ME 597 Project 2 Report

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Analysis of Permanent Magnet AC Motor Drive

March 31, 2025

1. Introduction

This project focuses on modeling a Permanent Magnet AC (PMAC) motor drive system which is a key component in hybrid electric vehicle design. The objective is to utilize a Simulink model that implements a sine-triangle pulse width modulation (PWM) strategy with third-harmonic injection. The simulation aims to demonstrate the system's ability to quickly track commanded torque, as well as identify the torque limits imposed by electrical and mechanical constraints. The model includes a current control loop, inverter model, filters, and more in order to output graphs that provide insights into system efficiency and control effectiveness.

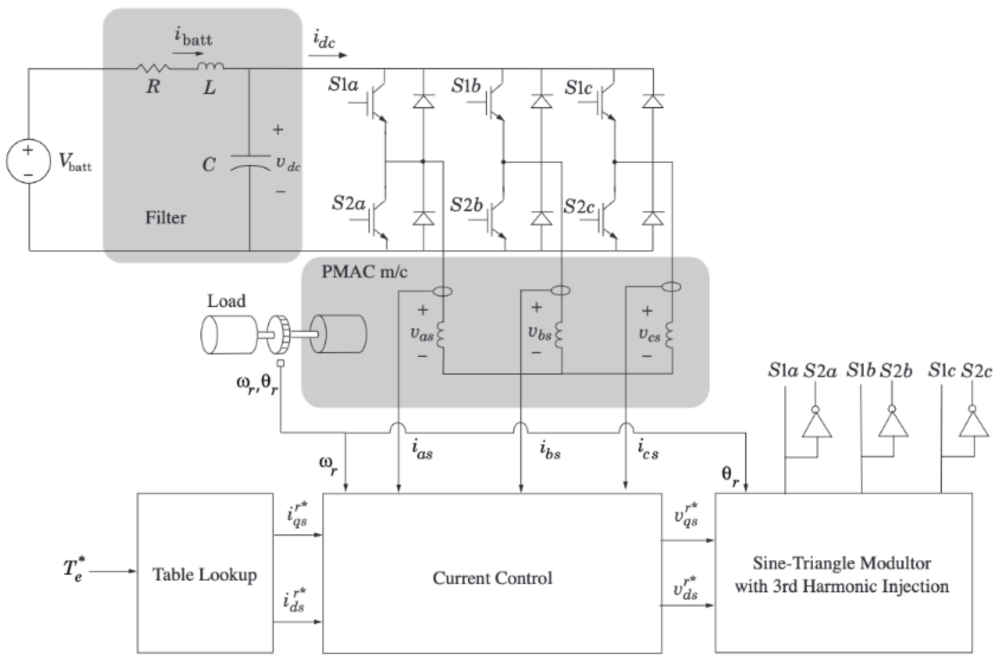


Figure 1: System Overview

2. Model Description

The developed model simulates a Permanent Magnet AC (PMAC) motor drive system powered by a 400 V DC battery and controlled through a closed-loop torque regulation scheme. The system consists of a DC source with an LC filter, a three-phase inverter modeled using ideal switches, a sine-triangle pulse width modulator with third-harmonic injection, and a PMAC motor. I_qs and I_ds values are obtained from a torque-dependent lookup table found through the Matlab script seen in Appendix B. These currents are regulated by a proportional gain controller to generate appropriate V_qs and V_ds voltages, which are fed into the modulator. The model simulates torque response, phase voltages and currents, battery current, and inverter voltage, allowing both steady-state and transient performance analysis.

