PROJECT 3 REPORT

HYBRID ELECTRIC VEHICLES

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ABSTRACT

The objective of the third project is to analyze the distinctive characteristics of a permanent magnet ac motor drive. Permanent Magnet Alternating Current (PMAC) motors are emerging as an alternative to the commonly used alternating current induction motor, which has for generations been the workhorse of almost any application involving converting electrical work into mechanical work. This is done by developing a Simulink model of the ac motor drive with a sine triangular modulator.

INTRODUCTION

Traditional AC induction motors use a magnetic field induced by electric current (hence the term induction) to turn the rotor. PMAC motors replace the conducting metal bars in the rotor with permanent magnets, usually made from alloys of rare-earth metals. They then use the magnetic field created by the permanent magnets to create torque and motion.

PMAC motors save energy when compared to AC induction motors, and have several other advantages. Since no electric current is induced in the rotor, PMAC motors have much lower electric resistive losses than AC induction motors. Consequently, they are more efficient (typically 2-4% at full load), run cooler than induction motors, and typically have higher power factors. PMAC motors also do not experience slip, and are considered synchronous motors. Finally, since the magnetic fields generated by rare-earth magnets are up to twice as powerful as other commonly used permanent magnets, PMAC motors can deliver the same torque as AC induction motors with a smaller, lighter motor.

The amount of energy savings from PMAC motors depends chiefly upon the number of service hours experienced by the motor, the motor size, and the motor loading profiles. Compared to AC induction motors, PMAC motors tend to better maintain efficiency at part-load conditions, both in terms of torque and speed. This makes PMAC motors an attractive alternative to induction motors in variable-speed applications.
PMAC motors may be implemented in both retrofit and new construction applications in the following sectors:

Industrial: delivering high torque at low speed – conveyors, mixers, and grinders

Commercial: pumps, fans, and blowers; high power density applications – agriculture, automotive, maritime, and off-grid

CIRCUIT

The block/circuit diagram of the permanent magnet ac motor drive that needs to be simulated is provided below.

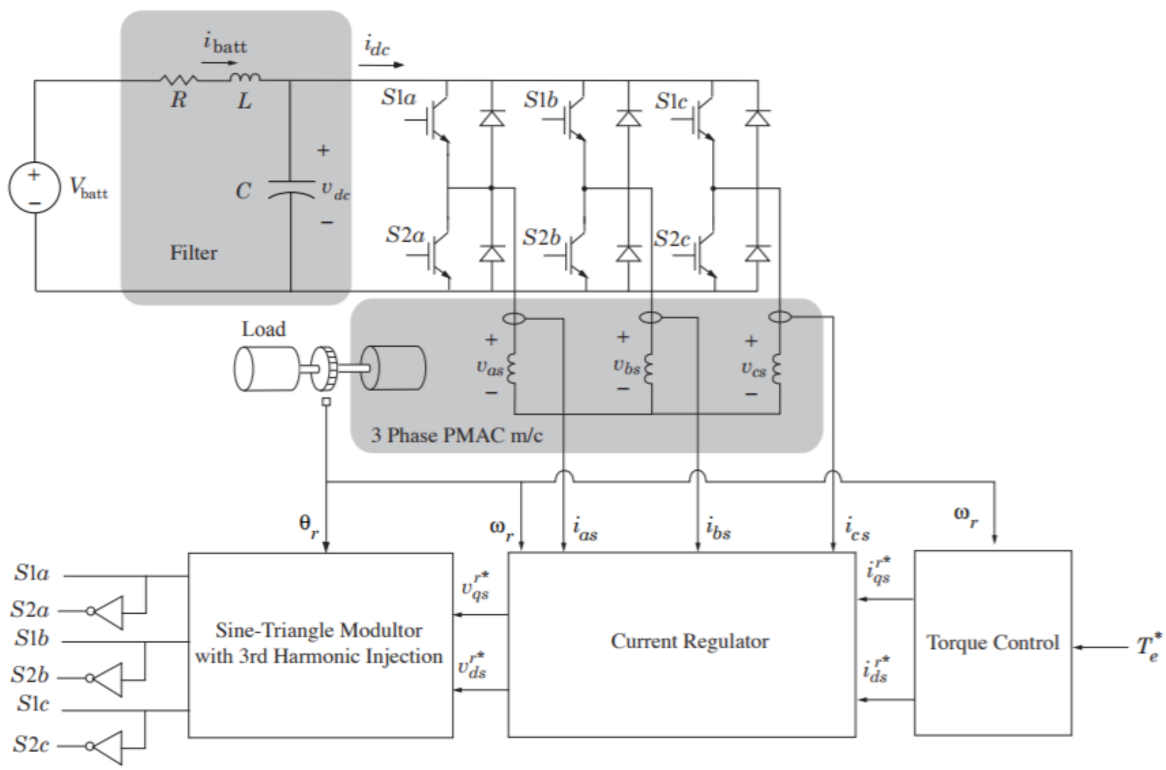


FIGURE 1. Circuit/block diagram.

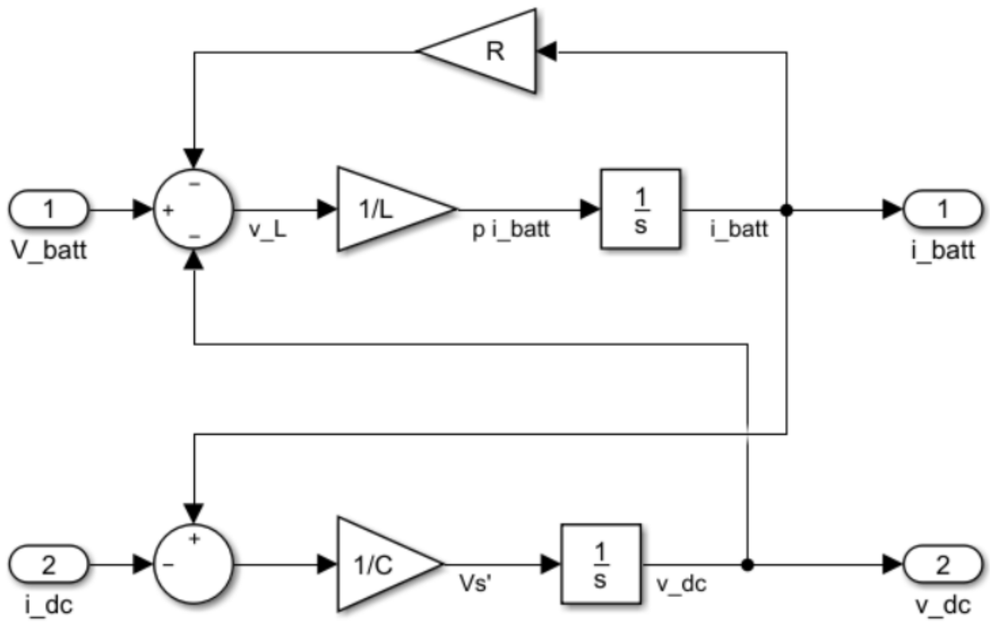
The main components of the motor drive are:

1. Filter
2. Current Regulator
3. Sine-Triangle Modulator
4. Invertor
5. Permanent magnet ac motor system

The detailed description of each component is given below.

