MIDDLE EAST TECHNICAL UNIVERSITY

Electrical and Electronics Engineering Department

# EE463 Static Power Conversion-I
# Project 1 Report


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## 1. Introduction

Simulink is a quite useful digital simulation environment for making simulations of dynamic systems. It allows us to understand how a circuit will behave and this a very useful tool in the processes of designing. It also allows us to quickly see how might small changes in the circuit can affect the output.

In this project, using the MATLAB Simulink we simulated diode bridge rectifiers in both single and three phase, with different kinds of loads such as R, RL and RC in order to observe their behaviours. Throughout the project, we assumed that the rectifiers are connected to the Turkish Grid.

This report includes the circuit schematics and simulation results for all three parts as well as our comments and interpretations about them.

## 2. Part 1

Simulink simulates the circuit by computing the successive time-steps. This process is known as solving the model. In order to do this task, simulink use different kinds of 'solver's. There are fixed or variable step solvers and discrete or continuous time solvers. Fixed-step solvers solve the system at regular time intervals, in other words time-step is the same from the beginning to the end of the simulation. However, variable-step solver have varying step-sizes during the simulation depending on the rapidness of the state changes.[1] For this project, we use 'powergui' at discrete mode as our solver method.

In this part of the project, we constructed a single phase diode rectifier with a resistive load of 100 Ω at the load side. It is supposed that the system is solved by using three different time steps. Our circuit is a dynamic system and time step is important to get specific behaviors of systems. Optimal time step can be determined by considering signal attributes and required real time for simulation. Minimizing time steps can improve the resolution of signal but it increases required real time for simulation.

In our case, three different step times, 1.5 msec, 10 µsec and 1 µsec are used.

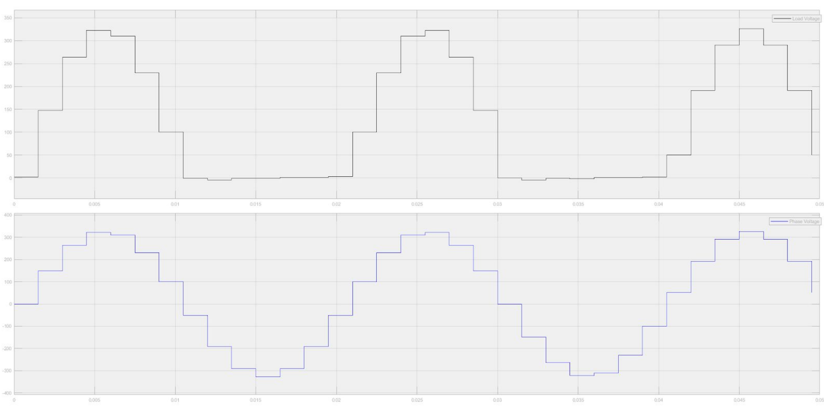

Figure 1 : Load and Source Voltage at 1.5 msec

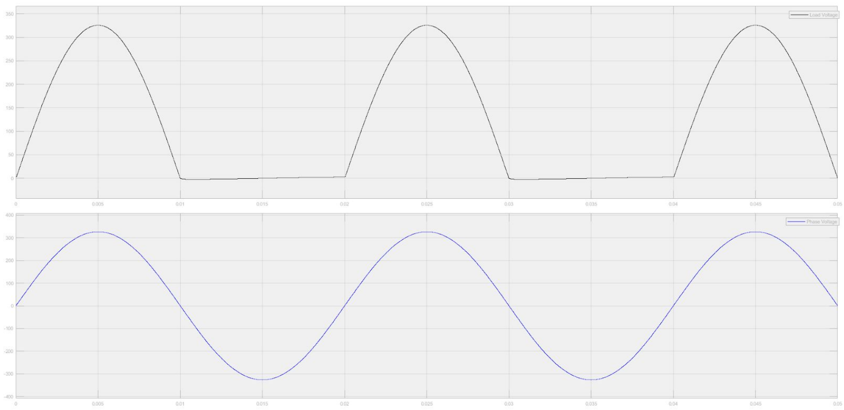

Figure 2 : Load and Source Voltage at 10 µsec

Figure 3 : Load and Source Voltage at 1 µsec

As can be seen Figure 1, 2 and 3 the same signal appears different for different values of step-size. For the 1.5 msec step size, there are some lost information about signal and the signal does not behave like a pure sinusoid. However, when 10 µsec and 1 µsec step times are used, the signal appears purely sinusoidal. The results are interpreted that smaller than enough step size for the signal behaves like continuous pair. In addition, there is an advantage of using 10 µsec time step, it decreases real time for simulation with respect to 1 µsec. So, 10 µsec step size can be chosen to observe the true waveform and smaller real time.

## 3. Part 2

In this part of the project, we constructed a single phase diode bridge rectifier with different types of loads as can be seen in Figure 4. We observed voltage and current waveforms.

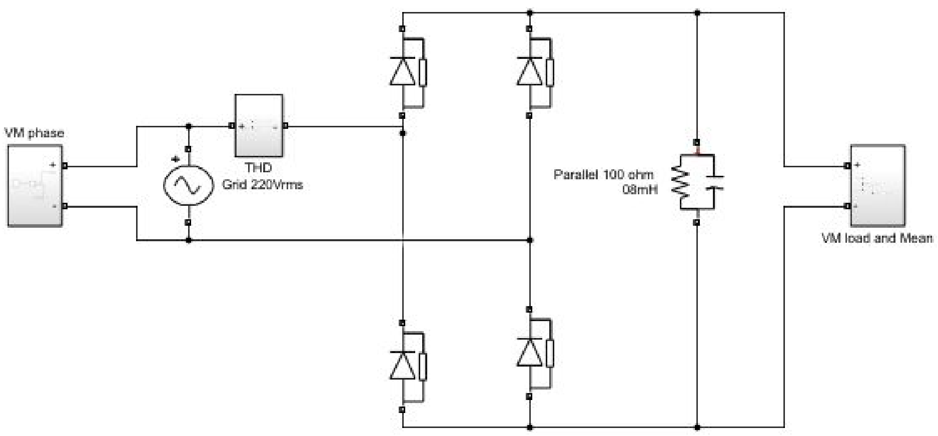


Figure 4 : Circuit Schematic of Part 2

### 3.1. Part 2.1

We simulated the above circuit with three different loads, namely a resistive load of R = 25 Ω, an RL load of R = 25 Ω , L = 10 mH and an RL load of an RL load of R = 25 Ω , L = 1 H.