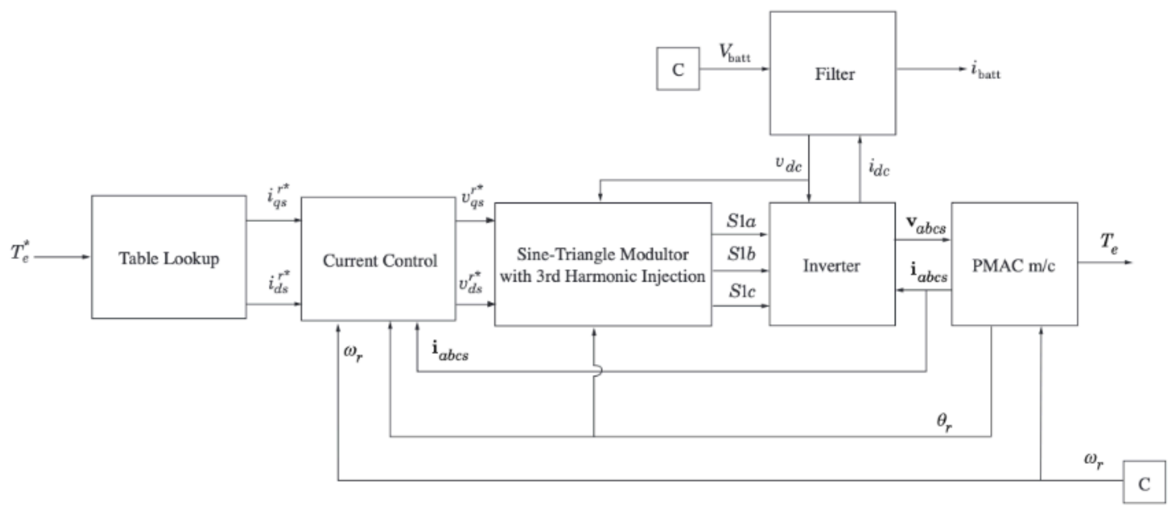


Figure 2: Top Level Block Diagram

3. Simulation Setup

The Simulink model was constructed based on the system architecture provided in the project guidelines, incorporating subsystems for the DC source and filter, inverter, sine-triangle modulator with third-harmonic injection, current controller, and PMAC motor. The model initializes using motor, filter, and control parameters provided in Appendix A. As mentioned previously, a script was used to generate a lookup table of optimal I_qs and I_ds values. During simulation, the rotor speed was held constant at 500 rpm while the commanded torque was stepped from 0 to 400 Nm and then to -400 Nm. The system was simulated long enough to observe steady-state behavior for each torque level, and key signals such as phase voltages, phase currents, battery current, DC link voltage, and torque output were graphed for analysis.

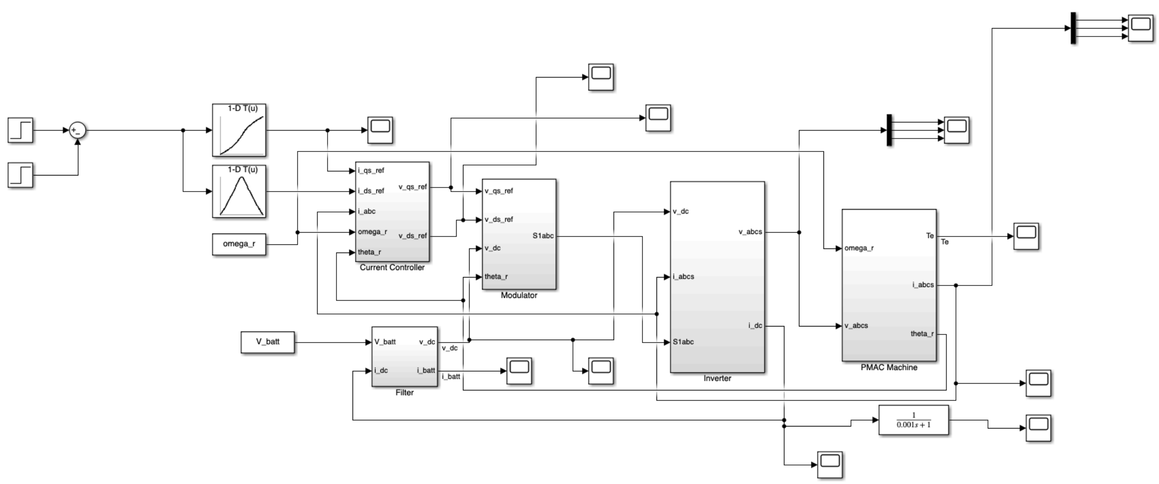


Figure 3: Simulink Model

4. Results & Discussion

The following section presents the simulation results and figures. This section will also highlight some key observations and discuss the significance of the results.

