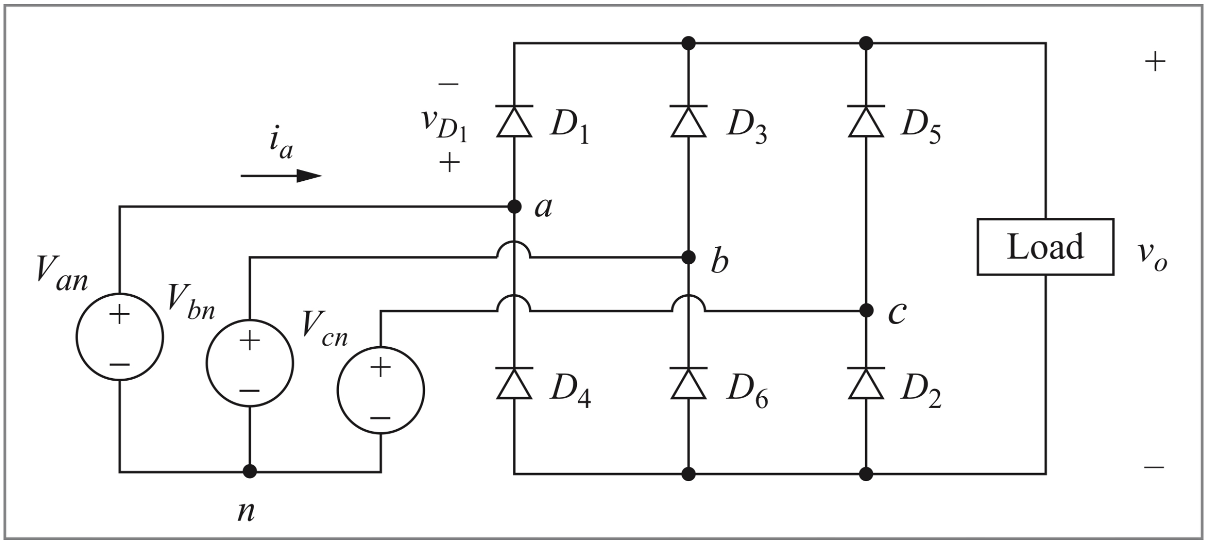
The AC-DC Converter



ID: 205308

Project 3

ECE 43300

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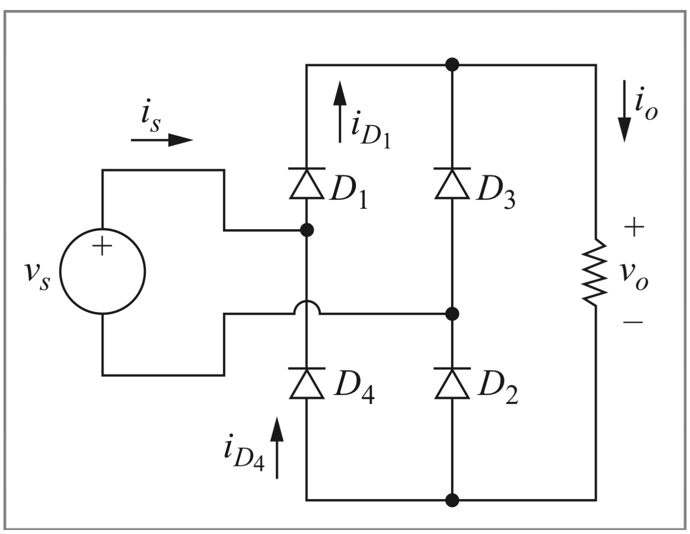
The AC-DC Converter

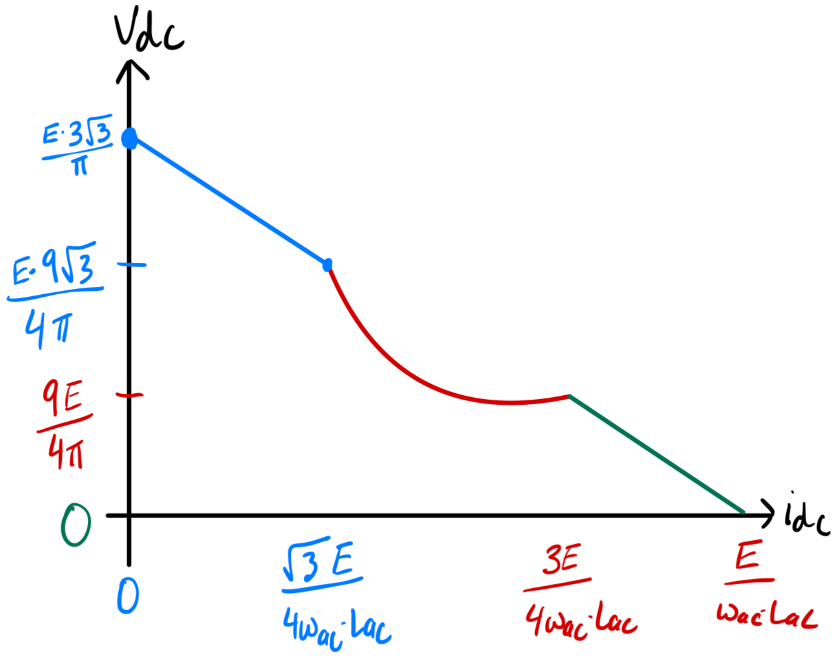
Abstract

The AC-DC converter's objective is to produce a voltage or current that is purely dc or has some dc component to it. The purpose of the full-wave rectifier is the same as the half wave while having some advantages. The average current from the ac source is zero thus it is a better output for us to use in transformers. This process is known as rectification since it straightens the direction of the current. The half-wave and full wave rectifiers outputs convert the whole of the input waveform to a constant polarity either positive or negative based on orientation. The full-wave rectifier converts both polarities of the input to a DC current to yield a higher average output voltage. The average or RMS no load voltage of a single-phase wave rectifier is $V_{dc} = 2 * V_{peak}/\pi$. This can simply be found by finding the average function of Vdc over one period. The resulted current would then just be $I_{dc} = 2 * V_{peak}/(R_{load} * \pi)$ since the current here is DC. These fundamental equations will be what governs the rectifier which gives us the output of a DC waveform from AC. In this experiment, I will explore the theory behind the three phase rectifier and how it functions based on the single-phase rectifier.



Theory

Single-phase rectifiers are commonly used in small power supplies or cheap domestic equipment due to the cost of manufacturing. However, the commercialized and industrial method of transforming a AC waveform to DC is through the three phase rectifier. This type of transformation still leads to harmonic distortion since the output of the type of rectifier is said to have 6 times the frequency of the input ac waveform. Each period of this frequency is set to have a set of diodes that will be turning on while another set is turning off. The offset for each interval being turned on or off is pi/3 radians. We can take the average of our output DC waveforms to find the resulted DC voltage that will be shown to our device. This is due to the fact that DC voltage is steady state and that is what the device will see over those average functions periods. Due to the nature of our circuit, we have some modes that we must account for due to the load resistance that will be placed in the circuit. During mode 1, the circuit acts like a linear relationship between Vdc and & Idc. Additionally during mode 2, the circuit acts in an exponential fashion. The commutation interval is the period on our waveform when the diodes are switching due to the voltage being greater from the a, b, or c voltage inputs additionally, this is from the result of the ac inductance on the source side which cannot instantaneously change the current and must gradually change the current. This would also be the part of our graph where the current is not in steady state since there would be more than one return or input in our circuit. To solve for the commutation interval, we can express an ODE with a KVL in our circuit. After expressing the ODE, we can take the integral of our Idc current with a definite boundary of 0 to the commutation interval. By taking the average of the output DC waveforms at the maximum value of our commutation interval, we can solve for a load line in each mode to model the circuit overall. Below is a model of the resulted circuit where the R_load determines where we are on the load line.



