MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE463 – Project 1

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A. INTRODUCTION

In today's global world, electricity or electrical energy is the main component of all kinds of operations since almost all of the working fields are in need electricity in the struggle of civilization and making the lives of people more comfortable. Since, there is a big issue like "Global Warming" and exhaust gasses are one of the main reasons of that problem, both the environmentalists and the managers of the industrial world evolve into the idea that electricity is one of the best energy resource when compared by means of both power and the sludges. Due to that, at every moment of today's daily lives, one can observe the result of that reality such as turbine generators located on highways, solar plants, electricity cars, and so on.

From this point of view, engineers -particularly Electrical and Electronics Engineers- dwell upon that issue in order to provide brand-new and efficient solutions to the human's needs. The working field of Power Electronics is an essential one to accomplish that and provide new methods, solutions and products both to industry and the end-users to make them be able to take the advantage of this infinite energy source: Electricity.

Engineers should be able to convert the AC electrical energy that is being generated at Power Plants into more useful type since the electronic devices generally work with DC voltages and currents. In order to achieve that, power conversion principles should be applied, and the course of Static Power Conversion-I aims to teach the background information of all those methodologies by making the learners fed with both theoretical knowledge and practical applications according to the syllabus of the course. The main ideology behind this course is to show students how power drawn from the grid can be converted into such form to both drive different kinds of materials like AC motors, DC motors, etc. and convert that energy into different types by using different topologies to drive all kinds of devices anywhere.

This report which is about the first simulation project of Static Power Conversion-I is concerned with the theoretical knowledge, mathematical approaches and practical applications of the first step of conversion which is rectification. Some given processes were investigated on rectifiers specifically the Diode Bridge Rectifiers and the fundamental theory of those topologies were examined according to analytical calculations and the comparisons of that calculations with the simulation results. The rectified voltage and current waveforms were analyzed and the details of those waveforms such as the maximum, minimum, peak-to-peak, mean, RMS values and the THD[1] information.

During the report one will be reading the details of three different topologies which are Single-Phase Half-Bridge Rectifier, Single-Phase Full-Bridge Rectifier and Three-Phase Full-Bridge Rectifier. One last note is in all the circuit schematics that are generalized by the usage of MATLAB-Simulink, generators represent the grid side of the network.

[1] Total Harmonic Distortion

B. SINGLE-PHASE HALF BRIDGE RECTIFIER

In practical applications, Single-Phase Half-Bridge Rectifiers are used in order to chop the negative component of the sinusoidal AC signal by usage of a diode that allows the current flow to the load in the positive cycles and block it in negative ones. By the reversing of the diode mounting direction, one can make the negative cycles pass and block the positive cycles. Since half of the signal is chopped due to the presence of the diode, there will not be a voltage on the load during the negative cycles -if diode is configured to pass the positive half ones-.

The AC source in the simulations are assumed as the Turkish grid which is $230V_{RMS}$ and $325V_{max}$ according to the equation of

$$V_{peak} = V_{RMS}\, x\, \sqrt{2}$$

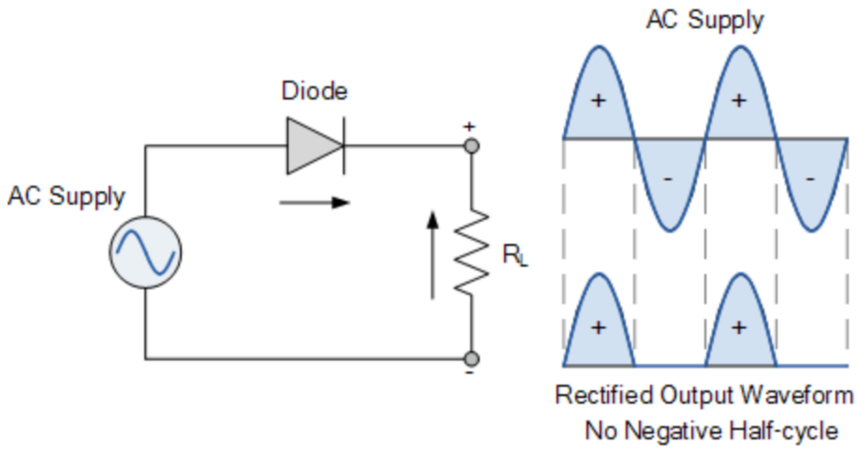

Figure 1: The Schematic, Input and Output Waveforms of SPHBR[2]

As one can easily observe from the given figure above, the main application of SPHBRs are chopping the half cycles of the input signal. The same circuit schematic for SPHBR with a resistive load of 100Ohms is constructed at Simulink-Simscape and the related results asked in the project description are collected.

[2] Single-Phase Half-Bridge Rectifier

1) Plotting the Output Voltage Waveform

If one tries to plot the output voltage waveform of a SPHBR, the expected result is a signal whose half cycles are chopped as explained earlier. The circuit schematic and the expected output voltage waveforms are given in the figures below:

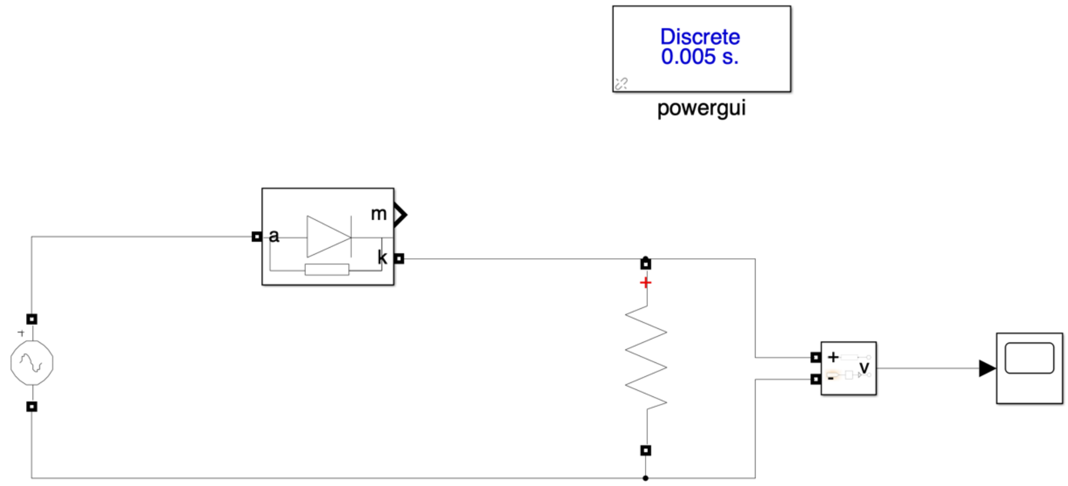

Figure 2: The Circuit Schematic of SPHBR

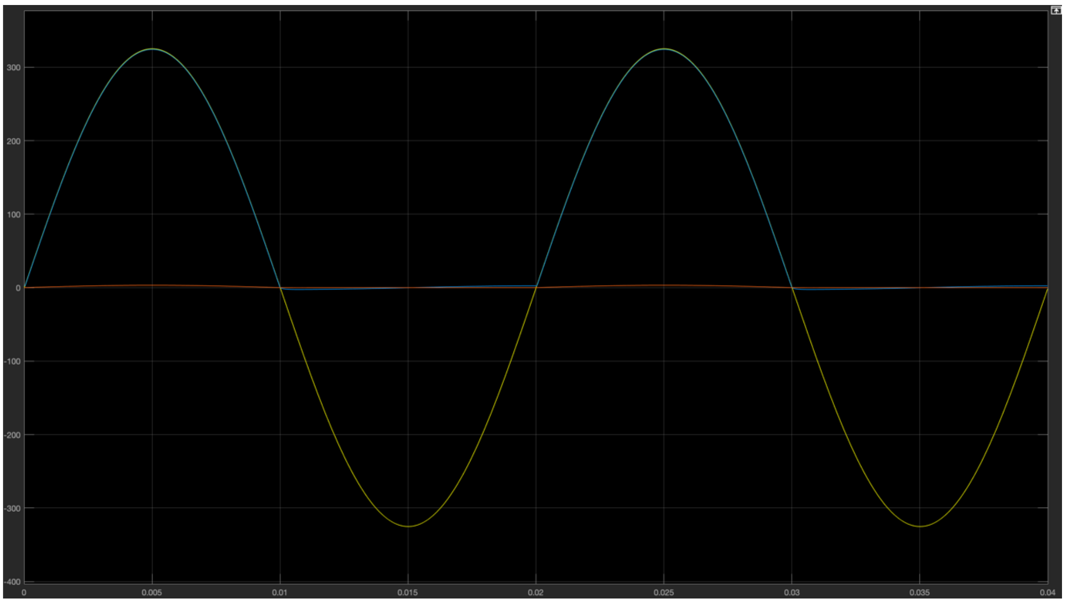

Figure 3: The Expected Output Waveform (Blue Trace) of Given Schematic

a) *Output Waveform for a Sample Time of 1ns*

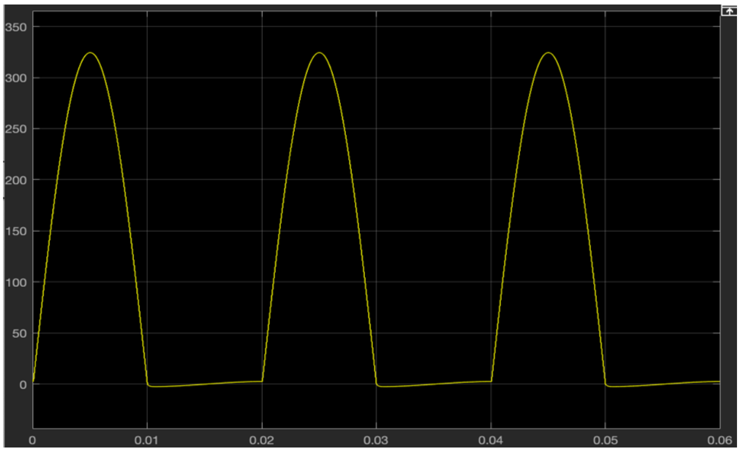

Figure 4: The Output Voltage Waveform for a Step Time of 1ns

b) *Output Waveform for a Sample Time of 0.5ms*

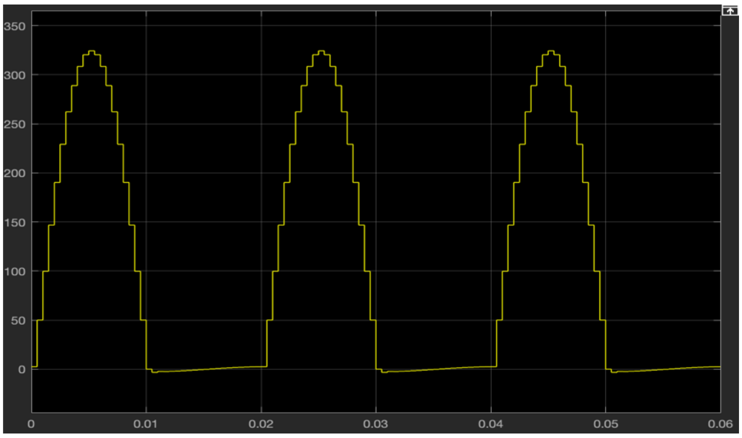

Figure 5: The Output Voltage Waveform for a Step Time of 0.5ms

c) *Output Waveform for a Sample Time of 5ms*

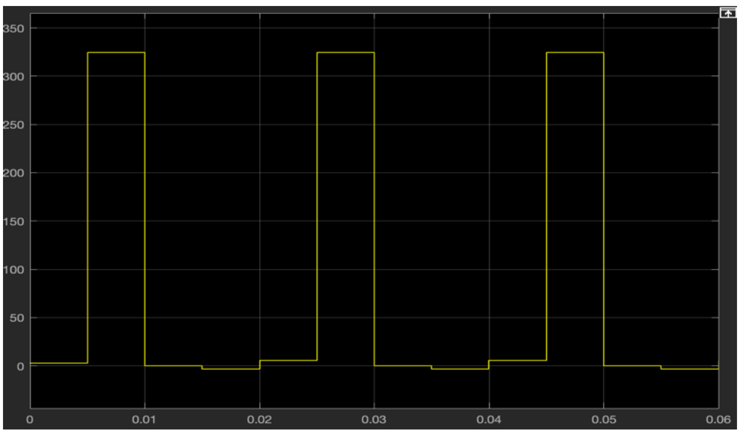

Figure 6: The Output Voltage Waveform for a Step Time of 5ms

2) Significance of the Sample Time

Since the topology of the circuit has not change, the expected output voltage is the same in overall shape, too. However, sample time change the shape of the simulated signal. According to Simulink Documentations[3]