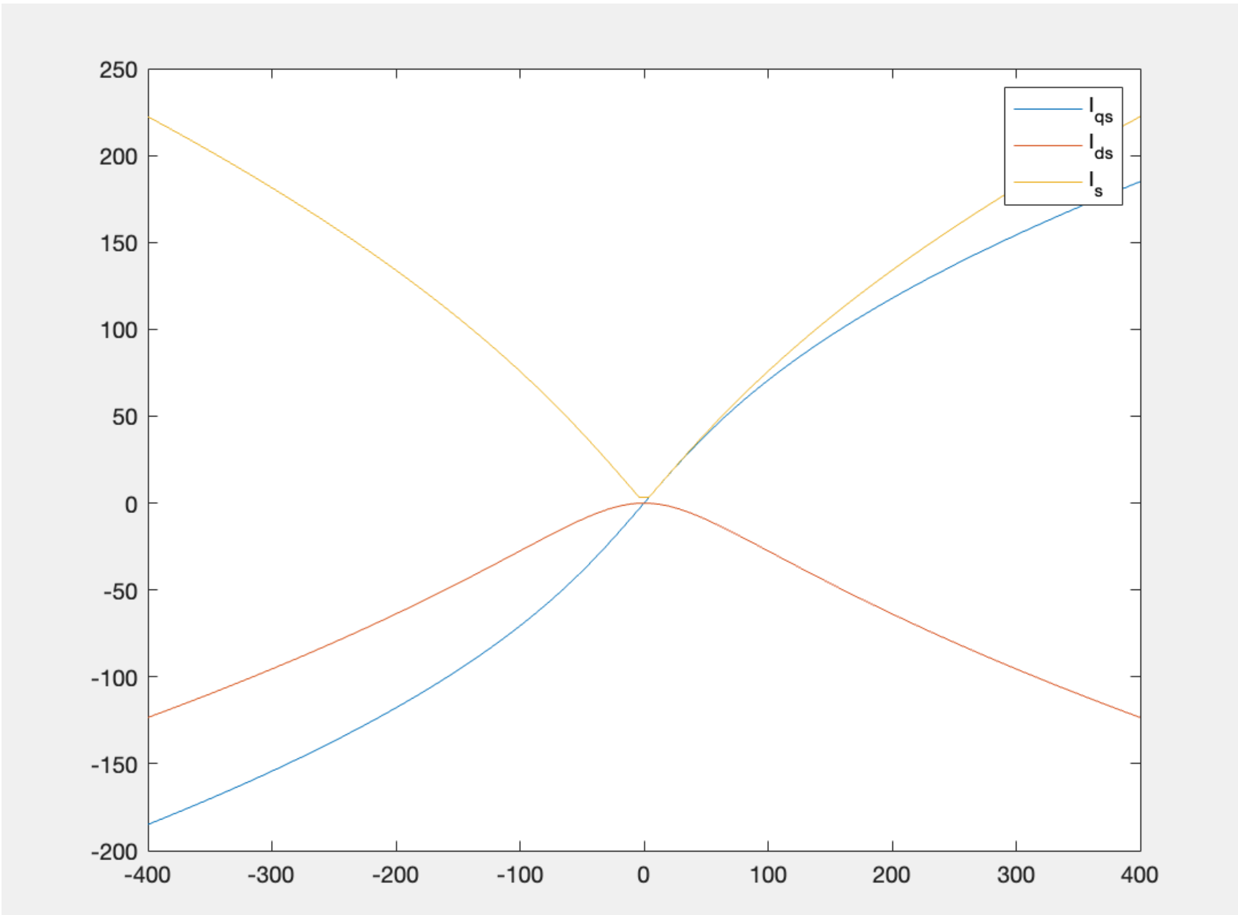


Figure 4: Current (A) vs Electrical Torque (Nm)

The simulation utilizes a Matlab script to generate a torque dependent lookup table for the I_qs and I_ds values. The graph in Figure 4 represents these currents plotted with respect to torque and is generated from the script in Appendix A.

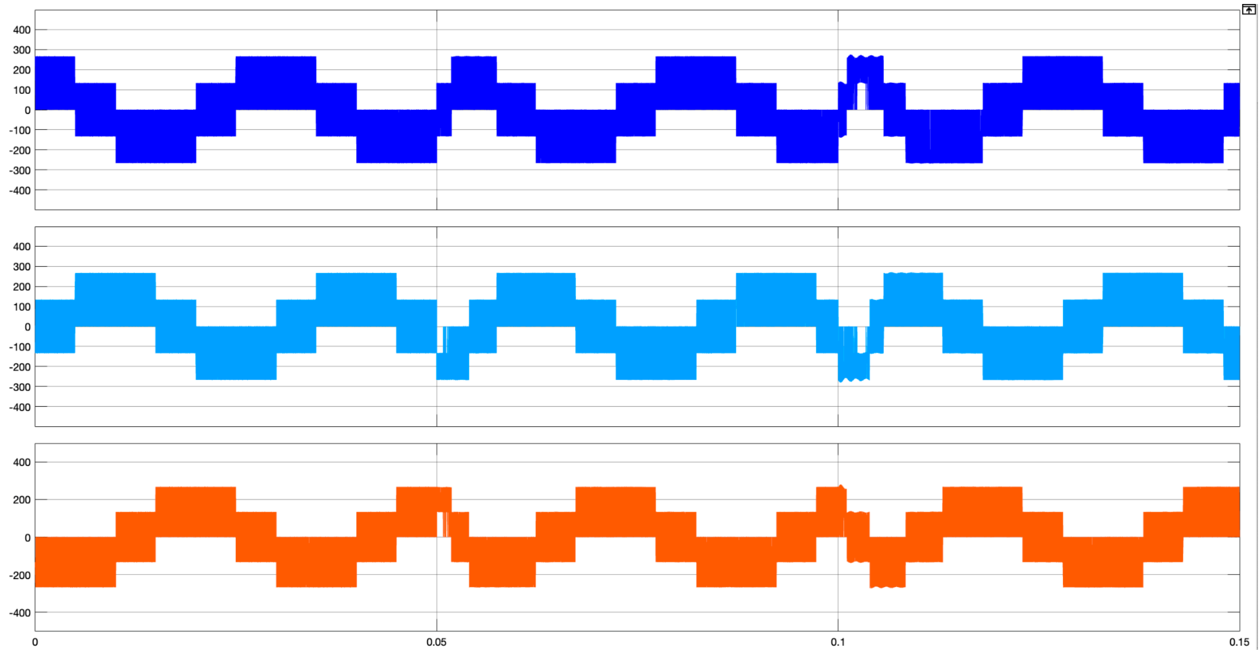


Figure 5: 3-phase Voltages vs Time (s)

