MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICAL ENGINEERING

EE 463 STATIC POWER CONVERSION I

Understanding Power and Controlled Rectifiers

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Introduction

In this homework, we tried to explain power relations and controlled rectifiers. We examined the power relations of controlled rectifier topologies by using our theoretical knowledge. Also, we used simulations to compare them with our analytical calculations. We will tried to find differences for different topologies for Fully and Half Contolled Rectifiers by using Simulink. Also, by looking each topologies features such as THD, output ripple and voltage waveforms, we will try to understand differences. For Question 3, we will try to find differences of pulse rectifiers for different number of pulsed rectifiers. We will examine them by using Simulink and try to understand their behaviour. We will conclude our report by comparing 6 and 12 pulsed rectifiers.

Question 1- Active Power Creation

a-)

$$v(t) = V_o + V_1 cos(2\pi f_1 t)$$

$$i(t) = I_o + I_1 cos(2\pi f_1 t) + \sum_{2}^{\infty} I_i cos(2\pi f_i t), f_1 \neq f_i : i \in [2, \infty)$$

Figure 1. Figures of Voltage source and supplied current

We can find active power of this voltage source by using this formula: $P_{av} = \frac{1}{T}\int_0^T \mathrm{v(t)i(t)}dt$

Therefore, average power is composed of DC and only fundemental frequency component. Harmonic terms does not appear on the average power formula since they become 0 with integration. However, the harmonic terms adds up to the apparent power and it decreases power factor which leads to heating and losses.

$$P_{av} = V_o I_o + \frac{1}{T}\int_0^T V_1 \cos(2\pi f_1 t)\, I_1 \cos\,(2\pi f_1 t)$$

The components to create a nonzero avtive power terms should have resistive elements.

b-)

We can conlude from part a that, to be able to create a nonzero active power, voltage and current must have a matching frequency component. The components to create a nonzero active power terms should also have resistive elements.

Question 2- Single Phase Controlled Rectifier

a-)

Single Phase Rectifier Fully Controlled

Input voltage is given as rms. So peak value of the input voltage is $Vrms * \sqrt{2} = Vpeak$, which is equal to 324.3 V. After that, from the integral calculations, average output voltage is calculated, as $Vaverage = \frac{\int_{\alpha}^{\pi} Vs*\sin(wt)*dwt \,+\, \int_{\pi}^{\pi+\alpha} Vs*\sin(wt)*dwt}{\pi} = \left(Vpeak * \frac{2}{\pi}\right) * \cos(\alpha) = 207.07 * \cos(\,\alpha)$. However, in addition topology has extra losses due to commutation, $4 * f * Ls * Id$. From the equation loss due to commutation is 4 * 50 * 2 * 0.01 = 4 V. So, total voltage is 203.7 * cos(a). For getting 40 A, output average voltage should be 160 V. For getting 160 V DC output, a value calculated as, a = arccos(160/203.7) = 38.2359 degree.

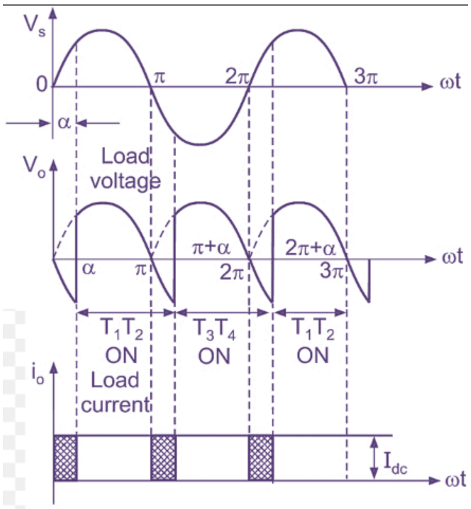

Figure 2. Voltage Waveform of RL Load Single Phase Fully Controlled Rectifier

Full Wave Thyristor Rectifier

Then, design of topology is implemented.

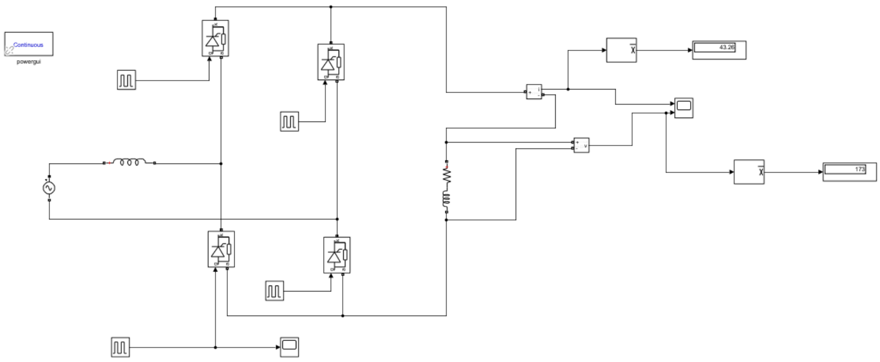

Figure 3. Matlab Simulink Schematic for Fully Controlled Rectifier

After creating topology, pulse generator is adjusted according to our calculations. We found a degree as 38.2359 degree. So, we must create a delay for firing angle. We calculate firing angle from equation, $Delay = \left(\frac{38.24}{360}\right) * \frac{1}{50}\ s$, from the equation delay is found as 0.0021244 s. So, this delay is implemented to pulse generator 1 and 3. Then, delay on the pulse generators 2 and 4 are adjusted as (0.00212 + 0.01) s, because this current way is used second interval of one full period. So, extra 1/100 s coming from this inference.

