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. This simulation will be used to show that it is possible to rapidly achieve the desired (commanded) torque (within 10's of milliseconds), as long as the commanded torque is within limits. A secondary objective is to establish the torque limits given pertinent drive system parameters. An equivalent circuit/block diagram of the drive system is depicted in Fig. 1. Filter, motor, and control parameters are provided in Tables 1 through 3, respectively. A top-level simulation block diagram is shown in Fig. 2. The inverter switches and diodes are assumed to be ideal allowing the inverter to be represented using standard Simulink components as shown in Fig. 3 (do NOT use SimPowerSystems or Simscape toolboxes). The sine-triangle modulator is depicted in Fig. 4, and the current control subsystem is detailed in Fig. 5.

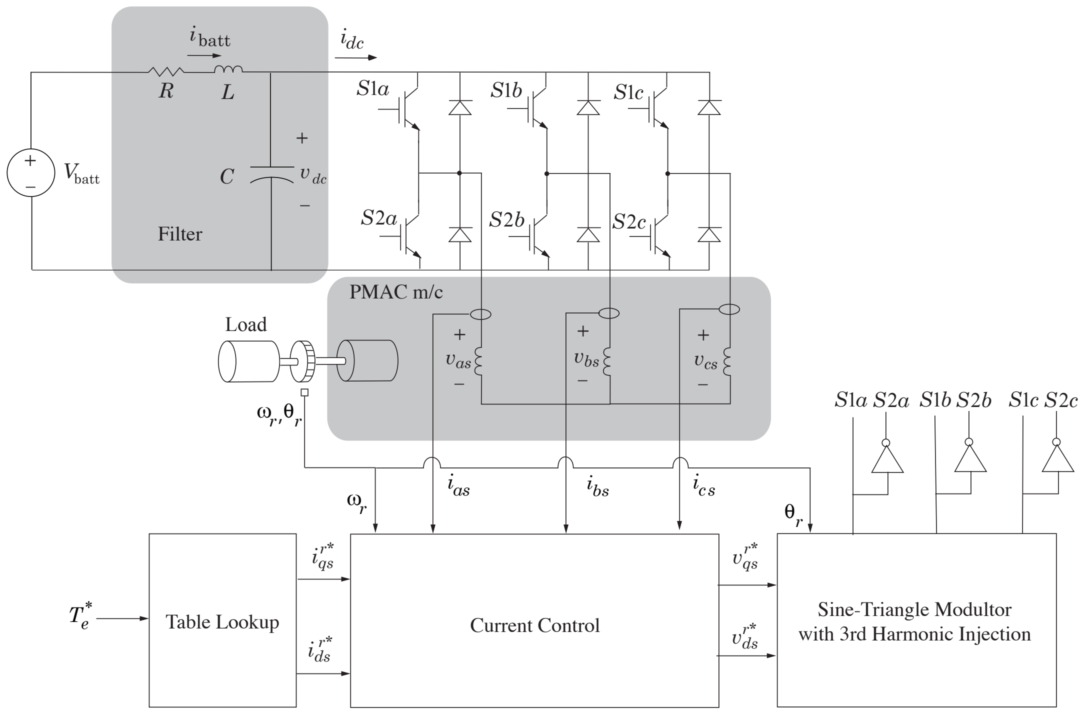

Figure 1: Circuit/block diagram.