FILTER

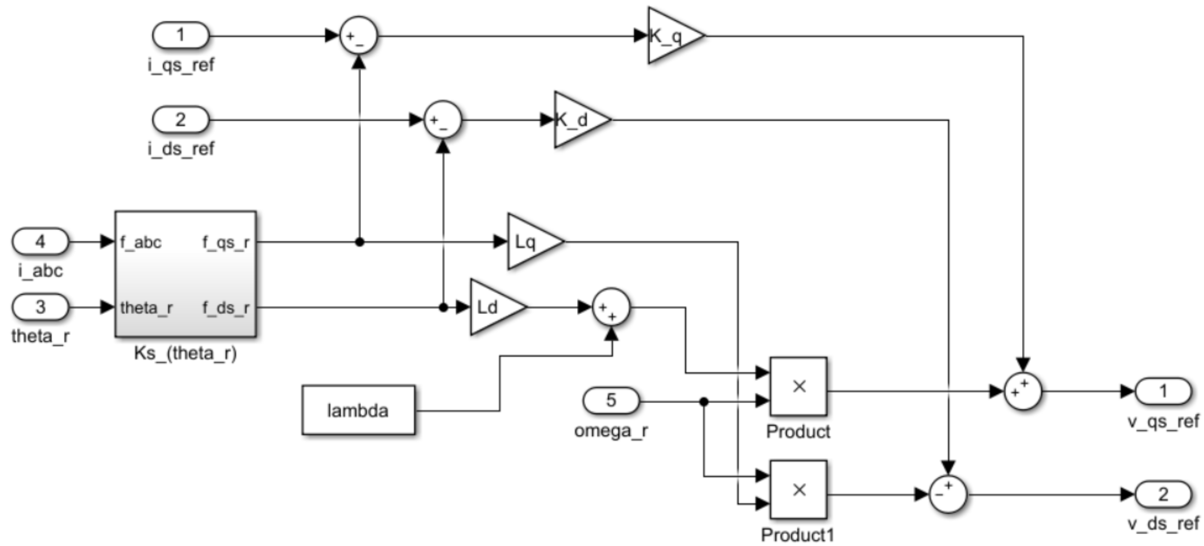
The filter takes in the battery voltage and the output current of the invertor subsystem as inputs and gives out the battery current and a dc voltage which is in turn provided as the input to both the inverter and the sine-triangle modulator. The block diagram of the filter subsystem is given below.



FILTER SUBSYSTEM MODEL

CURRENT REGULATOR

The purpose of a current regulator is to provide a constant current regardless of changes in the input voltage or load current. Here our current regulator takes in reference currents as inputs and gives out reference output voltages which are fed to the Sine-Triangular modulator. The block representation of the current regulator block is given below.



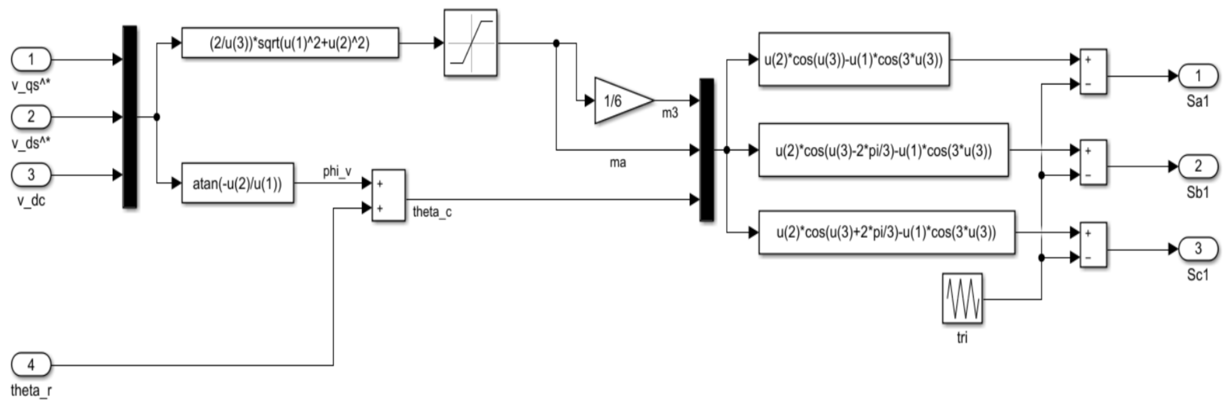
CURRENT REGULATOR SUBSYSTEM

SINE-TRIANGULAR MODULATOR

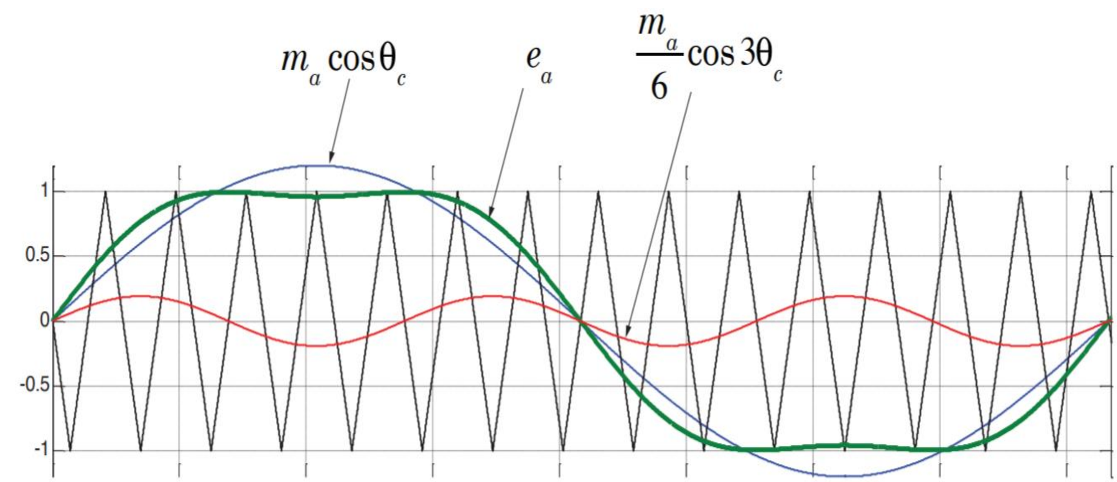
Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a modulation technique used to encode a message into a pulsing signal. Although this modulation technique can be used to encode information for transmission, its main use is to allow the control of the power supplied to electrical devices, especially to inertial loads such as motors

Here we use a sine triangular modulator for pulse width modulation. It takes in the reference voltages and a +/- 1 V 10-kHz triangular wave as a carrier. And it produces three switch outputs which are out of phase from each other. This helps the rotor rotate.