> "*The sample time of a block is a parameter that indicates when, during simulation, the block produces outputs and if appropriate, updates its internal state. The internal state includes but is not limited to continuous and discrete states that are logged.*"

For many kinds of engineering applications, specifically on simulations, the designer should control the rate of execution time interval in order to control and configure the output generation process by means of logging small data packages or big. If one uses a small sample time which is 1 ns in this example, the simulation block generates big data packages which makes the simulated output logs (both in data log and signal waveforms) more accurate and converged to more real results. However, since every decision is a renunciation, this accurate output data consumes longer times according to the smallness of the sample time.

When one makes the sample time bigger, it means the execution interval of the simulation block is made larger and the resultant output data is less. In other words, when a specific signal is analyzed by different sample times, if the sample time is bigger, that means the interval is bigger and the generated output data is less. If it is smaller, the output data is more, and one can think that a fix signal is divided into different parts according to the sample time. If that sample time is small, there are more output data and big data packages. When it is small, there are less.

This is a process on which the advantages and disadvantages should be traded of since it changes the accuracy, quantity of the output waveforms and time that will be consumed during the simulation. This is a design decision, but one should be aware of that, in order to get more accurate results smaller sample times should be used in the analysis.

[3] For further information visit: https://www.mathworks.com/help/simulink/ug/what-is-sample-time.html

3) Average Output Voltage and Input Current THD

According to the generalized equations, the average voltage of the output waveform is:

$$V_{avg} = \frac{1}{T}\int_0^T V_d \, . \, dt$$

$$= \frac{2. V_{RMS}\sqrt{2}}{2\pi}$$

$$= \frac{2 \, . \, 230 \, . \, \sqrt{2}}{2\pi}$$

$$= 103.536 \, V$$

The THD of the input current is:

$$I(t) = 0 \; when \, \frac{\pi}{\omega} < t < 0$$

$$I(t) = I_{max} \; when \; 0 < t < \frac{\pi}{\omega}$$

$$a_0 = \frac{1}{\pi}\int_0^{\pi} \sin(\omega t) \, . \, dt = \frac{1}{\pi}$$

$$a_n = 0 \; for \; n = 2,4,6 \ldots and \; a_n = \frac{-2}{(n-1).(n+1).\pi} \; for \; n = 1,3,5.. and \; b_1 = 0.5$$

$$THD = \frac{\sqrt{(0.21)^2 + (0.042)^2 + (0.018)^2}}{0.5}$$

$$= 0.43 \; \%$$

4) V_{avg} and THD Values with Simulation Tools

After the calculations of the values analytically, one can also use the Simulink simulation tools in order to collect the values. The values according to the simulation is given below in the figure:

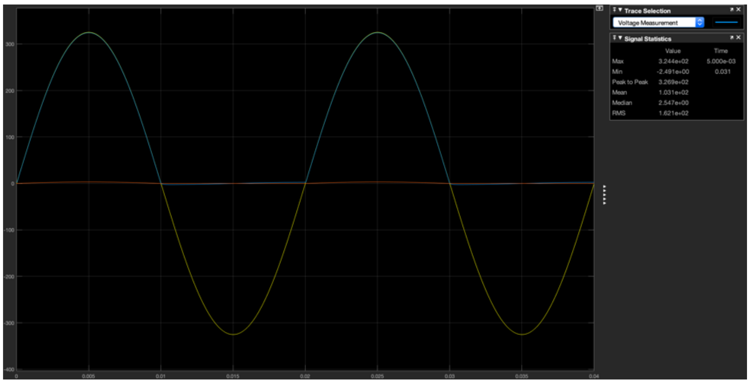

Figure 7: The Average Output Voltage Value

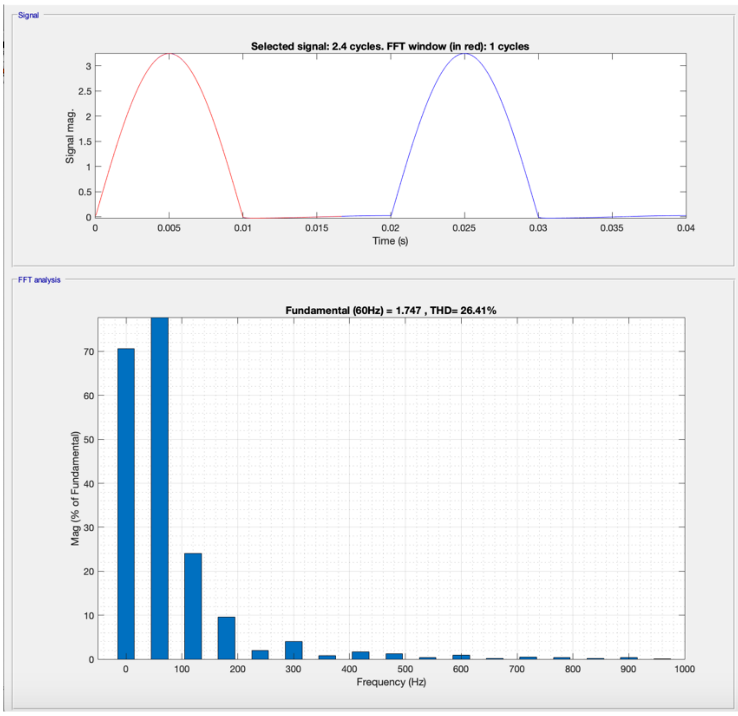

Figure 8: The THD Value of Input Current

As one can observe and compare according to the figures given above, the output average voltage is 103.1V which is very close to the result of analytical approach. However, there is a small difference between the analytical calculation of THD and the result taken from the simulation tool. That is because, the simulation tool can calculate according to both all the harmonic components and the sample time, so the result of the tool can be more accurate. When all the results are observed, one can simply understand the operational principles and the details of Single-Phase Half-Bridge Diode Rectifier: It chops the negative component of the applied signal.