Part 1a

The input to our 3 phase generator is providing such voltage of the forms:

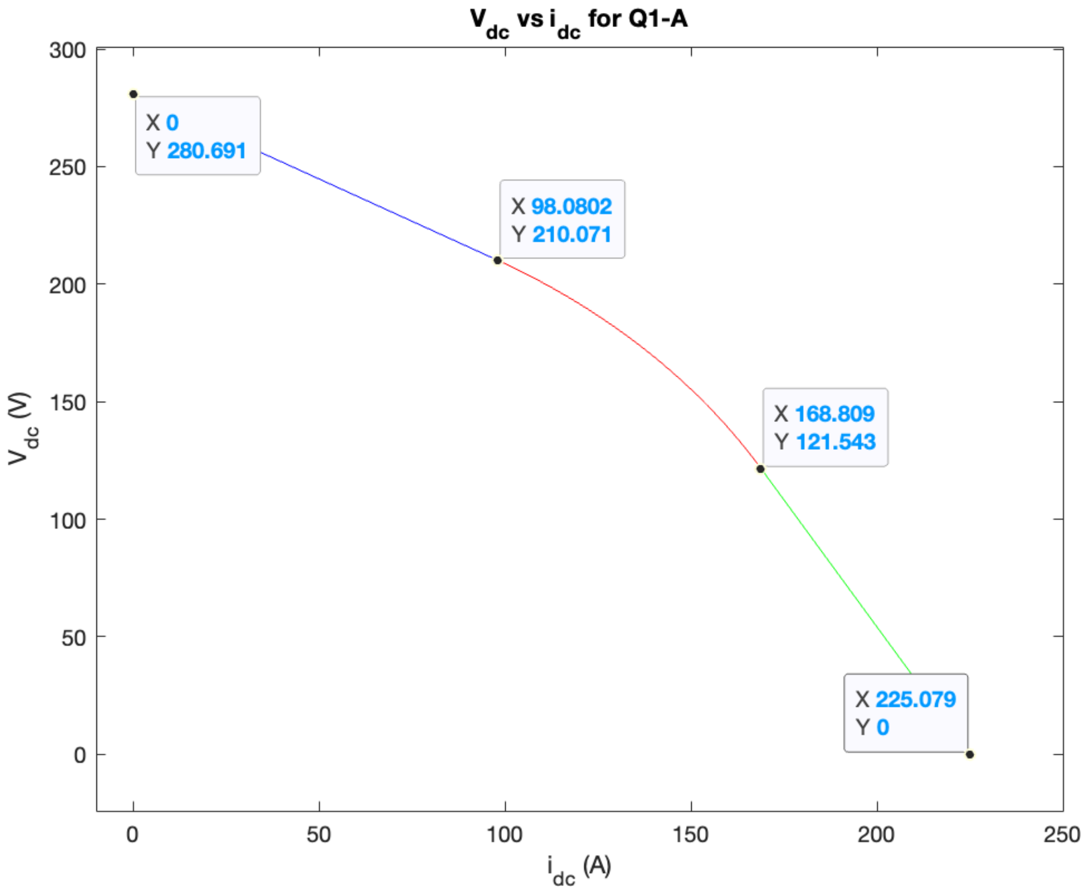
$e_{as} = \sqrt{2} * 120 * cos(377 * t)$

$e_{bs} = \sqrt{2} * 120 * cos(377 * t - 2 * \pi/3)$

$e_{cs} = \sqrt{2} * 120 * cos(377 * t + 2 * \pi/3)$

```
% given quantities
L_ac = 2e-3; % ac inductor
max_gamma = pi/3;
max_alpha = pi/6;
max_delta = pi/3;
f_ac = 60; % frequency of fundamental
T_ac = 1/f_ac; % period of fundamental
w_ac = 2*pi/T_ac;
gamma = 0:max_gamma/1000:max_gamma;
alpha = 0:max_alpha/1000:max_alpha;
delta = 0:max_delta/1000:max_delta;
E_given = sqrt(2)*120;
```

```
%% Part A
k = 0;
for N = 1:length(gamma)
    if (gamma(N) >= 0 && gamma(N) <= pi/3)
        V_dc_1(k+1) = (3*sqrt(3)*E_given/(2*pi))*(1+cos(gamma(N)));
        i_dc_1(k+1) = -(30000*cos(gamma(N))*sqrt(6)/377)+(30000*sqrt(6)/377);
    k = k+1;
    end
end
k = 0;
figure;
plot(i_dc_1,V_dc_1, 'b')
hold on

for N = 1:length(alpha)
    if (alpha(N) >= 0 && alpha(N) <= pi/6)
        V_dc_2(k+1) = 9*E_given*cos(alpha(N) + (pi/6))/(2*pi);
        i_dc_2(k+1) = sqrt(3)*E_given*sin(alpha(N) + (pi/6))/(2*w_ac*L_ac);
    k = k+1;
    end
end
k = 0;

plot(i_dc_2,V_dc_2, 'r')

for N = 1:length(delta)
    if (delta(N) >= 0 && delta(N) <= pi/3)
        V_dc_3(k+1) = 9*E_given*(1-sin(delta(N) + pi/6))/(2*pi);
        i_dc_3(k+1) = (1+sin(delta(N) + pi/6))*E_given/(2*w_ac*L_ac);
    k = k+1;
    end
end

plot(i_dc_3,V_dc_3, 'g')
ylim([-25 300])
xlim([-10 250])
xlabel("i_d_c (A)")
ylabel("V_d_c (V)")
title("V_d_c vs i_d_c for Q1-A")
```



Here is the load line for our generator circuit. We see the maximum power delivered would be at the maximum commutation of 60 degrees for mode 2 since that is where the idc vs vdc is the greatest. By doing 3 for loops, we can execute through each mode through each theta iteration and find the load line. The respective equations for each V_dc and I_dc were found by finding the average of the output function over the commutation interval as mentioned previously. Additionally mode 3 was not calculated for due to the complexity of the 4 diodes being on during the delta interval. We can divide these numbers by each other to find the R_load for the max and min at each point which would be:

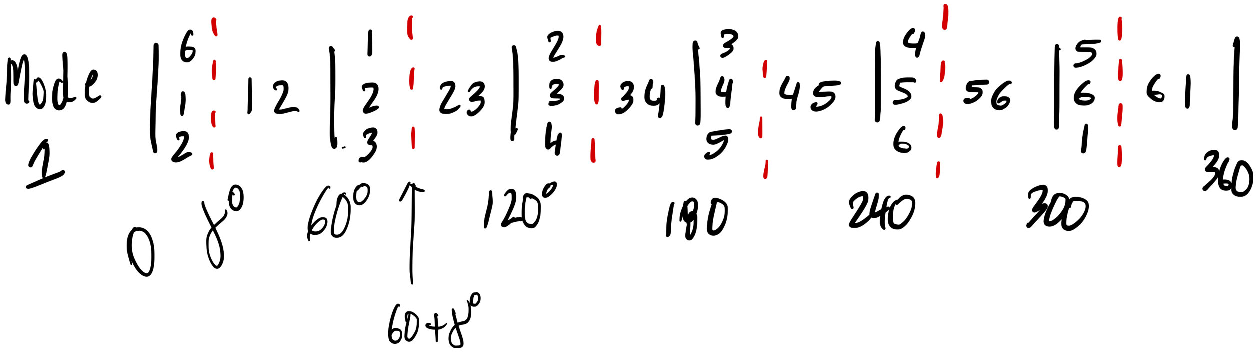
Mode 1 Limits: $9 * w_{ac} * L_{ac}/\pi \leq R_{load} \leq \infty$

Mode 2 Limits: $3 * w_{ac} * L_{ac}/\pi \leq R_{load} \leq 9 * w_{ac} * L_{ac}/\pi$

Mode 3 Limits: $0 \leq R_{load} \leq 3 * w_{ac} * L_{ac}/\pi$

Part 1b

Setting the commutation to a degree of 15 degree, we plot the phase-a, b, and c currents. The currents here were found by the diode switching shown below.



Let us take the first period to explore what is happening. The rest of the intervals will be similar but with different inputs being applied.

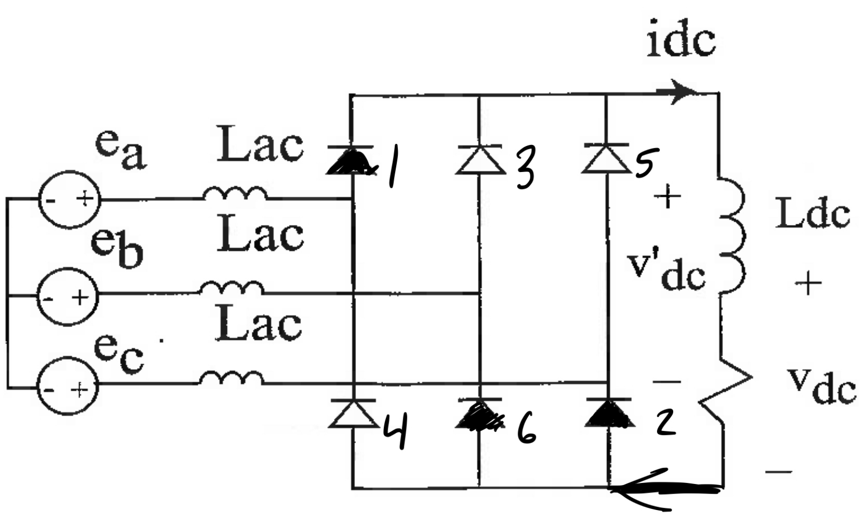
Between the 0 to gamma interval, the phase currents would be as shown below due to the diode switching and the return current. i_c could be expressed as negative i_b due to them being the opposite of each other since they are both in the return current line. Additionally, the interval bounds are determined by the interval that we are taking it with respect to in the diode switching. The upper bound is always with respect to theta so we can iterate over a phase for our circuit and see its response. The lower bound is what interval we are iterating over. The return current is with diodes 2 and 6 here so we take the difference in potential over the resistance that we have to find the current (V / R = I).