The Simulink block representation of the sine-triangular modulator and its general waveforms are given below.



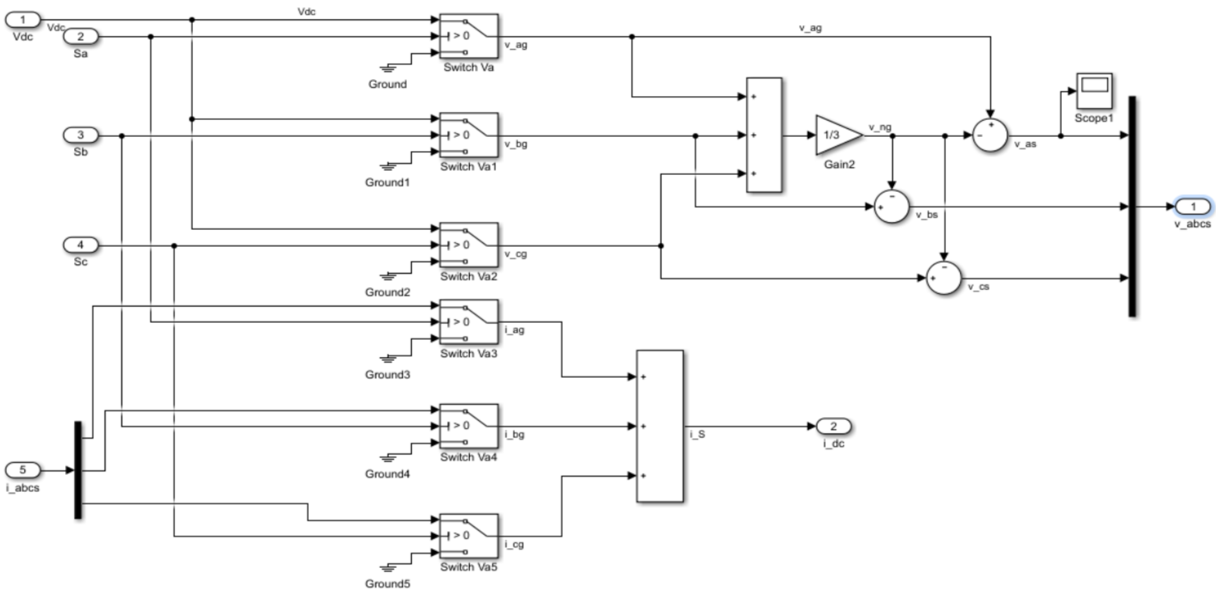
SINE-TRIANGULAR MODULATOR



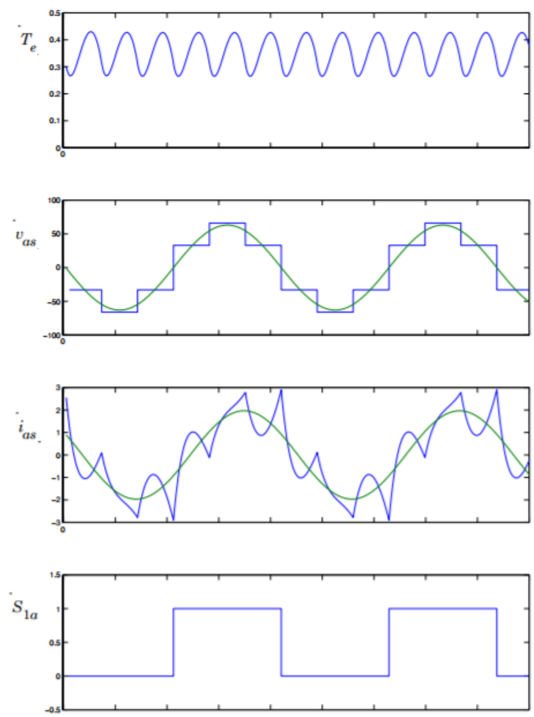
WAVEFORMS

INVERTER

The inverter subsystem takes in the switch outputs of the sine-triangular modulator and the DC voltage to calculate the AC voltage. The output from the inverter is fed into the permanent magnet ac motor subsystem and the AC current is fed back to the inverter module.
The Simulink model and the ideal waveforms of the invertor are given below.



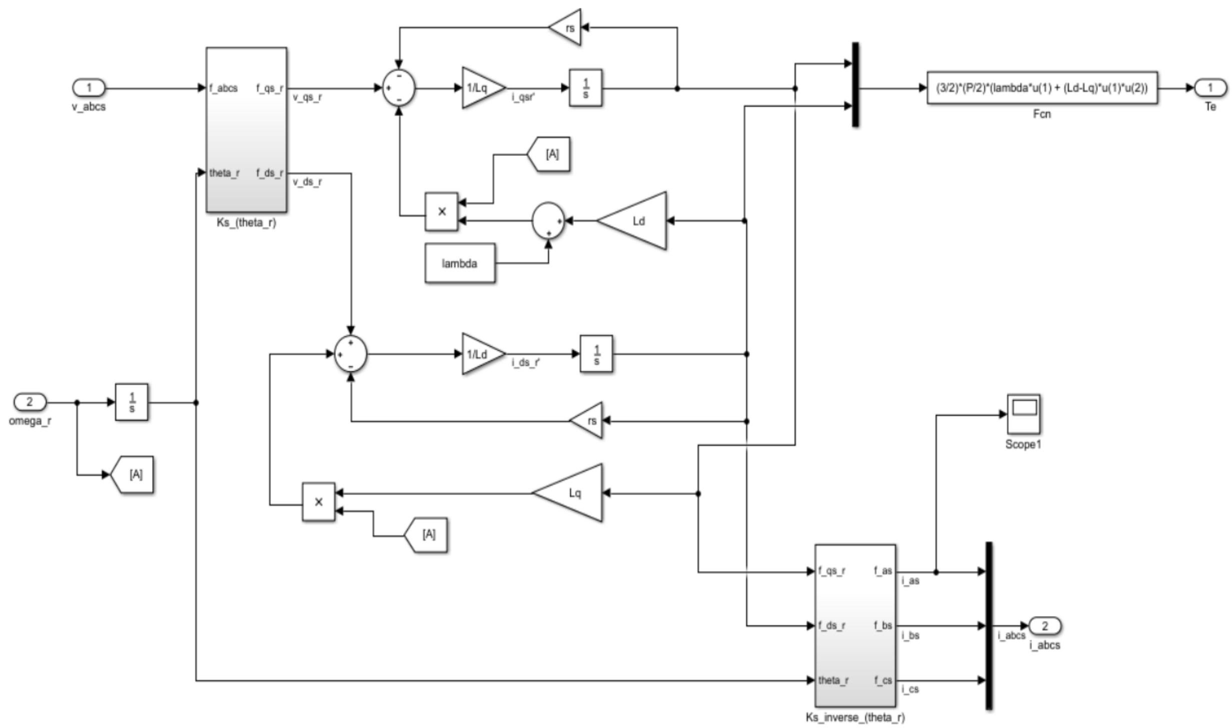
INVERTER SUBSYSTEM



WAVEFORMS

PERMANENT MAGNET AC MOTOR SUBSYSTEM

This system acts as the rotor torque controller. It takes in the outputs of the inverter subsystem and the speed of the engine to calculate the output torque.
The Simulink block diagram of the system is given below.