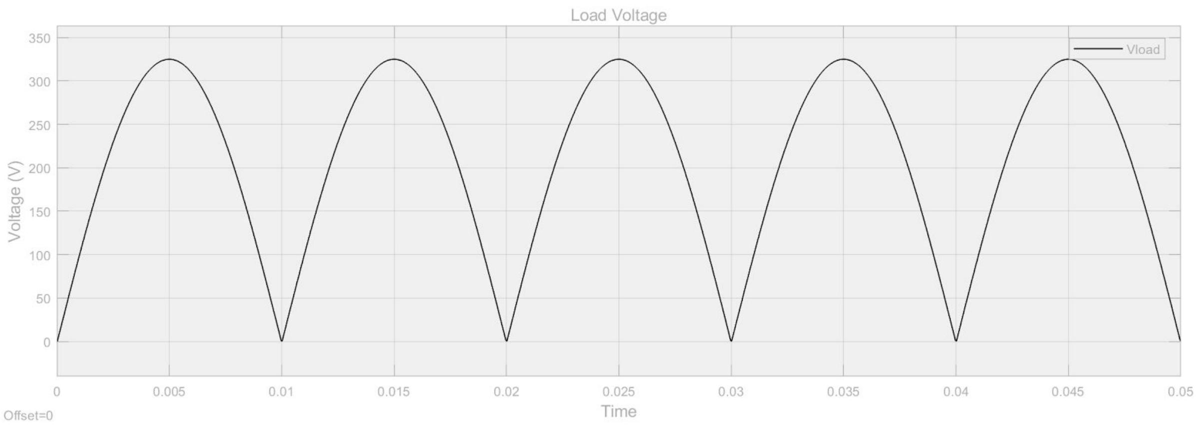


Figure 5: Voltage waveform of load voltage when the load is 25 Ω

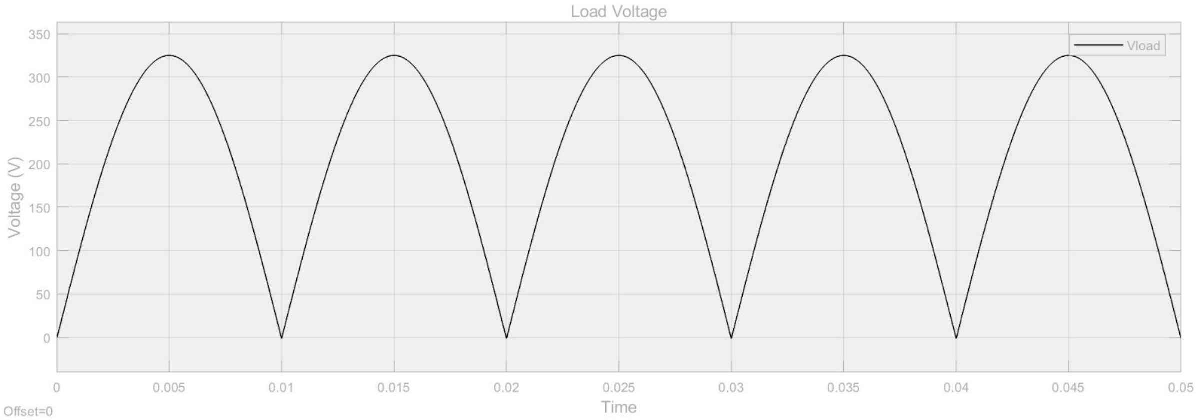


Figure 6 :Voltage waveform of load voltage when the load is 25 Ω , 10mH

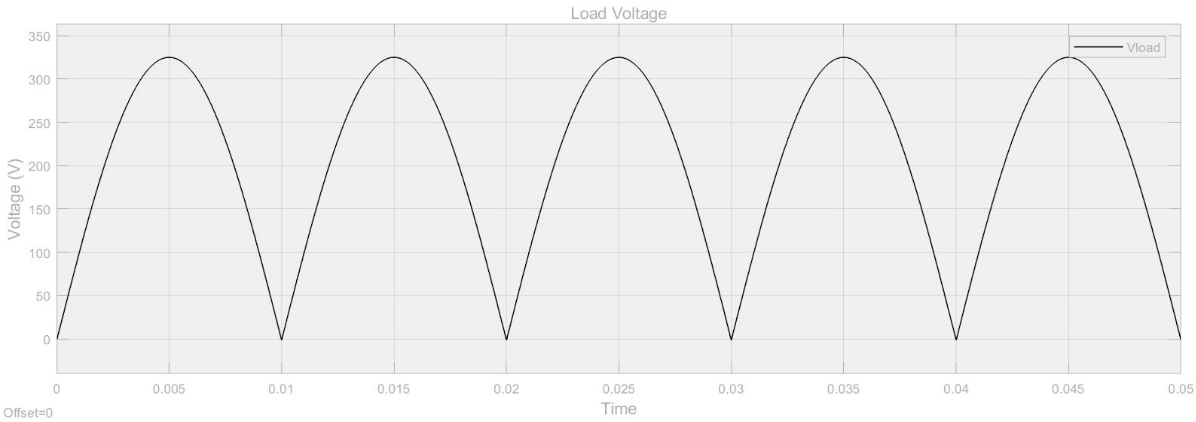


Figure 7 :Voltage waveform of load voltage when the load is 25 Ω , 1H

As one can see from Figures 5, 6 and 7 voltage waveform of the load does not change with any inductive component introduced to the load. This is because of the fact that an inductor connected to the load filter out the current, not the voltage. As inductance increases, the observed current waveform will be more like a DC current since an inductor acts as a current source as inductance goes to infinity. Moreover, the average value of the load voltages do not change either, hence the inductances that we introduced are on the load side, not on the source side. They do not affect the waveforms like a line inductance. Hence, commutation is not observed in this case.