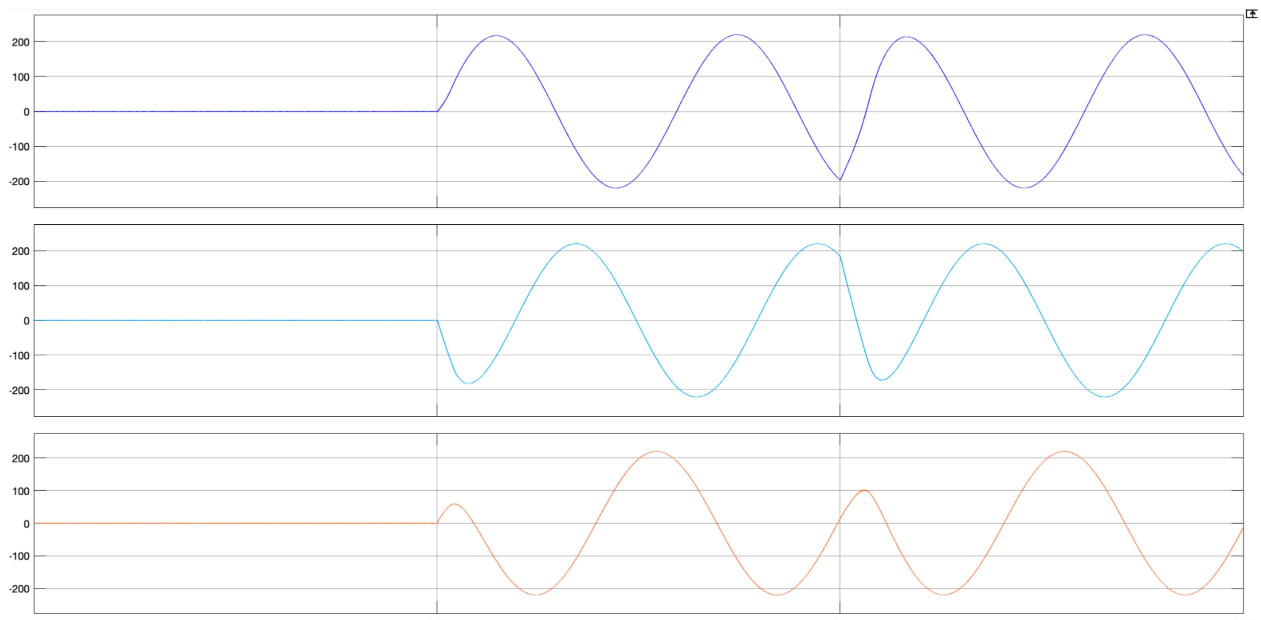


Figure 6: 3-phase Currents vs Time (s)

Figure 5 represents the 3-phase supply voltage with respect to time. The output can be observed to be a sinusoidal step output and there is a 120 degree phase shift between the 3 phases. Figure 6 on the other hand represents the 3-phase current. While still observing the 120 degree phase shifts, the current does not have the same choppy step output. The current output is smooth because current through the inductor is unable to change instantaneously like voltage.

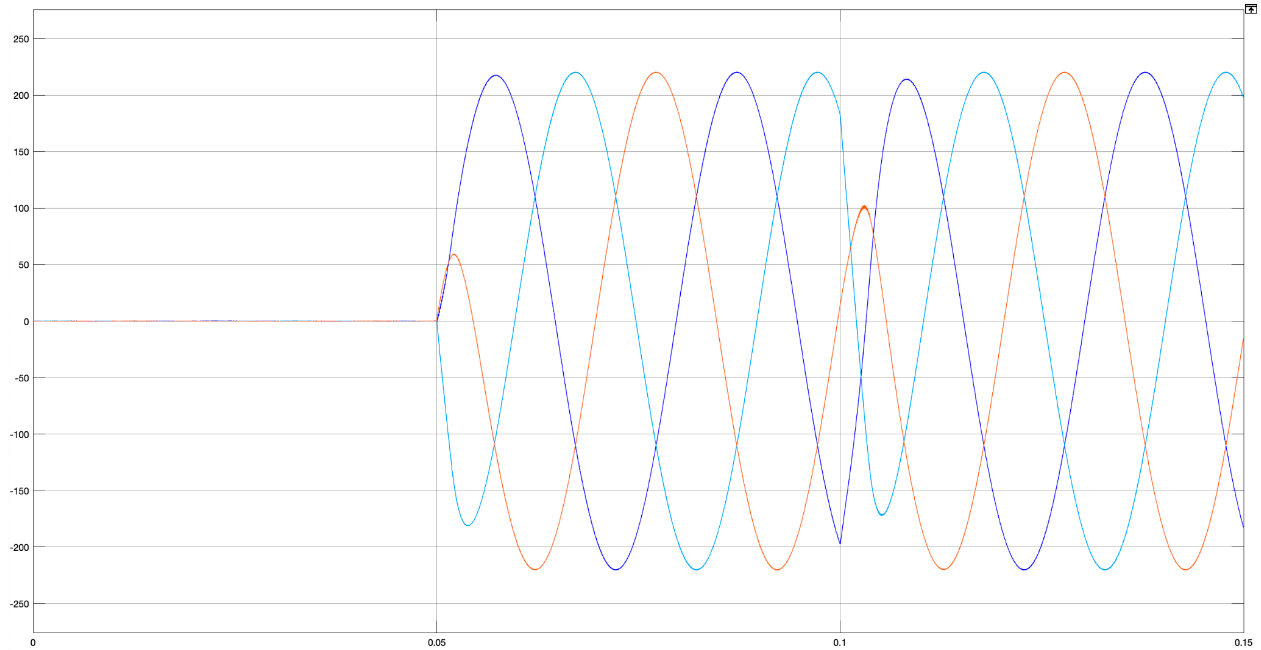


Figure 7: 3-phase Currents vs Time (s)

The 120 degree phase shift can be seen easily in Figure 7. The 3 currents from Figure 6 are overlaid onto one graph with the dark blue, light blue, and orange lines representing I_a, I_b and I_c respectively.