PERMANENT MAGNET AC SUBSYSTEM

CIRCUIT PARAMETERS

The circuit parameters are predetermined for the optimum performance of the system. They are represented by the figures below. At present we neglect all switch and diode losses.

TABLE 1. Source and Filter Parameters

V_{batt}	350 V
C	1 mF
L	1 μH
R	0.01 Ω

TABLE 2. Motor Parameters

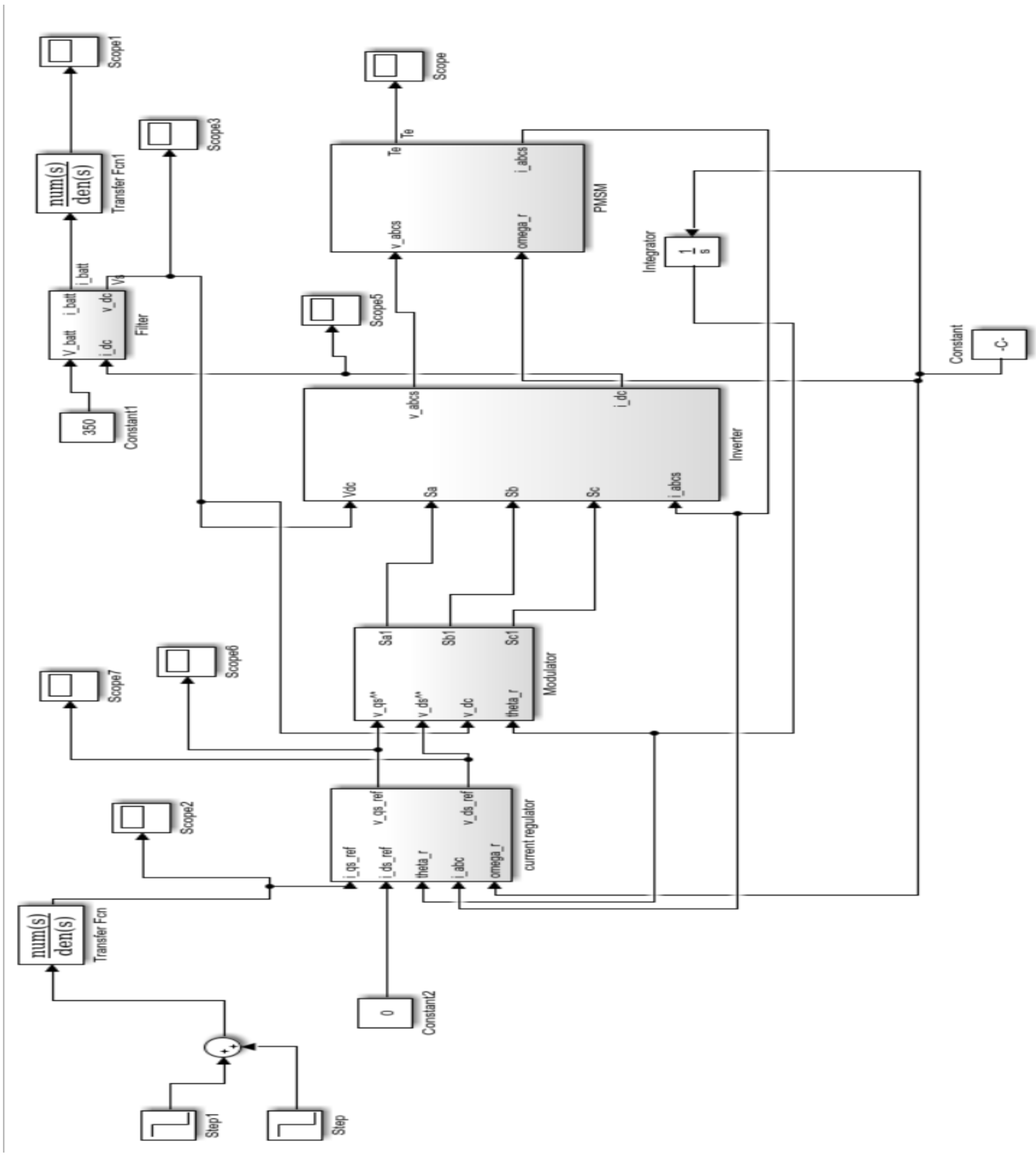
L_d, L_q	0.3 mH
r_s	0.01 Ω
λ'_m	0.1062 V-s/rad
P	6
$I_{\max}$	250 A

TABLE 3. Current Regulator Parameters

K_q	1 Ω
K_d	1 Ω

SIMULINK REPRESENTATION

The Simulink representation of the model is given by the figure below.



