MIDDLE EAST TECHNICAL UNIVERSITY
Electrical & Electronics Engineering

Simulation Project #1

EE 463

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Introduction

In this project, we are asked to design and simulate Single Phase Diode rectifier with different load types, i.e. R, RL, RC. Also, THD analysis will be done for that circuit. For real applications, commercially available products will be chosen and analyzed as well.

Q1) Single Phase Diode rectifier is built for Turkish Grid ($400V_{l\text{-}l}$ and 50 Hz) system. Since single phase diode rectifiers are connected to line to neutral, $230\sqrt{2} \approx 325V_{peak}$ is applied to the system.

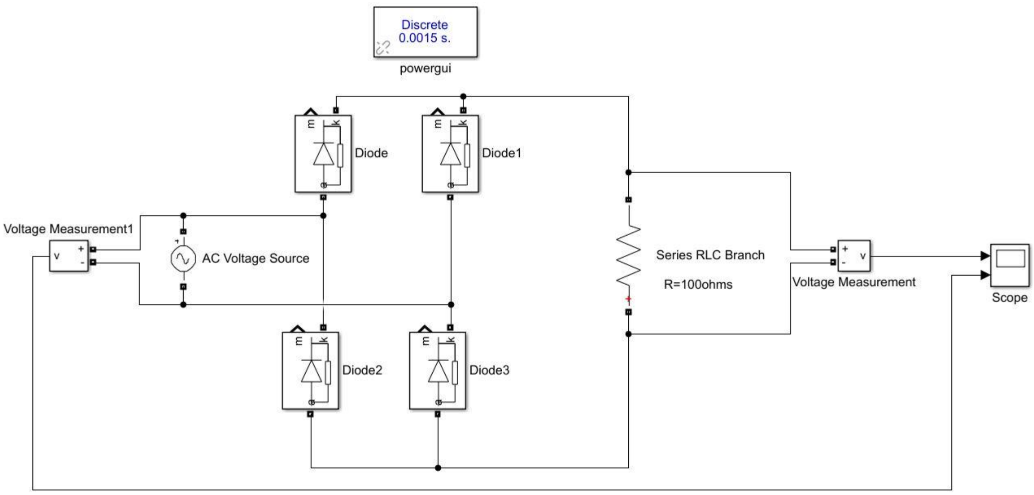

Figure 1: Single Phase Diode Rectifier with R_{LOAD} = 100 Ω.

As seen from Fig.1, 4 diodes are used with load resistance 100Ω. At first, I was having trouble with simulation in Simulink because I did not add 'powergui' GUI into the simulation subblock. Powergui is used for simulating any Simulink model containing Simscape™ Electrical™ Specialized Power Systems blocks. It stores the equivalent Simulink circuit that represents the state-space equations of the model.

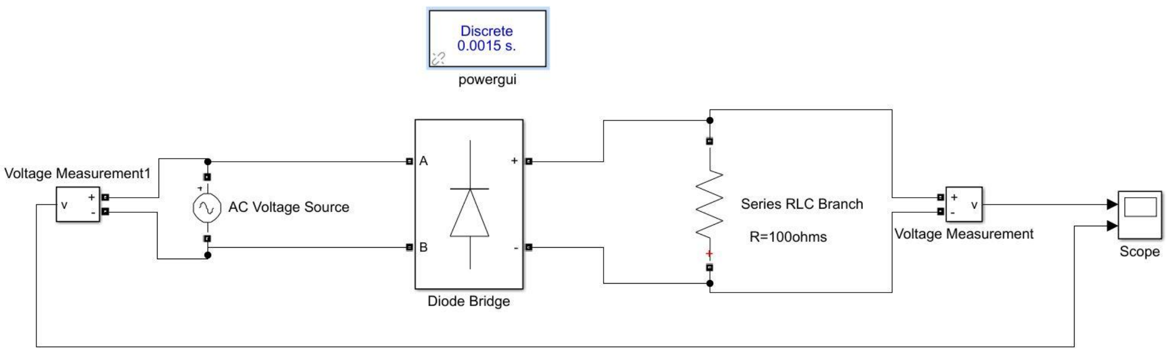

Figure 2: Single Phase Diode Rectifier with Diode Bridge and R_{LOAD} = 100 Ω.

Later on, I tried using Diode Bridge Rectifier subblock for simplification purposes. The subblock is shown in Fig.2. The simulation results are same with the model in Fig.1.

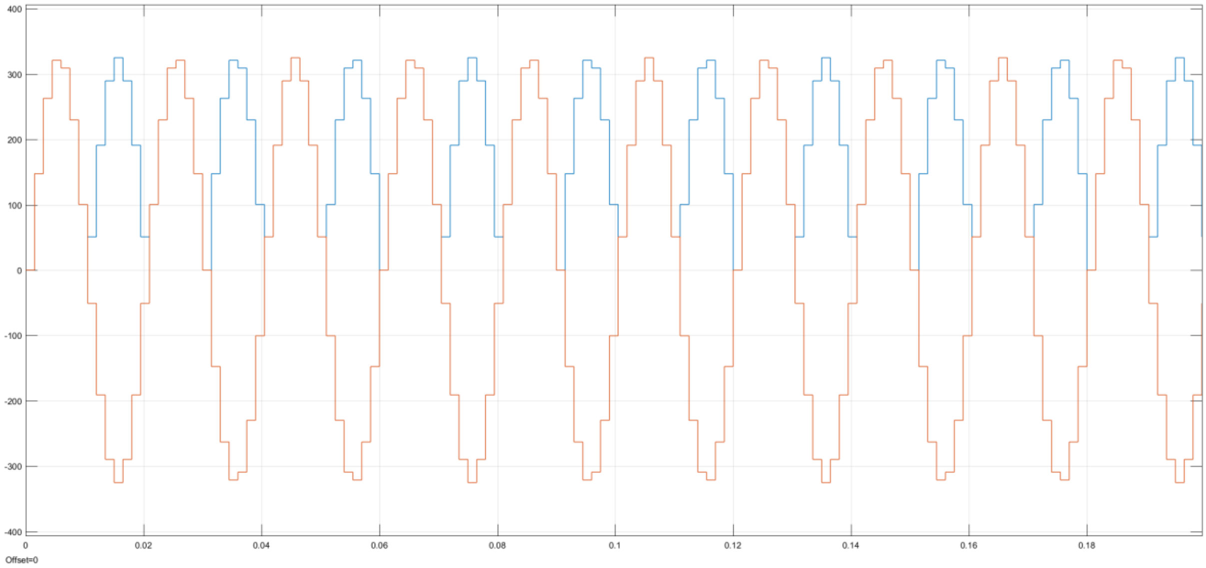

Figure 3: Input and output voltage waveforms of SPD Rectifier with step size 1.5mS

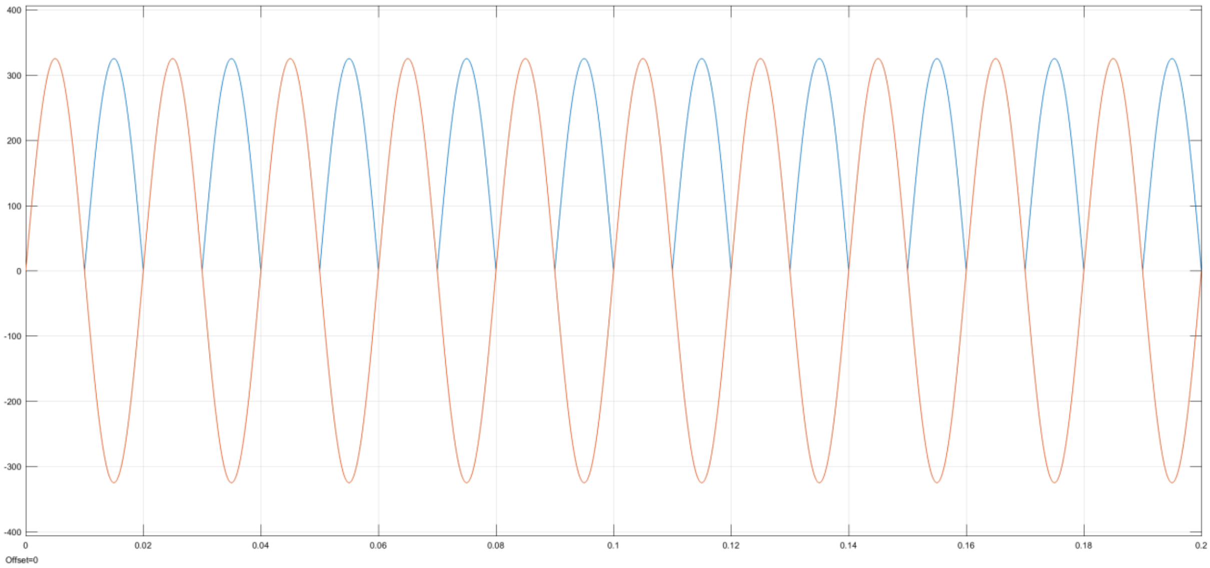

Figure 4: Input and output voltage waveforms of SPD Rectifier with step size 10μS

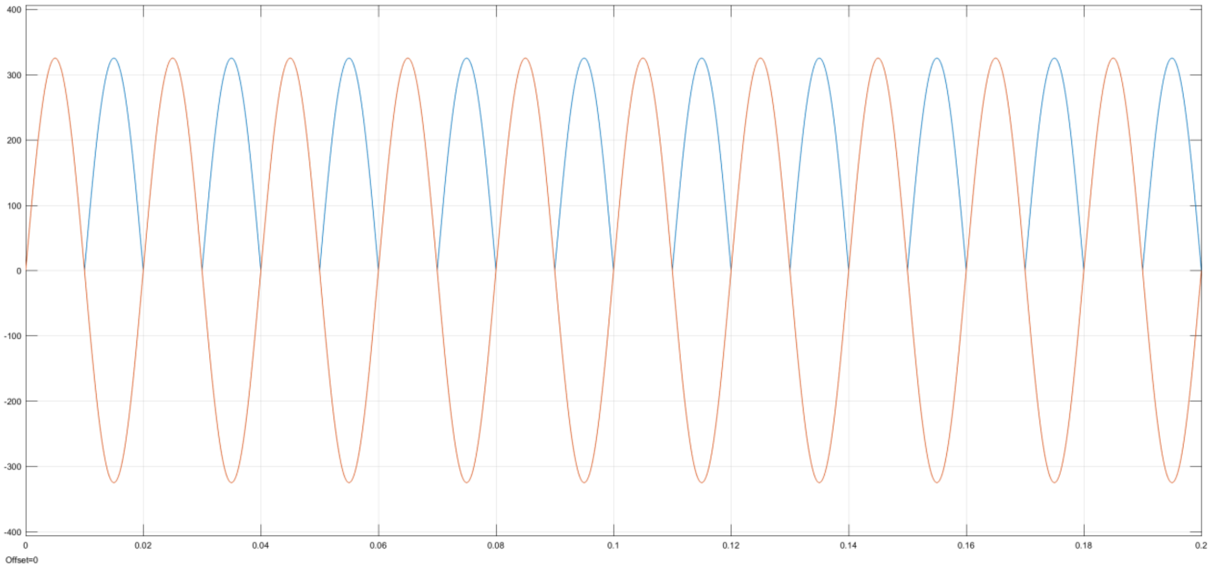

Figure 5: Input and output voltage waveforms of SPD Rectifier with step size 1μS

When we decrease the step size, the simulation results become more realistic because we are taking samples with narrow time intervals. This helps us to simulate the system very much a like to continuous system. It can be easily seen from Fig.3, Fig.4 and Fig.5 that decrease in the step size means more realistic analysis in continuous domain. The drawback here is microprocessor should work faster and we force it to work harder by increasing sampling rate.