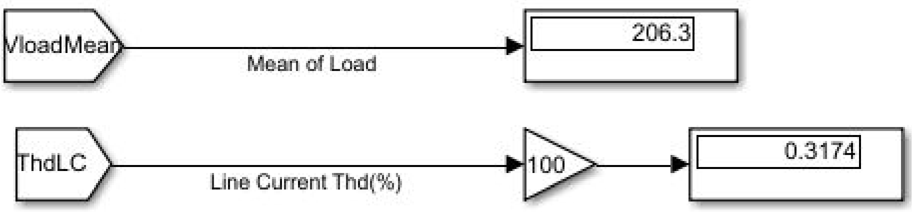


Figure 8 : Mean voltage of load current and THD of the source current, R=25 Ω

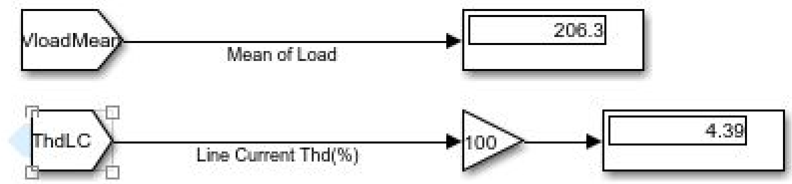


Figure 9 : Mean voltage of load current and THD of the source current, R=25Ω, L=10mH

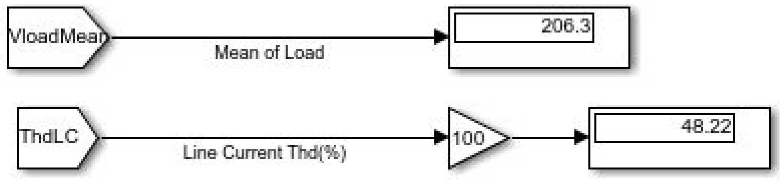


Figure 10 : Mean voltage of load current and THD of the source current, R=25Ω, L=1H

As the output current waveform resembles a DC waveform, it needs to draw a square wave-like current from the source side. As can be seen from the Figures 8, 9 and 10 the THD of the source side current get close to the value 0.48, which is the THD of a square wave.

## 3.2. Part 2.2

**Diode:**

Product Code:

FES8GT-E3/45GI-ND

Link:

[https://www.digikey.com/product-detail/en/vishay-semiconductor-diodes-division/FES8GT-E3-45/FES8GT-E3-45GI-ND/2152973](https://www.digikey.com/product-detail/en/vishay-semiconductor-diodes-division/FES8GT-E3-45/FES8GT-E3-45GI-ND/2152973)

Parameters:

We chose  a standard type diode. Standard type diodes have reverse recovery. It causes a delay at the turning off time. However, it is 50 ns in the diode that we chosen and it can be ignored at the circuit. In addition, our circuit operates connected to a grid voltage. The diode is under 330 volt at reverse operation. We chose a reverse breakdown voltage that is 400 Volt. So, there is some safety margin. Finally, it operates at 8A average current that is enough for our circuit.

Cost:

Cost is 1 USD for one unit. It is inexpensive.

**Rectifier Module:**

Product Code:

1560-1135-5-ND

Link:

https://www.digikey.com/product-detail/en/global-power-technologies-group/GHXS010A060S-D1/1560-1135-5-ND/5080053

Parameters:

The rectifier module consists of silicon carbide schottky diodes. Schottky diodes has no recovery time and it is an advantage when switching from on to off. Reverse breakdown voltage of the rectifier is 600 Volt and safety margin is very big. It can be counted as overdesign. In addition, current average is 10 Amps that can be used at our circuit.

Cost:

Cost is 36 usd for the one unit. It is expensive for considering the diodes.

Our circuit consist of 4 discrete diodes or 1 rectifier module. As mentioned above, both have some advantages and disadvantages. Advantages of using diodes is cost. It is inexpensive compared with the rectifier module. However, since discrete diodes are not schottky, they result in a delay at switching. Rectifier module consist of silicon carbide diodes and they provides us larger breakdown voltages. Considering of all them, cost is a critical point for the rectifier circuit. It causes that we chose diodes to establish our circuit.

## 3.3. Part 2.3

In this part of the project, we are asked to find a capacitor value so that the output voltage ripple is less than 20 percent of average output voltage.

In this purpose, we wrote a MATLAB code using our basic circuit theory knowledge. It is known that without a capacitor, output waveform would resembles a rectified sinusoid. Also, when an RC load is connected, we can calculate the time constant of the circuit during the capacitor voltage is decreasing. Knowing these, we determined the maximum and minimum voltage value points and the ratio between them for a ripple less the 20%. After determining the points, using the frequencies of these points, we found the time passed between the maximum and minimum points. Using the time and resistance values we found the time constant and hence the required capacitor value.

The related MATLAB code can be found at the Appendix.

The capacitor value needed for a ripple smaller than 20% of the average current is calculated as 0.3 mF. When this value is implemented in the circuit an output voltage waveform as in the Figure 11 is can be observed.

Also the maximum and minimum values of the ripple is measured with cursors and can be seen in Figure 12. It can be seen that, ripple at the output is 60 V which is approximately 20% of the average load voltage.