C. SINGLE-PHASE FULL-BRIDGE DIODE RECTIFIER

The Single-Phase Full-Bridge Diode Rectifiers are used to increase the efficiency of the output signals when compared to the SPHBRs explained in the previous chapter. One of the main advantages of Full-Bridge rectifier is making the bridge be able to pass the negative cycles in addition to the positive ones. This makes an output signal which is more converged one in comparison with the SPHBRs.

The Single-Phase Full-Bridge Rectifiers are composed of four diodes whose each pair are configured to pass positive and negative signals respectively. When the applied source signal is in its positive cycle -according to the figures- the D1 and D2 pass the voltages and currents to load side, and when the cycle is negative, D3 and D4 pass the signals to the load side and by the usage of this operational principle, both negative and positive signals are seen as a single-positive rippled signal at the output side.

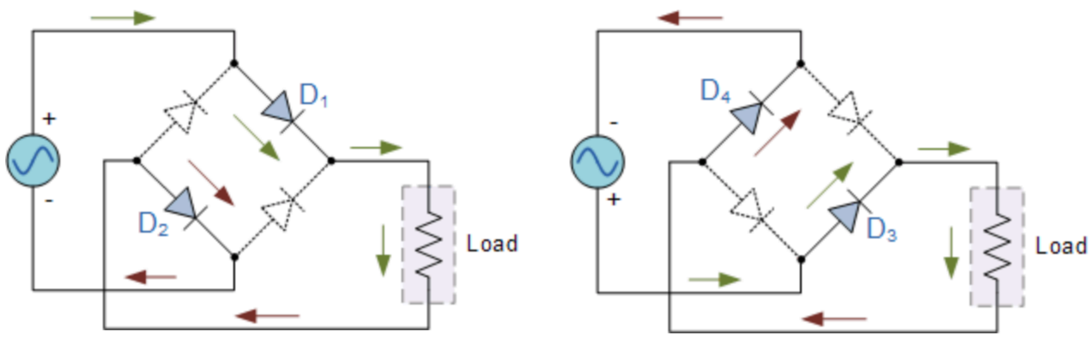

Figure 9: The Operational Principle of Full-Bridge Rectifiers

1) L_s and R_s Explanation

According to the given figure in the project definition, there is an R-L configuration which represent an inductance and the resistance before the signals enter into the Power-Electronic component. Those source inductance and source resistance represent the overall impedance of the network. In other words, the Thevenin equivalent of the grid side when seen from the input of the rectifiers.

As one knows, there is a default impedance of the network because of the cables, transformers, generators and all of those components' internal properties and those values affects the voltage drop, voltage, power loss, THD of the related bus i.e. the plug where the electricity is drawn.

Nss

2) Minimum Output Filter Capacitance

In this part of the project definition, it is asked to find a capacitance value by which the output peak-to-peak ripple voltage is 5% of the output mean voltage. When it is written mathematically, the equation is as:

$$\frac{V_{out(peak-to-peak)}}{V_{average}} \cong 0.05$$

With the usage of the simulation tool on Simulink and with a trial-and-error method, the findings are given according to the figure below:

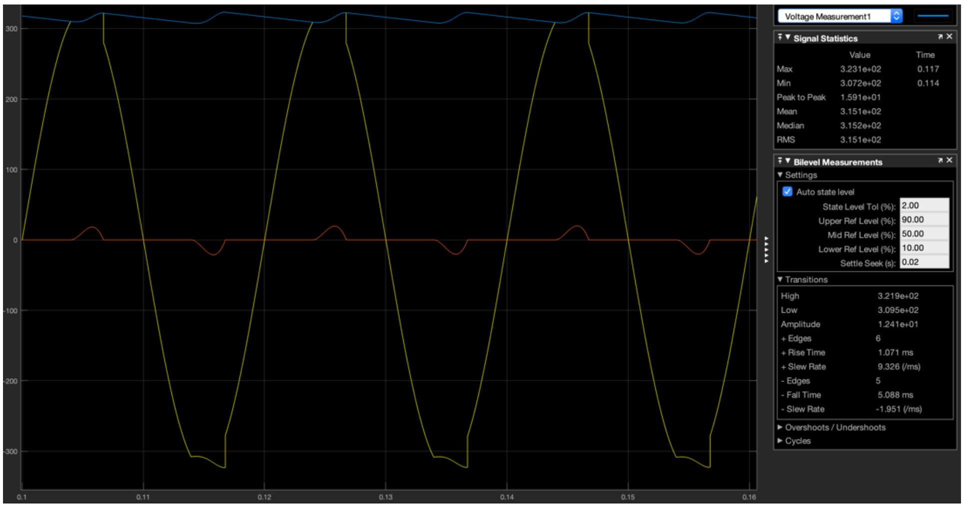

Figure 10: The Acquired Output Ripple Voltage Graph

The resultant values can be seen from the figure where the output mean voltage is 315.1V and the output peak-to-peak ripple voltage is 15.91V. When the given equation is used, one can calculate the ratio as:

$$\frac{15.91\,V}{315.1\,V} = 0.0504$$

Where it is 5% of the mean voltage. At that stage, the capacitance at the output side's value is measured as 1620µF. Since it is not a very huge capacitance value which means the charging and discharging times are not so large, the rippled output voltage can be observed as in the figure with the blue trace.

3) $V_o - V_{in} - I_{in}$ Graph

As it was given in the previous section, the relevant graph is given below:

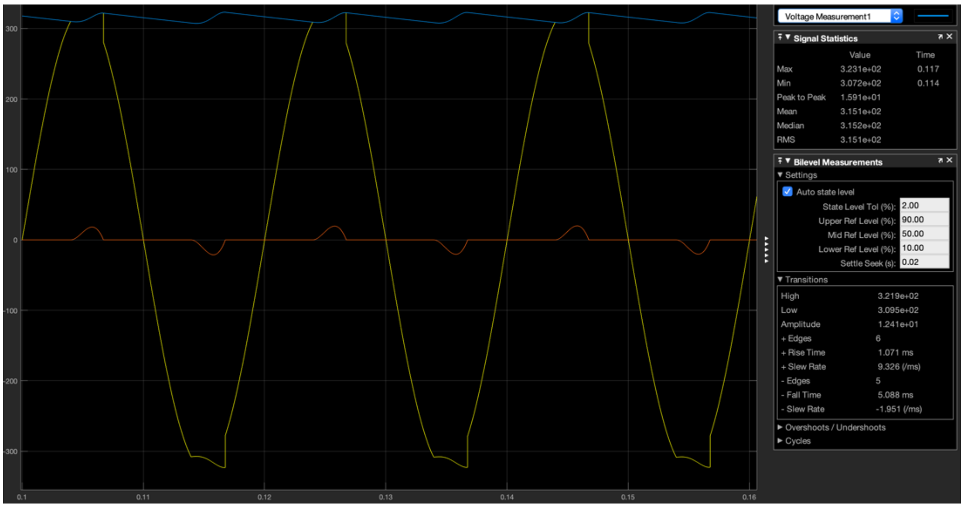

Figure 11: $V_o - V_{in} - I_{in}$ Plotted Signal Graph

4) $V_{out(mean)} - THD_{I_{in}} - PF$

As one can clearly observe from the signal statistics sub window given in Figure 11, the output mean voltage is 315.1V and which is almost twice higher than the Half-Bridge Rectifier's output average voltage.

The THD is found by the usage of FFT window in Simulink and is found as 123.91% because of the source inductance and resistance since they cause harmonics.

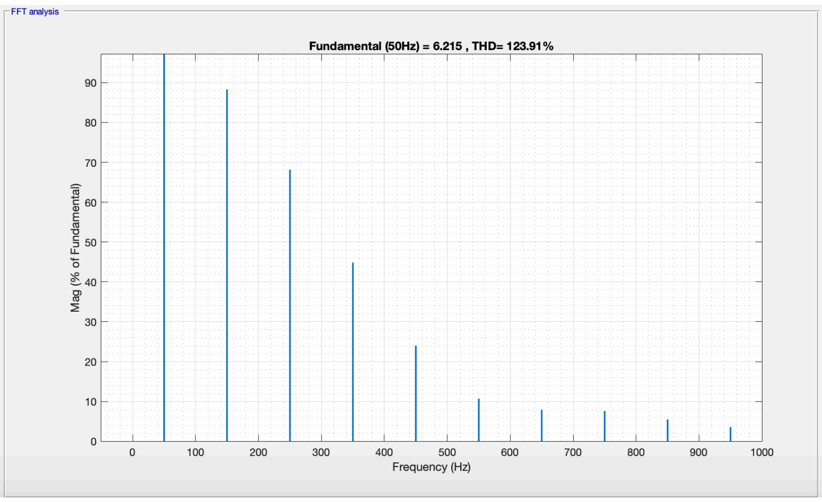

Figure 12: The THD Bar Graph of the Input Current

5) Output Waveforms Without L_s and R_s

The related output signal waveforms are collected via Simulink Scope and the graph is given below:

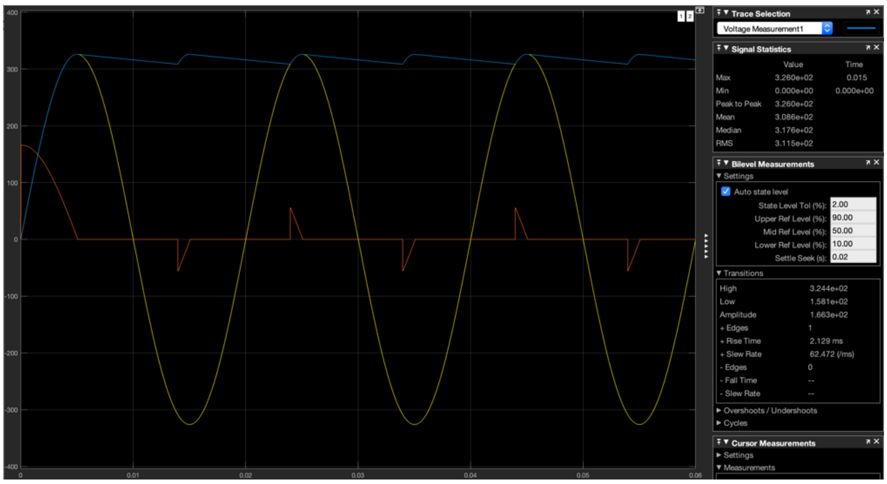

Figure 13: The Output Waveforms without L_s and R_s

When the two graphs are compared to each other, rippled output voltage is present on both two. However, if one focus on the beginning of the signal application, there is a transient i.e. a voltage spark before reaching to steady state because of the source inductance where it acts like an open circuit before being charged and a short circuit i.e. a current source after the charging process is completed. Both of the topologies work with the same logic by means of the current and voltage waveforms, however with the case of source inductance, there is a commutation where the current waveforms are a little more flatted when compared to the one without source inductance where the current waveform is sharpened i.e. make sharp jumps between its peaks. Besides, because of the existence of line inductance and the bridge diodes, the voltage waveform's peak points are different from the absent source inductance case since the two of the diodes are still in the conduction mode due to commutation even if it is not their cycles and the voltage waveforms differ.

6) Stresses on the Diodes

As all the components in the system resist to some stresses by means of maximum voltage, maximum current, thermal reasons, etc. the diodes should also resist to these requirements. The most important point of the diode is its breakdown voltage, current carrying capacity and forward voltage rating. It is obvious from the pre-given output waveforms; the diodes should be able to resist to a maximum current of -at least- 165A and 10A at steady state. Besides it should resist to a breakdown voltage of -at least- 326 Volts. After a research, the STTH6012[4] is chosen.

[4] For datasheet visit: https://www.st.com/resource/en/datasheet/stth6012.pdf

7) Efficiency

Since there is not source inductance, there will not be any reactive power on the system due to the source side. Only output filter capacitor and component's internal capacitance and inductance can cause a reactive power, but it is neglected, and the calculations are made with only active power.

With the usage of "Power Measurement Block" and "Display Block" the input and output powers of the rectifier is measured and found with the given equation:

$$\eta = \frac{P_o}{P_{in}}$$

$$= \frac{1.856kW}{1.057kW} = 175\%$$

Which is logical when the operation of converting the negative cycles into positive is taken into consideration.