$i_{cc} = -i_b$

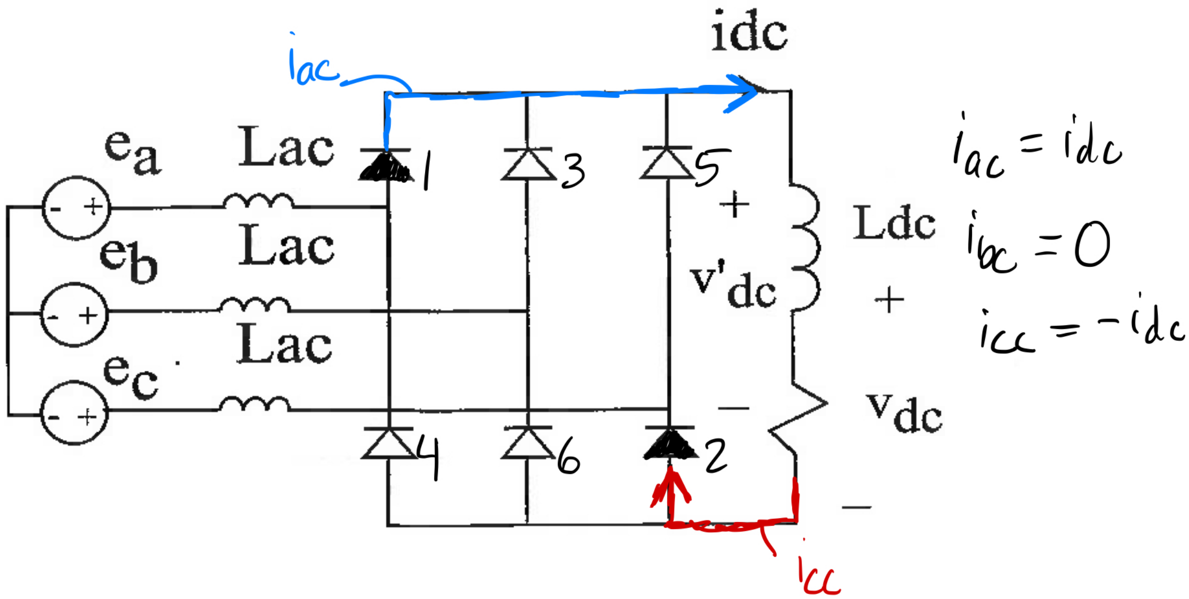
$i_{ac} = i_{dc}$

$I_{Return} = i_b - i_c$

$$i_{bc} = \int_0^{\theta} \frac{e_b - e_c}{2\omega_{ac} L_{ac}} \, d\theta$$



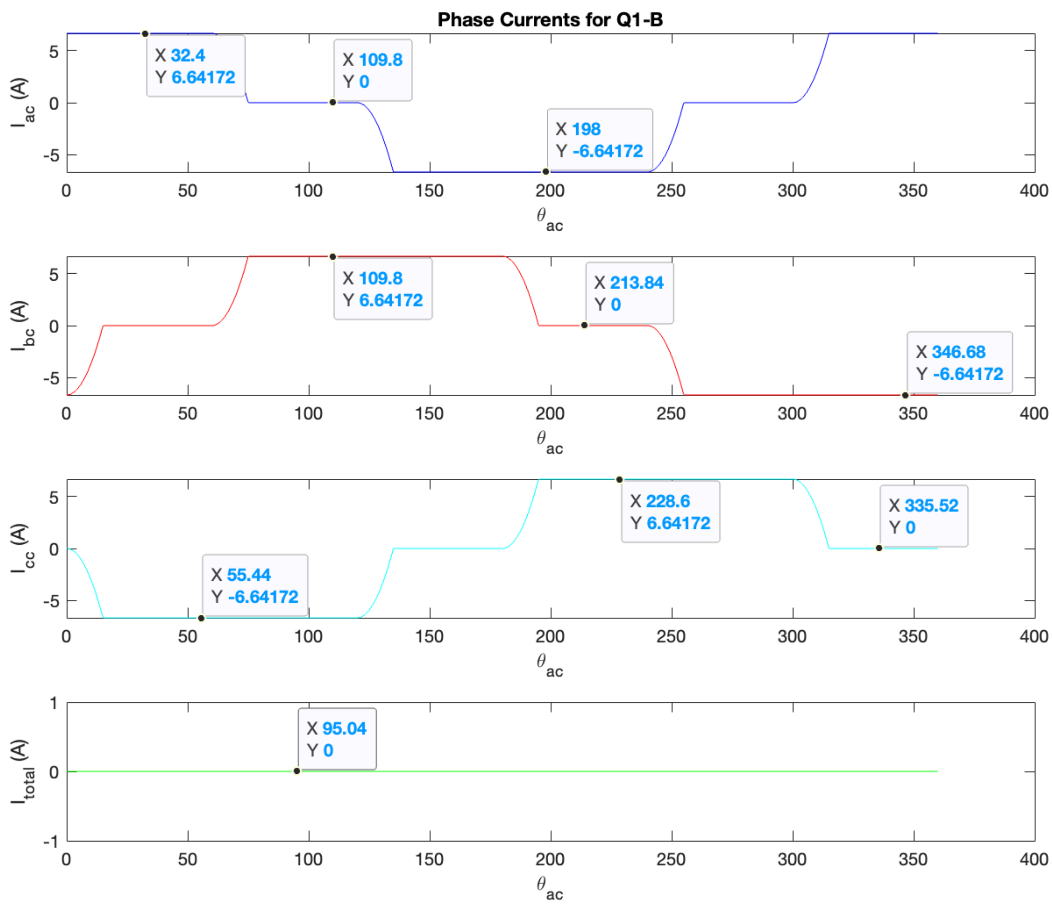
Next, we take the interval from gamma to gamma plus sixty in a similar fashion, however here only 2 diodes are on as compared to 3. This would mean that the integral is not coming into play since the currents have only have one return and one input. For this interval, the resulted input is from diode 1 which results in i_ac = i_dc and the return going from diode 2 which results in i_cc = - i_dc due to the nature of the c voltage phase being reversed when being entered from diode 2.



After taking the integral for all the periods, we see the resulted code by checking the theta value between what interval we are in with if statements. Additionally, the total current is calculated for since there is no loss in this circuit which should always be resulted as 0. The resulted idc and vdc found at the maximum commutation value was 6.6417 A and 275.9087 V. We can divide these values to find a **R_load of 41.5417 Ohms.**