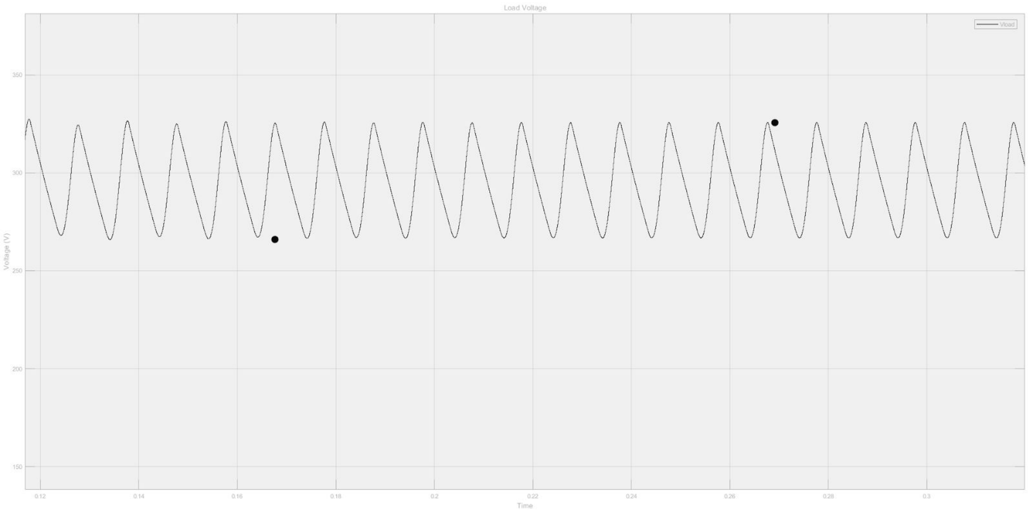

Figure 11: Ripple Calculation for Maximum and Minimum Voltage of Load

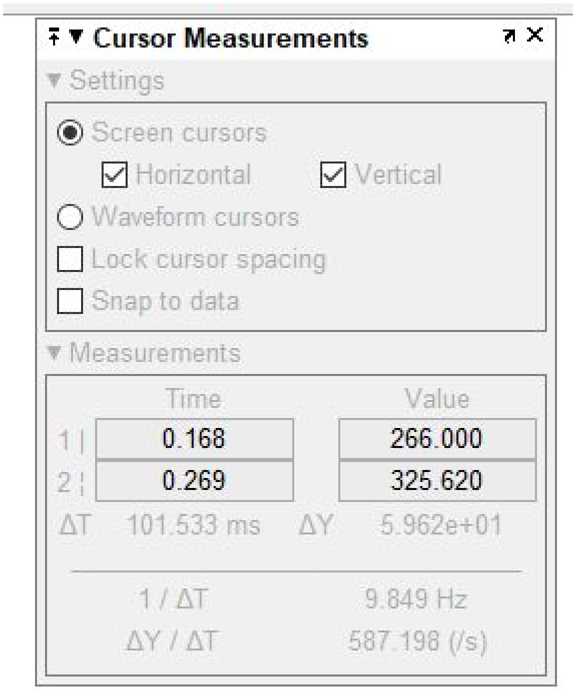


Figure 12: Voltage waveform of load voltage when the load R=100 and C=0.3 mF

**Capacitor :**

We chose 470 µF Aluminum Electrolytic Capacitor to use in our circuit.

Product Code:

338-3726-ND

Link:
https://www.digikey.com/product-detail/en/cornell-dubilier-electronics-cde/381LQ471M350A022/338-3726-ND/1699981

Parameters:

The capacitor is used for minimizing ripple that is at most 20 percentage of the average voltage. 330 µF capacitor corresponds our problem at boundary. We observed that capacitor tolerance is around +-20%. Then, we decided to choose 470 µF capacitor to use. In addition, our circuit operates at 330 V at steady state. So, we chose the rated voltage as 350V.

Cost:

The capacitor can be bought as one unit. Price per unit is 5.8  USD which is an affordable price.

## 3.4. Part 2.4

When a line inductance is introduced in the circuit, the load voltage waveform take the form that can be seen in Figure 13. One can see that the waveform is not a rectified purely sinusoid due to commutation. There is a period in which diodes continue to conduct for an extended time, leading all diodes to be ON for a small period of time, which leads a zero voltage at the load during the commutation. After the commutation, the load voltage will continue to follow rectified source voltage.

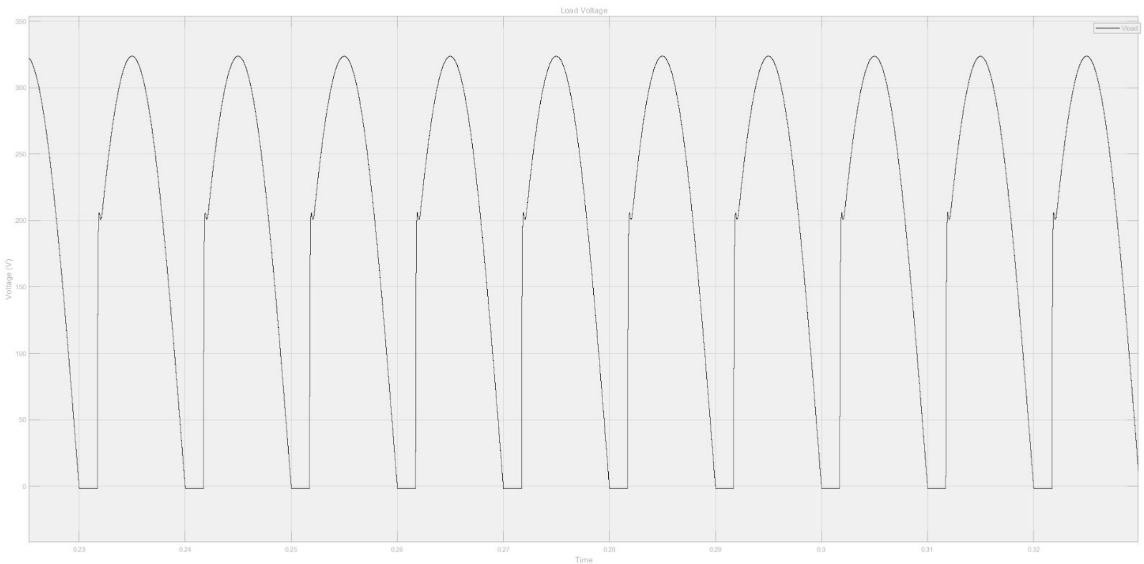

Figure 13 :Voltage waveform of load with line inductance of 10mH

As one can see from Figure 14, mean of the load voltage is decreased. Commutation makes the output voltage smaller because of the area lost due to it.

Furthermore, line inductance does not let current  to change suddenly. When there is a line inductance, changes in the line currents become more smooth. This smoothness at transition time make current include less distortion, in other words decreases its harmonic components. So, It reduces the THD of current and we observe a smaller THD (36.1%) with line inductance than without line inductance(48%).

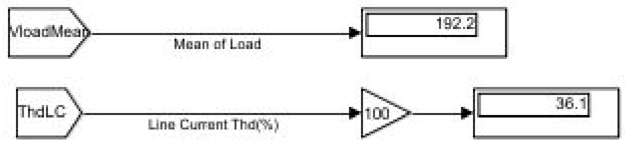


Figure 14 : Mean voltage of load current and THD of the source current, R=25 Ω, L=1H

## 3.5. Part 2.5

In this part, we constructed the circuit in the Figure 15.

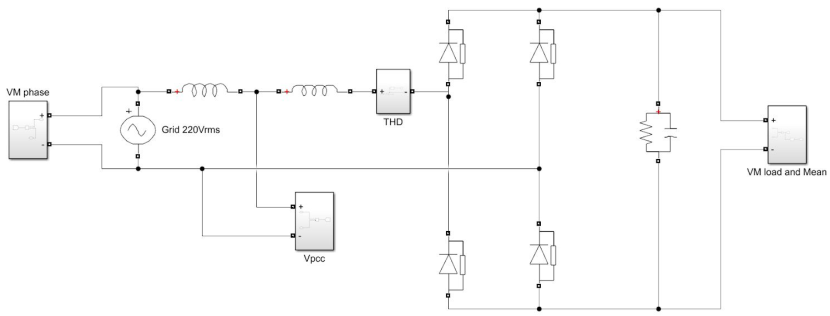


Figure 15 : Figure 5.25 of the textbook

The line inductance is split into two and the voltage is measured from middle point between them which is the point of common coupling. Resulting waveform can be seen in Figure 16. As one can notice, we observed a distortion at the Vpcc. This distortion is due to the current harmonics resulted by the nonlinear load.