D. THREE-PHASE FULL-BRIDGE DIODE RECTIFIER

1) Output Signal Waveforms

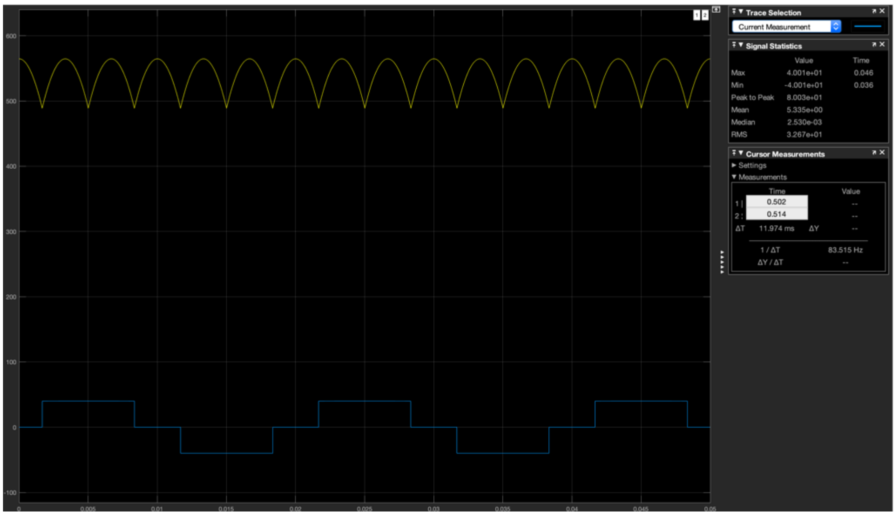

Figure 14: Output Voltage (Yellow) and Phase A (Blue) Current Graph

When the Three-Phase Full-Bridge d-Diode Rectifier is used, the output voltage waveform acts like a six-phase bridge rectifier due to the diodes' voltages i.e. when the voltage applied to any diode is larger it conducts and since there are six diodes the average output voltage is larger. It is found as 533.5V with the usage of simulation tools.

2) Analytical Calculation of Average Output Voltage

According to generalized equations, the average output voltage can be found as follows:

$$V_{out} = \frac{1}{\frac{\pi}{3}} \int_{\pi/6}^{\pi/2} [(\sqrt{2}.V_{RMS}.\sin(\omega t)) - (\sqrt{2}.V_{RMS}.\sin(\omega t - 120)).d\omega t]$$

$$V_{out} = \frac{3}{\pi}.\sqrt{2}.V_{RMS}[-\cos(\omega t) + \cos(\omega t - 120).\,\Big|_{\frac{\pi}{6}}^{\frac{\pi}{2}}$$

$$V_{out} = \frac{3}{\pi}.\sqrt{2}.V_{RMS}.\sqrt{3} = \frac{3\sqrt{2}}{\pi}.V_{RMS}$$

$$= 310.609V_{l-l}.\sqrt{3} = 537.99V_{l-n}$$

Where the results are very close to each other. The reason of the difference is the voltage drops on the diodes.

3) Harmonics Analysis of the Waveforms

With the usage of FFT window of Powergui block and the change of maximum frequency to 1500 Hz in order to find the 30th harmonics, the results are given in the bar graph below

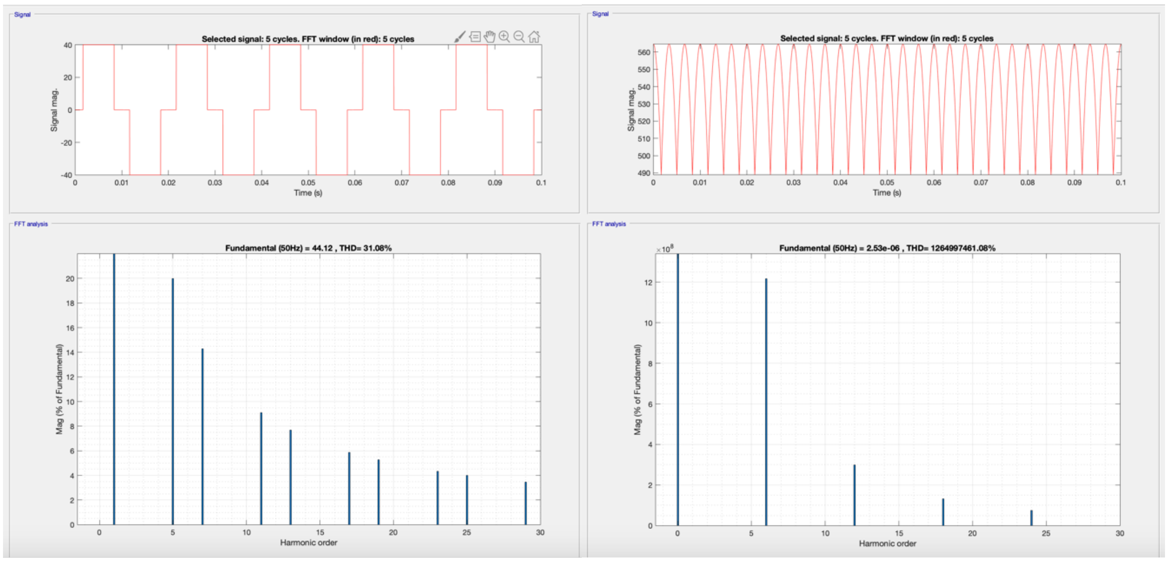

Figure 15: The Input Current (Left) and Output Voltage (Right) Harmonics Bar Graphs

When the input current and output voltage graphs are examined by means of harmonics, one can clearly observe the absence of multiples of 3 harmonics in the system. That is because there are three phases and due to the three-phase rectification, the frequency changes to 150 Hz which causes an elimination of the 3 and multiples of 3 harmonics in the system. That is the most important observation.