Table 1: Source and Filter Parameters

V_{batt}	400 V
C	2 mF
L	20 μH
R	0.01 Ω

Table 2: Motor Parameters

L_d	2 mH
L_q	3.3 mH
r_s	0.02 Ω
λ'_m	0.2 V-s/rad
P	8
$I_{\max}$	225 A

Table 3: Current Regulator Parameters

K_q	2 Ω
K_d	2 Ω

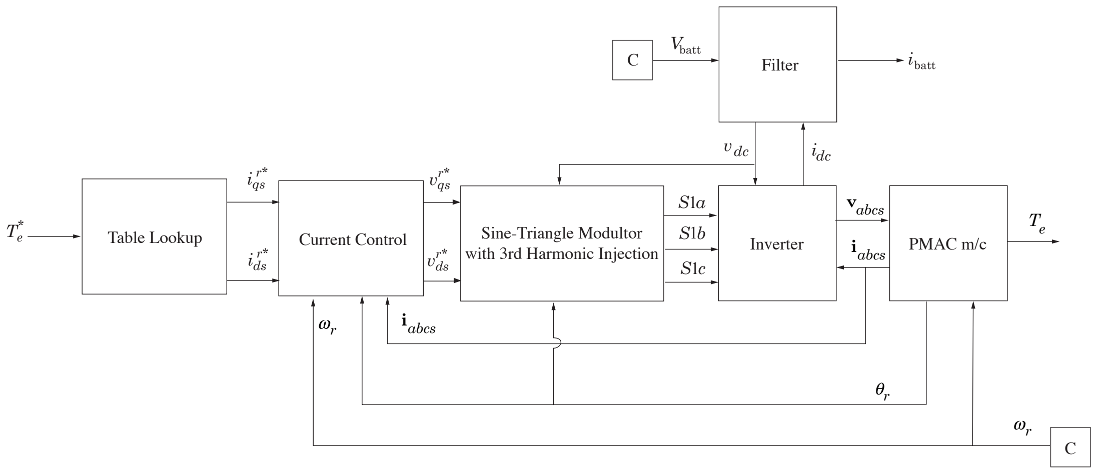

Figure 2: Top-level simulation block diagram.

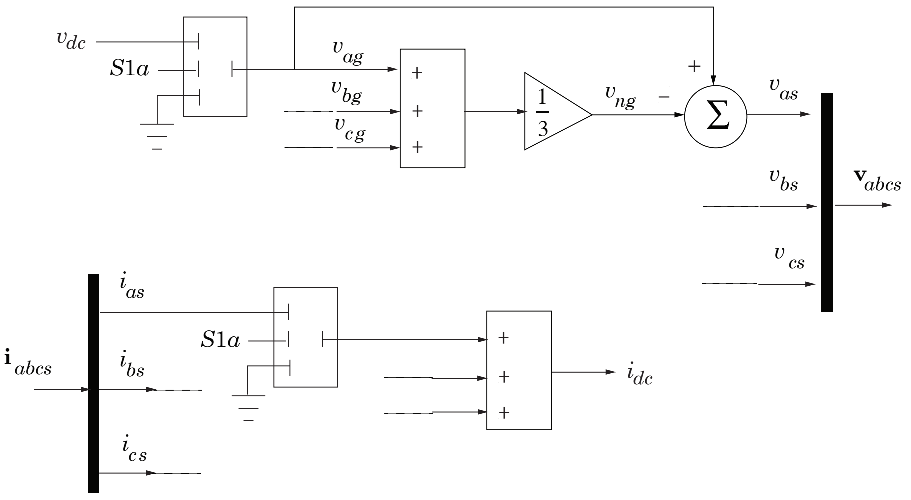

Figure 3: Inverter subsystem model.

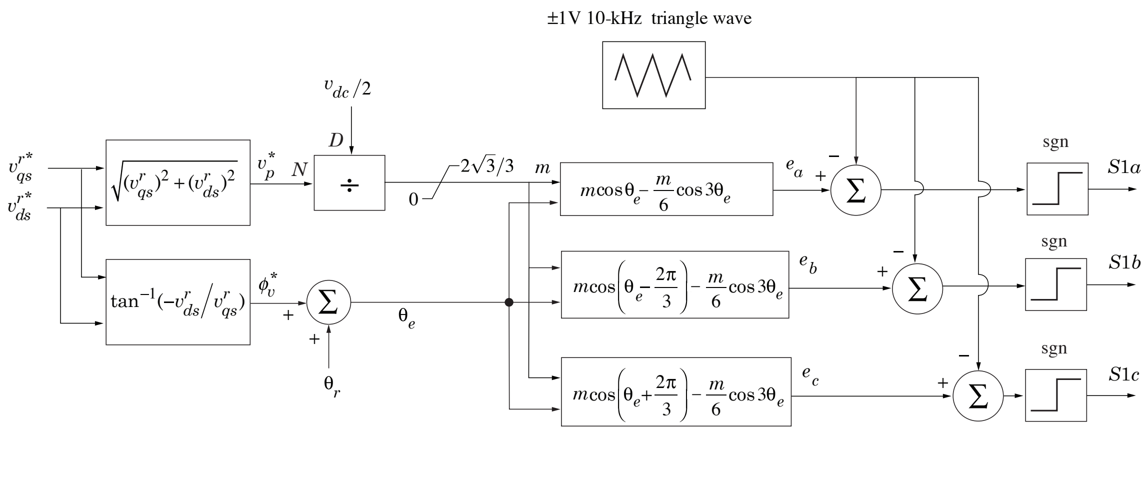
±1V 10-kHz triangle wave
$v_{dc}/2$
D
v_{qs}^{r*}
v_{ds}^{r*}
$\sqrt{(v_{qs}^r)^2+(v_{ds}^r)^2}$
v_p^*
N
$\div$
$2\sqrt{3}/3$
0
m
$m\cos\theta_e - \frac{m}{6}\cos 3\theta_e$
e_a
$\tan^{-1}(-v_{ds}^r/v_{qs}^r)$
ϕ_v^*
Σ
θ_e
θ_r
$m\cos\left(\theta_e - \frac{2\pi}{3}\right) - \frac{m}{6}\cos 3\theta_e$
e_b
$m\cos\left(\theta_e + \frac{2\pi}{3}\right) - \frac{m}{6}\cos 3\theta_e$
e_c
sgn
$S1a$
$S1b$
$S1c$