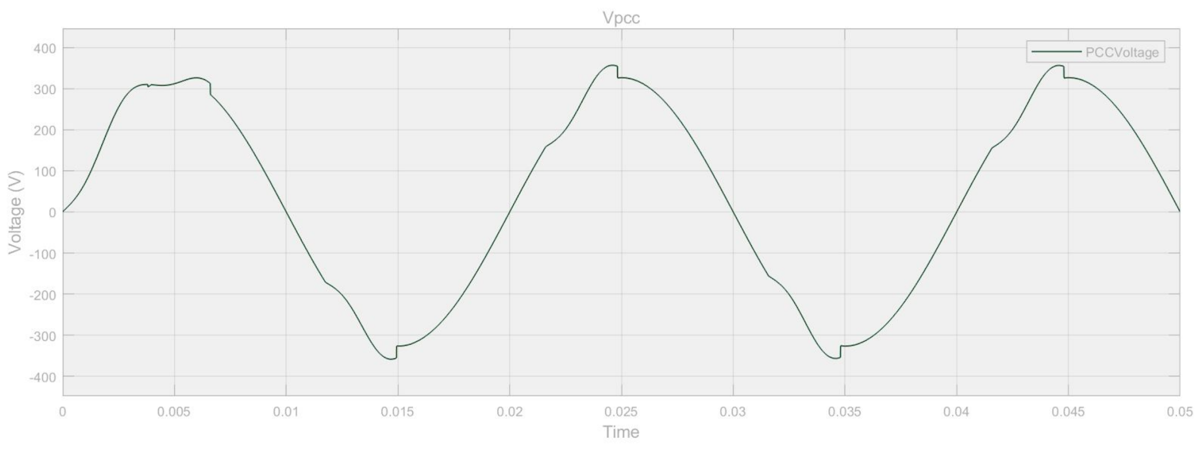

Figure 16 : Voltage at the common coupling point

# 4. Part 3

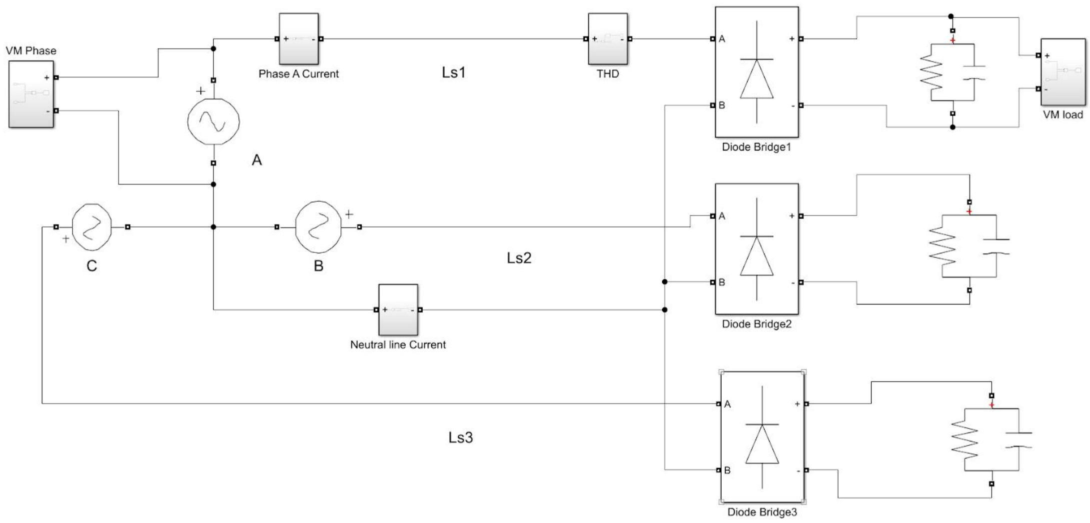


Figure 17 : Circuit schematic of part 3

For Part 3, the circuit in the Figure 17 is constructed.

## 4.1. Part 3.1

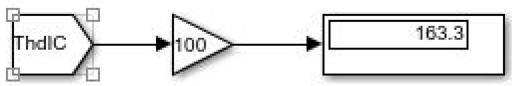


Figure 18: THD of the input current

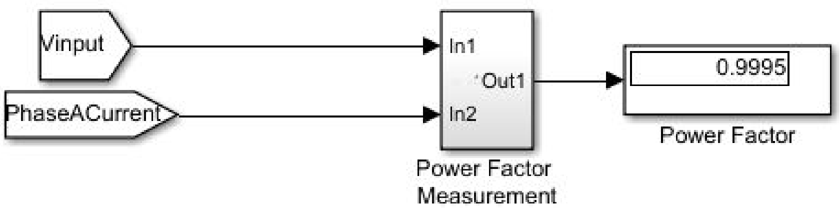


Figure 19: PF of the input current

Power factor and the total harmonic distortion of the input current can be seen in Figure 18 and 19.