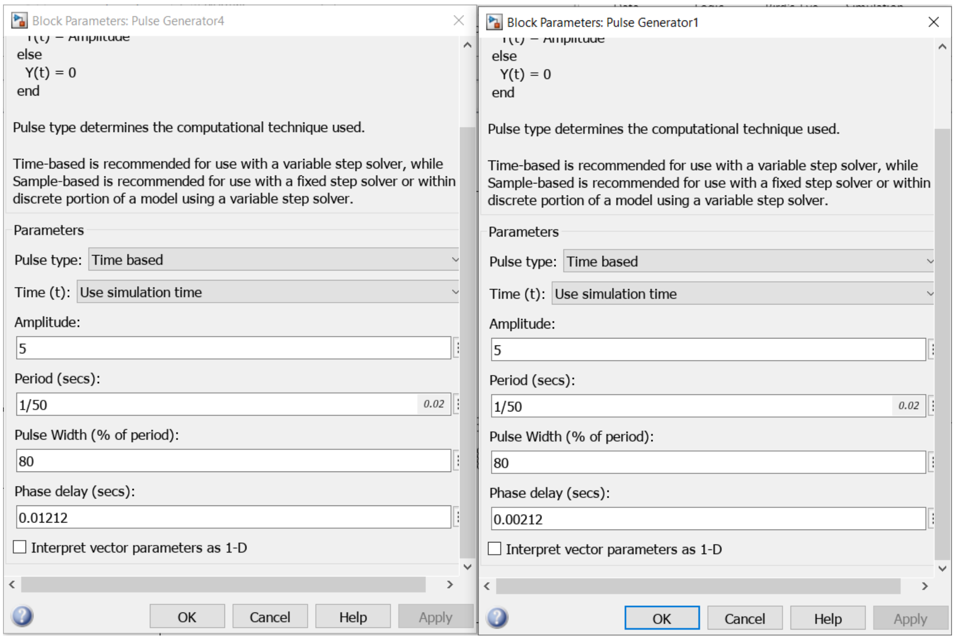

Figure 4. Pulse Generator Implementations for Fully Controlled Rectifier

Then simulation was run, after adjusting.

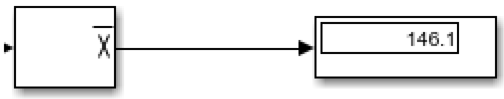

Figure 5. Average Output Voltage of Fully Controlled Rectifier

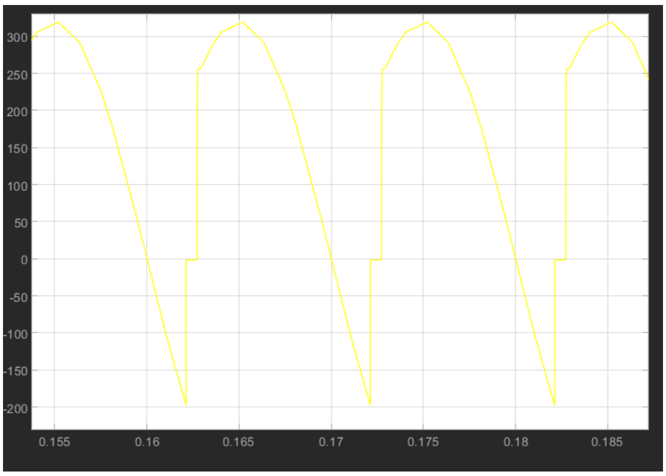

Figure 6. Output Voltage Waveform of Fully Controlled Rectifier

Results are given in Figure 5 and 6. Output average voltage is measured as 146.1 V. It is very similar to our theoretical calculations. However, because of the losses in the thyristors and voltage drop on the load inductor, some voltage drops can be seen.

Figure 7. Average Output Current of Fully Controlled Rectifier

Resulted average output current can be seen in Figure 7. From the calculation, $Current = 146.1 / 4 = 36.525\ A$. So, our theoretical calculations match with simulation results. Again, some non-idealities in the rectifier and voltage drop on load inductance, we see some small differences.

Single Phase Rectifier Half Controlled

For single phase rectifier half controlled, used diodes are work like Free-Wheeling Diode. So, output voltage cannot go below 0 V. It will stay at 0 V when voltage is exactly zero and jump to voltage when thyristors are fired. With this information, we made calculations.