SIMULINK REPRESENTATION

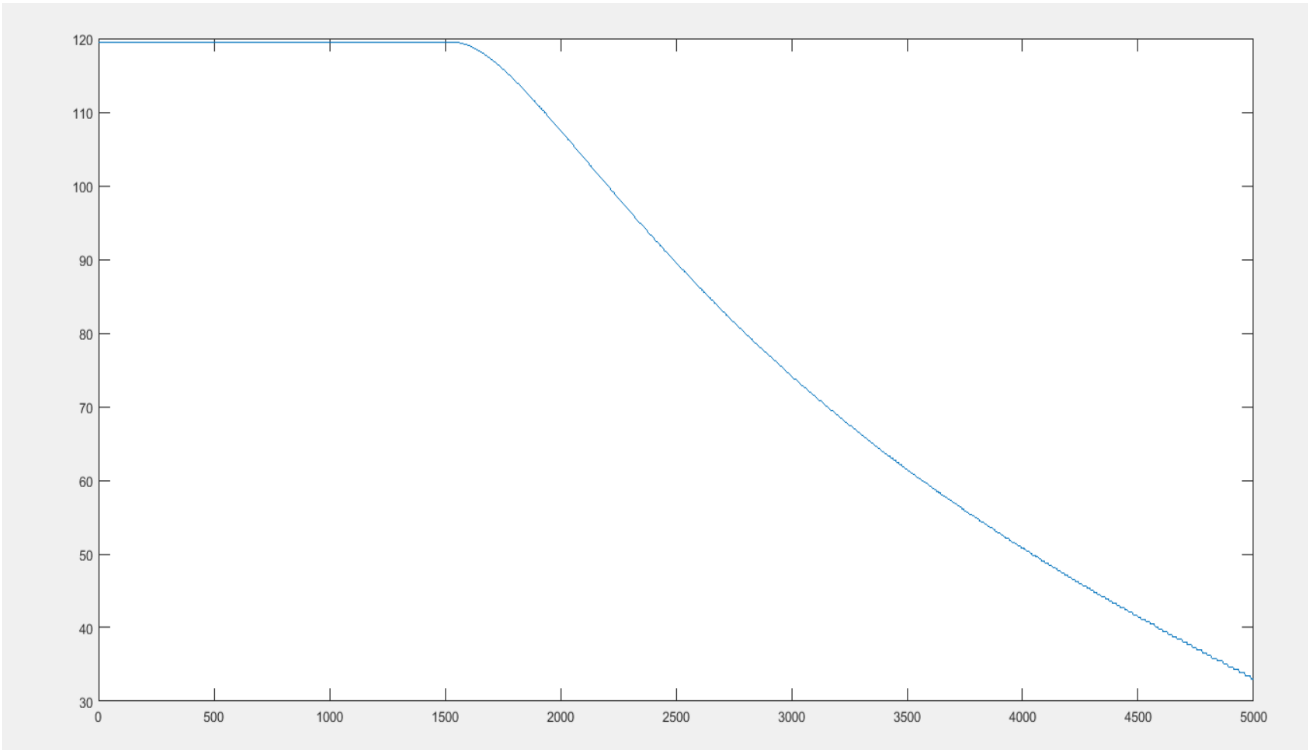
QUESTION 1

Write a Matlab script that calculates and plots the maximum torque-versus-speed characteristics of the given drive system. Plot maximum torque versus speed and maximum mechanical power versus speed.

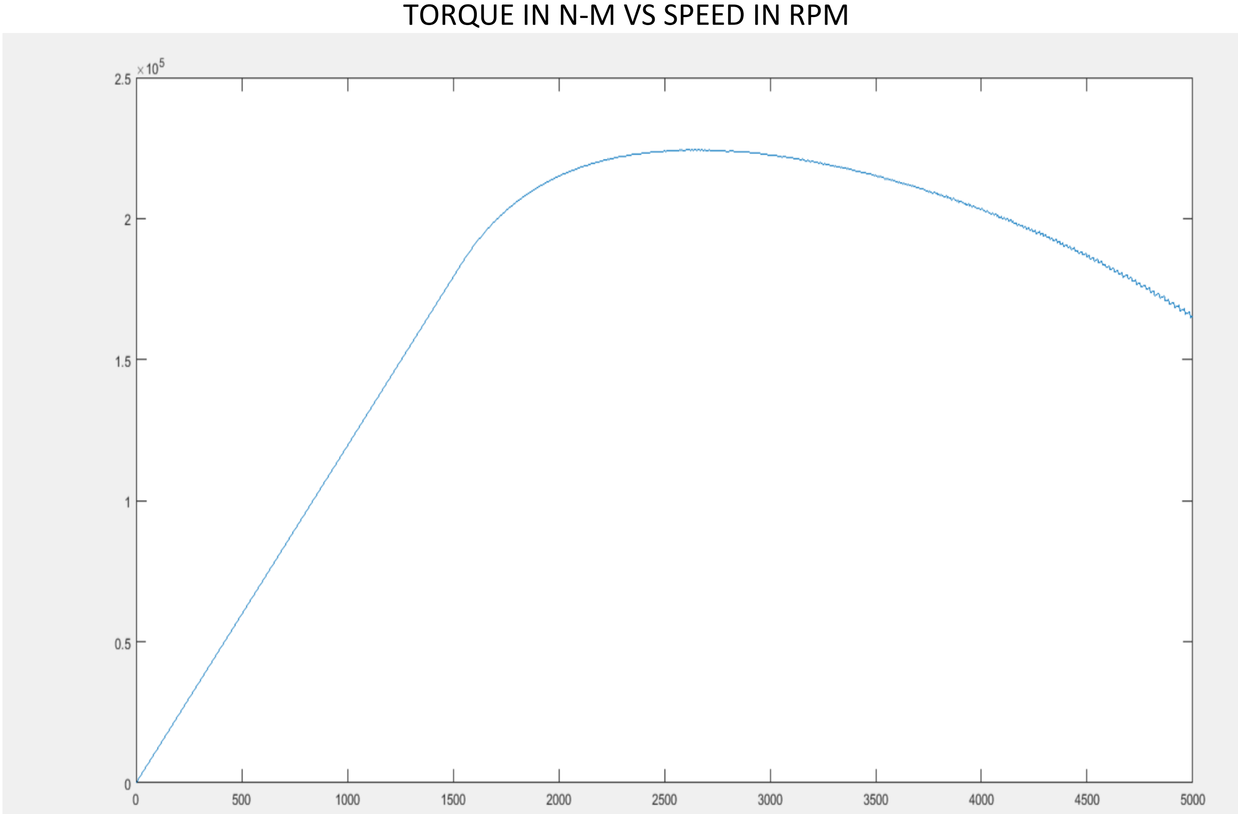
The code snippet for calculation of both for calculation of torque vs speed and power vs speed is provided below.

```
wr = linspace(0,5000,nw);
ids = -linspace(0,Imax,ni);
for i = 1 : nw
   Temax = 0;
   for j = 1 : ni
      iqs = sqrt(Imax^2 - ids(j)^2);
      vqs = rs*iqs + wr(i)*(Ld*ids(j) + lambda);
      vds = rs*ids(j) - wr(i)*Lq*iqs;
      vp = sqrt(vqs^2 + vds^2);
      if(vp < Vmax)
         T = 1.5*(P/2)*lambda*iqs;
         if(T > Temax)
            Temax = T;
         end
      end
   end
   Te(i) = Temax;

   p(i) = wr(i)*Te(i)
end

plot(wr,Te)
plot(wr,p)
```

The values of iqs, vqs, vds, vp are calculated as shown above to get the plot characteristics. The plots required are presented below. The torque remains constant at the maximum value of 120 N-m and starts decreasing at 1500 rpm and gradually decreases till 5000 rpm. The power vs speed plot follows the torque vs speed with the power increasing to a maximum of 212 Kw at 2500 rpm after which it starts dipping down.



TORQUE IN N-M VS SPEED IN RPM



POWER IN WATTS VS SPEED IN RPM

QUESTION 2

Determine Iqs needed to develop 100 N-m at a mechanical speed of 3000 rpm. Assume I r∗ ds = 0. Using steady-state equations, calculate required Vqs and Vds . Calculate the average power supplied to the motor and the average steady-state source current Ibatt. Repeat for Iqs set to negative value (corresponding to -100 N-m).