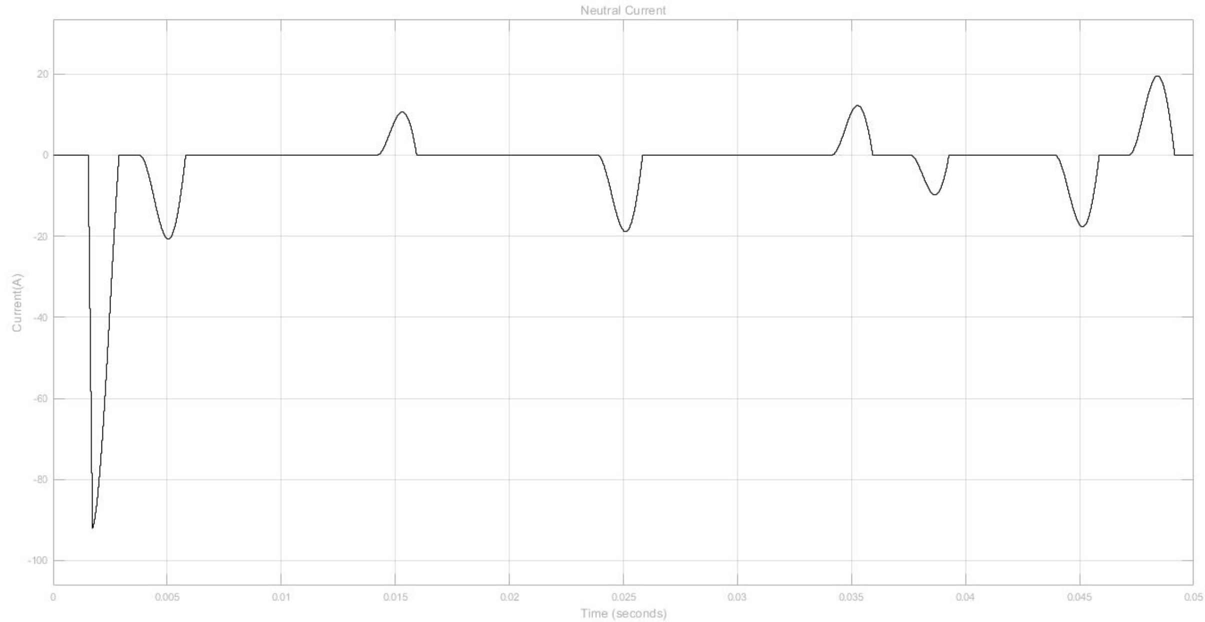


Figure 20: The neutral line current

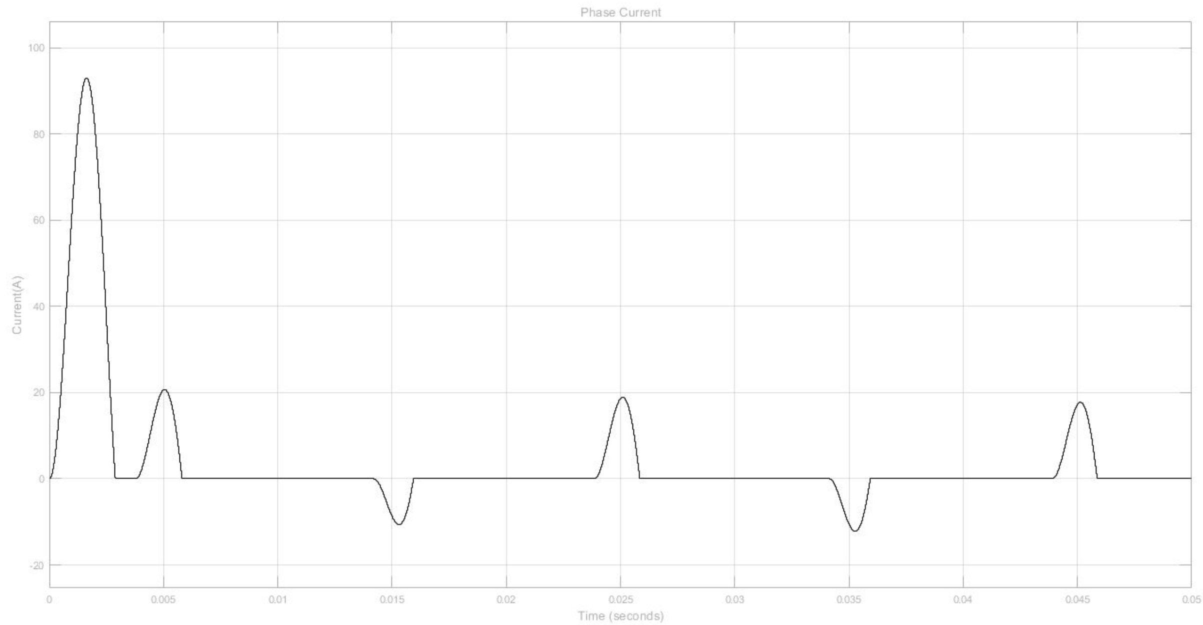


Figure 21: Phase A current

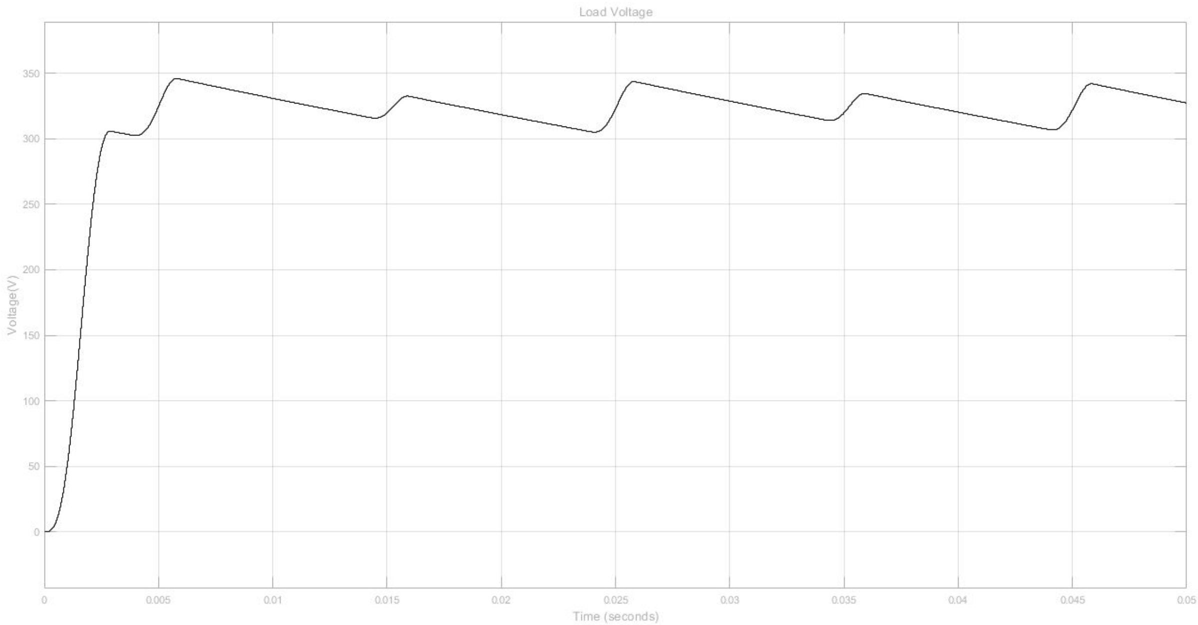


Figure 22: Diode bridge 1 output voltage

The neutral line current, phase A current and the output waveform at the load side of diode bridge 1 can be seen in Figure 20, 21 and 22 respectively.