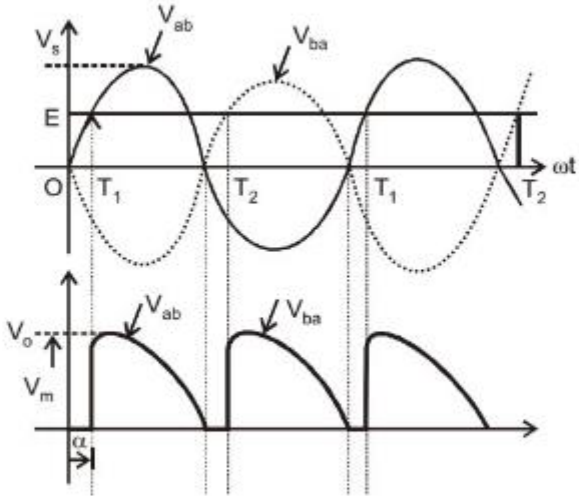

Figure 8. Average Voltage Waveform of Half Controlled Rectifier

From this waveform, we can do calculations for getting 40 A output current. As we did previous part, our expected average voltage should be 160 V again. From the equation, $Vout = (\,1/\pi)\int_a^{\pi} Vs * \sin(wt) * dwt = ((1+\cos(a)) * Vs)/\pi$, we understand that firing angle should be $arccos(0.5757) = 54.85$ degree, and commutation loss is taking into account. After these calculations, same pulse generator formulas are implemented to pulse generator.

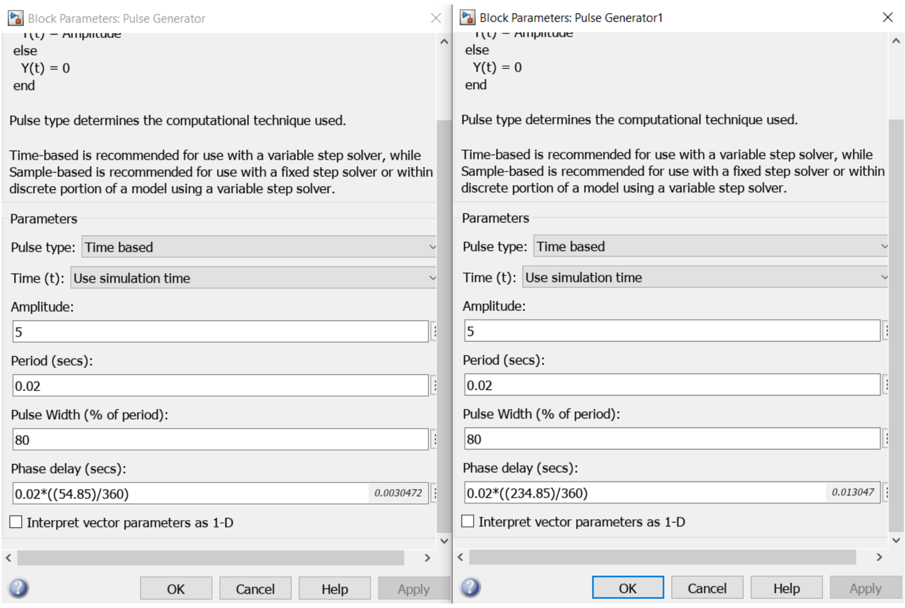

Figure 9. Pulse Generator Implementations for Half Controlled Rectifier

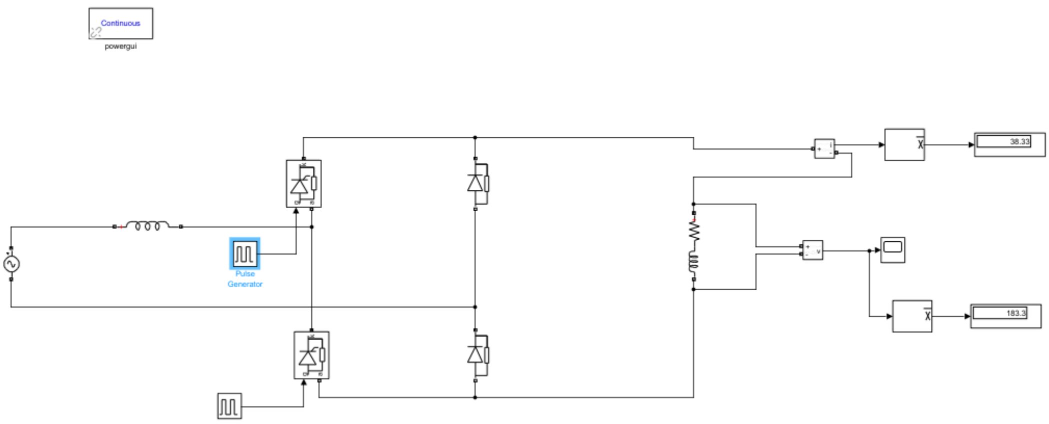

Figure 10. Matlab Simulink Schematic for Half Controlled Rectifier

Afterwards, the simulation results were saved.