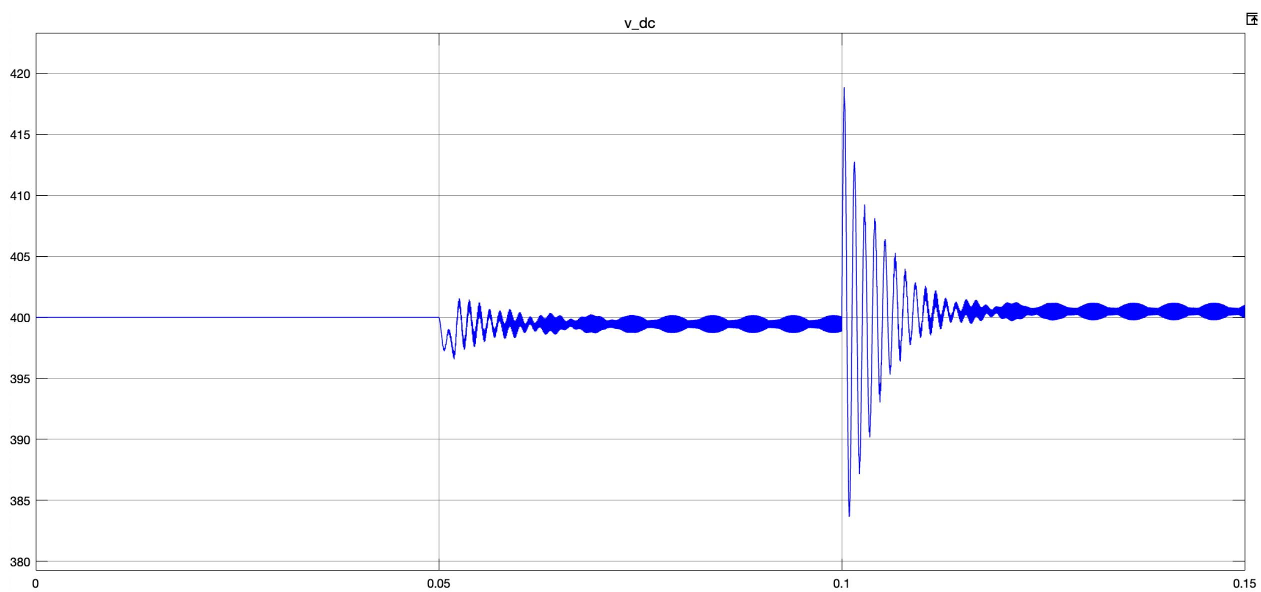


Figure 8: DC Voltage vs Time (s)

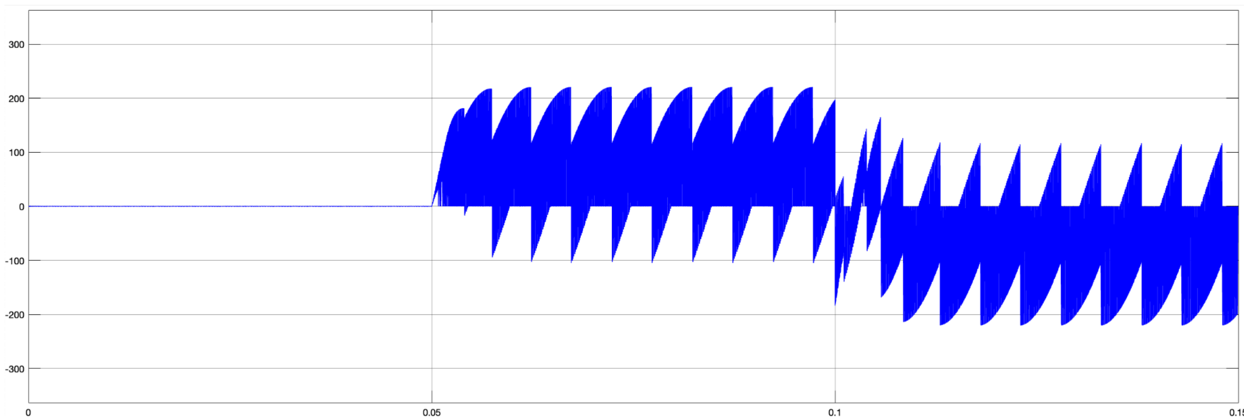


Figure 9: Unfiltered DC Current vs Time (s)

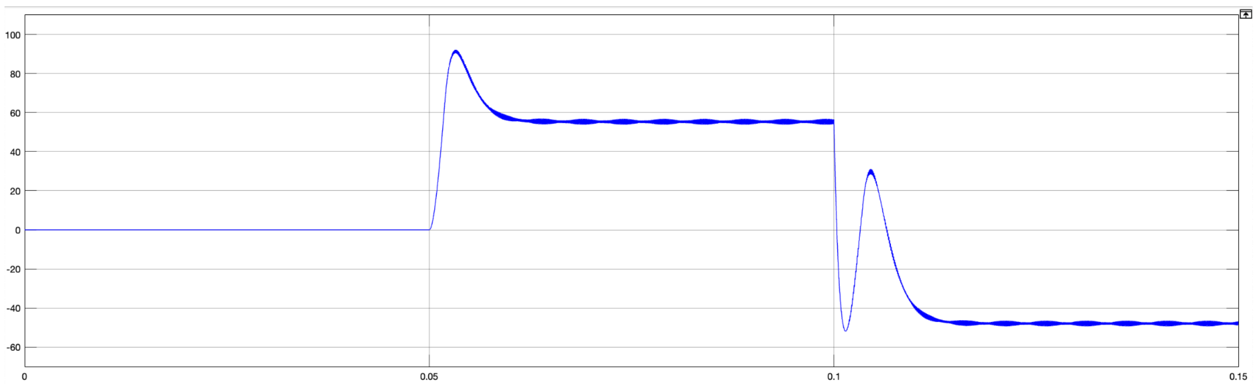


Figure 10: Filter DC Current vs Time (s)

A filter with a time constant of 0.001 is used to smooth the DC current curve. Figure 9 shows the unfiltered DC current with respect to time and Figure 10 shows the filtered DC current curve.

