The objective of the this project is to develop a Simulink-based semi-detailed simulation of a permanent-magnet AC motor drive that utilizes a sine-triangle modulator with third-harmonic injection. An equivalent circuit/block diagram is depicted in Fig. 1. Filter, motor, and control parameters are provided in Tables 1 through 3, respectively. For the modulator, use a 20-kHz triangular modulating waveform. Use subsystem blocks to organize the simulation into manageable subsystems as depicted in Fig. 2. The inverter switching (inside block labelled "Inverter" in Fig. 2) may be represented using standard Simulink components as shown in Fig. 3 (do NOT use SimPowerSystems or Simscape toolboxes). Assume all switches and diodes are ideal.

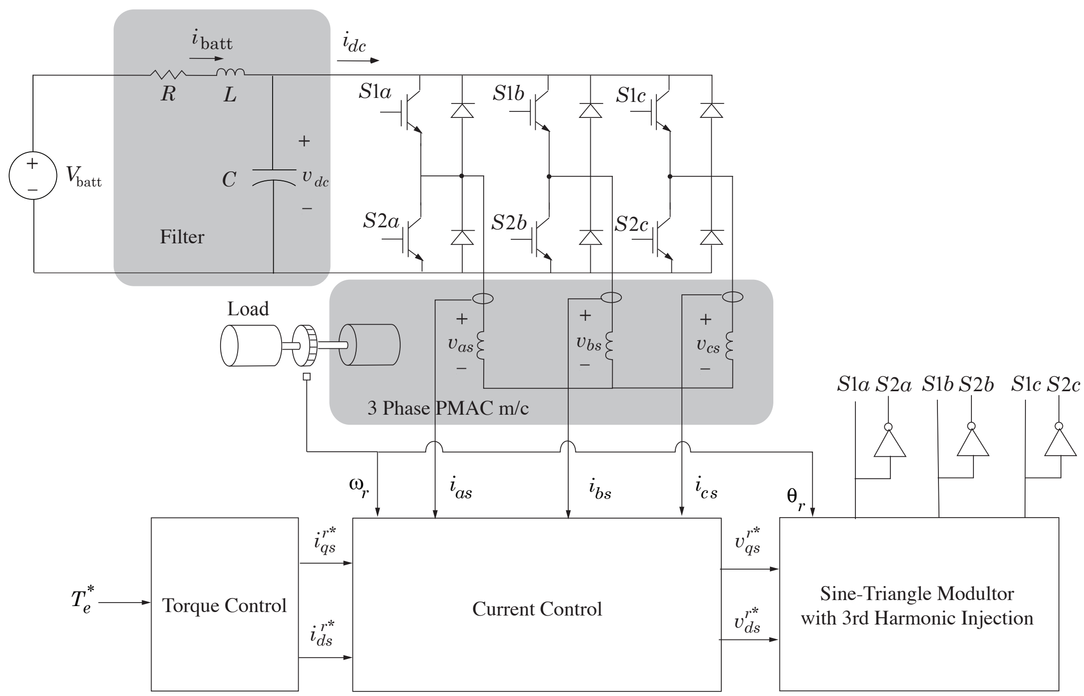

Figure 1: Circuit/block diagram.

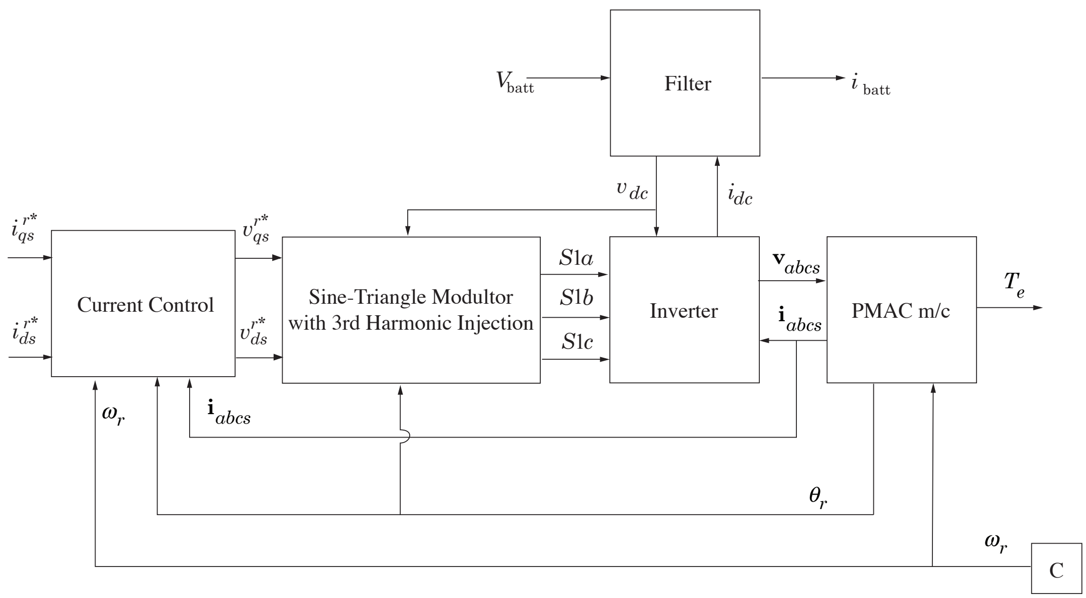

Figure 2: Top-level simulation block diagram.