Q2) The step size is taken as 1µS for this question.

2-1. Note that mean values are shown in the circuit schematic.

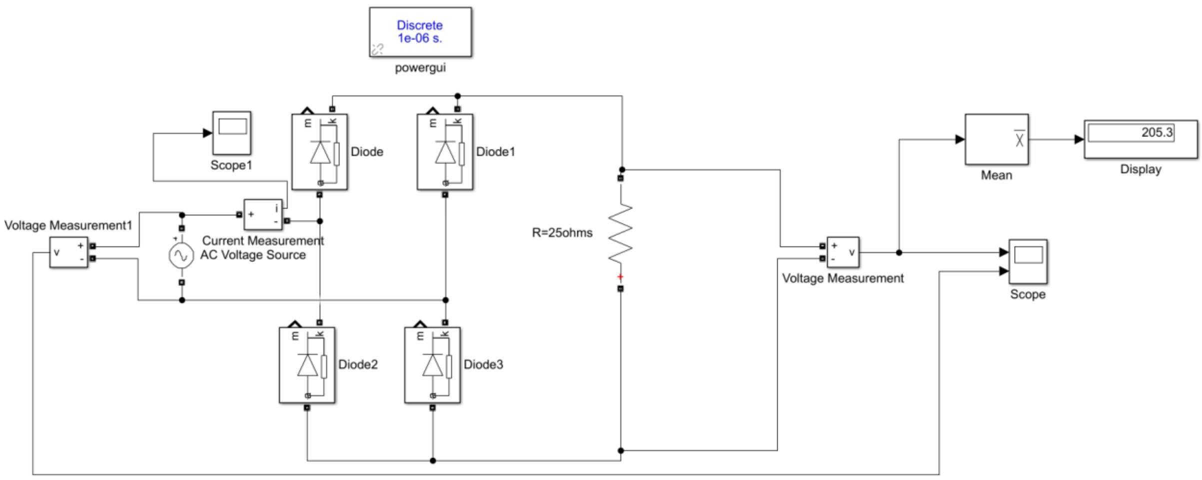

Figure 6: Circuit simulated for R Load

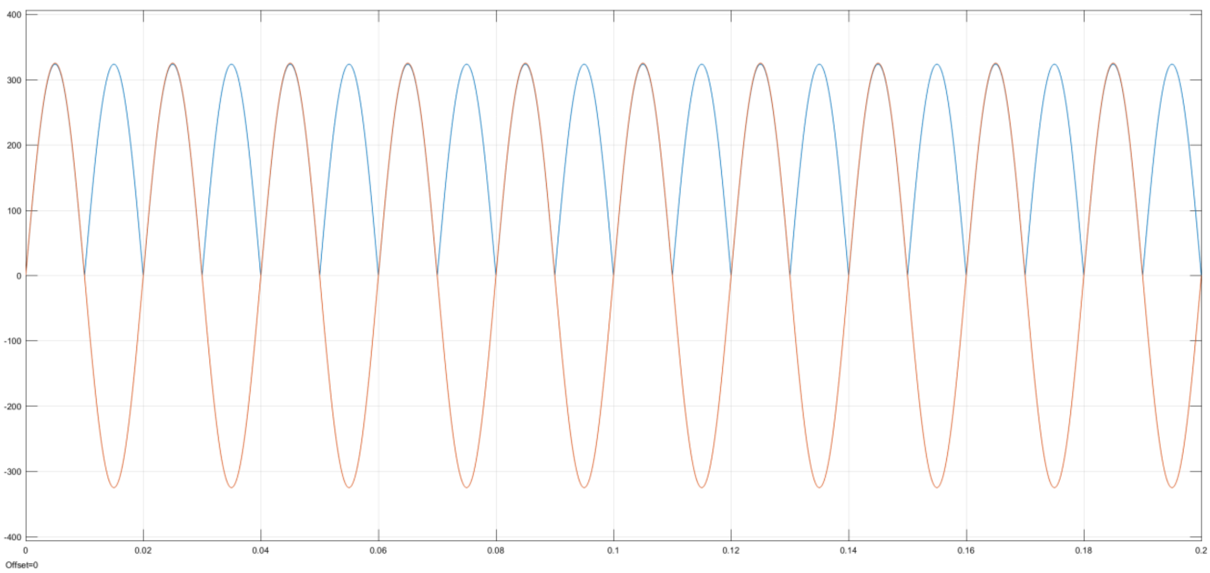

Figure 7: Input and output voltage waveforms of SPD Rectifier with R_{LOAD} 25Ω.

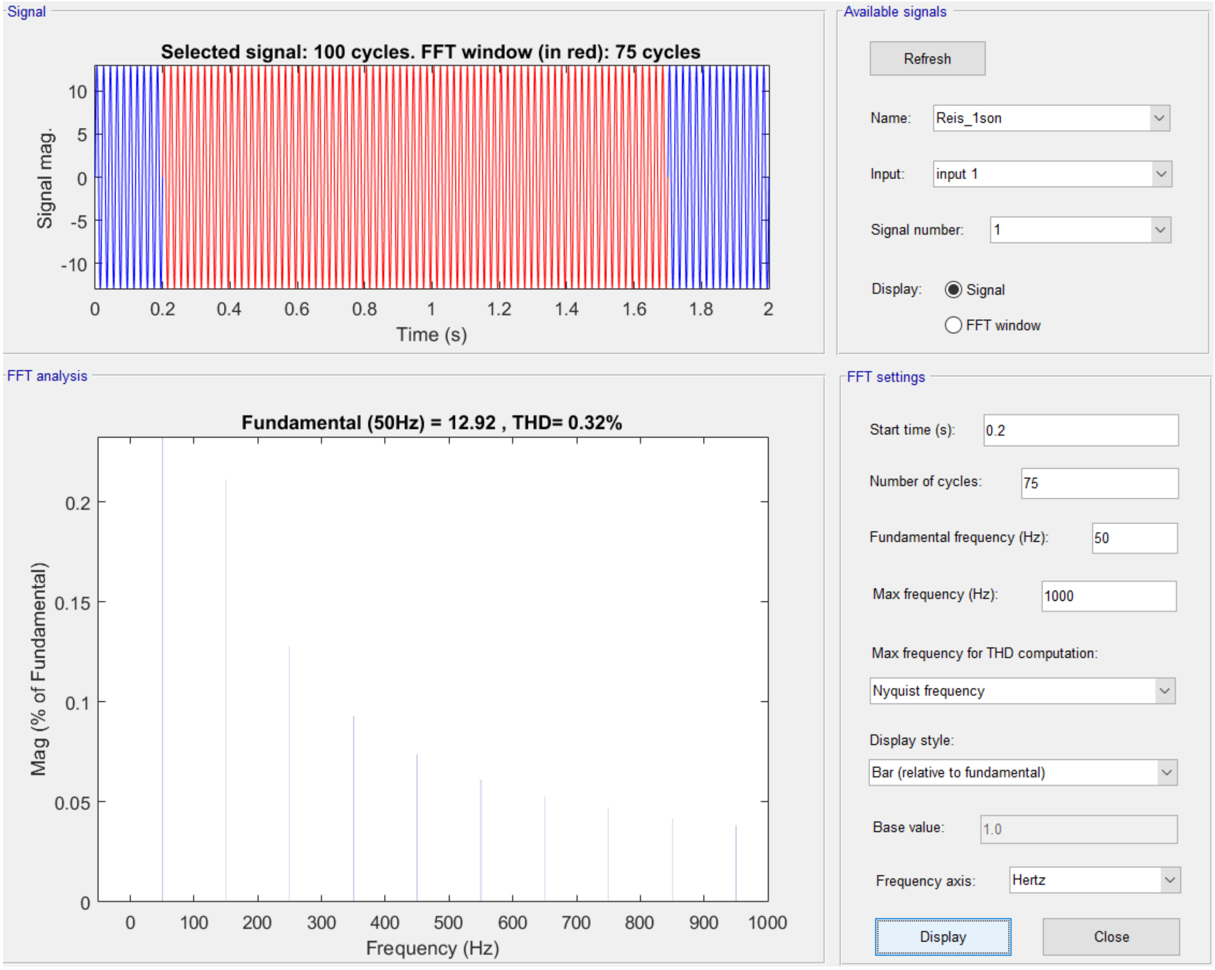

Figure 8: THD of SPD Rectifier
with R_{LOAD} 25Ω.

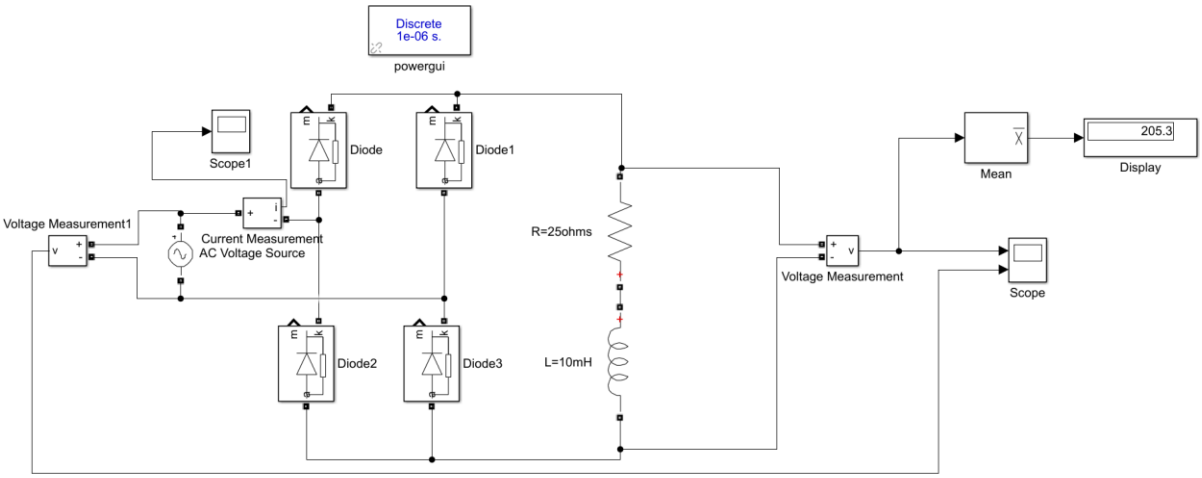

Figure 9: Circuit simulated for R_{LOAD} 25Ω and L_{LOAD} 10mH.