## 4.2 Part 3.2

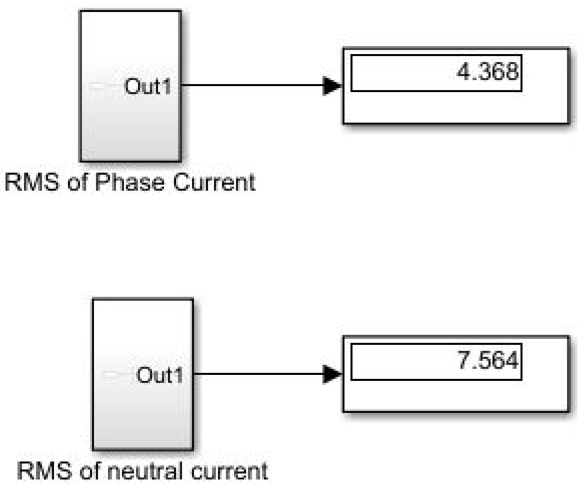


Figure 23 : RMS currents of phase and line

The RMS values of phase current and neutral line current can be seen in Figure 23. The rms current of phase A is equal to phase B and phase C if the load is balanced. In order to find the RMS of the neutral current, following node equation can be used.

$$Ineutral = sqrt(Ia^2 + Ib^2 + Ic^2)$$

Formula 1: Neutral line RMS current calculation

As calculated by using Formula 1, we observe that simulation result is valid.