4) For $L_s = 1mH$ Case

For $L_s = 1mH$ case the expected result is a signal which is impose upon commutation. The results are given in the figure:

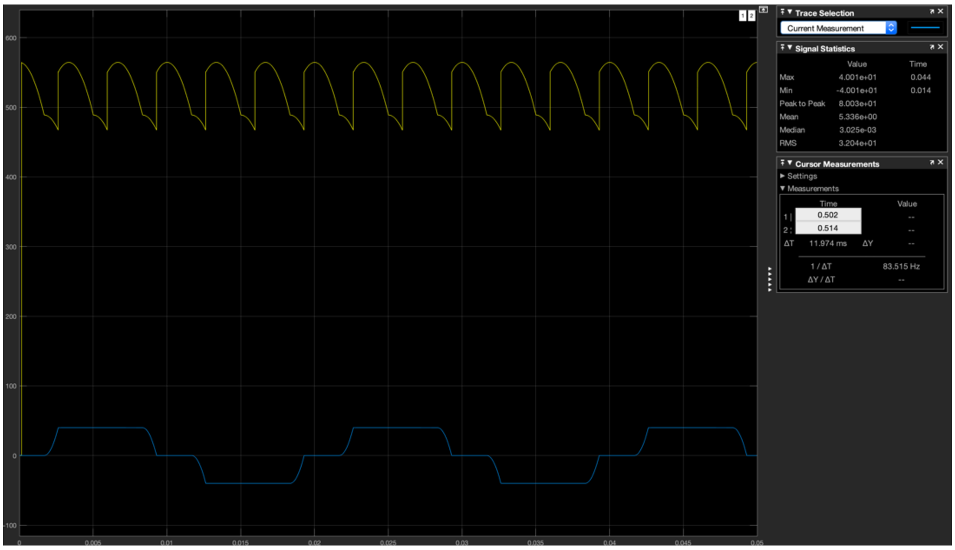

Figure 16: Output Voltage and Input Current Waveforms for $L_s = 1mH$ Case

When the current waveforms are examined, there is a flattening situation due to the line inductance's commutation cause. That is a practical situation where the observation of sudden sparks cannot be seen since there is always an inductance in the network.

Besides, the output voltage graph is changed because of simultaneous conductions of the diodes until one irrelevant diode is cut-off. Until the conduction of next half-cycle's diode, the voltage goes in the negative direction.

Nss

5) Harmonic Content for $L_s = 0$, $L_s = 1mH$ and $L_s = 10mH$ Cases

The harmonic contents of the input current according to the given three different cases are given in figures below. The important observation was that when the line inductance is increased, the total harmonic distortion of the current is decreased.

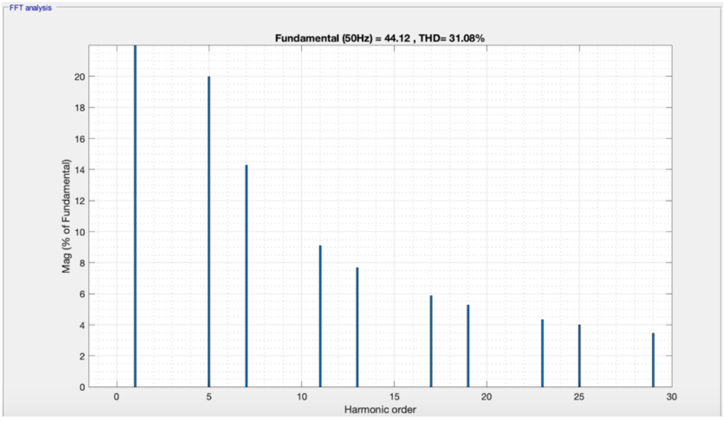

Figure 17: The Harmonic Bar Graph of Input Current for $L_s = 0$

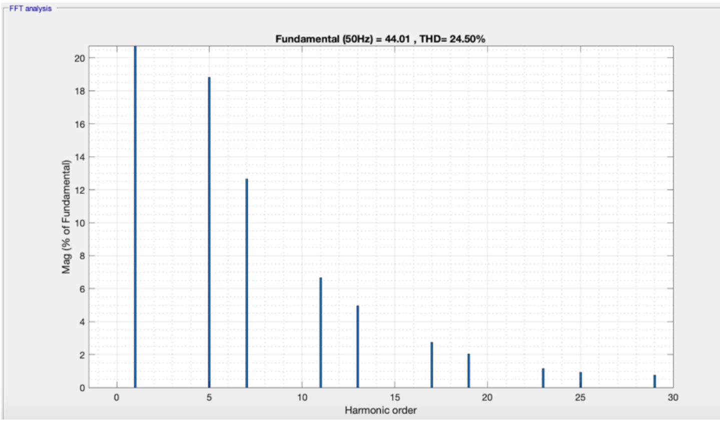

Figure 18: The Harmonic Bar Graph of Input Current for $L_s = 1mH$

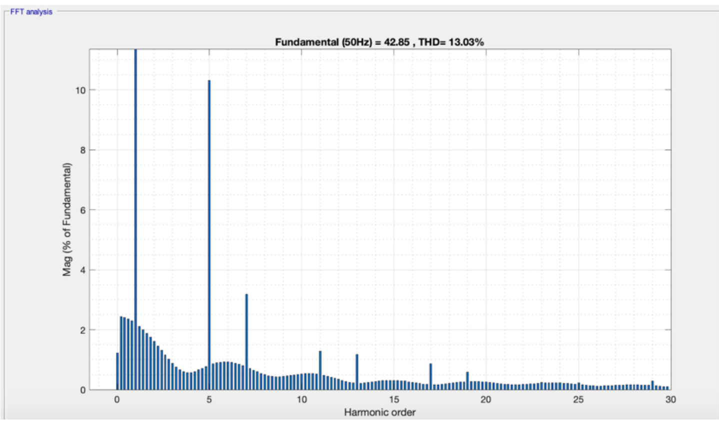

Figure 19: The Harmonic Bar Graph of Input Current for $L_s = 10mH$

E. FEEDBACK

The learner has spent 5 hours in total in order to fully analyze the project. The first 2 hours are to construct, simulate and observe the results of the circuit diagrams on Simulink and the list 3 hours to construct the project report.