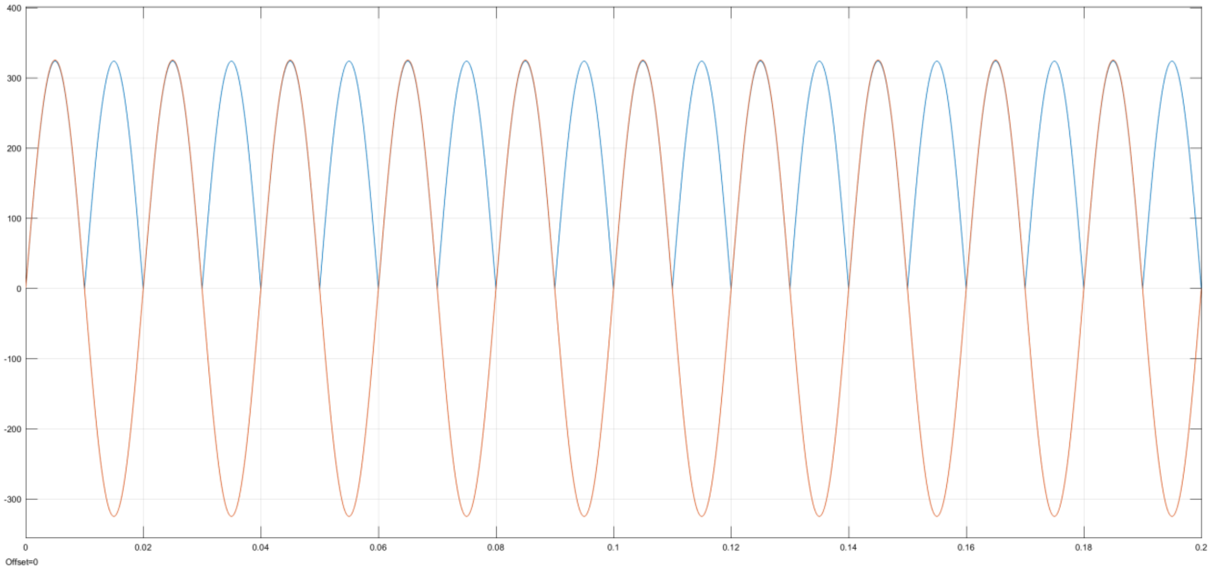

Figure 10: Input and output voltage waveforms of SPD Rectifier
with R_{LOAD} 25Ω and L_{LOAD} 10mH.

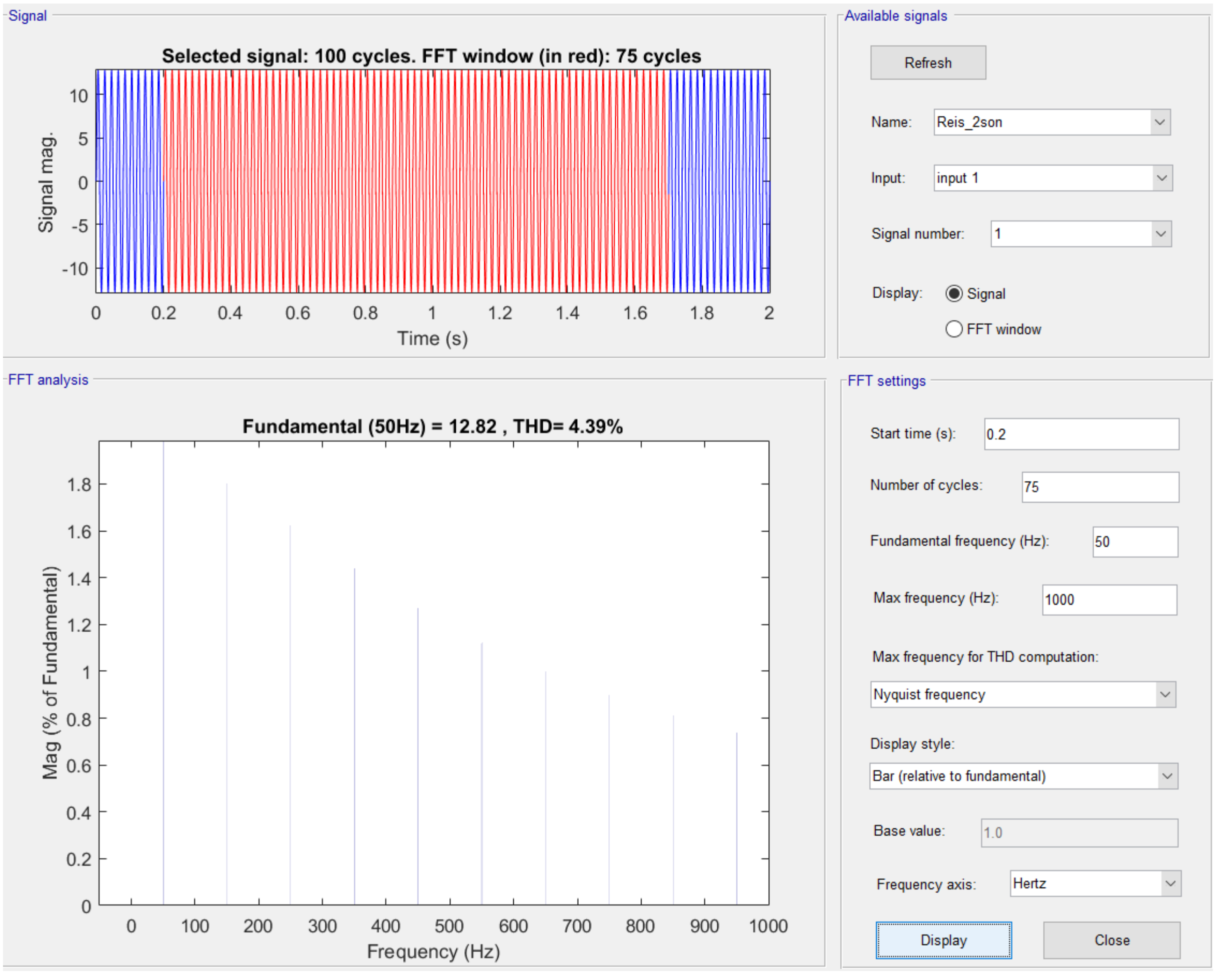

Figure 11: THD of SPD Rectifier
with R_{LOAD} 25Ω and L_{LOAD} 10mH.

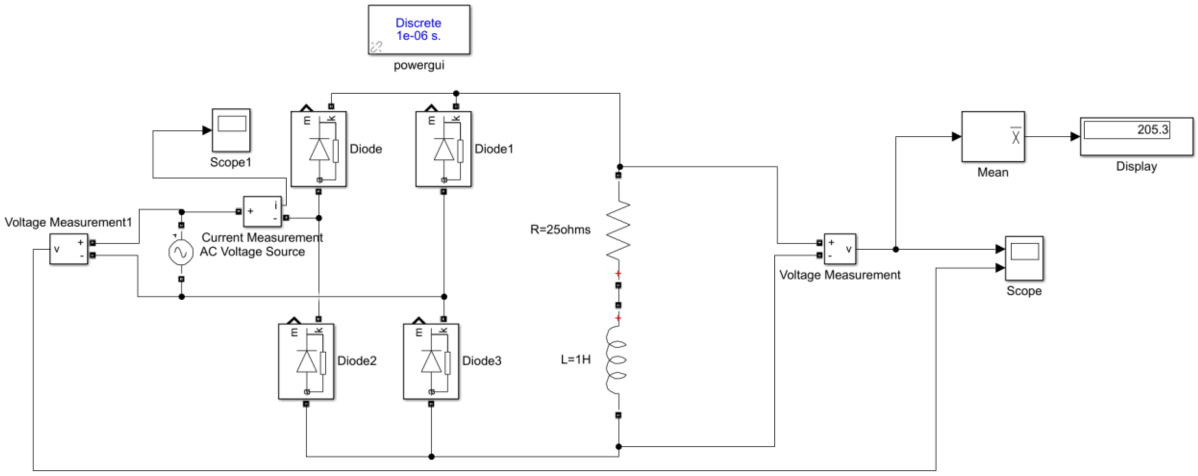

Figure 12: Circuit simulated for R_{LOAD} 25Ω and L_{LOAD} 1H.

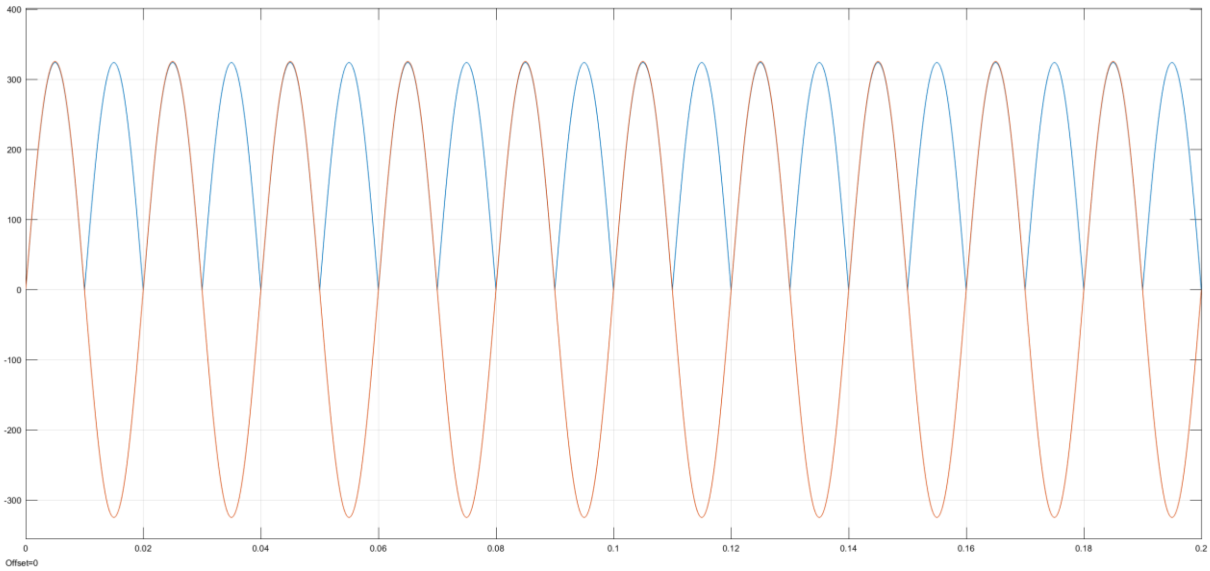

Figure 13: Input and output voltage waveforms of SPD Rectifier with R_{LOAD} 25Ω and L_{LOAD} 1H.