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

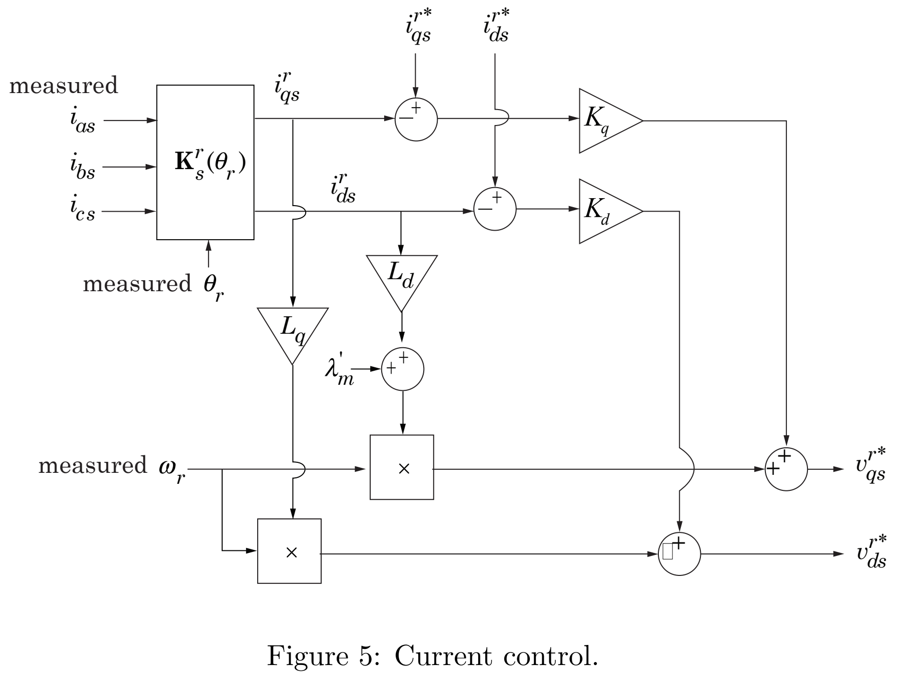

Figure 5: Current control.

1. Write a Matlab script to determine and plot optimal I_{qs}^r and I_{ds}^r as a function of desired torque. In this case, the objective is to minimize the peak stator current $I_s = \sqrt{(I_{qs}^r)^2 + (I_{ds}^r)^2}$ subject to the constraint $T_e = \frac{P}{2}\frac{3}{2}\left[\lambda_m I_{qs}^r + (L_d - L_q)\, I_{qs}^r I_{ds}^r\right]$. Consider the following Matlab code snippets to do this. The vectors `I_qs`, `I_ds`, and `T_e` established in this step will be used to implement a table lookup in the Simulink model.

```
...
% use interior-point algorithm
T_e = linspace(-400, 400, N);
options = optimoptions('fmincon','Algorithm','interior-point');
for i=1:N
    param.Te = T_e(i);
    iqd = fmincon(@(iqd)myfun(iqd), [0;0],[],[],[],[],[],[],...
                           @(iqd) mycon(iqd),options);
    I_qs(i) = iqd(1);
    I_ds(i) = iqd(2);
end

save I_qs I_qs
save I_ds I_ds
save T_e T_e
...

-------------------------------------------------------
function y = myfun(iqd)
  global param
  % define function to minimize
  y = sqrt(iqd(1)^2 + iqd(2)^2);
end


--------------------------------------------------------
function [c, ceq] = mycon(iqd)
  global param
  % define constraints
  c = [];     % no inequality constraints
  ceq(1) = param.Te - 1.5*(param.P/2)*(param.lambda_m*iqd(1)...
                 +(param.L_d - param.L_q)*iqd(1)*iqd(2));
end
```