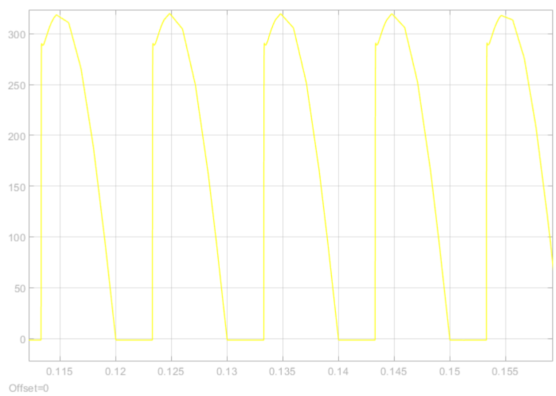

Figure 11. Output Voltage Waveform of Half Controlled Rectifier

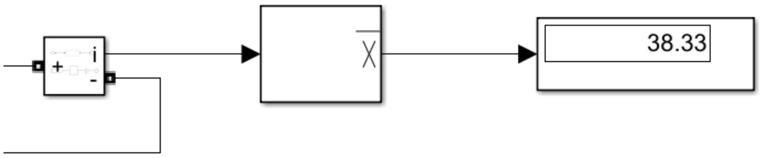

Figure 12. Average Output Current of Half Controlled Rectifier

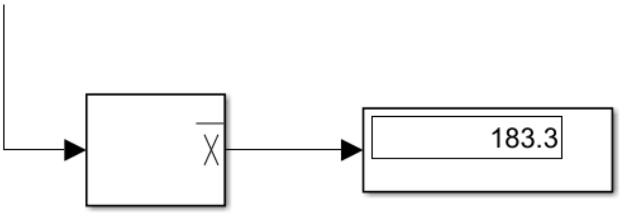

Figure 13. Average Output Voltage of Half Controlled Rectifier

From the results, our theoretical expectations are very similar with simulation results. They have small deviations; these deviations may cause from many reasons. Diodes and thyristors are not ideal. They have forward voltages and leakage currents. In addition, they have internal resistances. In addition, expected output voltage is not exactly same, 12.5% deviation is available. When we calculate total resistance at output, which is $183.3/38.33 = 4.78\ \Omega$, this value is not expected.

b-)