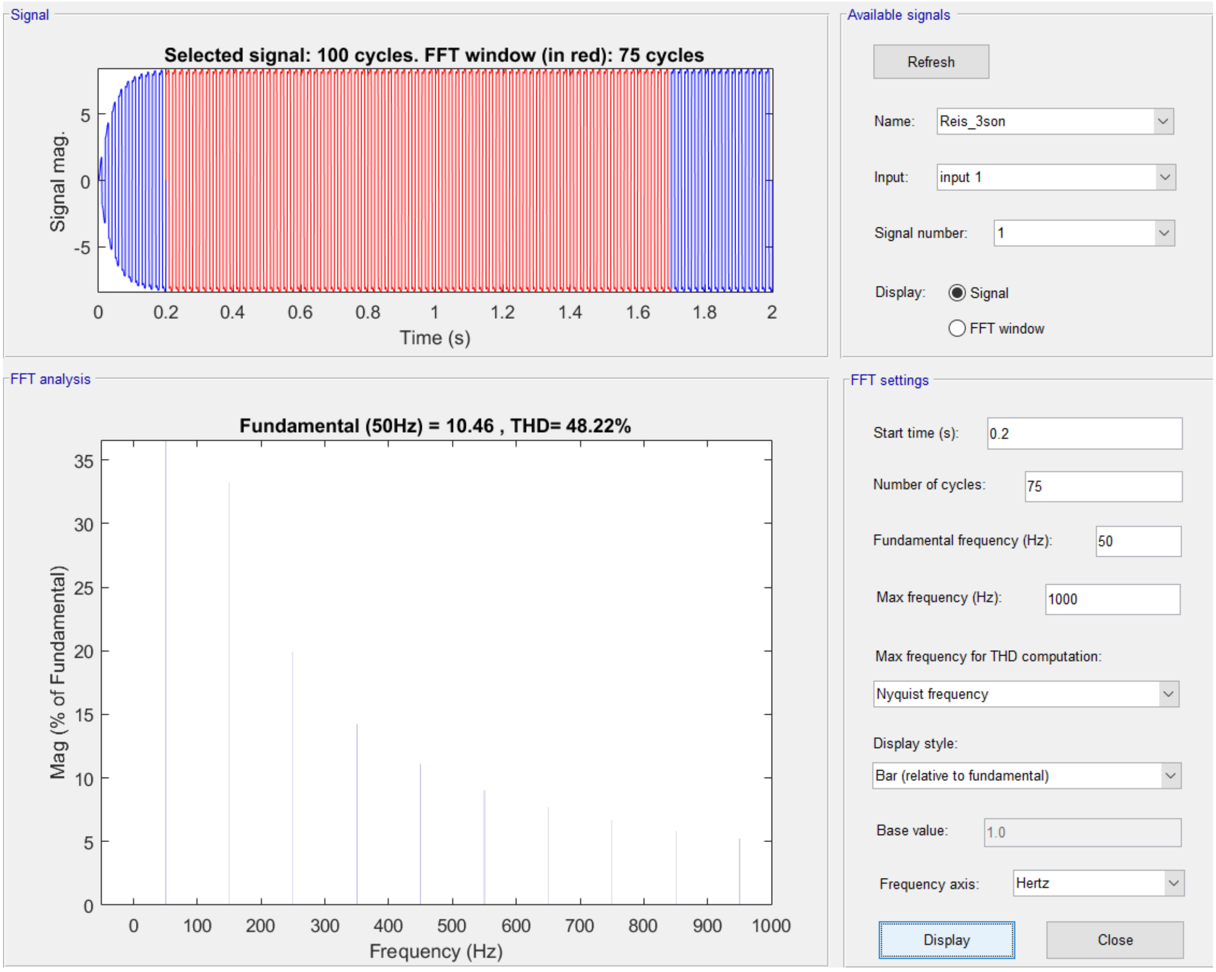

Figure 14: THD of SPD Rectifier
with R_{LOAD} 25Ω and L_{LOAD} 1H.

In conclusion, it is realized that THD of the line currents increases as we increase the inductance values at the load which implies when the current drawn from the load is more likely to ideal current source, THD increases. It can be also seen from the current waveforms that when we increase the inductance value, line current changes its form from sinusoidal to square. That is the reason why THD increases. Also, note that when we have 1H of inductance which is slightly higher value, we can behave load as ideal current source as in ideal it is infinity inductance. Hence, THD of 1H load is found as %48 which we also found in the lecture mathematically.

When the average values are considered, in all cases with different types of loads, V_{MEAN} are same and equal to 205.3V as it is measured from the Mean block of the Simulink. It concludes that even the inductance value is increases, average voltage is not affected from it and it stays constant.

2.2-

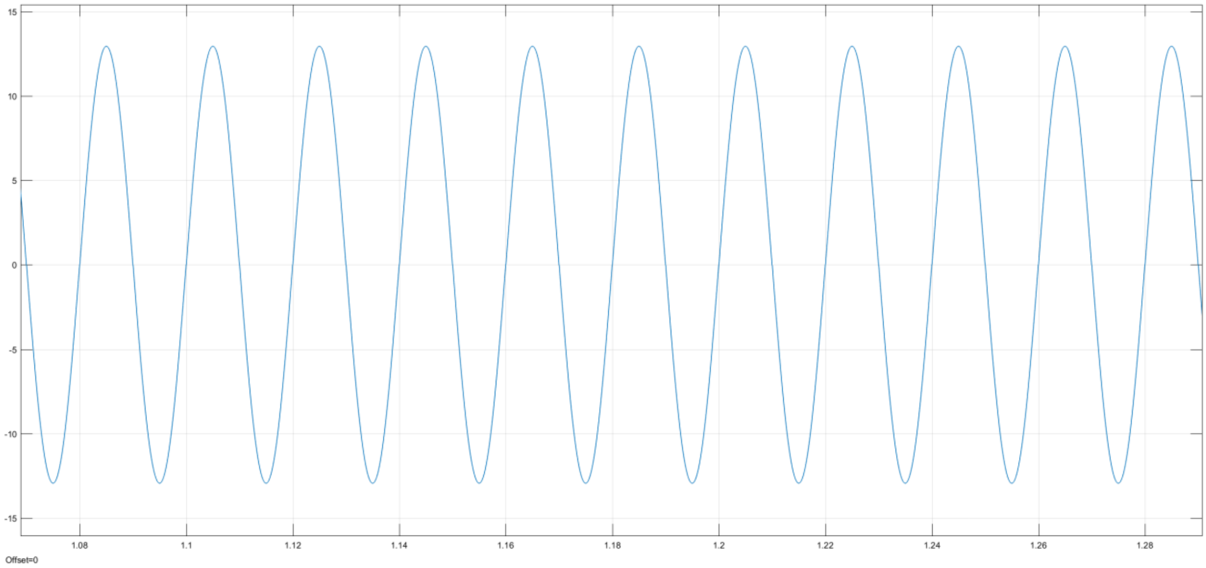

Figure 15: Current waveform on supply

Figure 13 illustrates the drawn main current waveform of rectifier. As seen from the Figure 13, I need to choose a diode which is capable of handling 13A and more in conduction and reverse action. Also, I need to consider breakdown voltage. As illustrated above in Figures, my diodes should be durable up to 325 V. Then, I searched on Digikey for discrete elements. I have chosen MUR1540G of On Semiconductor Company This diode is chosen with considerations of safety margins.

Some important features of diode:

- V_{RRM} = 400V
- $I_{F(AVG)}$ = 15A
- V_F =1.25V(typ)
- t_{RR} =60nS
- T_J = -65°C to 175°C

Safety margin for V_{RRM} is 75 V which is suitable, maybe same cases unnecessary to have these high value but it is OK. Forward current is 15A which is enough for system to operate properly but it is somehow critical value. Forward voltage drop is a bit high but we can tolerate it. Reverse recovery time is great and operating temperature is -65°C to 175°C which is a general number and it is good.

Price = $1.25

Link for diode:
https://www.digikey.com/product-detail/en/on-semiconductor/MUR1540G/MUR1540GOS-ND/919901

Let's now choose a rectifier module for our system. Same considerations with the selection of diodes are valid. I have chosen GBPC15-04 of Vishay General Semiconductor.

Some important features of rectifier module:

- V_{RRM} = 400V
- $I_{F(AVG)}$ = 15A
- V_F =1.1V(typ)
- T_J = -55°C to 150°C
- C_J = 300pF

Safety margin for V_{RRM} is 75V which is same as diodes. It is suitable for our project. Forward current is 15A which holds same reasons with the diode. Forward voltage drop is now less and it is good news. Operating temperature is -55°C to 150°C which is same as diode semiconductors and it is good. Junction capacitance is a low value which results in lower switching loss.

Price = $4.74

Link for rectifier module: https://www.digikey.com/product-detail/en/vishay-semiconductor-diodes-division/GBPC1504-E4-51/GBPC1504-E4-51-ND/2139813

As compared with 2 options, voltage and current values are chosen same as it is researched for that. In diodes, we have more voltage drop in every diode about 1.25 V and it is too much compared with the rectifier module. However, rectifier module is not able to work in the temperature range of diode used rectifier. There can also make more comparisons between two but this comparison is enough for our case.

2.3-

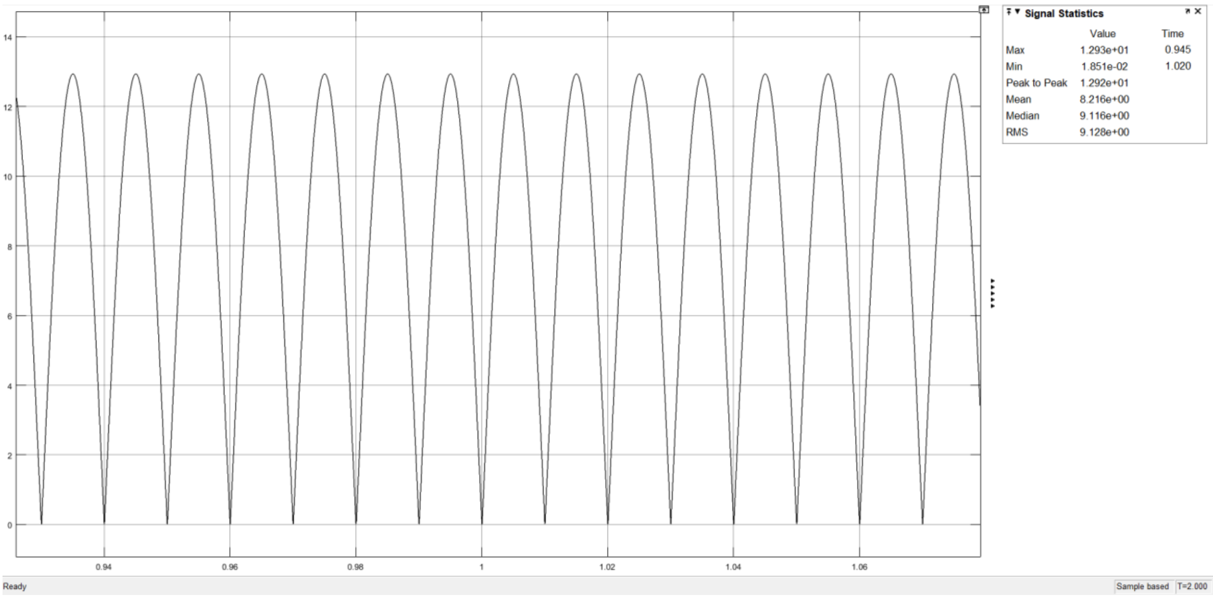

Figure 16: Output current waveform with R_{LOAD} = 100Ω.

As shown in Figure 16, mean value of output current is about 8A. The calculation of smoothing capacitor is based on this information [1].

$$Vripple = \frac{Iload}{f \times C}, Volts\ where\ Vripple = \%Ripple \times Vmean \tag{1}$$

From equation (1), $C = \frac{Iload}{f\times Vripple}, F = \frac{8A}{100Hz\times\%20\times 203.5V} = 2000\mu F$

Note it is said in [1] that the main advantages of a full-wave bridge rectifier is that it has a smaller AC ripple value for a given load and a smaller reservoir or smoothing capacitor than an equivalent half-wave rectifier. Therefore, the fundamental frequency of the ripple voltage is twice that of the AC supply frequency (100Hz) where for the half-wave rectifier it is exactly equal to the supply frequency (50Hz). Hence, frequency taken as 100Hz. Ripple is %20 of average voltage value. As a result, output capacitor is 2mF = 2000µF.