2. Assume the *mechanical* rotor speed is 500 rpm and the desired torque is 400 N · m. Given the values of I_{qs}^r and I_{ds}^r established in (1), calculate (using Park's equations) the steady-state values of V_{qs}^r and V_{ds}^r. Calculate the power supplied to the motor. If the inverter is composed of ideal switches and dc filter losses are small, the power supplied to the motor in the steady state will be close to the average power supplied by the battery. Knowing the battery voltage, estimate the average steady-state battery current. Repeat these calculations assuming the desired torque is −400 N · m.

3. Using the supplied subsystem models, implement a Simulink model of the drive system in accordance with Figure 2. Simulate a step change in T_e^* from 0 to 400 N · m and then to −400 N · m allowing the system to reach steady state before applying each step change. Assume that the mechanical speed is constant (500 rpm) throughout the study. Plot v_{as}, i_{as}, v_{dc}, i_{dc}, i_{batt}, and T_e, all versus time. Each plot should include a discussion of the associated results. From the simulated plots of $i_{\text{batt}}(t)$ and $T_e(t)$, estimate their average steady-state values when T_e^* is equal to 400 and −400 N · m. Compare with steady-state values calculated in (2). Also, verify that the peak value of simulated $i_{as}(t)$ is close to $\sqrt{(I_{qs}^r)^2 + (I_{ds}^r)^2}$.

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 labeled 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 close to what they should be based upon steady-state calculations. One bounus point will be awarded for submitting the project on the due date.

Bonus (2 points)

Write a Matlab script that calculates and plots the first-quadrant maximum-torque-versus-speed characteristics of the given drive system. Assume that $V_{s,\max} = \sqrt{3}V_{\text{batt}}/3$ (modulation limit). Consider the following code snippet to do this. Plot maximum torque (in N-m) versus *mechanical* speed (in rpm), maximum mechanical power (in kW) versus mechanical speed (in rpm), and the I_s and V_s (peak fundamental current and voltage) needed to achieve maximum torque (plot these versus mechanical speed in rpm). At what rotor speed does the does the voltage constraint start to limit the maximum toque? At what rotor speed is the power maximum? What is the maximum power?

```
...
% use interior-point algorithm
options = optimoptions('fmincon','Algorithm','interior-point');

...
for i=1:N
    param.w_r = omega_r(i);
    iqd_forMaxT = fmincon(@(iqd_forMaxT)myfun(iqd_forMaxT),...
        [0;0],[],[],[],[],[],[],...
        @(iqd_forMaxT) mycon(iqd_forMaxT),options);
    Iqd_forMaxT(i,:) = iqd_forMaxT;
    Te_max(i) = -myfun(Iqd_forMaxT(i,:));
end
...

function y = myfun(iqd)
  global param
  % define function to minimize
  % maximizing torque equivalent to minimizing negative torque
  y = -1.5 * param.P/2 * ...
       (iqd(1)*param.lambda_m + (param.L_d - param.L_q)*iqd(1)*iqd(2));
end


function [c, ceq] = mycon(iqd)
  global param
 % define constraints
  v_q = param.r_s*iqd(1) + param.w_r*(param.lambda_m + param.L_d*iqd(2));
  v_d = param.r_s*iqd(2) - param.w_r*param.L_q*iqd(1);

  c(1) = sqrt(iqd(1)^2 + iqd(2)^2) - param.Is_max;
  c(2) = sqrt(v_q^2 + v_d^2) - param.Vs_max;

  ceq = []; % no equality constraints

end
```