F. APPENDICE – I: The Circuit Diagrams

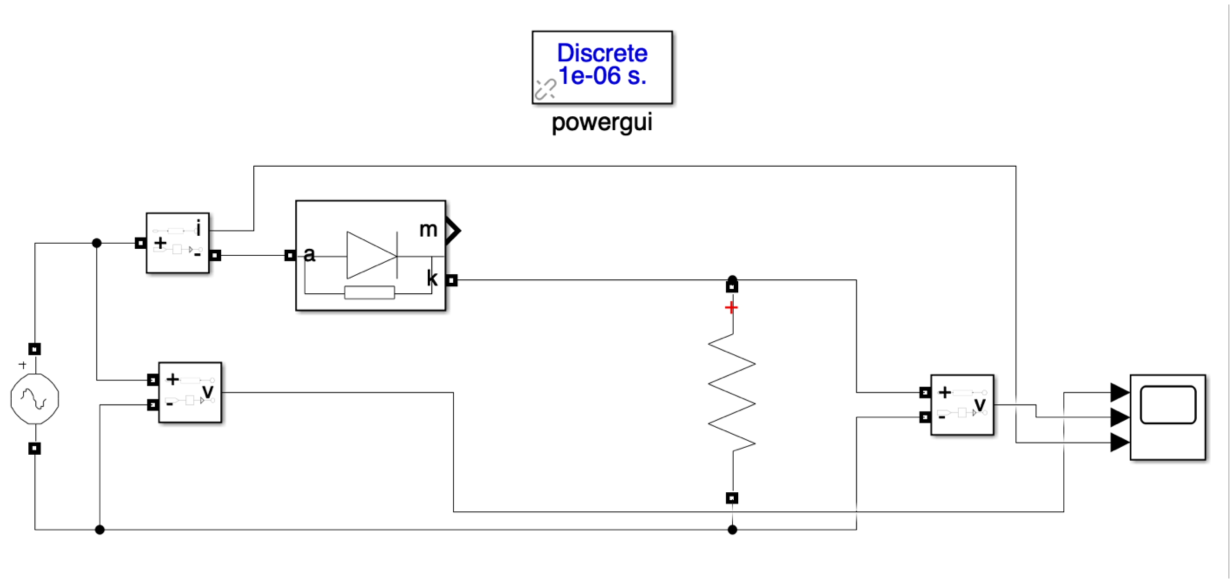

Figure 20: The Schematic of Single-Phase Half-Bridge Rectifier

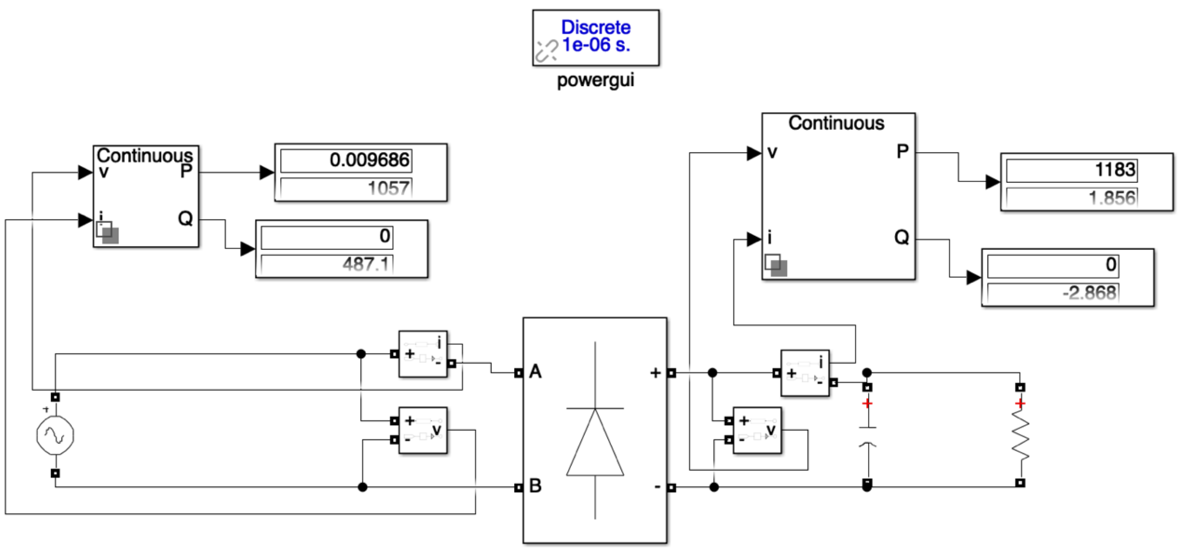

Figure 21: The Schematic of Single-Phase Full-Bridge Rectifier

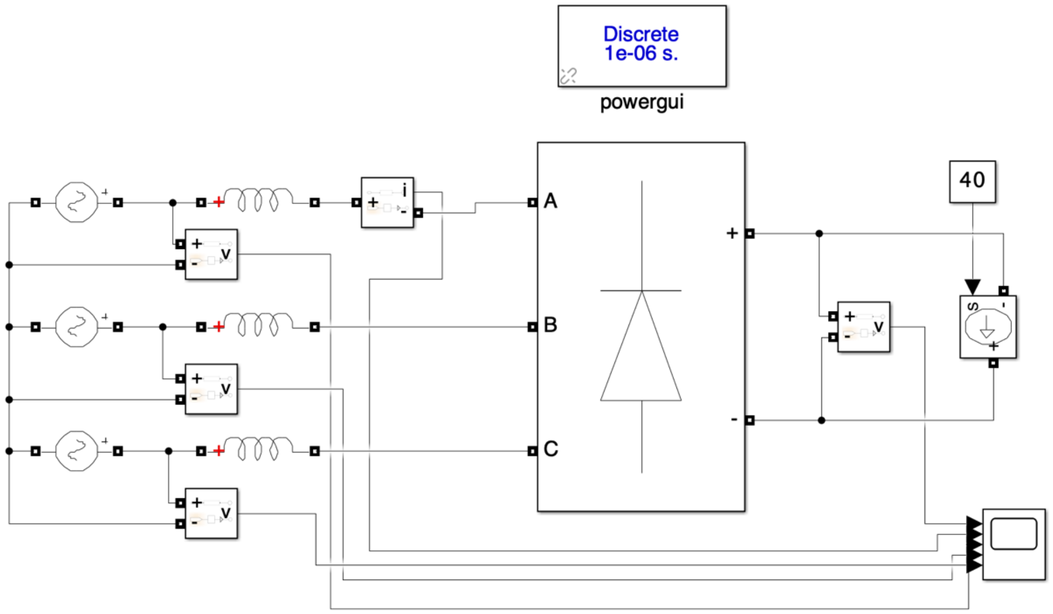

Figure 22: The Schematic of Three-Phase Full-Bridge Rectifier