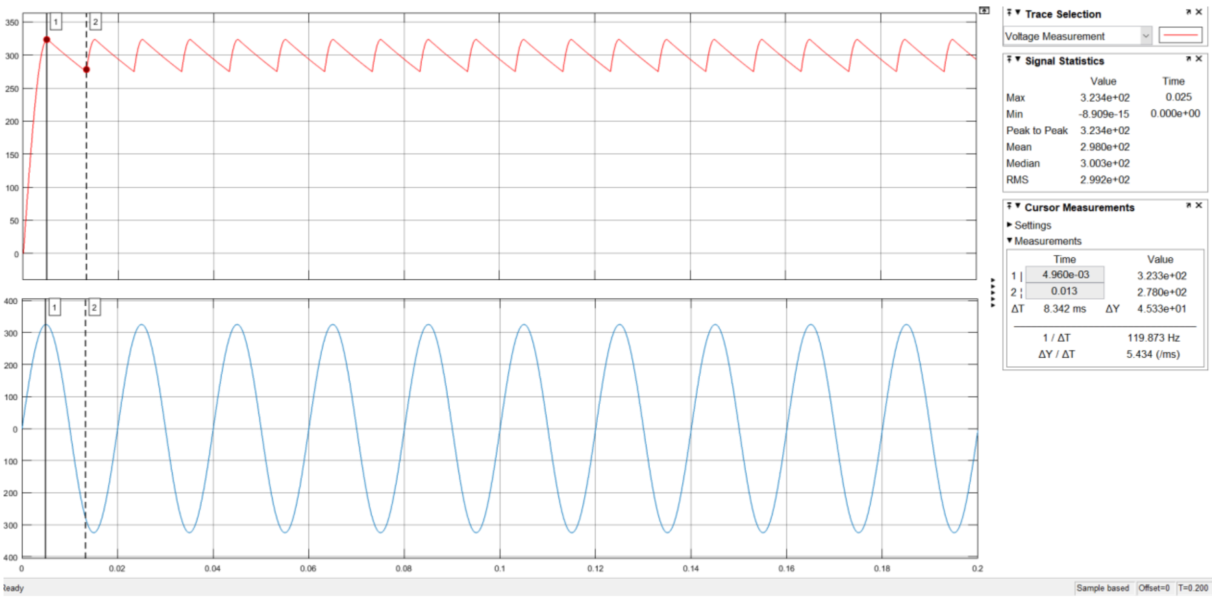

Figure 17: Output voltage with smoothing capacitor and input voltage waveform.

As seen in Figure 17, V_{AVG} = 300V with 2000µF capacitor. $V_{P\text{-}P,ripple}$= 45V. Hence, $V_{P\text{-}P,ripple}$ is %20. It is %15. Therefore, we can select a lower valued capacitor but this one makes our job done. Let’s now choose a commercial diode.

ALS70H202KE400-ND of KEMET is chosen as a bulk capacitor. The features of it:

V_{Rated} =400V
C = 2000µF
Aluminum Electrolytic Capacitor

Price: $18

This capacitor is highly reliable and it has high capacitance and voltage rating. That is why it is a little bit expensive but it is suitable for our need.

Link for capacitor: https://www.digikey.com/product-detail/en/kemet/ALS70H202KE400/ALS70H202KE400-ND/6871053

2.4-

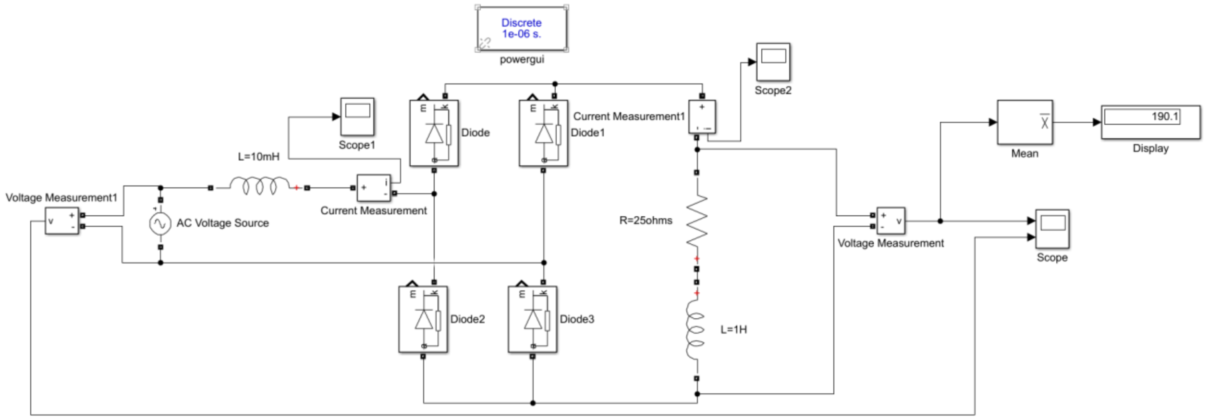

Figure 18: Simulated circuit

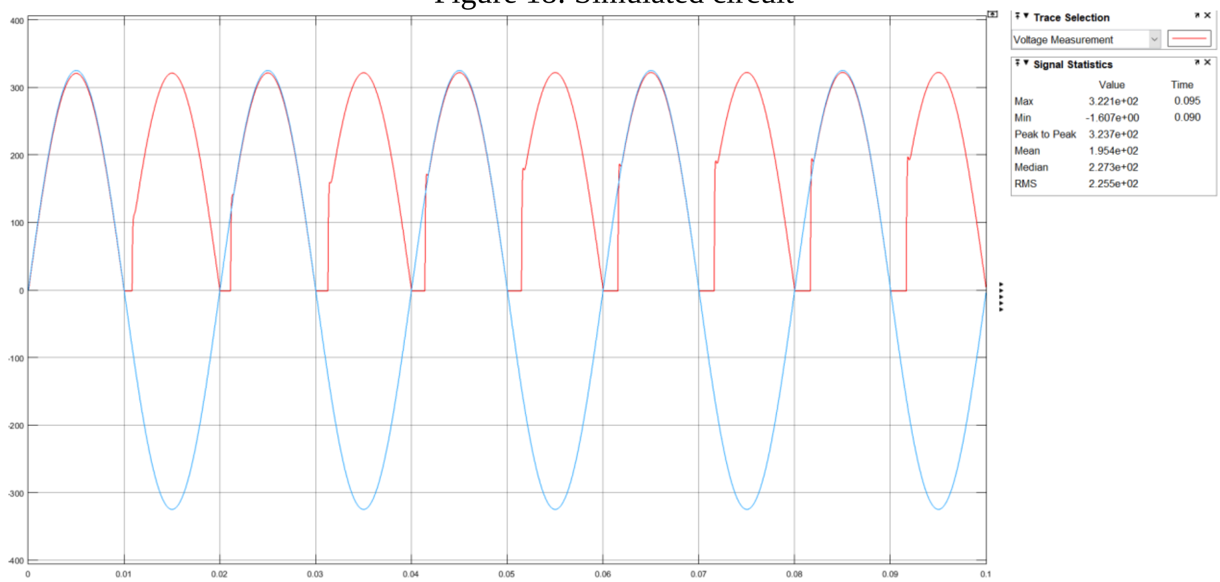

Figure 19: Input and output voltage waveforms of SPD Rectifier with R_{LOAD} 25Ω and L_{LOAD} 1H and L_S 10mS.

As seen from figure 18 and 19, we have seen the effect of commutation on the grid side. Voltage waveform is distorted with the effect of commutation which resulted in decrease in V_{MEAN}. This is because the inductor cannot charge or discharge suddenly. It requires some time for that. At this period, there is a moment in which 4 diodes are one and output is shorted. That is the reason we see 0 Voltage at the output during commutation.

2.5-

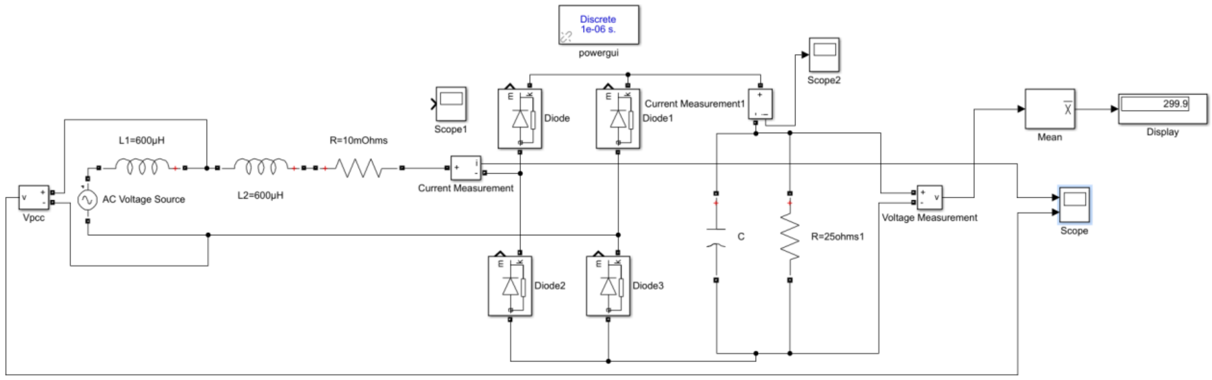

Figure 19: Simulated circuit

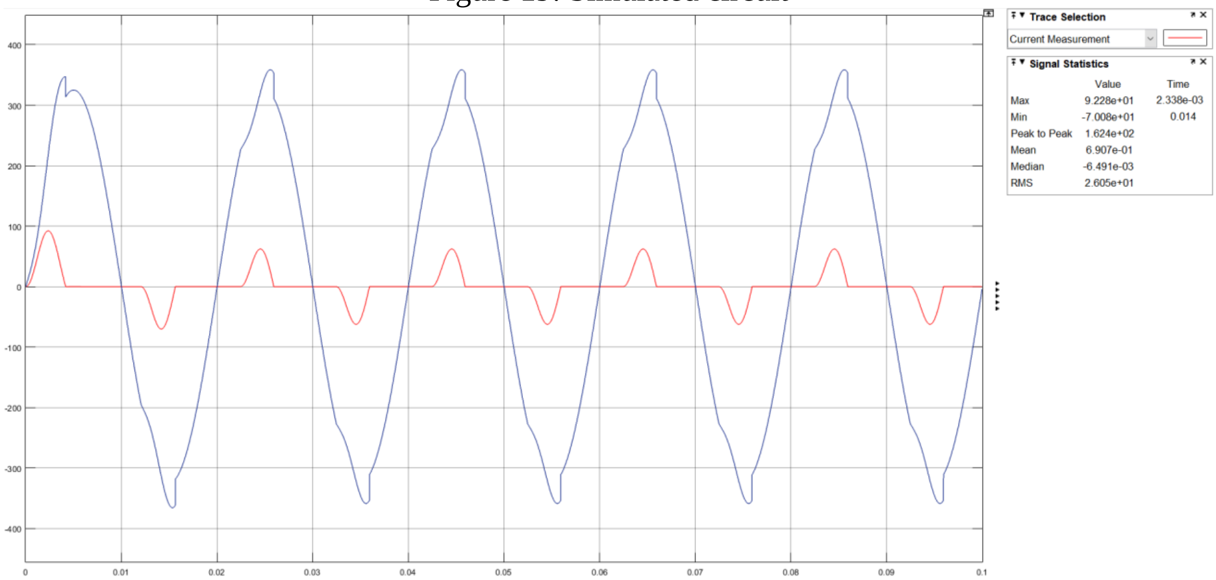

Figure 20: V_{PPC} voltage and input current waveforms of SPD Rectifier with R_{LOAD} 25Ω and L_{S1} 600µH and L_{S2} 600µS.

Output voltage is being distorted by the harmonics of current drawn. The ratio of distortion is also given in Mohan as [2]:

$$v_{(PCC)dis} = -L_{S1} \sum_{h \neq 1} \frac{di_{sh}}{dt} \tag{2}$$

Therefore, we have a decrease in output voltage and distortion in the waveform due to harmonics.

Q3) The step size is taken as 1µS for this question as well.