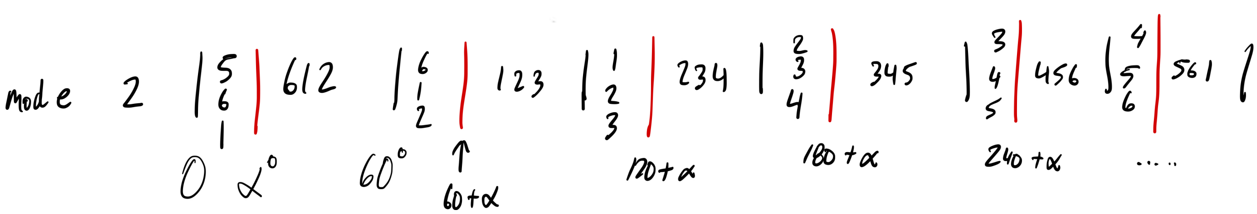
```matlab
%% Part B
k = 0;
max_gamma = pi/12;
max_theta = 2*pi;
theta = 0:max_theta/1000:max_theta;

V_dc = (3*sqrt(3)*E_given/(2*pi))*(1+cos(pi/12)); % 275.9087 V
i_dc = -(30000*cos(pi/12)*sqrt(6)/377)+(30000*sqrt(6)/377); % 6.6417 A
R_load_PartB = V_dc/i_dc; % 41.5417 Ohms

for N = 1:length(theta)
    if (theta(N) >= 0 && theta(N) <= max_gamma) % Commutation
        i_ac(k+1) = i_dc;
        i_bc(k+1) = ((sqrt(3)*(1-cos(theta(N)))*E_given)/(2*w_ac*L_ac))-i_dc;
        i_cc(k+1) = -i_bc(k+1) - i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_gamma && theta(N) <= pi/3)
        i_ac(k+1) = i_dc;
        i_bc(k+1) = 0;
        i_cc(k+1) = -i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > pi/3 && theta(N) <= max_gamma + pi/3) % Commutation
        i_ac(k+1) = (E_given*(-sin((3*theta(N)-2*pi)/3)+sin(theta(N))-sqrt(3)))/(2*L_ac*w_ac) + i_dc;
        i_bc(k+1) = -i_ac(k+1) + i_dc;
        i_cc(k+1) = -i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_gamma + pi/3 && theta(N) <= 2*pi/3)
        i_ac(k+1) = 0;
        i_bc(k+1) = i_dc;
        i_cc(k+1) = -i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > 2*pi/3 && theta(N) <= max_gamma + 2*pi/3) % Commutation
        i_ac(k+1) = (E_given*(-sin((3*theta(N)+2*pi)/3)+sin(theta(N))-sqrt(3)))/(2*L_ac*w_ac);
        i_bc(k+1) = i_dc;
        i_cc(k+1) = -i_ac(k+1) - i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_gamma + 2*pi/3 && theta(N) <= 3*pi/3)
        i_ac(k+1) = -i_dc;
        i_bc(k+1) = i_dc;
        i_cc(k+1) = 0;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end
```

```
    if(theta(N) > 3*pi/3 && theta(N) <= max_gamma + 3*pi/3) % Commutation
        i_ac(k+1) = -i_dc;
        i_bc(k+1) = (sqrt(3)*E_given*(-cos(theta(N))-1))/(2*L_ac*w_ac) + i_dc;
        i_cc(k+1) = -i_bc(k+1) + i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_gamma + 3*pi/3 && theta(N) <= 4*pi/3)
        i_ac(k+1) = -i_dc;
        i_bc(k+1) = 0;
        i_cc(k+1) = i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > 4*pi/3 && theta(N) <= max_gamma + 4*pi/3) % Commutation
        i_bc(k+1) = (E_given*(sin((3*theta(N)-2*pi)/3)-sin(theta(N))-sqrt(3)))/(2*L_ac*w_ac);
        i_ac(k+1) = -i_bc(k+1) - i_dc;
        i_cc(k+1) = i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_gamma + 4*pi/3 && theta(N) <= 5*pi/3)
        i_ac(k+1) = 0;
        i_bc(k+1) = -i_dc;
        i_cc(k+1) = i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > 5*pi/3 && theta(N) <= max_gamma + 5*pi/3) % Commutation
        i_bc(k+1) = -i_dc;
        i_cc(k+1) = (E_given*(sin((3*theta(N)+2*pi)/3)-sin(theta(N))-sqrt(3)))/(2*L_ac*w_ac) + i_dc;
        i_ac(k+1) = -i_cc(k+1) + i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_gamma + 5*pi/3 && theta(N) <= 2*pi)
        i_ac(k+1) = i_dc;
        i_bc(k+1) = -i_dc;
        i_cc(k+1) = 0;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    k = k+1;
end
```



Part 1c

Setting the commutation to a degree of 60 degree and the delay of 15 degrees to max mode 1 and get into mode 2, we plot the phase-a, b, and c currents. The currents here were found by the diode switching shown below.



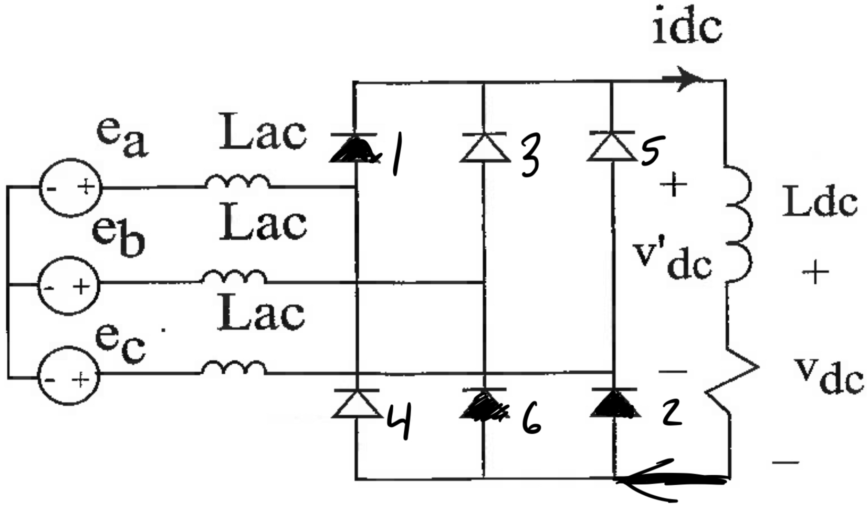
Let us take the first period to explore what is happening. The rest of the intervals will be similar but with different inputs being applied.

$$i_{cc} = -i_b$$

$$i_{ac} = i_{dc}$$

$$I_{Return} = i_b - i_c$$

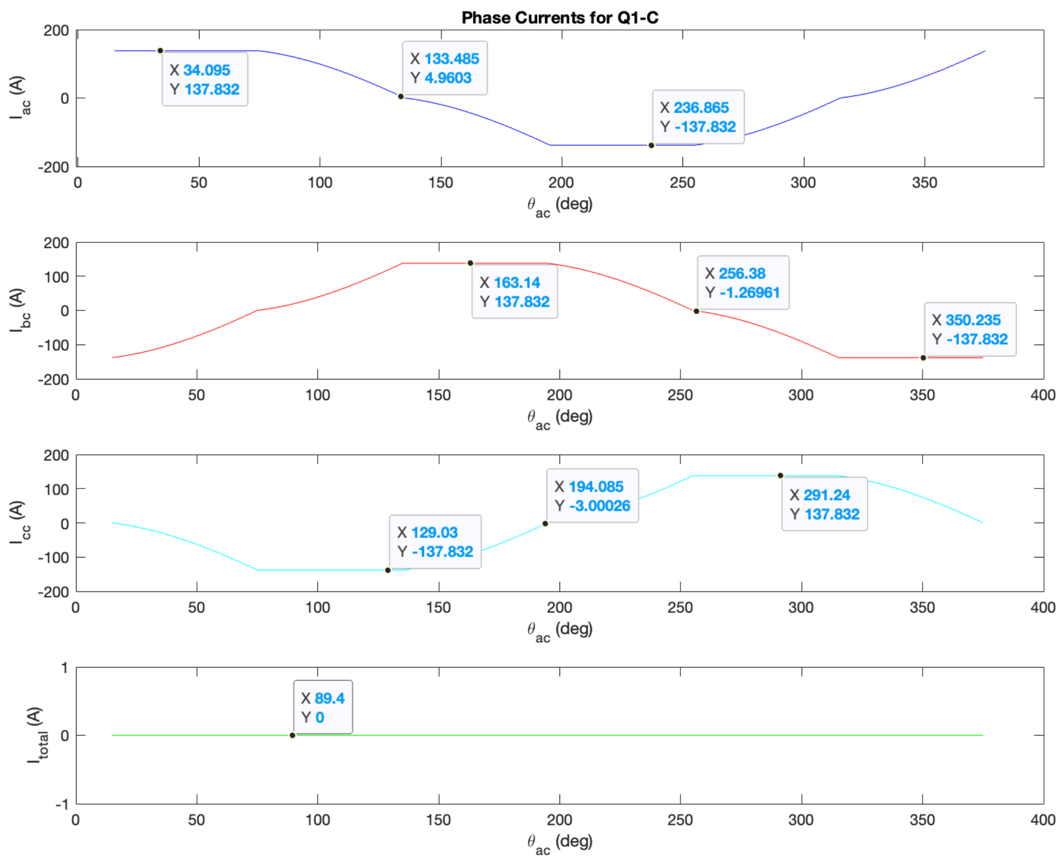
$$i_{bc} = \int_{15^\circ}^{\theta^\circ} \frac{e_b - e_c}{2 w_{ac} L_{ac}} \, d\theta$$



Between the 0 to alpha interval, the phase currents would be as shown below due to the diode switching and the return current. i_c could be expressed as negative i_b due to them being the opposite of each other since they are both in the return current line. Additionally, the interval bounds are determined by the interval that we are taking it with respect to in the diode switching. We can shift our while graph by 15 degrees to make the first interval easier to analyze since the diodes are always on for 60 degrees rather than the value of the commutation interval specified in the mode. For example, we can take the first interval to be 612 diodes which would be the result in the same integral for current and the same diodes being on. The only difference would be the integral bounds. The upper bound is always with respect to theta so we can iterate over a phase for our circuit and see its response. The lower bound would be the interval that we are iterating over so for this example, 15 degrees. The return current is with diodes 6 and 2 here so we can take the maximum dc voltage over the maximum dc current at the largest commutation value to find the resistance (V / R = I). Additionally, since we always have 3 diodes on, we can cut the number of intervals into half and always have 2 exponential curves in the phase currents either decreasing or increasing.