This question asks us to calculate the desired I_qs, V_qs, V_ds, average power and battery current with the values of the torque and the motor speed provided.
We make use of the steady state equations to calculate the required parameters. The steady state equations are given by the figure below.
The power is given by = Torque*Speed and,
Battery current = Power/ Battery voltage

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda'_m I^r_{qs} + (L_d - L_q) I^r_{qs} I^r_{ds}\right]$$

Subject to

$$\sqrt{\left(I^r_{qs}\right)^2 + \left(I^r_{ds}\right)^2} < I_{\max} \quad \left(\text{nonlinear inequality constraint}\right)$$

$$\sqrt{\left(V^r_{qs}\right)^2 + \left(V^r_{ds}\right)^2} < V_{\max} \quad \left(\text{nonlinear inequality constraint}\right)$$

$$V^r_{qs} = r_s I^r_{qs} + \omega_r \lambda'_m + \omega_r L_d I^r_{ds} \quad \left(\text{linear equality constraint}\right)$$

$$V^r_{ds} = r_s I^r_{ds} - \omega_r L_q I^r_{qs} \quad \left(\text{linear equality constraint}\right)$$

STEADY STATE EQUATIONS

For the first part of the question the motor torque is given to be 100 N-m and motor speed is 3000*(2*3.14/60)*3 rpm. Power is calculated by the formula, Power = 1.5*Vqs*Iqs and battery current is calculated by dividing the power by the battery voltage Vbatt.

The I_ds is equal to zero. Our answers are given below.

1. I_qs = 209.2488 Amps.
2. V_qs = 102.1329 Volts.
3. V_ds = -59.1337 Volts.
4. Power = 31977 Watts.
5. I_batt = 90.71 Amps.

For the second part of the question everything remains the same except the motor torque which is made -100 N-m. Our answers are given below.

1. I_qs = - 209.2488 Amps.
2. V_qs = 97.942 Volts.
3. V_ds = 59.1337 Volts.
4. Power = - 30723 Watts.
5. I_batt = - 86.88 Amps.

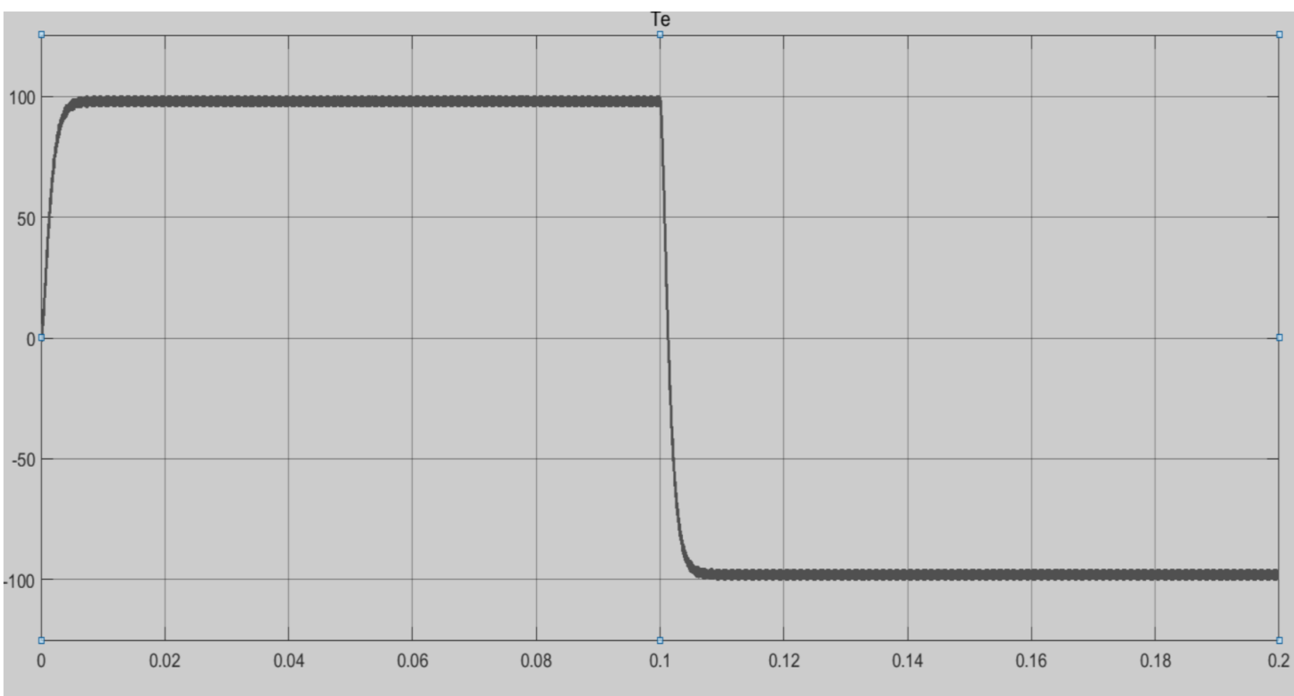
QUESTION 3

Simulate a step change in Iqs from 0 to the value calculated in (2) to minus the value calculate in question 2 allowing the system to reach steady state before applying each step change. Assume that the mechanical speed is constant (3000 rpm). Plot vas, ias, vdc, idc, ibatt, and Te. Each plot should include a discussion of the associated results. Compare average ibatt and Te with calculated values from question 2.

As calculated form the above question we provide the required I_qs input as 209.2488 Amps for a sample period of 0.1 seconds and -209.2488 Amps for a sample period of 0.1 seconds and plot the required parameters. The mechanical speed is constant and is 3000 rpm.

Torque(Te)

The torque values are generated by the Permanent magnet ac motor subsystem. It uses the standard torque formula to calculate it.
In question 2 we provided a 100 N-m torque as the input to get a required current of 209 Amps and a -100 N-m torque for a required current of -209 Amps. Thus, if replicated the other way around we are supposed to get a torque of 100N-m for the first 0.1 second sample period and -100N-m torque for the second 0.1 sample period. We get the same output as shown by the graph below. The transition from a 100 N-m to a -100 N-m happens gradually. To reduce a surge in torque peak at 0.1 seconds the values of K_d and K_q has been reduced down to 0.5 each or introduce a transfer function in the input.