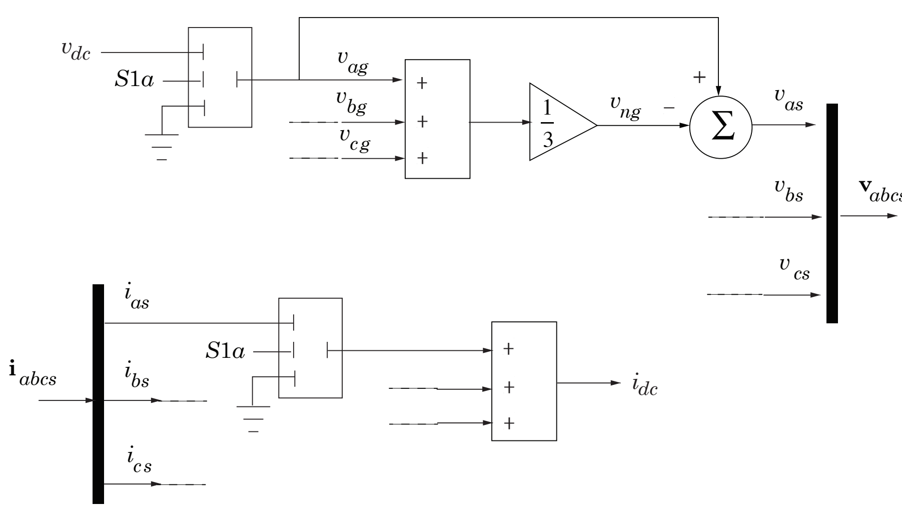

Figure 3: Inverter subsystem model.

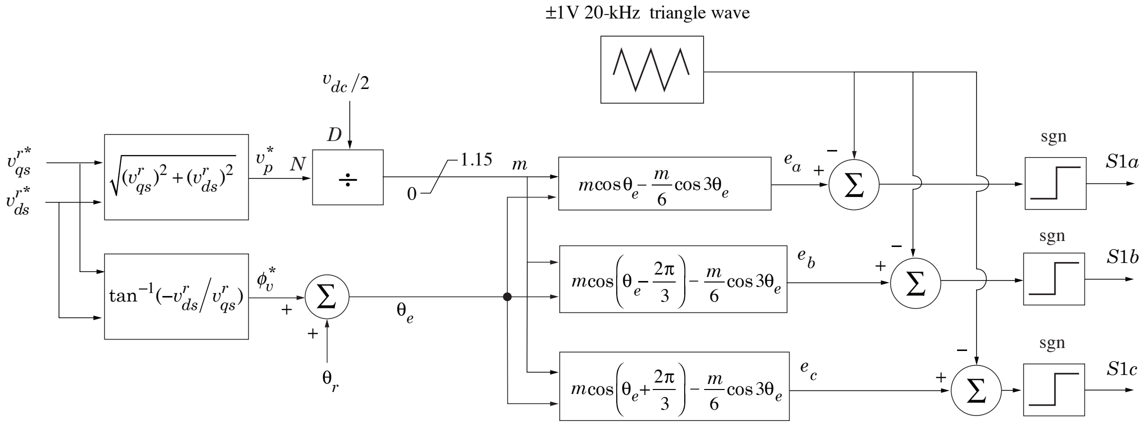

Figure 4: Sine-triangle modulator with third-harmonic injection.