After taking the integral for all the periods, we see the resulted code by checking the theta value between what interval we are in with if statements. Additionally, the total current is calculated for since there is no loss in this circuit which should always be resulted as 0. The resulted idc and vdc found at the maximum commutation value was 137.8322 A and 171.8873 V. We can divide these values to find a **R_load of 1.2471 Ohms.**

```
%% Part C
k = 0;
max_alpha = pi/12;
max_theta = max_alpha + 6*pi/3;
theta = max_alpha:max_alpha/1000:max_theta;
V_dc = (9*E_given/(2*pi))*cos(max_alpha+(pi/6)); % 171.8873
i_dc = (sqrt(3)*E_given/(2*w_ac*L_ac))*sin(max_alpha+(pi/6)); % 137.8322
R_load_PartC = V_dc/i_dc; % 1.2471

for N = 1:length(theta)
    if(theta(N) >= max_alpha && theta(N) <= max_alpha + pi/3) % Commutation
        i_ac(k+1) = i_dc;
        i_bc(k+1) = (sqrt(3)*E_given*(cos(pi/12)-cos(theta(N))))/(2*L_ac*w_ac)-i_dc;
        i_cc(k+1) = -i_bc(k+1) - i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_alpha + pi/3 && theta(N) <= max_alpha + 2*pi/3) % Commutation
        i_ac(k+1) = -(E_given*(sqrt(2)*(sin((3*theta(N)-2*pi)/3)-sin(theta(N))+sin((5*pi)/12))+1))/(2^(3/2)*L_ac*w_ac) + i_dc;
        i_bc(k+1) = -i_ac(k+1) + i_dc;
        i_cc(k+1) = -i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_alpha + 2*pi/3 && theta(N) <= max_alpha + 3*pi/3) % Commutation
        i_ac(k+1) = -(E_given*(sqrt(2)*(sin((3*theta(N)+2*pi)/3)-sin(theta(N))-sin((17*pi)/12))+1))/(2^(3/2)*L_ac*w_ac);
        i_bc(k+1) = i_dc;
        i_cc(k+1) = -i_ac(k+1) - i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_alpha + 3*pi/3 && theta(N) <= max_alpha + 4*pi/3) % Commutation

        i_ac(k+1) = -i_dc;
        i_bc(k+1) = (sqrt(3)*E_given*(cos((13*pi)/12)-cos(theta(N))))/(2*L_ac*w_ac) + i_dc;
        i_cc(k+1) = -i_bc(k+1) + i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_alpha + 4*pi/3 && theta(N) <= max_alpha + 5*pi/3) % Commutation
        i_bc(k+1) = (E_given*(sqrt(2)*(sin((3*theta(N)-2*pi)/3)-sin(theta(N))+sin((17*pi)/12))-1))/(2^(3/2)*L_ac*w_ac);
        i_ac(k+1) = -i_bc(k+1) - i_dc;
        i_cc(k+1) = i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    if(theta(N) > max_alpha + 5*pi/3 && theta(N) <= max_alpha + 6*pi/3) % Commutation
        i_bc(k+1) = -i_dc;
        i_cc(k+1) = (E_given*(sqrt(2)*(sin((3*theta(N)+2*pi)/3)-sin(theta(N))-sin((29*pi)/12))-1))/(2^(3/2)*L_ac*w_ac) + i_dc;
        i_ac(k+1) = -i_cc(k+1) + i_dc;
        i_total(k+1) = i_ac(k+1) + i_bc(k+1) + i_cc(k+1);
    end

    k = k+1;
end
```



Part 1d

Analyzing the load line that we have for the circuit we have created in 1a, we see that the maximum power yield by the circuit would be in mode 2 since that is where the the Vdc * Idc = max(Power). We can use the maxindex function of MATLAB to find where on the load line the maximum power would be by multiplying our vectors of Vdc and Idc. Additionally, this can be simply determined from part c since we are in mode 2 and we have calculated the resistance at the maximum power output using the delay for that mode. Therefore, it can be concluded that the maximum power delivered to the DC load would be **23691 W at a resistance of 1.2471**.

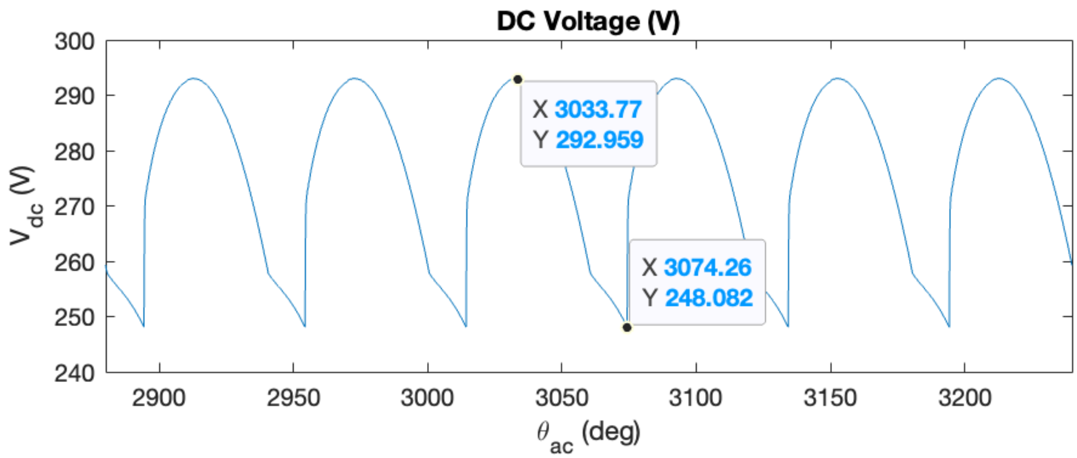
Part 2

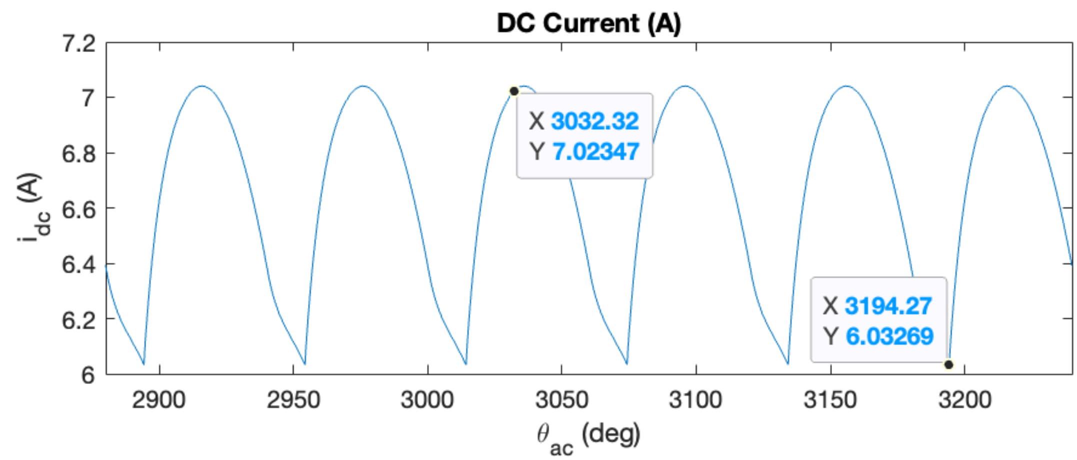
In this task, we actually simulate the circuit and its expected circuit conditions using the equations of Vdc and Idc along with logic of diode switching to determine upper and lower level voltages. If the phase current is greater than zero then it is equal to the diode current since the diode would be conducting then, however if it is less than zero then the diode current is zero. Additionally, since the dc current is the sum of the diode currents since they are our inputs, we can say that the sum of the diode currents is always equal to the waveform of the DC current output. This will be implemented in the MATLAB code through the use of logic if-else statements. We must then calculate the Vdc value since it will be used to calculate the upper and lower voltages for our diodes. The Vdc equation was derived in office hours by the GTA using an approximation technique. This approximation was done using the equation: $V_{dc} = L_{dc} * di_{dc}/dt \;\; + V_{dc} - > R_{load} * i_{dc}$. The resulted equation is dependent on the delta_tau and a backwards euler that we are iterating over since that is the number of terms we are breaking down into for time. Additionally, the epsilon value was used as a comparator to find the upper and lower voltages with respect to the diode. When the diode current was greater than the comparator, the level voltage for that diode would be equal to Vdc, and when it was less than the negative magnitude of the comparator, the level voltage would zero since we only care about what is after the comparator when the diode is on. Finally, we take level voltage for the diodes using the comparator to find the Va, Vb, Vc points to calculate the next iteration of phase currents. The average voltage and current can be found using the average function that was developed from previous projects over a certain period. We can also iterate this over all periods to get an average of the entire waveform for the whole output. This is graphed with Vdc vs Idc to show the fluctuations in load current compared to load voltage. Starting the simulator up, I input a **R_load of 41.5417 Ohms** to trigger it into mode 1 since it is the resistance from part 1 and above our cutoff resistance of 2.16 Ohms using the boundary conditions equation.