Single Phase Rectifier Half Controlled

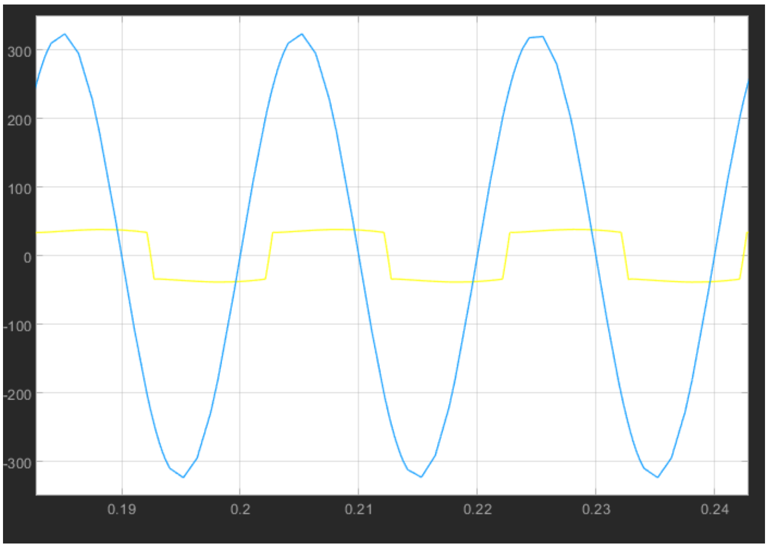

Figure 14. Input Voltage and Current Waveform of Fully Controlled Rectifier

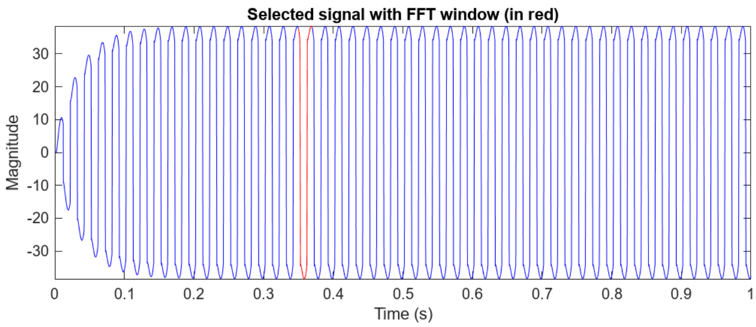

Figure 15. FFT Window of Fully Controlled Rectifier

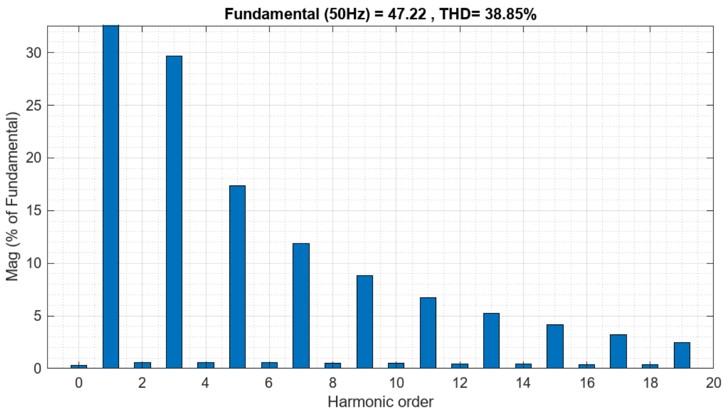

Figure 16. FFT Analysis of Fully Controlled Rectifier

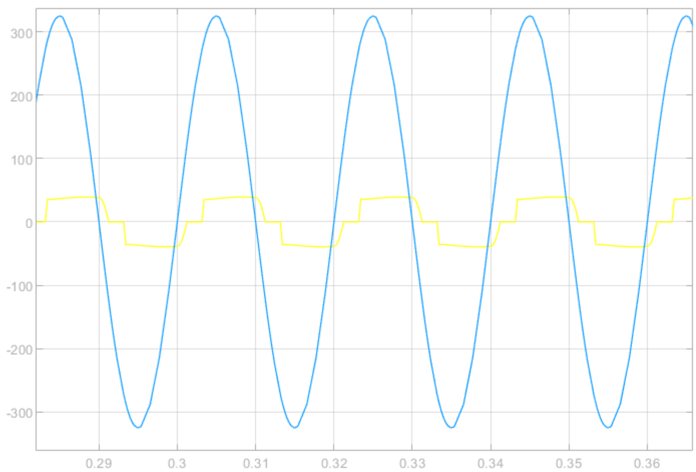

Figure 17. Input Voltage and Current Waveform of Half Controlled Rectifier

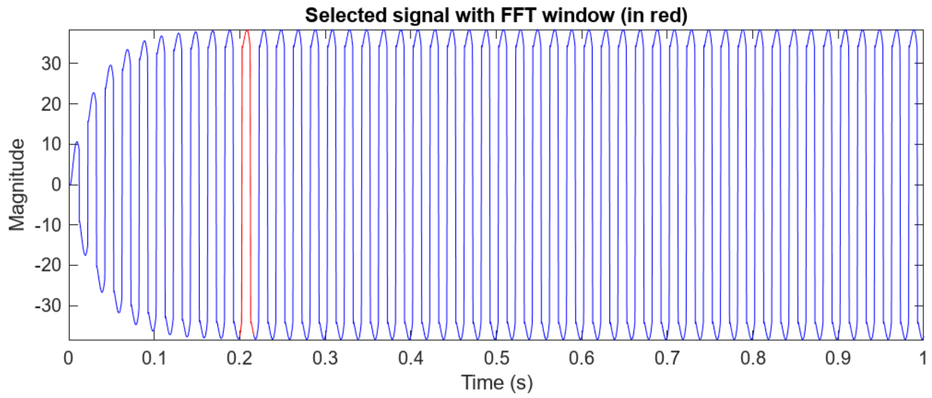

Figure 18. FFT Window of Half Controlled Rectifier

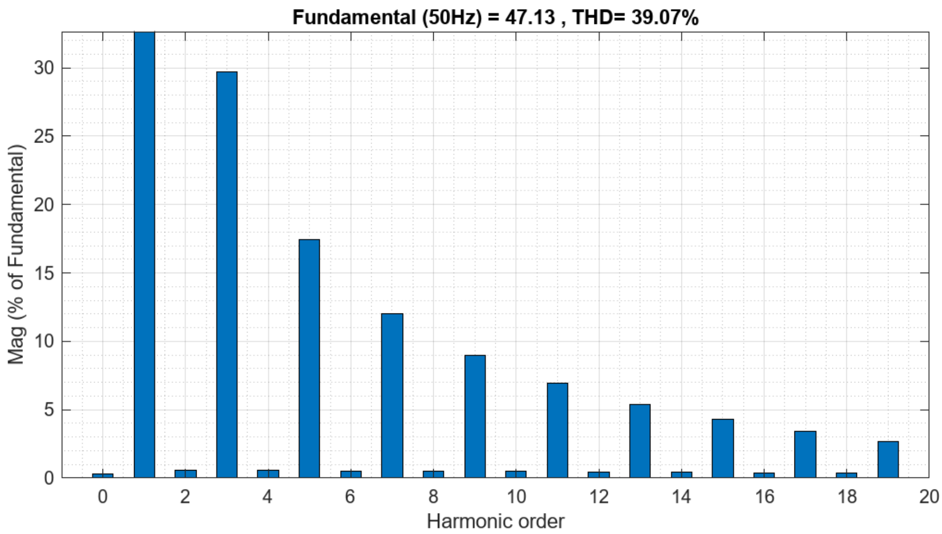

Figure 19. FFT Analysis of Half Controlled Rectifier

c-)

Single Phase Fully Controlled Rectifier

Advantages:

- Enhanced Control: Manages the entire AC cycle, providing better regulation of output voltage and current.
- Reduced Harmonics: Offers improved control, leading to reduced harmonic distortion in the output waveform.
- Wider Applicability: Suitable for a broader range of applications due to its superior control capabilities.
- It performs two-quadrant operation i.e., forward motoring and reverse braking operation
- It has inversion mode

Disadvantages:

- Complexity: Requires additional control circuits and more components, increasing complexity and cost.