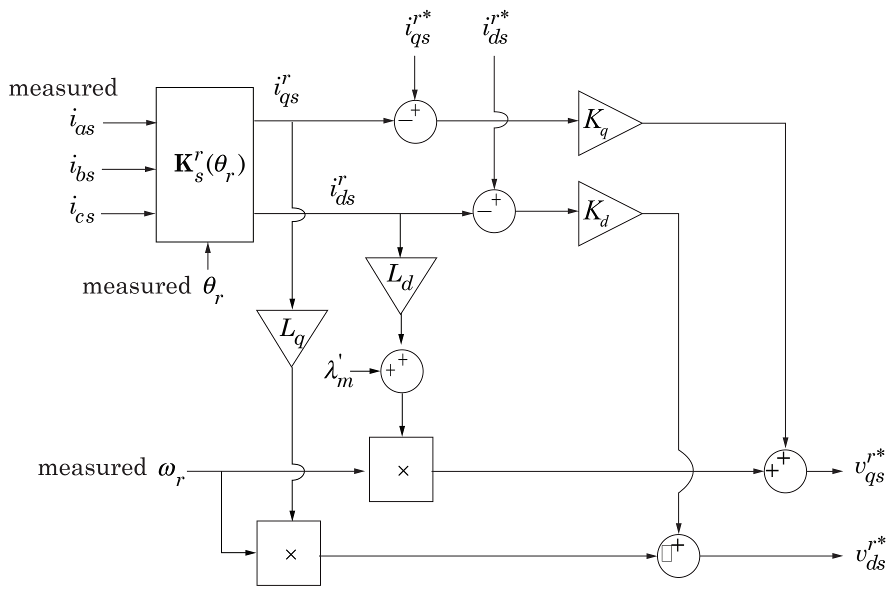

Figure 5: Current control.

1. Write a Matlab script that calculates and plots the first-quadrant maximum torque-versus-speed envelope of the given drive system. Consider the following code snippet. Plot maximum torque (in N-m) versus *mechanical* speed (in rpm), maximum mechanical power (in kW) versus mechanical speed (in rpm), and the I^r_{ds} needed for maximum torque (plot this versus mechanical speed in rpm).

```
...
w_r = linspace(0, 5000, N_w); % in radians per second
I_ds = linspace(-I_max, I_max, N_i); % in A
for i =1:N_w
    Te_max(i) = 0;
    % perform one-dimensional search for optimal I_ds, I_qs
    for j = 1:N_i
        I_qs = sqrt(I_max^2 - I_ds(j)^2);
        V_qs = rs*I_qs + w_r(i)*(Ld*I_ds(j) + lambda_m);
        V_ds = ...
        V_p = sqrt(V_qs^2 + V_ds^2);
        if(V_p < V_max) % viable but not necessarily optimal solution
            Te = 1.5*(P/2)*(lambda_m*I_qs + (Ld-Lq)*I_qs*I_ds(j));
            if(Te > Te_max(i)) % best viable solution thus far
                Te_max(i) = Te;
                % save optimal I_ds for plotting vs speed
                optimumI_ds(i) = I_ds(j) ;
            end % if
        end % if
    end % j loop
end % i loop
...
```

2. Determine I^{r*}_{qs} needed to develop 200 N-m at a *mechanical* speed of 2000 rpm assuming $I^{r*}_{ds} = 0$. Using steady-state equations, calculate required V^{r*}_{qs} and V^{r*}_{ds}. Verify that given V_{batt} is sufficient. Calculate the average power supplied to the motor and the average steady-state battery current $\hat{I}_{\text{batt}}$. Repeat for I^{r*}_{qs} set to negative value (corresponding to -100 N-m).

3. Simulate a step change in I^{r*}_{qs} from 0 to the value calculated in (2) to minus the value calculate in (2) allowing the system to reach steady state before applying each step change. Assume that the mechanical speed is constant (2000 rpm). Plot v_{as}, i_{as}, v_{dc}, i_{dc}, i_{batt}, and T_e. Each plot should include a discussion of the associated results. Compare average i_{batt} and T_e with calculated values from (2).

Grading will be based upon the following criteria: documentation, results, discussion, and analysis (supporting calculations). Documentation should be sufficient to allow someone else to duplicate all results based upon information in your report. Each plot (figure) should be labelled and numbered. Each figure should include a discussion to describe the salient features of its content and any conclusions derived therefrom. Supporting calculations (analysis portion of grade) should verify that the average values of simulated v_{dc}, i_{dc}, i_{batt}, and T_e, and the peak value of i_{as} are what they should be based upon steady-state calculations.

Bonus (2 points)

For the steady-state operating condition in Part 2, establish the value of I_{ds}^{r*} that minimizes the peak ac current ($\sqrt{(I_{qs}^r)^2 + (I_{ds}^r)^2}$). Determine the resulting "interacting" and "reluctance" components of torque. Determine the reduction in motor losses. This may be done using a Matlab script that implements a 1-D search for optimal I_{ds}^r, or you may set this up as a constrained minimization problem that is solved using the built-in Matlab function `fmincon`.

Table 1: Source and Filter Parameters

V_{batt}	600 V
C	1 mF
L	5 μH
R	0.01 Ω

Table 2: Motor Parameters

L_d	0.8 mH
L_q	1.0 mH
r_s	0.07 Ω
λ_m'	0.266 V-s/rad
P	8
$I_{\max}$	250 A

Table 3: Current Regulator Parameters

K_q	2 Ω
K_d	2 Ω