Modulation. Round this voltage up to the nearest tenth and assume that this is your dc source \( V_{dc} \). Choose one of the modulation techniques that you think is appropriate. Implement the Elementary Volts/Hertz controller for your motor. Assume frequency modulation ratio \( m_f = f_{\text{sw}}/f_b = 30 \).

(a) Start the drive system with zero initial conditions and commanded rotor speed \( \omega_{rm}^* = 100 \text{ rad/sec} \) at \( t = 5.0 \text{ s} \). Step-change the commanded rotor speed to \( \omega_{rm} = 200 \text{ rad/sec} \) and continue to run the model till \( t = 8.0 \text{ s} \). Plot variables \( v_{as\rightarrow f}, i_{as}, i_{dc\rightarrow f}, P_{dc\rightarrow f}, \Psi_m, T_e, T_m, \omega_{rm}, \omega^*_m, \text{ and } d \) (combine variables \( T_e \) and \( T_m \), \( \omega_{rm} \) and \( \omega^*_m \), and plot them together for better comparison). Here, the filtered voltage \( v_{as\rightarrow f} \) and current \( i_{dc\rightarrow f} \) are obtained by passing the respective signals through the low-pass filter \( H_f(s) = 1/(s \tau + 1) \), where \( \tau \approx 2e - 3 \), and \( P_{dc\rightarrow f} = v_{dc} \cdot i_{dc\rightarrow f} \). Observe and briefly explain the transient and accuracy with respect to operating at the desired speed.

(b) Harmonics: Plot several cycles of \( v_{as} \) and \( i_{as} \) corresponding to the steady state at full load at \( \omega_{rm}^* = 200 \text{ rad/sec} \) from the step (a). Calculate the harmonic spectrum (using FFT) for both waveforms and compare them. How are the harmonics in current and voltage similar/different? Increase \( m_f = f_{\text{sw}}/f_b = 50 \), and calculate/plot the harmonic spectrum \( v_{as} \) and \( i_{as} \) and explain how are the harmonics related to the switching frequency, and what changes in voltage and current harmonics?

(c) Slew-rate limit (SRL): Experiment by adding a SRL that you think will improve the transient response. Repeat the study (a) with your choice of slew-rate limit to show its effect. Briefly explain the improvements, explain the transients and accuracy with respect to operating at desired speed.

(d) Derive all parameters and implement the Fully-Compensated Volts/Hertz control discussed in class.

Repeat the study in step (c) with your SRL and compare the results, particularly in \( T_e, \omega_{rm} \) and \( \omega_{rm}^* \). How well this control performs? What is the speed error compared to previous cases (a) and (c)?

(e) Closed-Loop Speed Control. Assume that you added a speed sensor (position encoder). Add the Regulator Control (see page 496 in the book) to your rotor speed control loop. Now you have a closed-loop speed control of the motor. Consider the Regulator time constant \( \tau_{\text{reg}} \approx (0.05 \ldots 0.2)H \), where
\[
H = \left( \frac{1}{2} \right) \left( \frac{2}{P} \right) \frac{J\omega_b}{T_b}.
\]
Limit the integrated error in speed to \( \pm \omega_b/10 \) (apply this limit to the integrator saturation limits). Repeat study of step (a) and plot the same set of variables. Observe and briefly explain the transient and accuracy with respect to operating at the desired speed.

**Comment on the overall results:** Present and analyze the steady-state error of the rotor speed in each case. What is the stator current and dc current during the transients? Based on the plotted value of \( d \) for the given dc source, do you have enough dc voltage? What are the advantages and/or disadvantages of these speed-control schemes? What is the effect of slew-rate limit? What is the impact of increasing/decreasing the switching frequency of VSI?
Part 2. Indirect Field-Oriented Control of Induction Motor