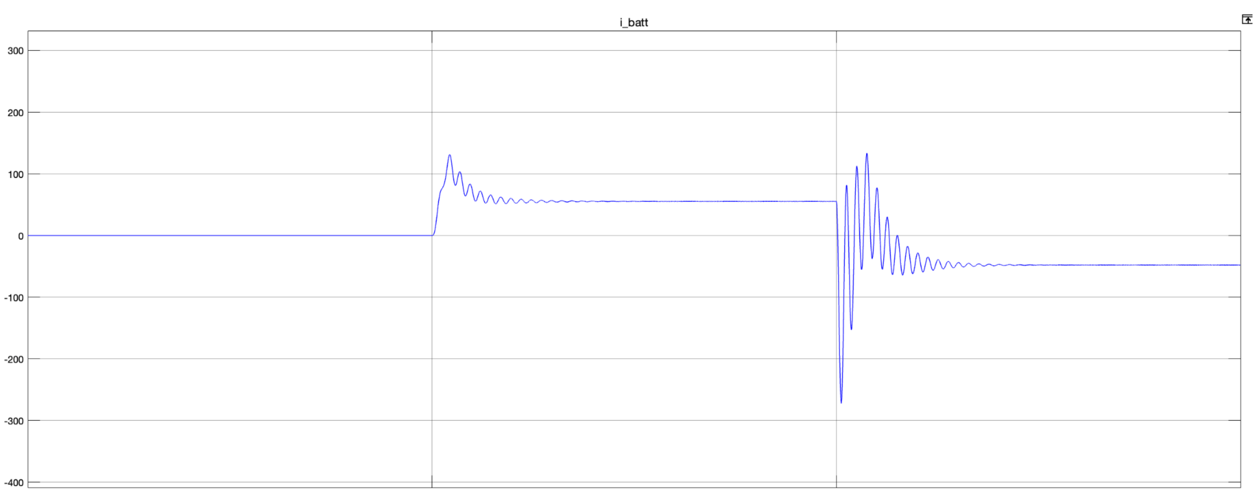


Figure 11: Battery Current vs Time (s)

The battery current graphed with respect to time can be seen in Figure 11. The values for the current at 400 Nm and -400 Nm are approximately 55.15A and -47.82A respectively. These values are equal to those seen in the filtered DC current output in Figure 10.

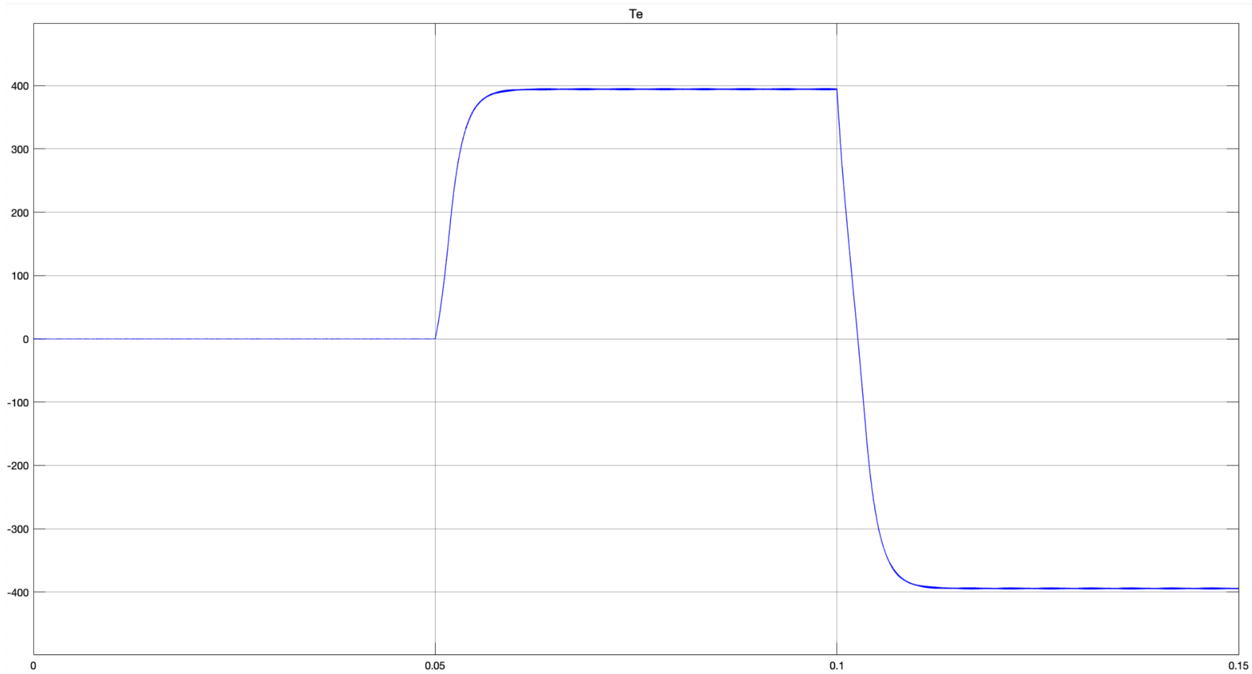


Figure 12: Electric Torque vs Time (s)