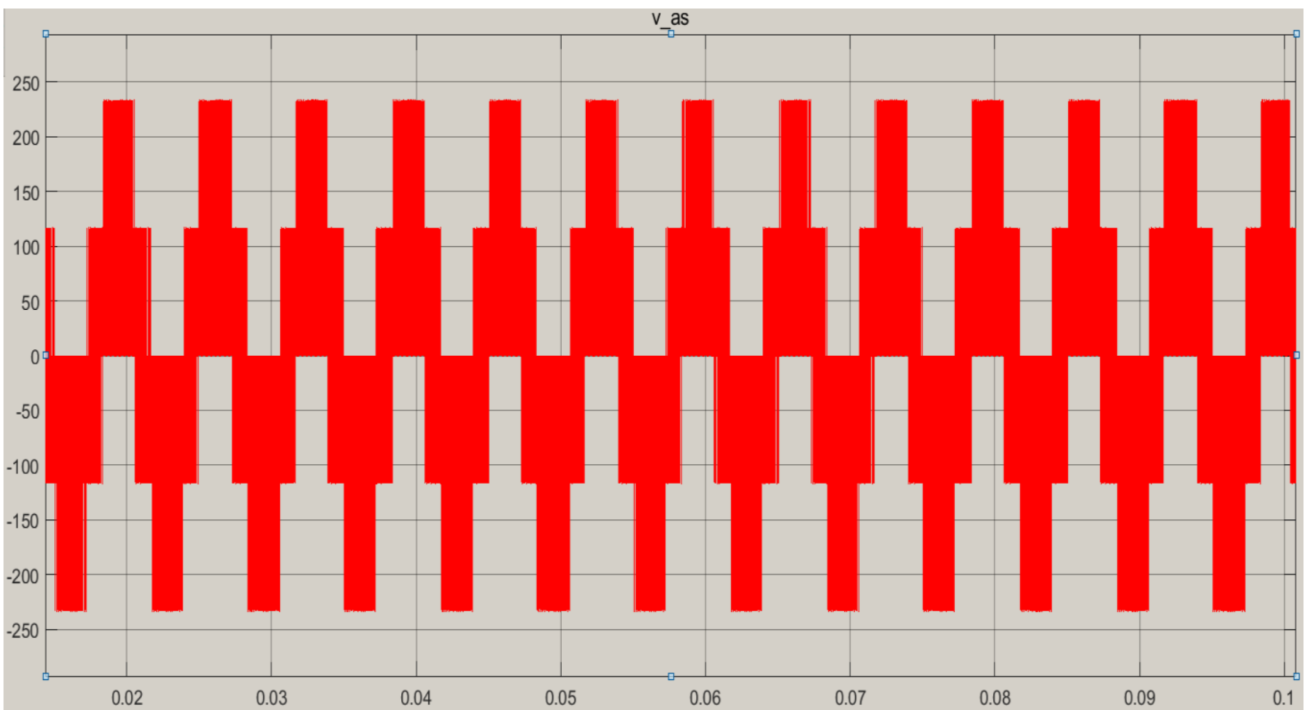
TORQUE IN N-M VS TIME IN SECONDS

Voltage(Vas)

The voltage Vas is calculated using the inverter subsystem. The formulae for calculating Vas, Vbs and Vcs are given below. All the voltages will peak at different sample periods. The peak values Vas is around 232Volts and -232 Volts. Since some amount of noise is present in the voltage calculation we don't get the perfect waveform. But it clearly represents a step wave resembling a sine waveform. The plot for Vas is provided below.

$$v_{ag} = v_{an} + v_{ng}$$
$$v_{bg} = v_{bn} + v_{ng}$$
$$v_{cg} = v_{cn} + v_{ng}$$

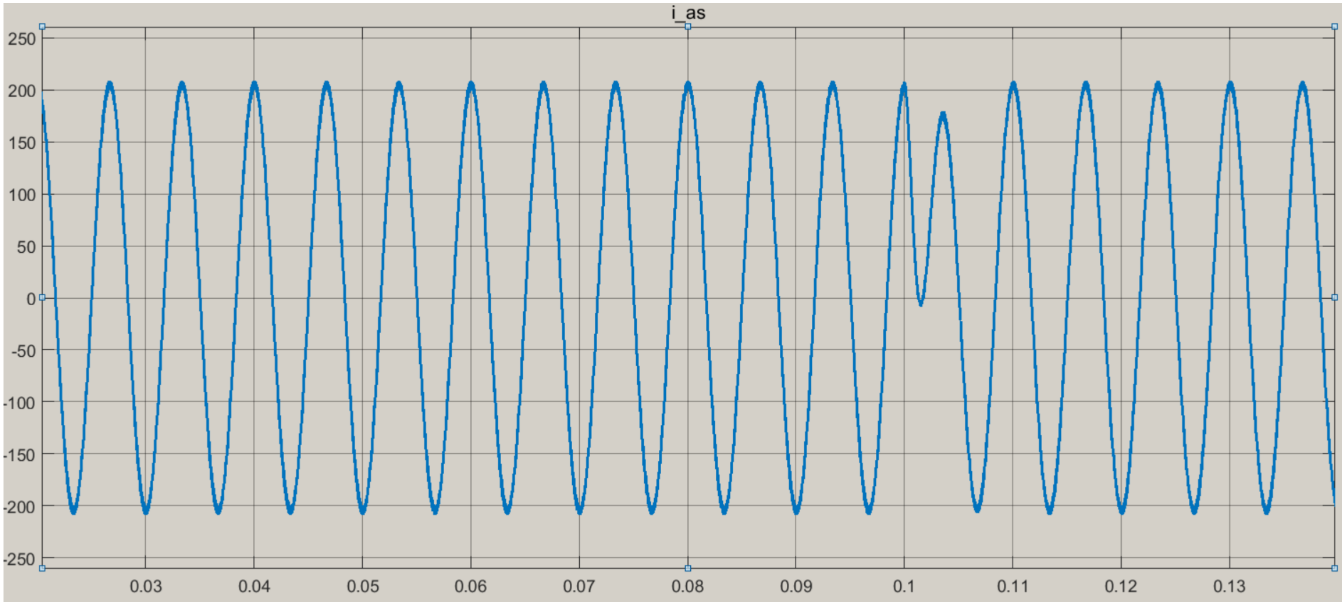
FORMULAE



VOLTAGE(Vas) IN VOLTS VS TIME IN SECONDS

Current(Ias)

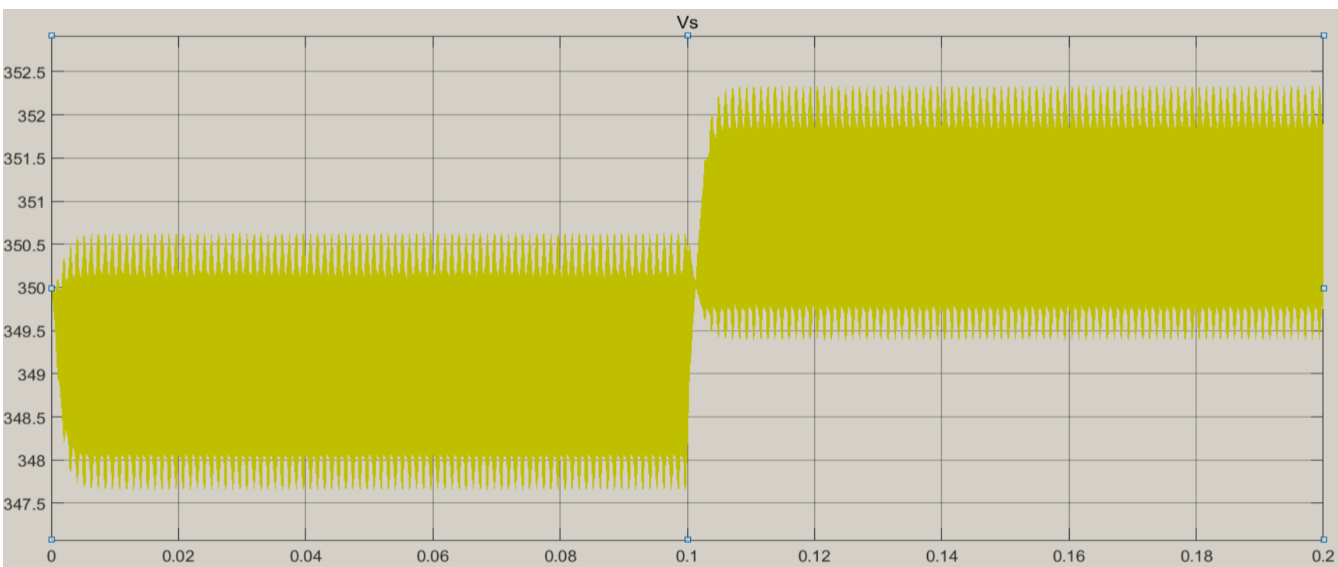
The current Ias is calculated in the permanent magnet AC drive. It is used to calculate Iabcs which is the sum of Ias, Ibs and Ics. It basically behaves as a sine wave and takes a slight dip at 0.1 seconds as shown in the plot below. It ranges in the amplitude range of -200 to +200 Amps.