3.1-

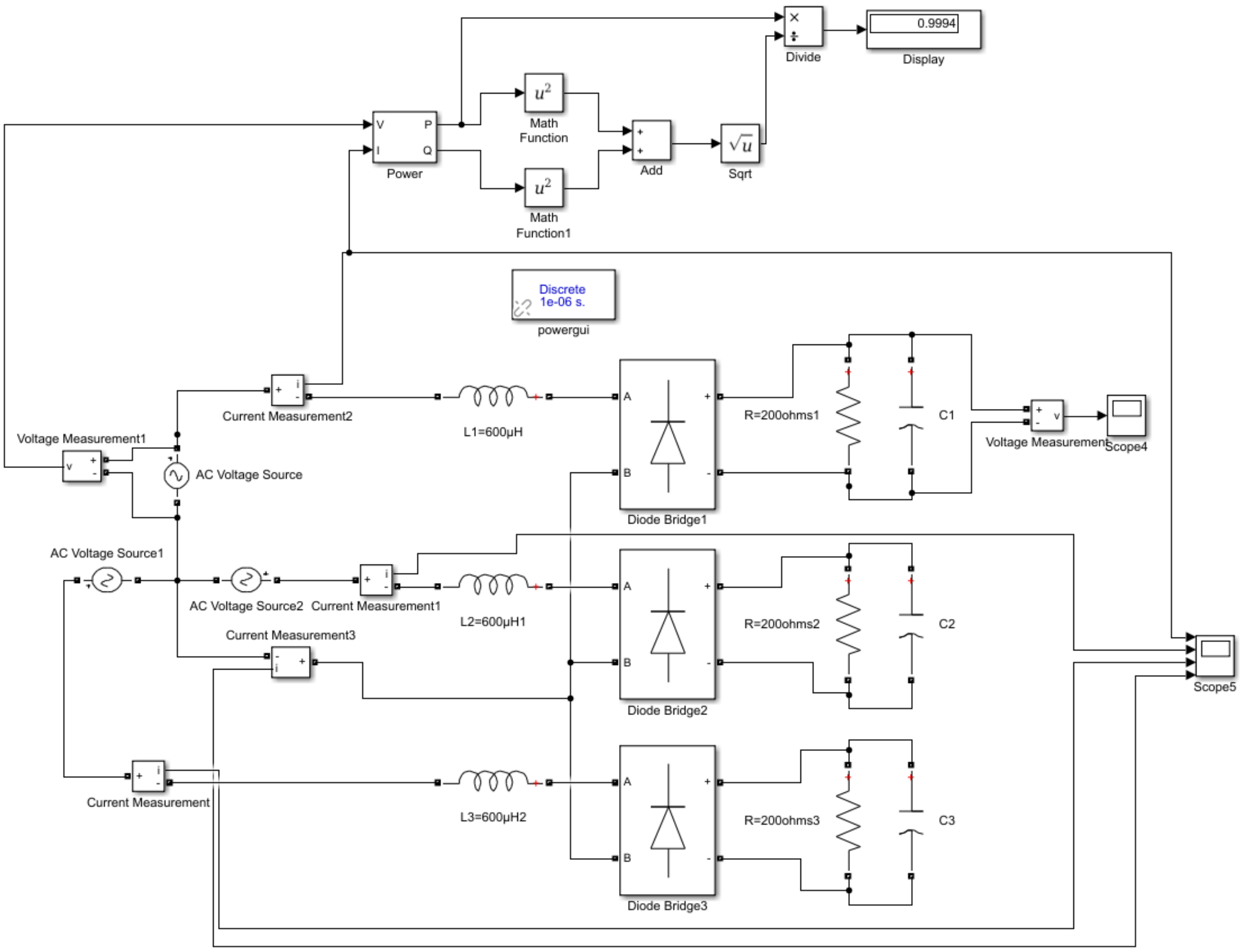

Figure 21: Schematic of single-phase rectifiers operated with 3ϴ grid with neutral wire

For Power Factor calculations, I have used math operators of Simulink. As seen from Figure 21, PF = 0.99.

Note that RMS value calculations will be done from Scope5/Signal statistics.