- Higher EMI: May produce higher electromagnetic interference due to the rapid switching of semiconductor devices.
- Higher Cost: Due to the additional components and complex control systems, it is generally more expensive.
- Low Power Factor

Applications:

- DC motor drives
- UPS: Utilized in UPS systems to ensure continuous power supply during outages
- Industrial Power Systems: Employed in industrial power systems where precise control and reduced harmonics are critical
- AC/DC converter

Single Phase Half Controlled Rectifier

Advantages:

- Simplicity: Requires fewer components and less complex control circuitry
- Cost-effectiveness: Due to its simpler design, it's generally less expensive to implement
- Reliable for Resistive Loads
- High power factor
- Internal F.W.D. exist
- Low ripples, required filter circuit's cost and complexity

Disadvantages:

- Limited Control: Controls only one half-cycle of the AC input, limiting its ability to regulate output voltage and current
- Harmonics: Generates more harmonic content in the output waveform due to abrupt transitions during diode switching
- It performs only one quadrant operation, forward motoring
- Limited control
- No inversion mode

Applications:

- Heating systems
- Basic Motor Drives
- Simple Power Supplies
- AC/DC converters

Their operational similarities and differences are commented in the advantages and disadvantages sections.

Question 3- Alternative Rectifier Topologies

a-)

The diagram we see in the Figure 20 is a 12-pulse rectifier circuit. It is used generally in **HVDC** systems and some electrical aircraft applications. It is adventagous with less ripple and less harmonics. Its harmonics is related with 12n +- 1 (11th,13rd…). Its output voltage stability is better regard to 6 pulse full bridge rectifiers which will result in a impovement in power quality. However, the complexity of this topology and cost makes a disadvantage for using this topology.

Since it is the conversion 3 phase AC/DC conversion, we can find full bridge rectifiers in this topology. Most common is 6-pulse. It has 6 diodes in the circuit to create a DC waveform. Its ripple is higher since we use only 6 diodes to contribute. Usage of higher pulses are considered and we are using more pulses to achieve better voltage stability. 24 and 48 pulses are possible. 12-pulsed rectifiers can be achieved by adding 2 of 6-pulsed rectifiers with series to the circuit.

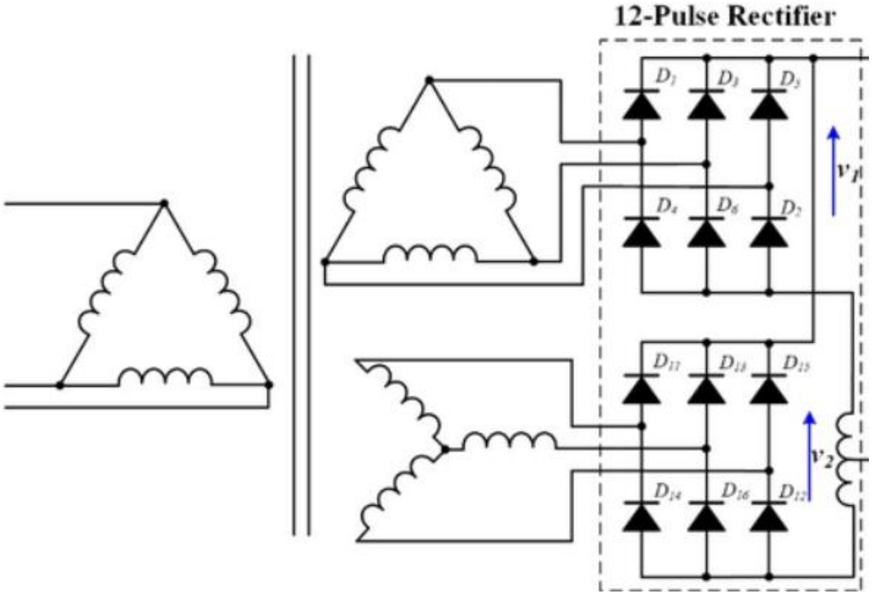

Figure 20. 12 Pulse Rectifier

b-)