As seen in Figure 12, the torque output does not change 100% instantaneously as stated in some instances. However, in the context of a mechanical system, the unit of measurement is so minimal that it can be stated to be instantaneous as a simplification. It is important to note that the reason there is a slight delay is because of the system's inductors. The inductor current dictates how the torque shifts occur.

This project successfully demonstrated the modeling, simulation, and analysis of a Permanent Magnet AC (PMAC) motor drive system using a sine-triangle PWM strategy with third-harmonic injection. Through the use of the Simulink model and MATLAB scripts, the system was shown to provide key insight on PMAC motors as discussed throughout the report. Furthermore, hand calculations were conducted to validate the values found in the simulation. These calculations can be found in Appendix E. Overall, the project provides a strong foundation for understanding PMAC drive behavior in hybrid electric vehicle applications.

5. Appendix

Appendix A: Parameters

	Parameters	Values
Source and Filter Parameters	V_{batt}	400 V
	C	2 mF
	L	20 μH
	R	0.01 Ω
Motor Parameters	L_d	2 mH
	L_q	3.3 mH
	r_s	0.02 Ω
	λ'_m	0.2 Vs/rad
	P	8
	I_{max}	225 A
Current Regulator Parameters	K_q	2 Ω
	K_d	2 Ω

Appendix B: MATLAB main code

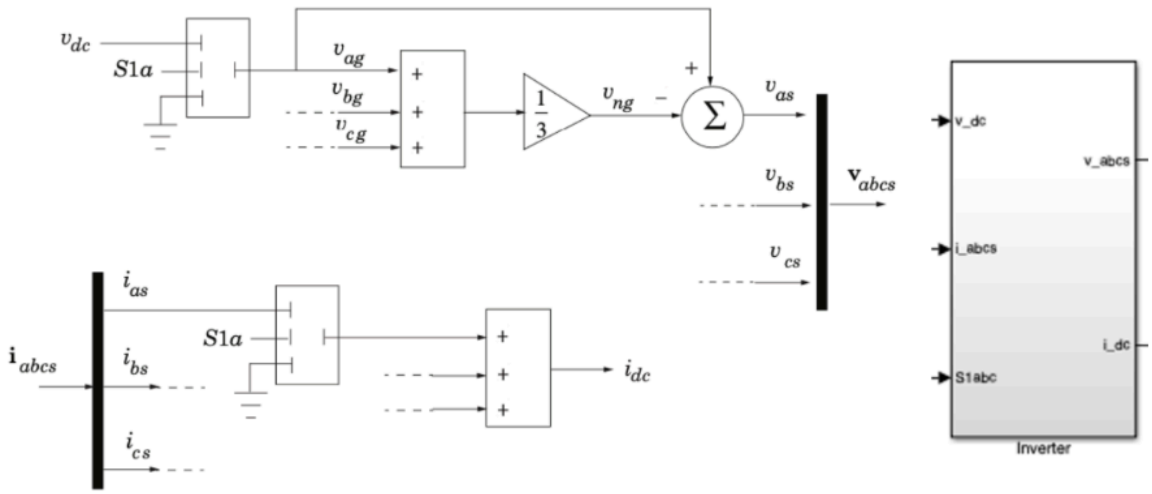
```
clear

close all

global param

% motor parameters

param.P = 8; % number of poles

param.lambda_m = 0.2;  %flux constant V-s/rad

param.r_s = 0.02;  % stator resistance in ohms

param.L_d = 2e-3; %stator inductance in H

param.L_q = 3.3e-3; %stator inductance in H

param.Is_max = 225; % amperes

V_dc = 400;

param.Vs_max = V_dc *sqrt(3)/3; % volts

N = 100;

T_e = linspace(-400, 400, N);

options = optimoptions('fmincon','Algorithm','interior-point'); % run
interior-point algorithm

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

figure(1)
```

```
plot(T_e, I_qs, T_e, I_ds, T_e, sqrt(I_qs.^2 + I_ds.^2));

legend('I_{qs}','I_{ds}','I_s')

save I_qs I_qs

save I_ds I_ds

save T_e T_e
```