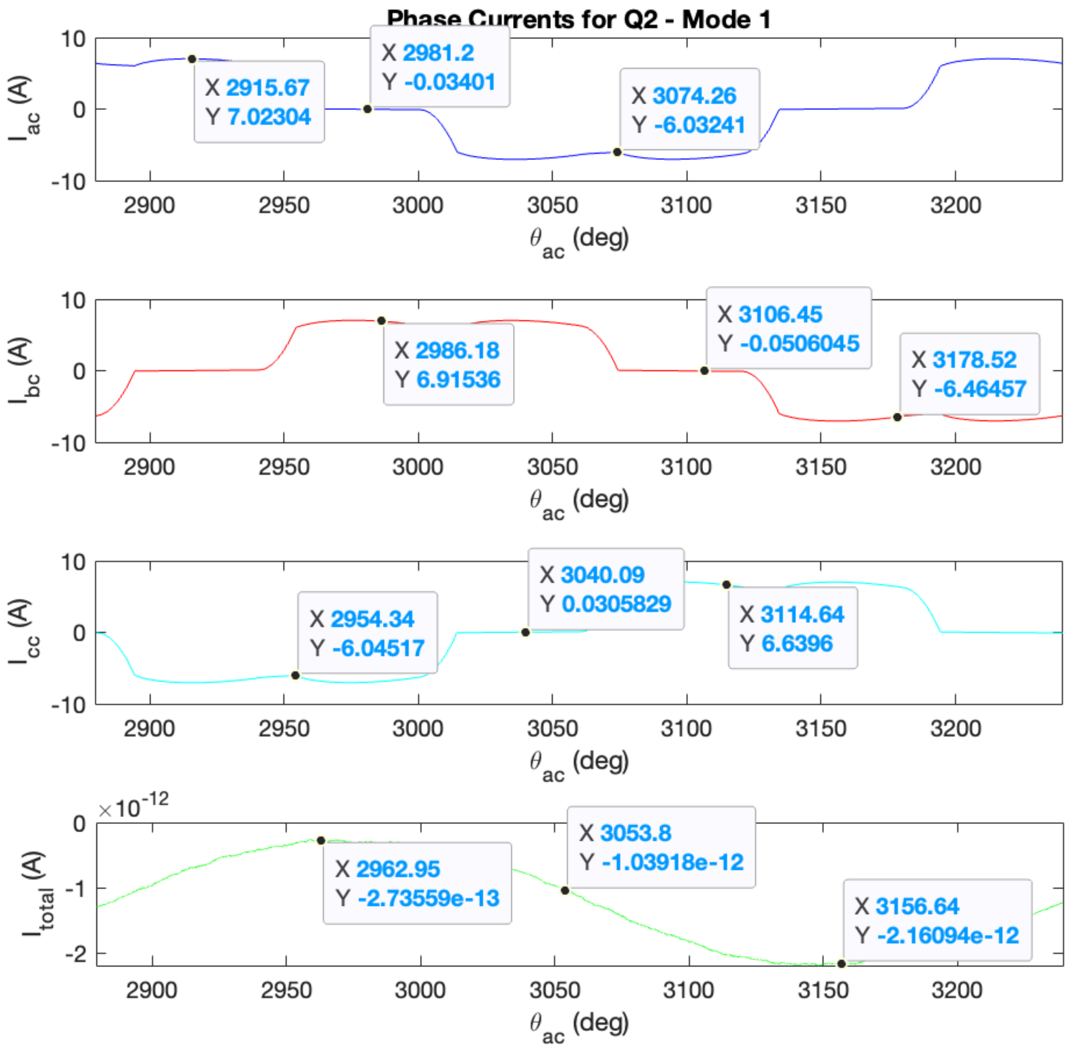
```
% given quantities
L_ac = 2e-3; % ac inductance source
L_dc = 6e-3; % dc inductance
R_load = 41.5417; % load resistance for mode 1
f_ac = 60; % frequency of fundamental
T_ac = 1/f_ac; % period of fundamental
w_ac = 2*pi/T_ac;
E_given = sqrt(2)*120; % input voltage
delta_t = 10^-7; % Time Step
t_end = 9*T_ac; % Simulation End Time
k = 1;
t(k) = 0;
v_dc(k) = 0;
i_dc(k) = 0;
tau = 10^-5;
epsilon = .1;
i_a(k) = 0;
i_b(k) = 0;
i_c(k) = 0;
```

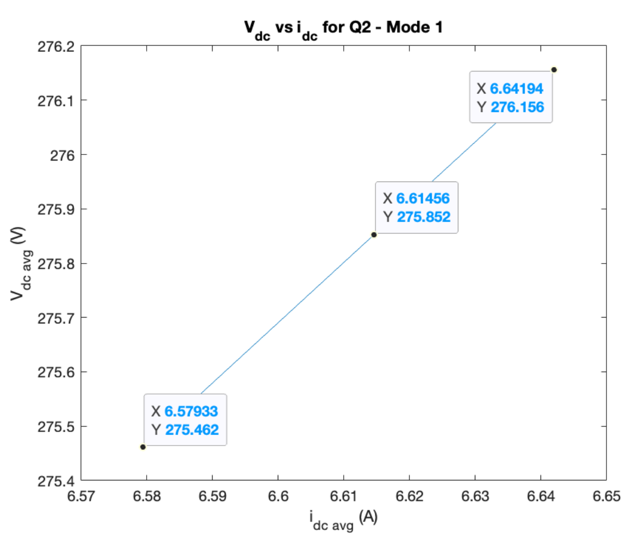
```
while t(k) < t_end
    if i_a(k) > 0
        i_d1(k+1) = i_a(k);
    else
        i_d1(k+1) = 0;
    end

    if i_b(k) > 0
        i_d3(k+1) = i_b(k);
    else
        i_d3(k+1) = 0;
    end

    if i_c(k) > 0
        i_d5(k+1) = i_c(k);
    else
        i_d5(k+1) = 0;
    end

    i_dc(k+1) = i_d1(k+1) + i_d3(k+1)+ i_d5(k+1);

    v_dc(k+1) = (tau/(tau+delta_t)) * (v_dc(k) + ((L_dc/tau) * (i_dc(k+1) - i_dc(k))) + ((R_load*i_dc(k+1)*delta_t)/tau));

    if i_a(k) >= epsilon
        v_aL(k+1) = v_dc(k+1);
    elseif i_a(k) <= (-1*epsilon)
        v_aL (k+1) = 0;
    else
        v_aL(k+1) = ((v_dc(k+1)*i_a(k))/(2*epsilon)) + (v_dc(k+1)/2);
    end

    if i_b(k) >= epsilon
        v_bL(k+1) = v_dc(k+1);
    elseif i_b(k) <= (-1*epsilon)
        v_bL(k+1) = 0;
    else
        v_bL(k+1) = ((v_dc(k+1)*i_b(k))/(2*epsilon)) + (v_dc(k+1)/2);
    end

    if i_c(k) >= epsilon
        v_cL(k+1) = v_dc(k+1);
    elseif i_c(k) <= (-1*epsilon)
        v_cL(k+1) = 0;
    else
        v_cL(k+1) = ((v_dc(k+1)*i_c(k))/(2*epsilon)) + (v_dc(k+1)/2);
    end

    va(k+1) = ((2/3)*v_aL(k+1)) - ((1/3)*v_bL(k+1)) - ((1/3)*v_cL(k+1));
    vb(k+1) = ((2/3)*v_bL(k+1)) - ((1/3)*v_cL(k+1)) - ((1/3)*v_aL(k+1));
    vc(k+1) = ((2/3)*v_cL(k+1)) - ((1/3)*v_aL(k+1)) - ((1/3)*v_bL(k+1));

    i_a(k+1) = i_a(k) + ((delta_t*(e_as(k+1)-va(k+1)))/L_ac);
    i_b(k+1) = i_b(k) + ((delta_t*(e_bs(k+1)-vb(k+1)))/L_ac);
    i_c(k+1) = i_c(k) + ((delta_t*(e_cs(k+1)-vc(k+1)))/L_ac);

    t(k+1) = t(k) + delta_t;

    k = k+1;
end
```

```
for N = 1:t_end/T_ac
    v_dcavg(N) = avrg(v_dc,N*T_ac,delta_t);
    i_dcavg(N) = avrg(i_dc,N*T_ac,delta_t);
end

theta = t * w_ac;

e_as(k+1) = E_given*cos(w_ac*t(k));
e_bs(k+1) = E_given*cos((w_ac*t(k)) - ((2*pi)/3));
e_cs(k+1) = E_given*cos((w_ac*t(k)) + ((2*pi)/3));
```