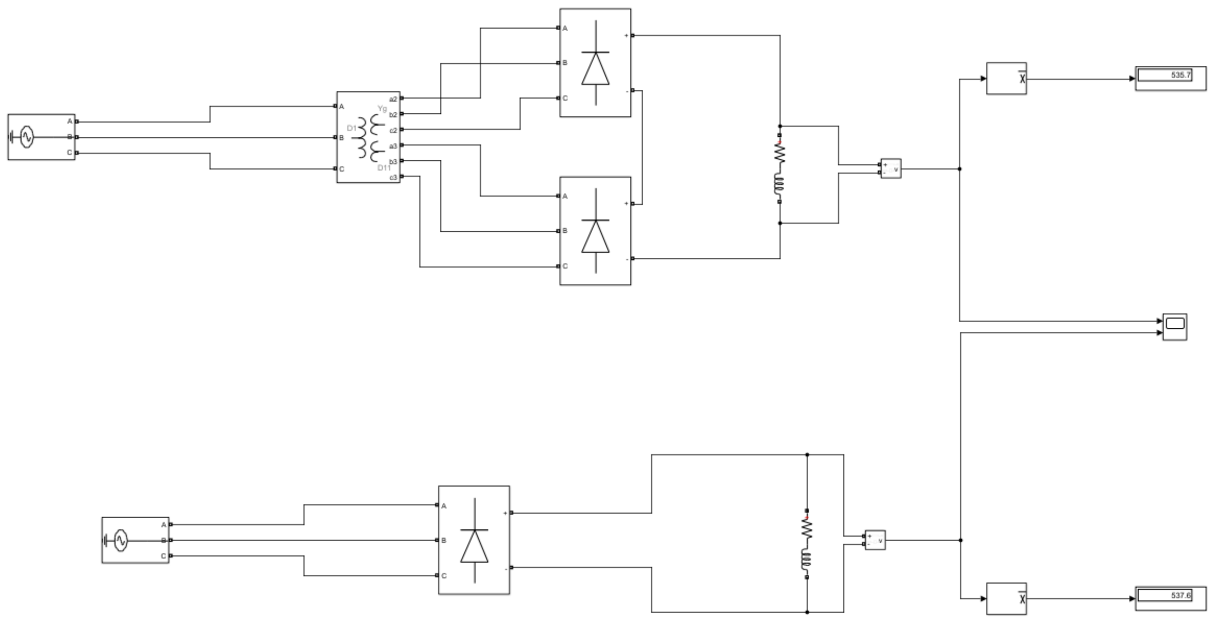

Figure 21. Simulink Schematic for Comparing 12-Pulse and Full Bridge Diode Rectifier

For comparing the 12-pulse rectifier and full bridge diode rectifier, schematic as seen in Figure 21 is designed and implemented in Matlab Simulink.

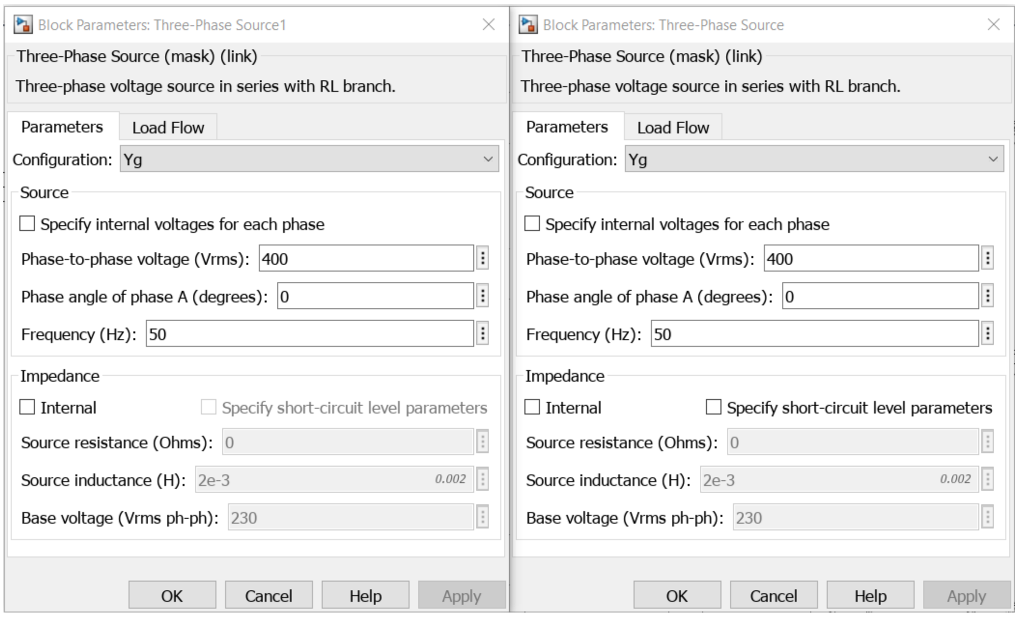

Figure 22. Input Voltage Sources

In Figure 22, implemented 3-phase voltages can be seen. They are same for both systems. Then for the 12-pulse rectifier three-phase transformer is used. Input voltage connection type is Y connection, then for the first bridge rectifier, again Y connection is implemented and for the second bridge rectifier, delta connection is implemented. Then, for getting same output voltage, ratio of windings are adjusted.