Develop a Simulink model of an Indirect Field-Oriented Control (IFOC) strategy as discussed in class. Use the same motor, and dc source as in Part 1, but assume mechanical load \( T_m = T_b \frac{P^2}{4\omega^2} \omega^2 \). You can use a Current Source Inverter (CSI) with Hysteresis Modulation (choose a reasonable tracing error \( \varepsilon \)) or with Delta Modulation (choose a reasonable sampling frequency \( f_{samp} \)). Calculate or estimate the flux magnitude required for the nominal operation and use this value as the flux command \( \Psi_{dr}^{e*} \). Simulate the following transient:

(a) Start the model with zero initial conditions and zero torque command. At \( t = 4 \) s, step-change the torque command to \( T_e^{*} = 1500 \) N·m. Then, at \( t = 5.0 \) s, step-change the torque command to \( T_e^{*} = -2000 \) N·m and continue to run the model till \( t = 6.0 \) s. Plot variables \( v_{as-f} \), \( i_{dc-f} \), \( P_{dc-f} \), \( i_{as} \), \( \| \Psi_{qdr} \| \), \( T_e \), and \( \omega_{rm} \). Comment on results. How does \( \Psi_{dr}^{e*} \) and \( T_e \) deviate from the command values? What is the shape of \( i_{as} \) and \( v_{as-f} \) in different time intervals? Based on \( i_{dc-f} \) and \( P_{dc-f} \), what can you say about the power flow in different intervals? As you observe, is it possible to use the FOC to control the torque?

(b) Harmonics: Plot several cycles of \( v_{as} \) and \( i_{as} \) corresponding to the full load at \( T_e^{*} = 1500 \) N·m from the step (a). Calculate the harmonic spectrum (using FFT) for both waveforms and compare them. How the harmonics in current and voltage are similar/different? Experiment by changing current tracing error \( \varepsilon \) or \( f_{samp} \), and re-calculate the harmonic spectrums for one more case. How are the harmonics related to the switching frequency? How are the harmonics in VSI in Part 1 step (b) compare to this case?

(c) Investigate the effect of your drive performance on the knowledge of rotor resistance: i) Assume that the value of the rotor resistance in your machine is 30% higher, and repeat the study of step (a); Assume that the value of the rotor resistance is 30% lower, and repeat the study of step (a). As you observe in cases i) and ii), explain the influence of the rotor resistance information as compared to the ideal case in step (a).

(d) VSI: Assume a correct value of the rotor resistance. Now replace the CSI with the VSI (similar to the one used in Part 1) and implement the current control as we discussed in class (see notes, pp. 29-30). Repeat the study of step (a), first with the current derivatives and then without the derivatives (see p. 30). Comment of the result and the role/effect of including the derivative terms in the control. Also, compare the overall drive system response in step (a) and step (d). What are the pros and cons of using or not using the current derivatives; as well as using CSI vs. VSI?

(e) Closed-Loop Speed Control. Add a PI control to regulate the motor speed in a closed loop. Assume \( K_p = 150 \), \( K_i = 10K_p \), and limit the integral portion of the controller command as well as the overall torque command to \( \pm 1.2T_b \). Implement the following study: Start the model with \( \omega_{rm}^{*} = 0 \). Then, at \( t = 4 \) s, step the speed command to \( \omega_{rm}^{*} = 100 \) rad/sec and continue to run the model till \( t = 8.0 \) s. Plot variables \( v_{as-f} \), \( i_{as} \), \( T_e \), and \( \omega_{rm} \). Compare the results with Part 1 (a), (c)-(e).

(f) Remove the limit in the integral portion of the controller and repeat step (e). Experiment with controller gains to achieve the drive performance that you would like to have. Compare and comment on the results of (e) and (f). What is the effect of limits in PI controller?

Comment on the overall results. What is the steady-state speed error of the closed loop control in Part 2 with CSI and VSI? How does this compare to the controllers in Part 1? What are the advantages/disadvantages (in terms of currents, torque, speed of response, etc) of speed-control schemes in Part 1 vs. Part 2? What is the effect of limits in PI controller in Part 2? What are the advantages/disadvantages of using VSI vs. CSI?