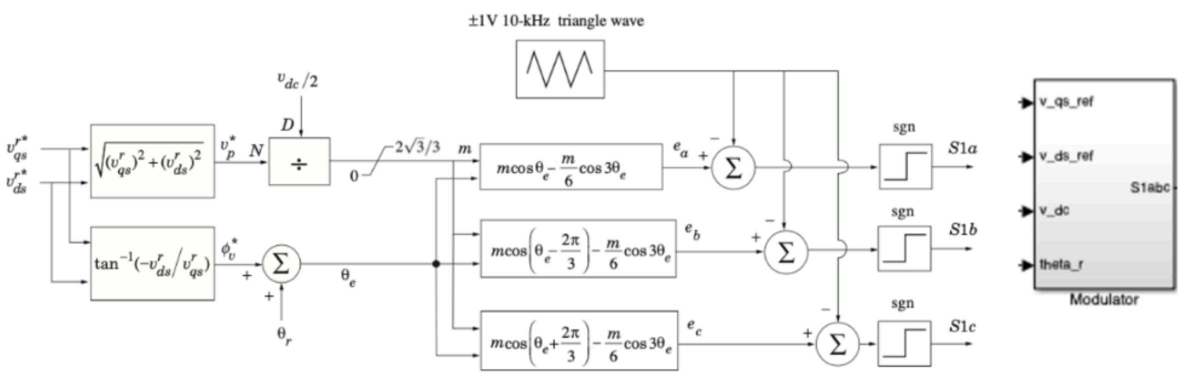
Appendix C: MATLAB initialization code

```
clear all

% motor parameters

P = 8; % number of poles

lambda_m = 0.2;  %flux constant V-s/rad

r_s = 0.02;  % stator resistance in ohms

L_d =  2e-3; %d-axis inductance in H

L_q =  3.3e-3; %q-axis inductance in H

% Filter parameters

L = 20e-6; % inductance in H

R = 0.01; % resistance in ohms

C = 2e-3; % capacitance in F

V_batt = 400;  % battery voltage

% Current Control gains

K_q = 2; % in ohms

K_d = 2;

% define electrical rotor speed (w_rm = 500 rpm)

omega_r = 500 * 2*pi / 60 * P/2; % rad/s

% load lookup table data

load I_qs

load I_ds

load T_e
```

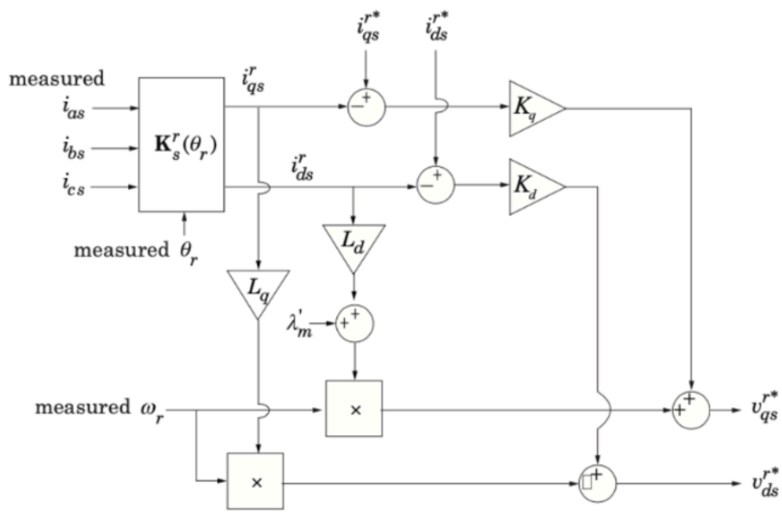
Appendix D: Simulink Subsystems

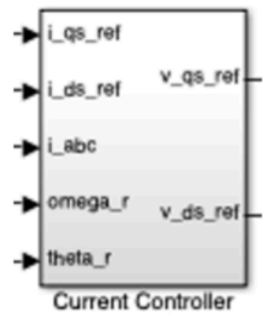


1. Inverter Subsystem Model



2. Sine-Triangle Modulator with Third-Harmonic Injection





3. Current Control

Appendix E: Hand Calculations

Equations:

$$V_{qs}^{r} = r_s I_{qs}^{r} + \omega_r L_d I_{ds}^{r} + \omega_r \lambda_m'$$

$$V_{ds}^{r} = r_s I_{ds}^{r} - \omega_r L_q I_{qs}^{r}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_m' I_{qs}^{r} + (L_d - L_q) I_{qs}^{r} I_{ds}^{r}\right]$$

$$P_e = \frac{3}{2}\left(V_{qs}^{r} I_{qs}^{r} + V_{ds}^{r} I_{ds}^{r}\right)$$

Commanded Torque = 400 Nm

$$V_{qs} = (0.02)(184.97) + (209.93)(2E{-}3)(-123.4) + (209.43)(0.2)$$
$$= -6.102 \text{ V}$$

$$V_{ds} = (0.02)(-123.4) - (209.43)(3.3)(184.47)E{-}3$$
$$= -130.30 \text{ V}$$

$$P_e = \frac{3}{2}(-1129.168 + 16079.02) = 22{,}424.78 \text{ W}$$

$$I_{batt} = I_{dc} = P_e / V_{batt} = 22.424 \text{ kW} / 400 \text{ V}$$

$$= 56.062 \text{ A}$$

Commanded Torque = -400 Nm

$$V_{qs} = (0.02)(-184.97) + (209.43)(2E-3)(-123.4) + (209.43)(0.2)$$
$$= -13.503 \text{ V}$$

$$V_{ds} = (0.02)(-123.4) - (209.43)(3.3E-3)(-184.97)$$
$$= 125.37 \text{ V}$$

$$P_e = \frac{3}{2}(2497.6499 - 15470.4112)$$
$$= -19499.14 \text{ W}$$

$$I_{batt} = -19.459/400 = -48.64 \text{ A}$$