## 4.3 Part 3.3

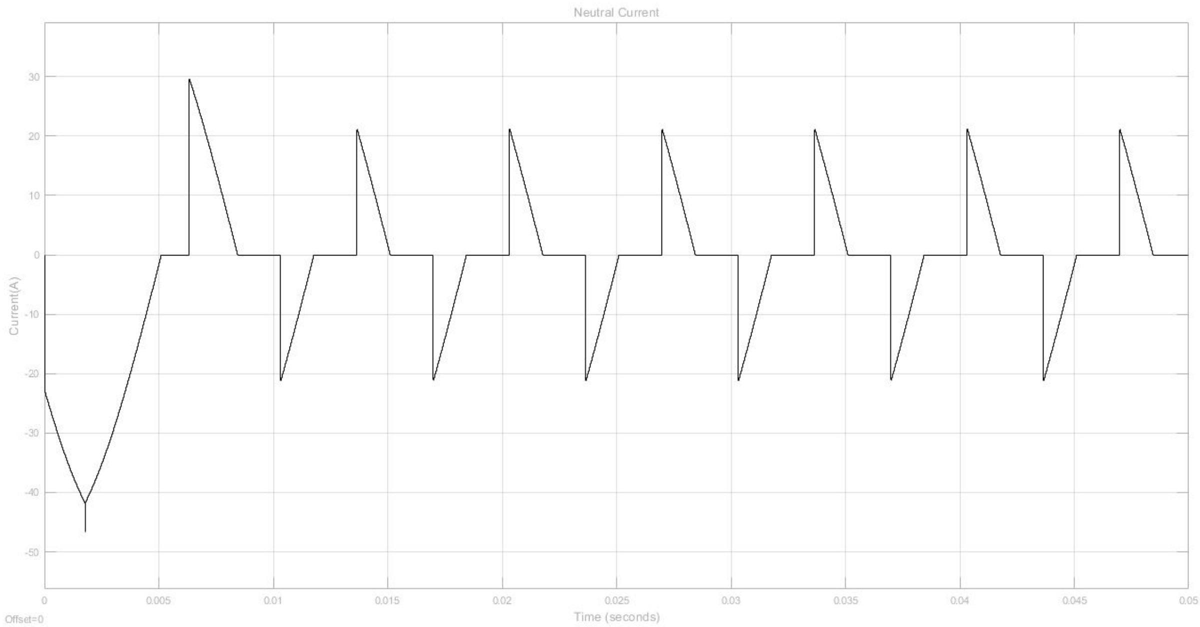


Figure 24 : The neutral line current when line inductance is zero

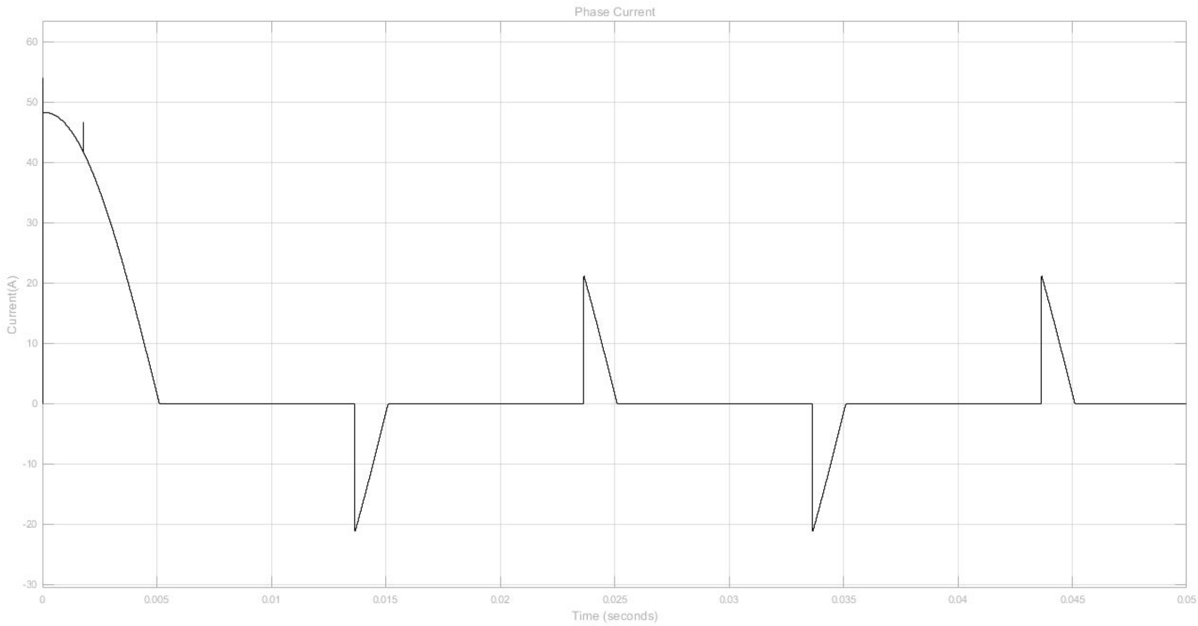


Figure 25 : Phase A current when line inductance is zero

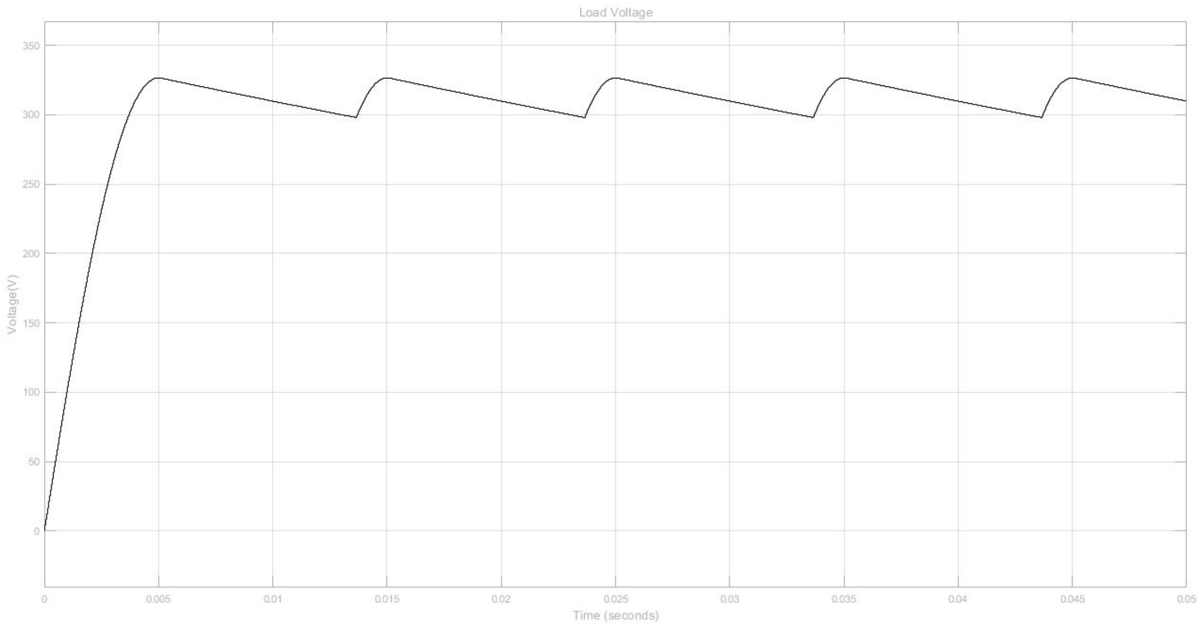


Figure 26: Diode bridge 1 output voltage when line inductance is zero

The neutral line current, phase A current and the output waveform at the load side of diode bridge 1 when there is no line inductance can be seen in Figure 24, 25 and 26 respectively.

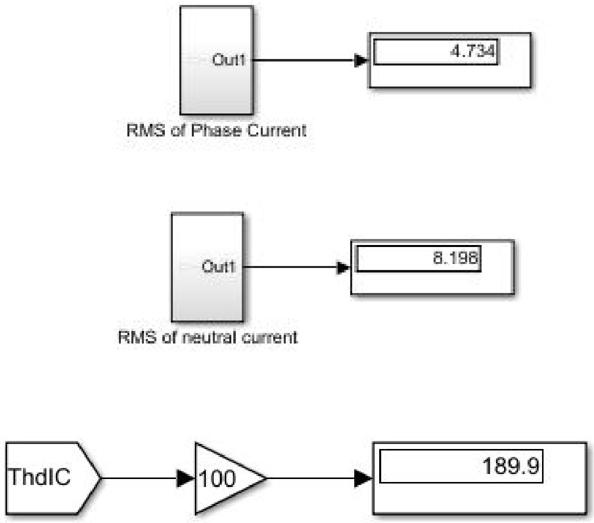


Figure 27 : THD of the input current when line inductance is zero

The RMS values of phase current and neutral line current and THD of the phase current when there is not a line inductance can be seen in Figure 27.

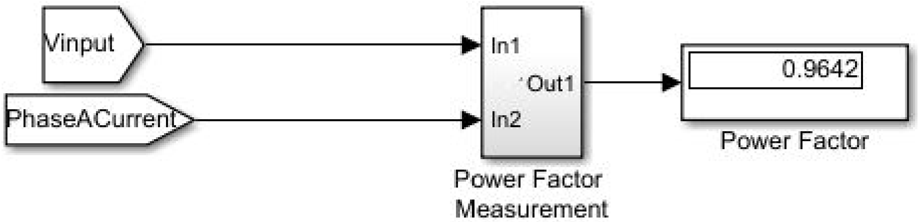


Figure 28: PF of the input current when line inductance is zero

Power factor of the input current can be seen in Figure 28. Our measurements are not similar to what we expect. We expect that increasing inductance would cause power factor to decrease. However, we did not observe that. We already know that, inductance affects the smoothness of the line current. Hence, increasing line inductance led current to include less distortion, hence a smaller THD.

## 5. Conclusion

In this report, we represented the results of Project-1 alongside with our understandings of every separate part of the project. We Included parts in the report with the same order given in the project description.

In part 1 we conclude that when our step-size is not small enough some of the samples of the signal are lost. Hence we have some information lost at the resultant waveform. However, after some value, decreasing the step time does not affect the resulting waveforms.

In part 2, we learn that in order to filter out the current, an inductor can be connected to the load. Likewise, to filter out the output voltage in order to obtain a DC-like waveform, a capacitor should be used at the load. Moreover, we learn how to search and choose proper circuit components (diodes and capacitors, in our case) to serve our purpose. Furthermore, we observed that when line inductances are introduced to the circuit, commutation happens and distorts the output voltage leading a decrease at the average value. At the last section of the part 2, we observe the effect of a non-linear load on the common coupling point voltage.

In part 3, we saw that a 3-phase rectifier can be build by using 3 of the single phase rectifiers. Line inductances affect the RMS and THD value of phase voltages. Line inductance causes that phase differences between line current and input voltages.

To conclude, a basic rectifier circuit can be installed by using diodes. The basic blocks can be used for increasing number of phases. Besides, capacitors and inductors are used for filtering output voltage or current. Moreover, line inductances due to grid causes commutation to occur which leads a smaller output voltage. Hence, we can adjust output of the rectifier by using suitable capacitance and inductance.

## 6. References


[1] Modeling Dynamic Systems. (n.d.). Retrieved November 24, 2018, from [https://www.mathworks.com/help/simulink/ug/solvers.html](https://www.mathworks.com/help/simulink/ug/solvers.html)


## 7. Appendix

**Capacitance Calculation Script:**

```
% Rip is wanted ripple value in percentange
% y is a capacitance value that provides that ripple
% R is a resistance value

function y= CapacitenceCalculator(Rip,R)

% Full wave rectifier

% wt= linspace(0,10*pi,10000);

% LoadVoltage= sin(wt); %% it is output voltage for fully resistance load
```

```
MaxPoint= pi/2;

if Rip==100
   y=0;

else
   Rip=Rip/100;
   MinPoint=asin((1-Rip));
end

Delta=MaxPoint+MinPoint;
DeltaTime= Delta/(2*pi*50);

y= -DeltaTime/( log((1-Rip))*R); %% apply exponential to determine capacitance

end
```