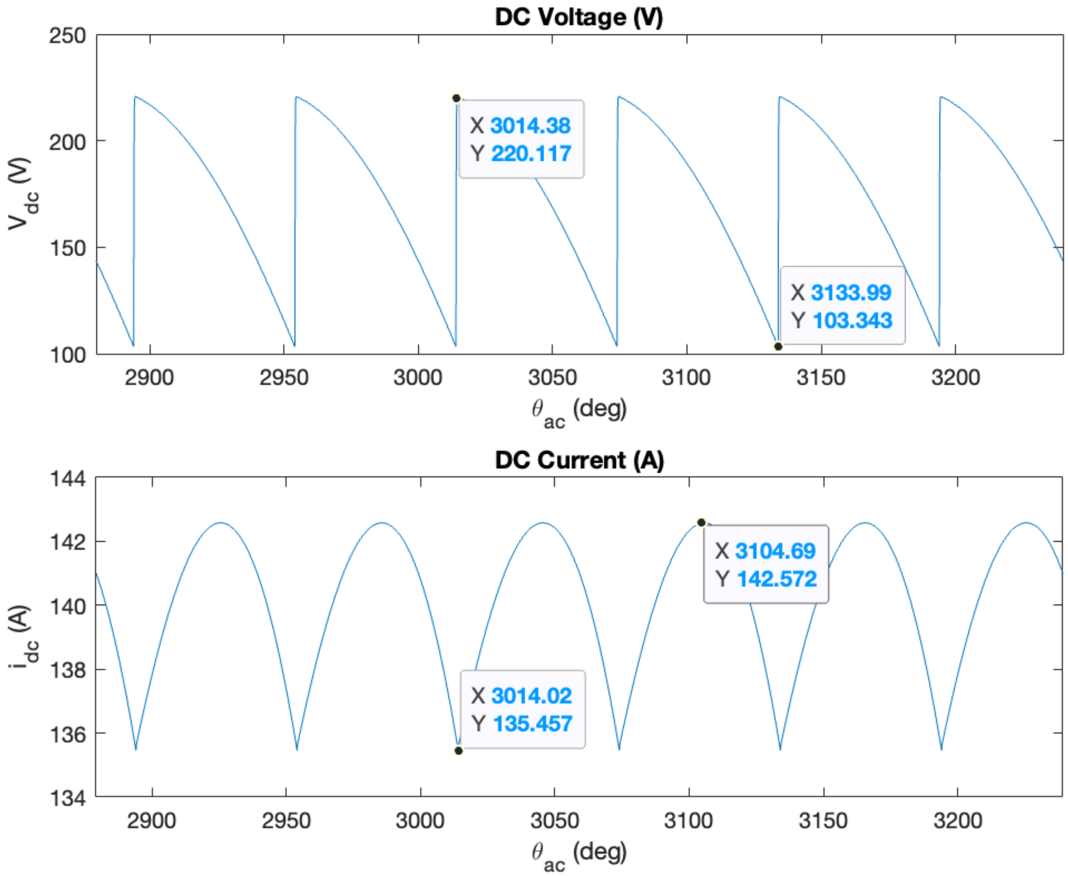


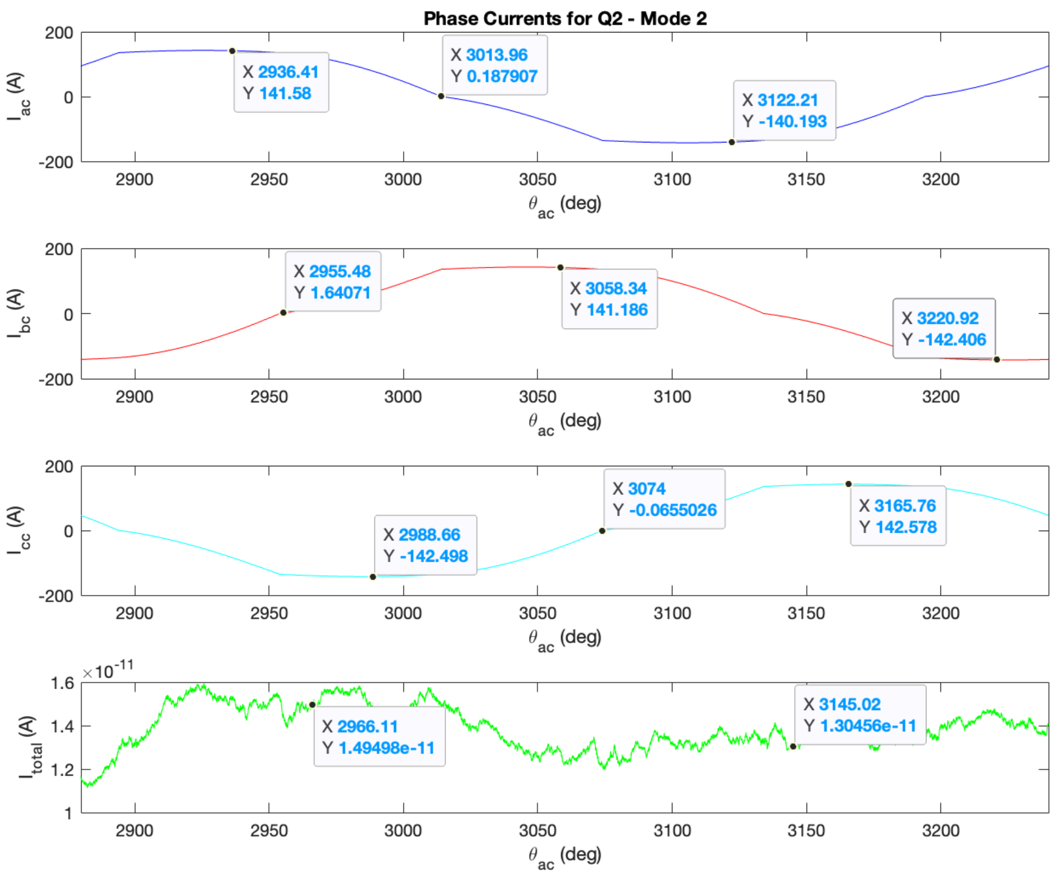


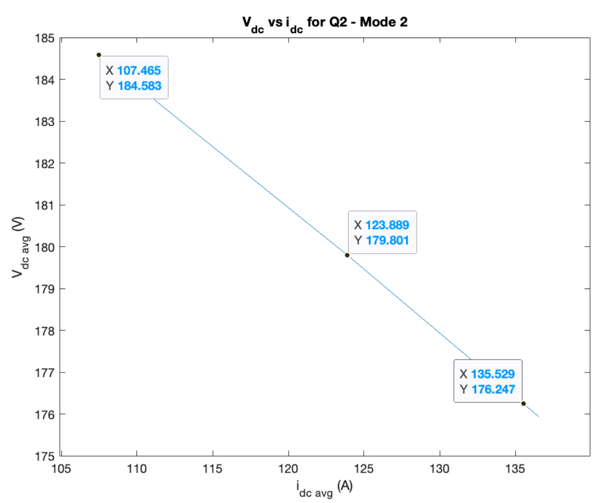

Phase Currents for Q2 - Mode 1
I_ac (A)
θ_ac (deg)
X 2915.67
Y 7.02304
X 2981.2
Y -0.03401
X 3074.26
Y -6.03241
I_bc (A)
X 2986.18
Y 6.91536
X 3106.45
Y -0.0506045
X 3178.52
Y -6.46457
I_cc (A)
X 2954.34
Y -6.04517
X 3040.09
Y 0.0305829
X 3114.64
Y 6.6396
I_total (A)
×10^-12
X 2962.95
Y -2.73559e-13
X 3053.8
Y -1.03918e-12
X 3156.64
Y -2.16094e-12