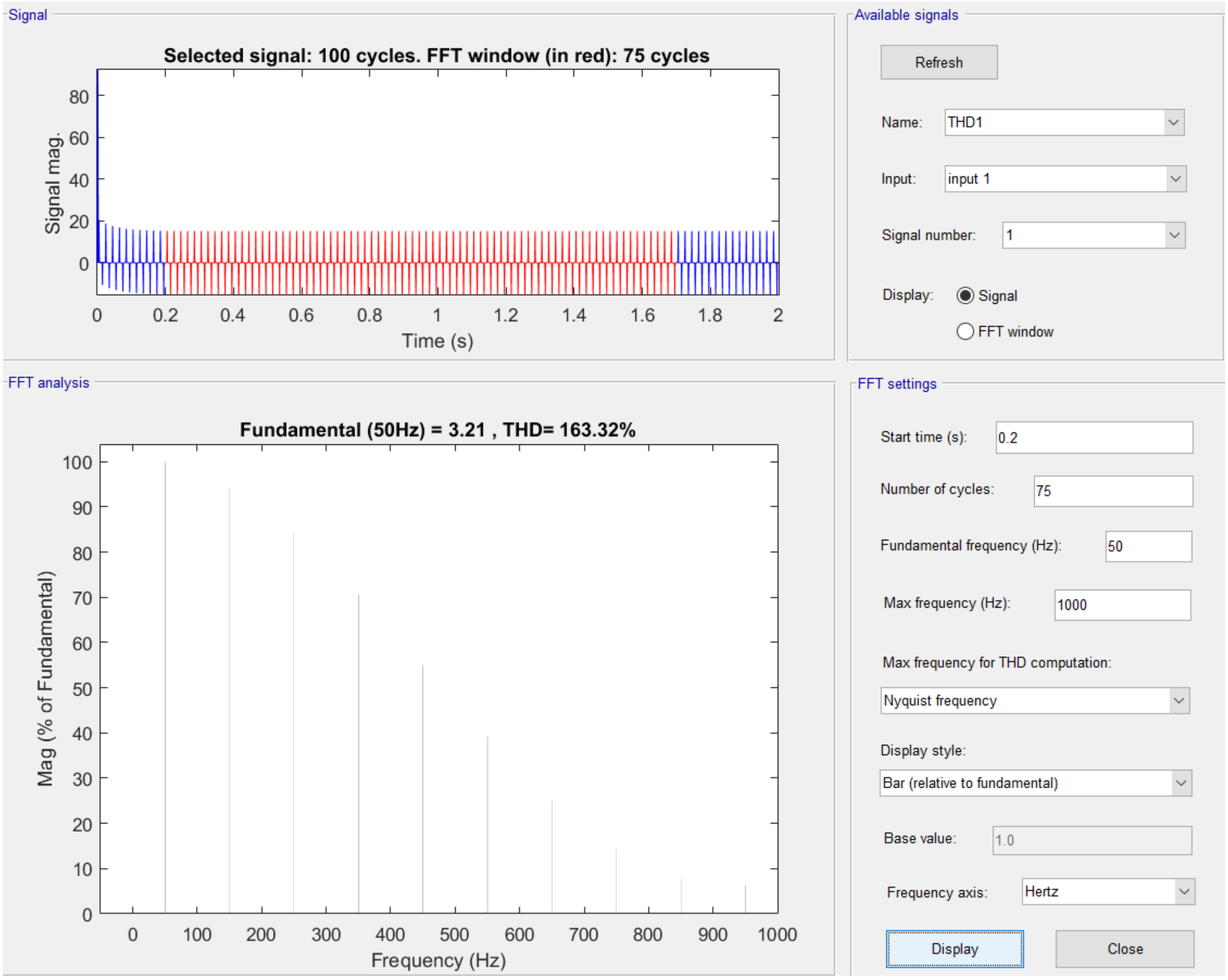

Figure 22: THD of line current

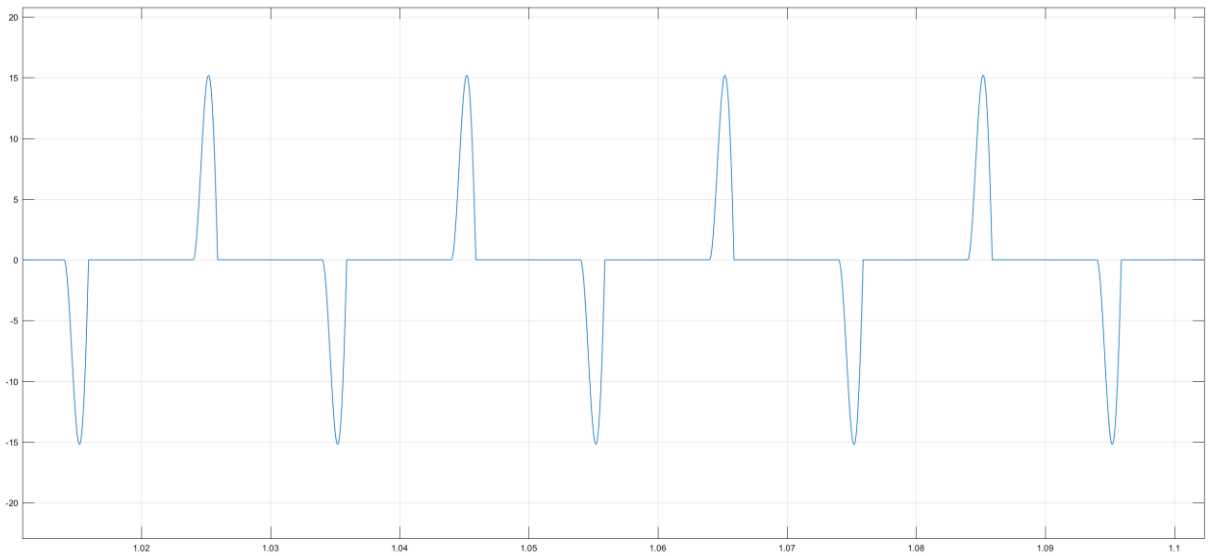

Figure 23: Current waveform of Phase A

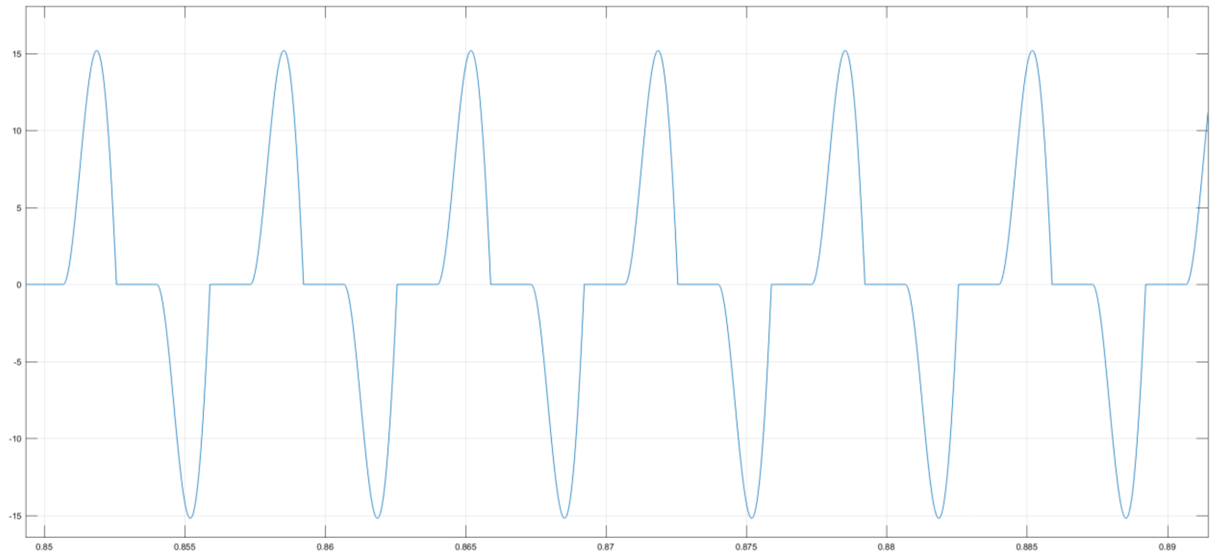

Figure 24: Current waveform of Neutral wire

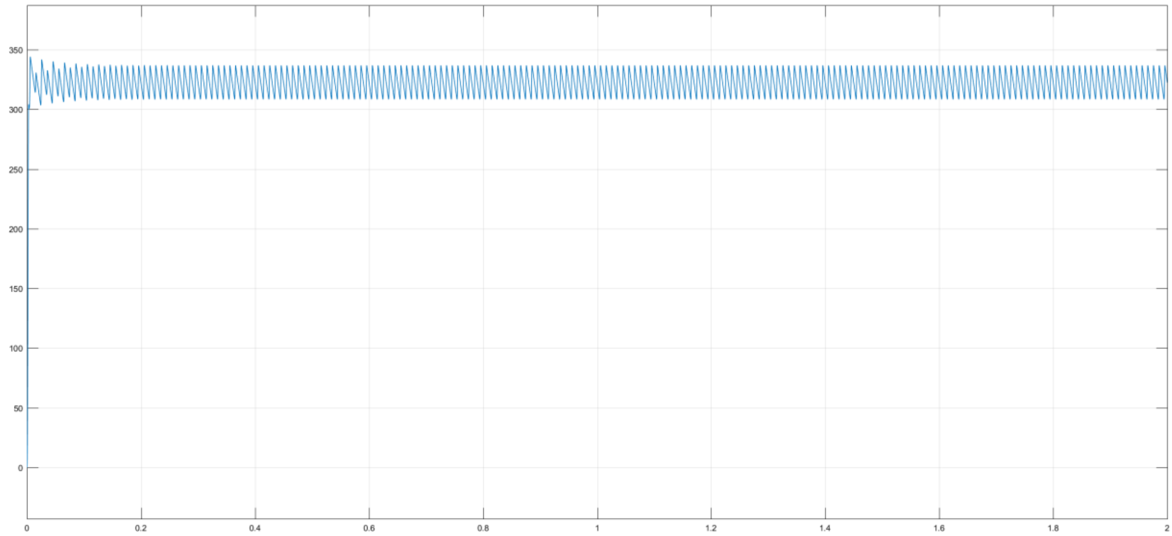

Figure 25: Voltage waveform of Diode Bridge 1

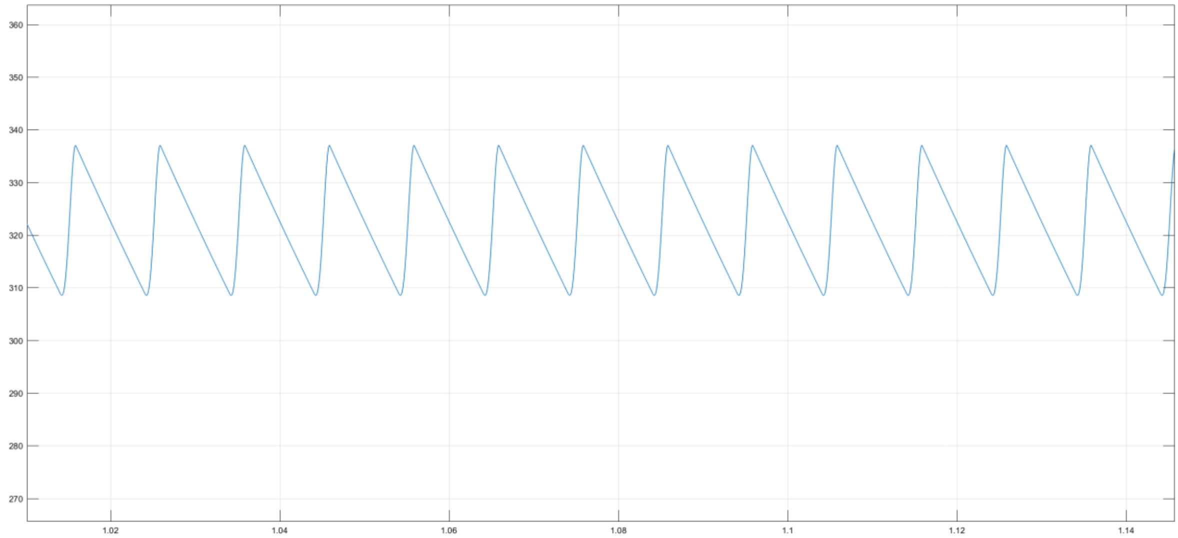

Figure 26: Voltage waveform of Diode Bridge 1 zoomed in

3.2- Note that following values are found using Signal Statistics part of Simulink/Scope.

Line	**I_{RMS} (A)**
Phase A	4.35
Phase B	4.29
Phase C	4.35
Neutral Line	7.5

Table 1: Rms values of line currents

As shown in Figure 22, THD is found as %163. RC load and line inductors cause commutation on the circuit. Also, RC load behaves different than RL loads. In RC loads, output behaves like a constant voltage source. Whenever a phase voltage is greater than its output voltage, corresponding diode bridge is operating and there will be a current flow through RC load.

Neutral wire current is the sum of all phase currents. Since we have 120° of phase difference, its frequency is 3 times of phase frequencies as shown in Figure 24.

In Figure 25 and 26, output voltages are illustrated. We have little ripples in the output voltage. The ripples can be decreased by using a larger valued capacitance since it would increase the time constant RC. However, we would need to use a bigger capacitor for that case.

Each phase current is about 4.35A. In theory, neutral current is 4.35*√3=7.53A which is the case when we measure it from Simulink as shown in Table 1.

3.3-

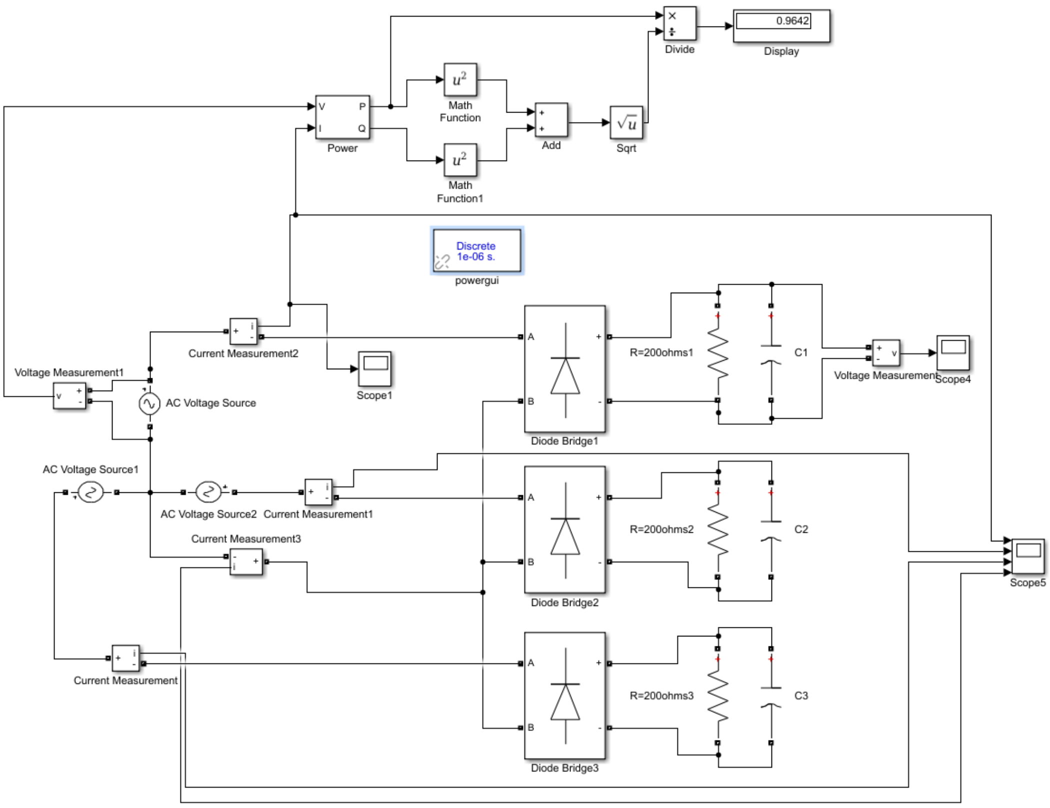

Figure 27: Schematic of single-phase rectifiers operated with 3Θ grid with neutral wire with L_S=0.

The same operations are applied for this circuit with L_S=0 for Power Factor calculations. As seen from Figure 27, PF = 0.964.

Note that RMS value calculations will be done from Scope5/Signal statistics.

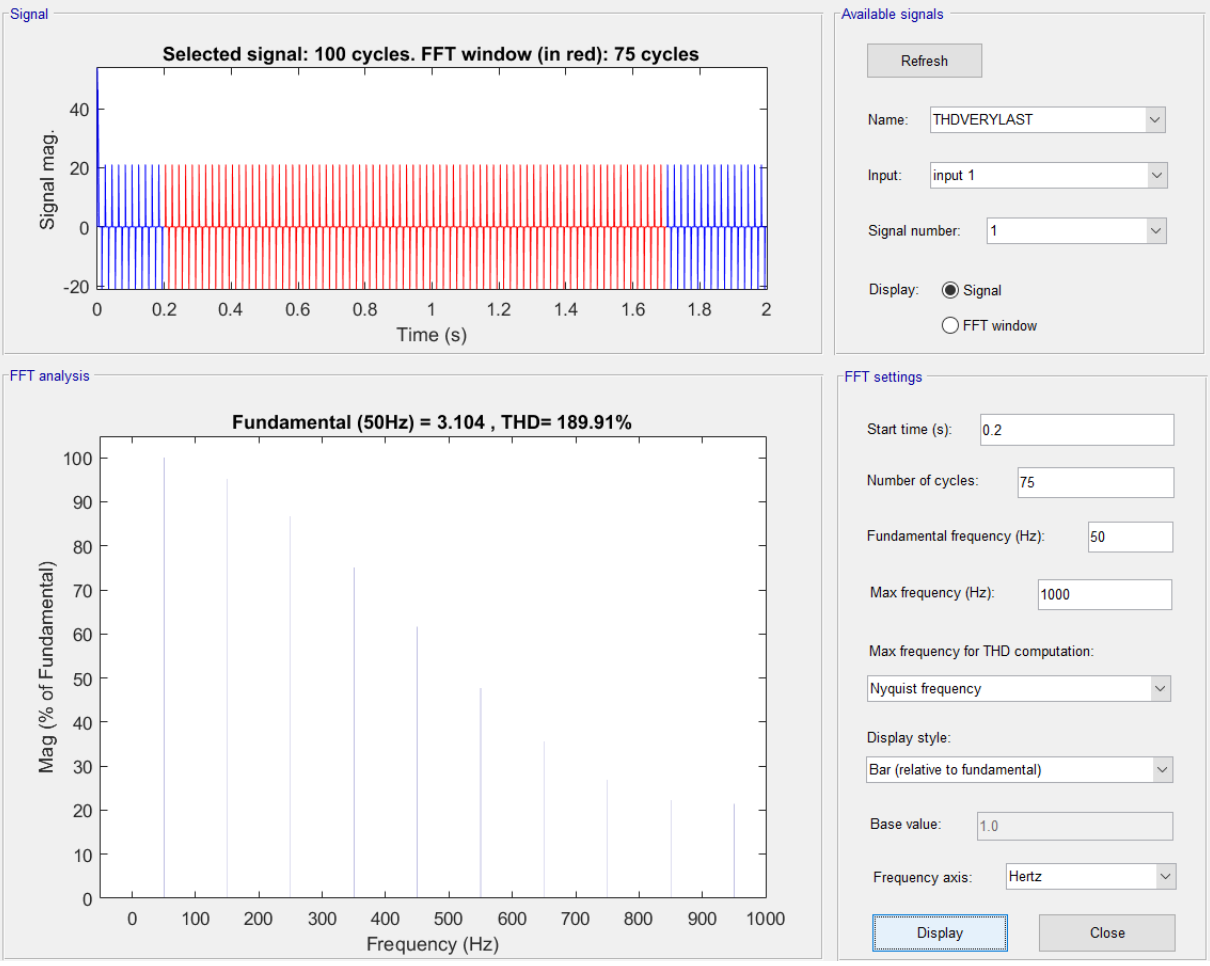

Figure 28: THD of line current with L_S=0.