CURRENT(Ias) IN AMPERES VS TIME IN SECONDS

Voltage(Vdc)

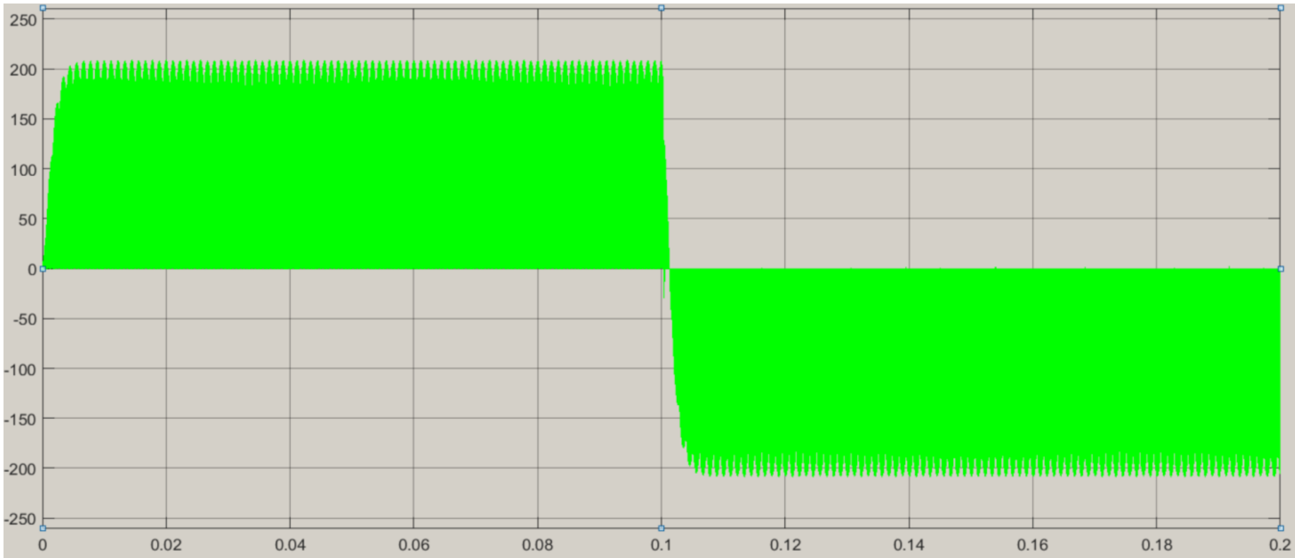
The voltage Vdc is obtained as an output from the filter subsystem and is used as an input to both the inverter and sine triangular modulator subsystems. The value of Vdc fluctuates around 350 Volts during the rum time as depicted by the plot below. We can see a lot of noise in the plot.



VOLTAGE Vdc IN VOLTS VS TIME IN SECONDS

Current(Idc)

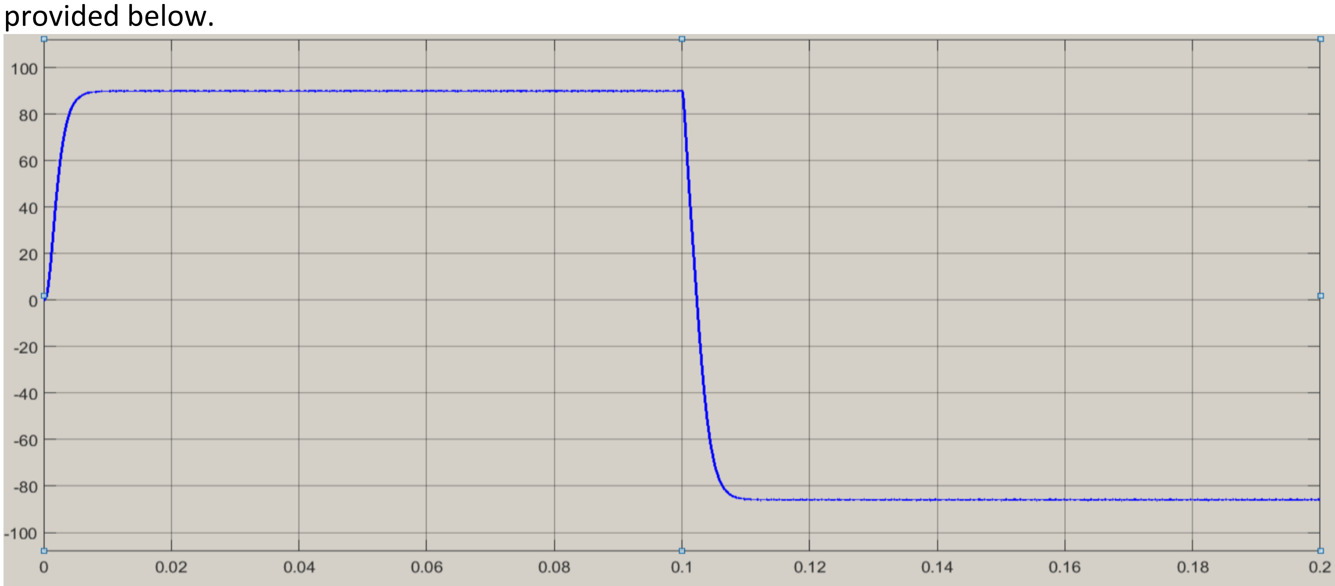
The current Idc is obtained by the sum of Iag, Ibg and Icg. It is obtained as an output from the inverter subsystem and is fed into the filter to calculate the values of Vdc. There is a lot of noise present in the plot and the signal has a range of -200 to +200 Amps as given by the plot below.



CURRENT Idc IN AMPERES VS TIME IN SECONDS

Battery Current (ibatt)

The battery current is calculated using the values of battery voltage and the power. It is the output from the filter subsystem. The value of battery current as calculated before is +90 Amps in the first cycle and -86 Amps in the second cycle. The plot of battery current vs time is provided below.



BATTERY CURRENT IBATT IN AMPERES VS TIME IN SECONDS

Conclusion

The model of the permanent magnet AC motor drive system is simulated using Matlab Simulink and the answers for the questions provided are calculated and plotted.