V_dc vs i_dc for Q2 - Mode 1
V_dc avg (V)
i_dc avg (A)
X 6.64194
Y 276.156
X 6.61456
Y 275.852
X 6.57933
Y 275.462

Simulating for an **R_load of 1.2471 Ohms** to get into Mode 2 since the cutoff resistance for mode 2 is 0.7204 Ohms and the resistance from part 1c is above that:



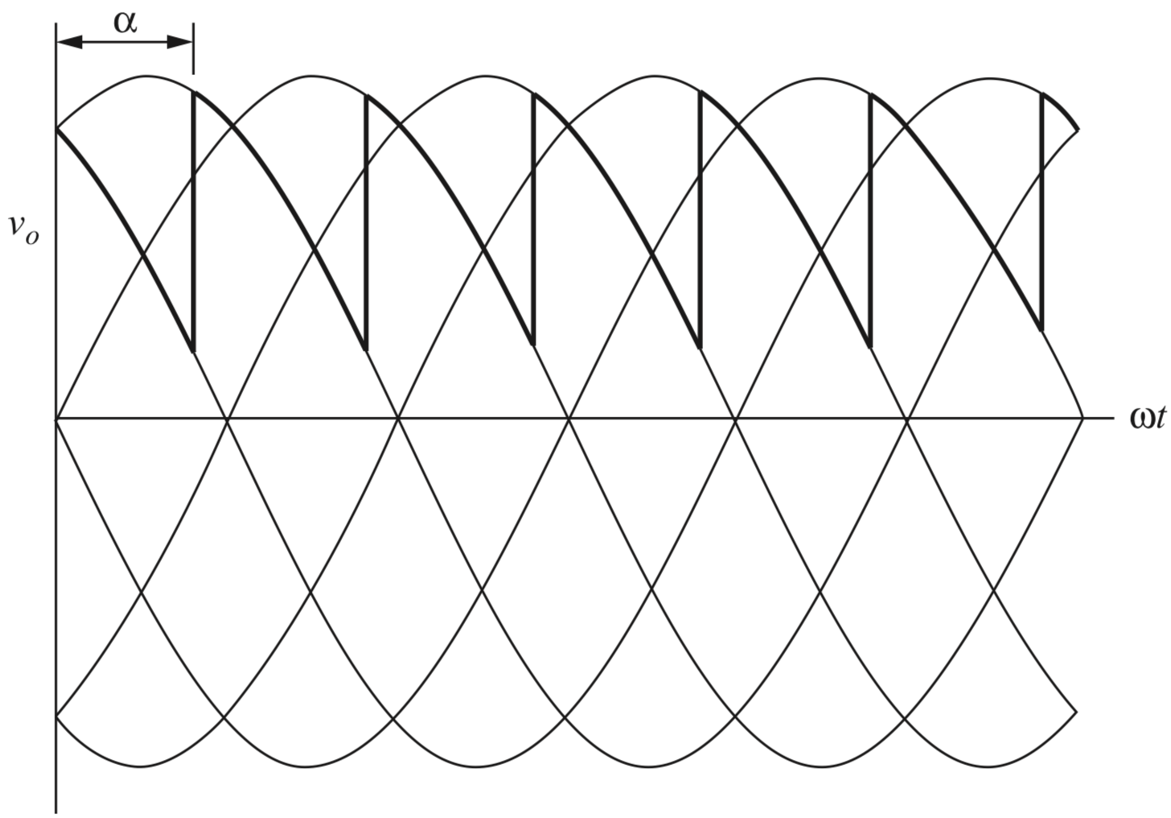

Phase Currents for Q2 - Mode 2
I_{ac} (A)
I_{bc} (A)
I_{cc} (A)
I_{total} (A)
θ_{ac} (deg)
$\times 10^{-11}$
X 2936.41
Y 141.58
X 3013.96
Y 0.187907
X 3122.21
Y -140.193
X 2955.48
Y 1.64071
X 3058.34
Y 141.186
X 3220.92
Y -142.406
X 2988.66
Y -142.498
X 3074
Y -0.0655026
X 3165.76
Y 142.578
X 2966.11
Y 1.49498e-11
X 3145.02
Y 1.30456e-11


V_{dc} vs i_{dc} for Q2 - Mode 2
$V_{dc\ avg}$ (V)
$i_{dc\ avg}$ (A)
X 107.465
Y 184.583
X 123.889
Y 179.801
X 135.529
Y 176.247

Comparing the first simulation to the analytical results that we derived in a manual method by plugging in the max of the commutation interval, we see that the resulted Idc avg and Vdc avg for the respective intervals are very close to each other. The percent difference between the two would be: 0.003613% and 0.089%. This means the circuit was very accurate in determining the average dc load current and voltage. Looking at the plots, the Vdc before average plot shows the voltage decreasing after half of the interval due to the inductor decreasing the current non-instantaneously. The phase currents look very similar to the graph of the analytical results. Let us compare i_ac, since i_bc, and i_cc will be similar. i_ac begins as idc at around 7.02 Amps for pi/3 radians, then decreases exponential as seen on the graph to around 0 then hovers around there for between gamma + theta and 2*pi/3. It decreases further to a value of -idc at -6.032 Amps for the next commutation interval. After that it stays -idc until 4*pi/3 radians to then increase exponentially for the next commutation interval. After that it stays at zero until 5*pi/3, only to increase further back exponentially to the value of +idc from the commutation interval and stay there until the end of the 2*pi radians. Of course these are with respect to a coefficient which repeats every 6 intervals. The simulation and analytical results have practically the same graphs and we can confirm this by looking at the total current at the end of the phase currents graphs. The total current is zero throughout the entire graph in the analytical result because we calculated other currents with the result of one integral and assumed that the return or input was the same between both diodes. This is tested in the simulation by the comparator wave and the logic of the diodes adding up to be the dc current. The simulation resulted in a total current average of -1.03 x 10^-12 Amps. I think this was mostly due to the tolerance of the calculations that we were performing and the decimal places that our input had. The more precision we have with our comparator and input variables, the more accurate our simulation would be.

Similar to the first simulation, the second simulation that we derived in a manual method by plugging in the max of the commutation interval, we 58588see that the resulted Idc avg and Vdc avg for the respective intervals are very close to each other. The percent difference between the two would be: 1.6849% and 2.664%.

This means the circuit was very accurate in determining the average dc load current and voltage. Looking at the plots, the Vdc before average plot shows the voltage decreasing after commutation interval due to the inductor decreasing the current non-instantaneously. This means that conduction is not starting until the gate signal is applied thus the signal is delayed and we can model that that delay by it being the exponential part of our waveform. Harmonics here would be still to the 6*fac. These harmonics could be combated by making an improvement in the circuit of quality by changing the 3 phase to a 3 phase six-pulse bridge rectifier where the harmonics would be small, this can be further taken also by daisy chaining two of them together.



(*b*)

The phase currents look very similar to the graph of the analytical results. Let us compare i_ac, since i_bc, and i_cc will be similar. i_ac begins as idc at around

141.58 Amps for pi/3 radians, then decreases exponential as seen on the graph to around 0. It decreases further to a value of -idc at -140.193 Amps for another pi/3 radians. All the intervals here would be 60 degrees due to the fact that we are in mode 2 and the gamma mode 1 factor is maxed out. After that i_ac stays -idc until 4*pi/3 + delay radians to then increase exponentially for the interval. After that it hits zero, only to increase further back exponentially to the value of +idc and stay there until the end of the last interval. Of course these are with respect to a coefficient which repeats every 6 intervals. The simulation and analytical results have practically the same graphs and we can confirm this by looking at the total current at the end of the phase currents graphs. The total current is zero throughout the entire graph in the analytical result because we calculated other currents with the result of one integral and assumed that the return or input was the same between both diodes. This is tested in the simulation by the comparator wave and the logic of the diodes adding up to be the dc current. The simulation resulted in a total current average of -1.35 x 10^-11 Amps. Again, I think this was mostly due to the tolerance of the calculations that we were performing and the decimal places that our input had. The more precision we have with our comparator and input variables, the more accurate our simulation would have been.