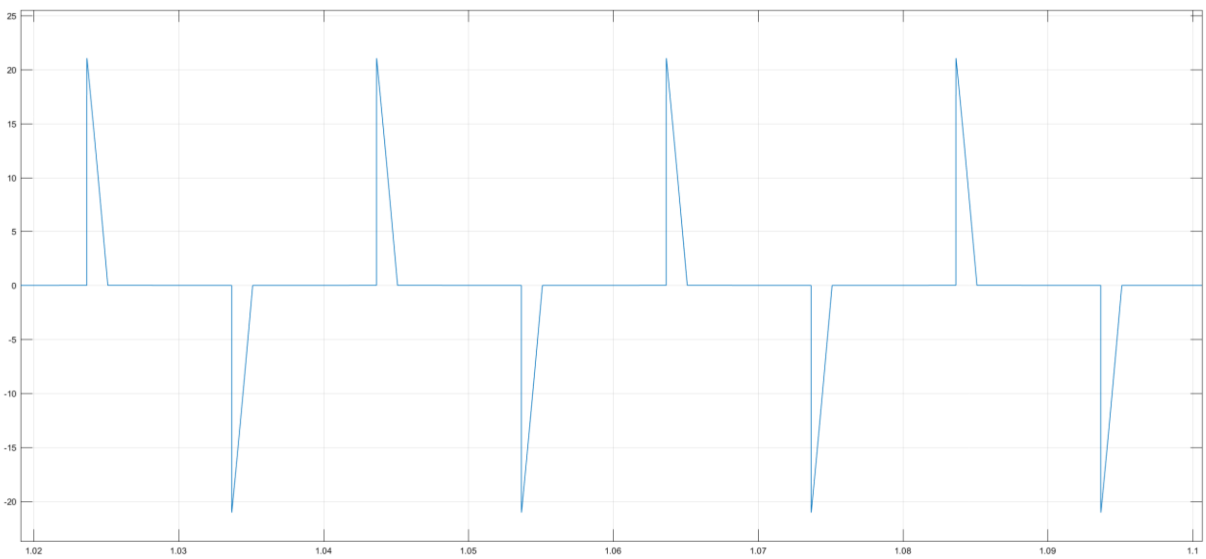
Figure 29: Current waveform of Phase A with L_S=0.

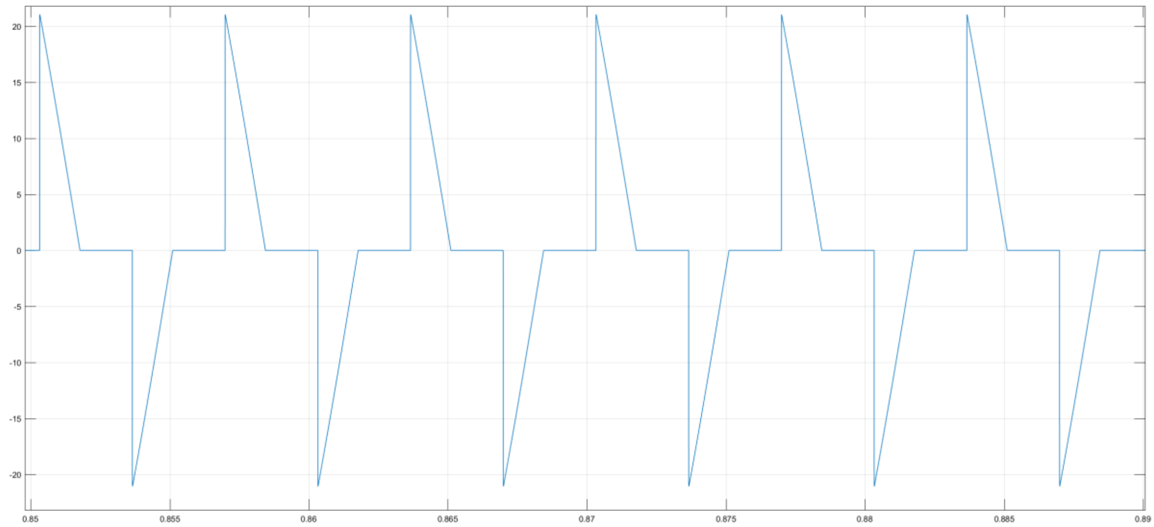

Figure 30: Current waveform of Neutral wire with L_S=0.

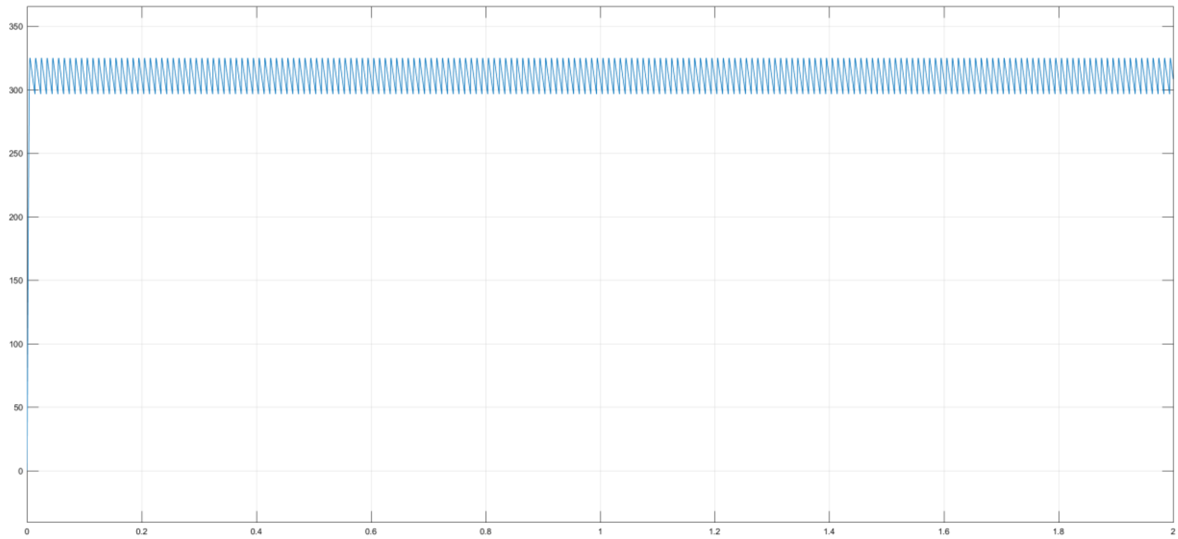

Figure 31: Voltage waveform of Diode Bridge 1 with L_S=0.

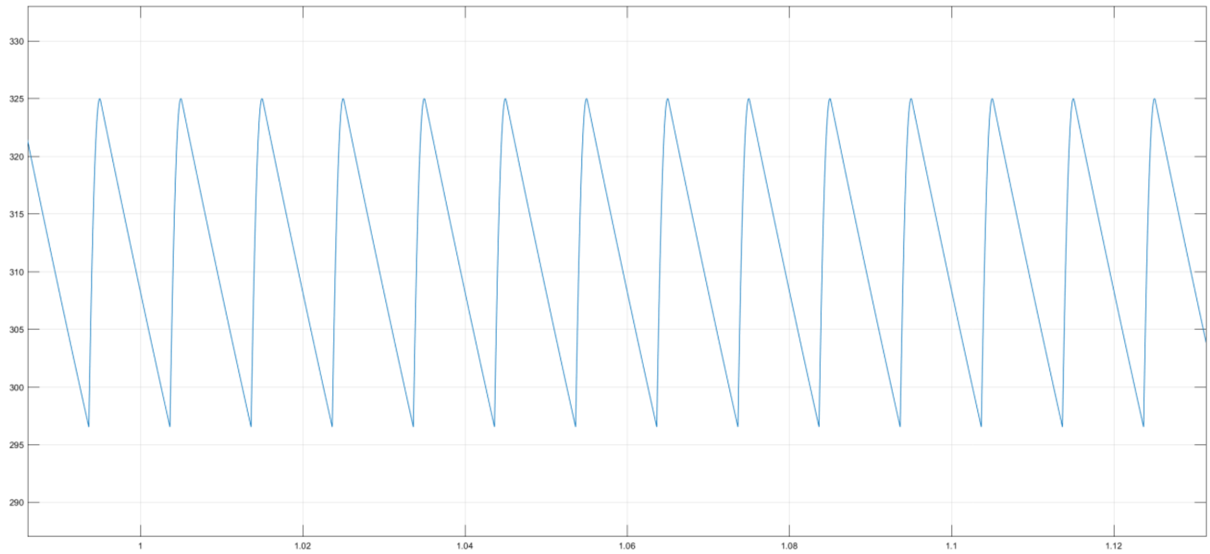

Figure 32: Voltage waveform of Diode Bridge 1 with L_S=0 zoomed in.

Note that following values are found using Signal Statistics part of Simulink/Scope.

Line	**I_{RMS} (A)**
Phase A	4.71
Phase B	4.70
Phase C	4.71
Neutral Line	8.15

Table 2: Rms values of line currents with L_S=0.

THD is now about %190 as shown in Figure 28. In theory, having a more likely square current waveform means more THD as it would include more harmonics with higher frequencies. Since we have now no line inductance, the transitions are sharper than before which means increase in THD.

$$PF = \frac{I_{S1}}{I_S} \times DPF \tag{3}$$

If we have sharper waveform, we would have lower I_{S1}. Hence, we have lower PF = 0.964.

Also, Rms value of neutral line current is increased since we removed inductance L_S from circuit which results in less impedance. From Ohm's Law, we have more current at neutral wire.

Frequency considerations are same with previous question.

Waveforms are now sharper because having inductors makes rising and falling edges softer. As shown in Figures 29 and 30, we have sharper transitions since we don't have inductances at supply sides.

References

[1] *Bridge Rectifier Ripple Voltage*. Retrieved from https://www.electronics-tutorials.ws/diode/diode_6.html

[2] Mohan, N., Undeland, T. M., & Robbins, W. P. (2002). *Power electronics: Converters, applications, and design*. New York: John Wiley.