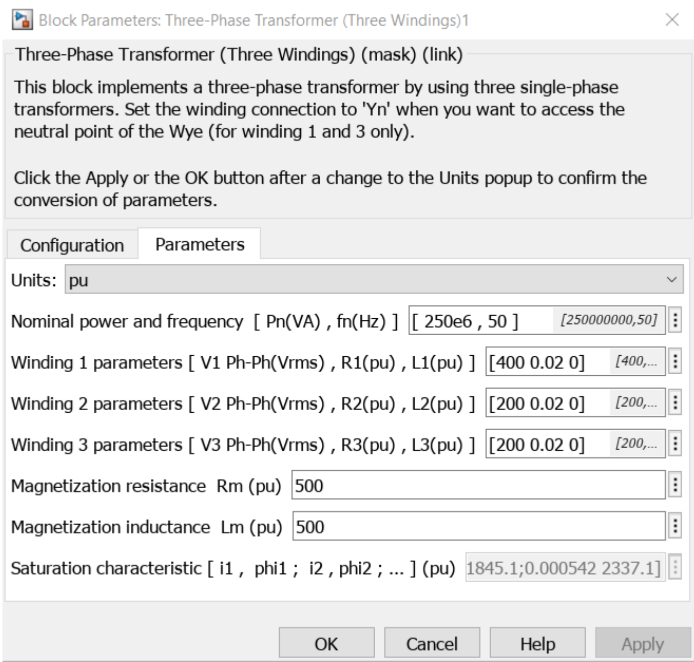

Figure 23. Windings Adjustments

Average output voltages for both systems are same. Both are around 540 V. From the expectations, losses on the 12-pulse rectifier higher than 6-pulse rectifier. Expected average output voltage 540 V from the equation $(3 * \sqrt{2} * Vll)/\pi$ = 540 V. However, because of the losses output voltages are 537 V and 535 V.

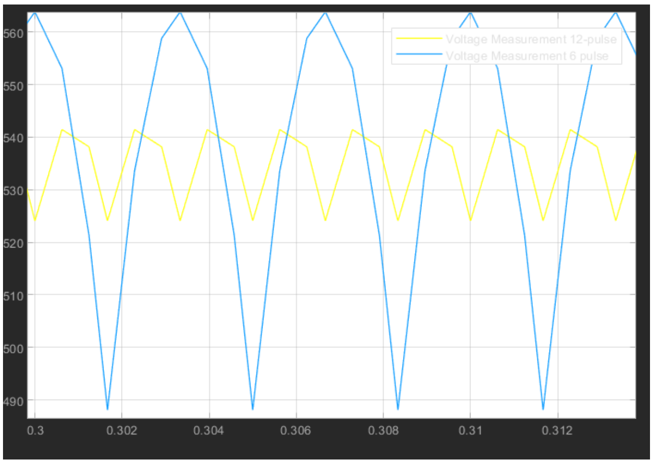

Figure 24. Output Voltage Waveforms of 12-Pulse and 6-Pulse Rectifiers

Resulted output voltage waveforms can be seen in Figure 24. From this graph, we can say that ripple of 6-pulse rectifier higher than 12-pulse rectifier. So, stability of the 12-pulse rectifier is better. In addition, we can see that, frequency of the pulse in 12-pulse rectifier twice of the 6-pulse rectifier. Their average output voltages are same.

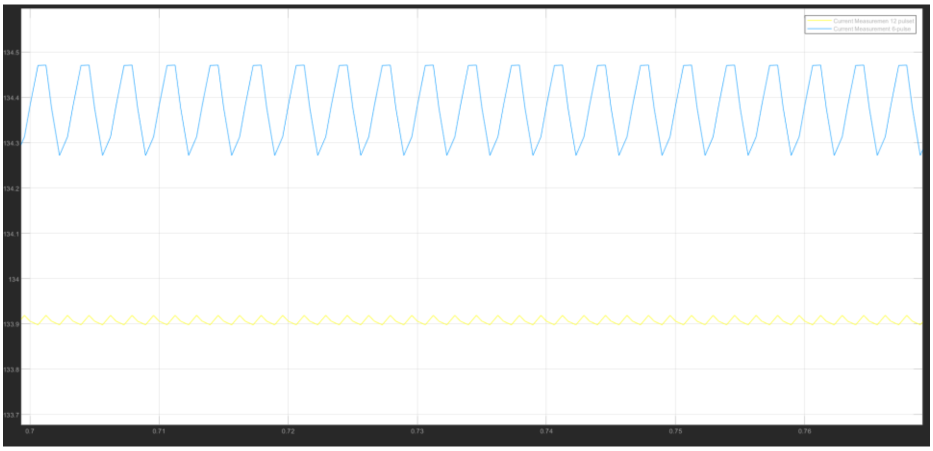

Figure 25. Output Current Waveforms of 12-Pulse and 6-Pulse Rectifiers

After that current waveforms are printed. Then, THD of both topologies are found.

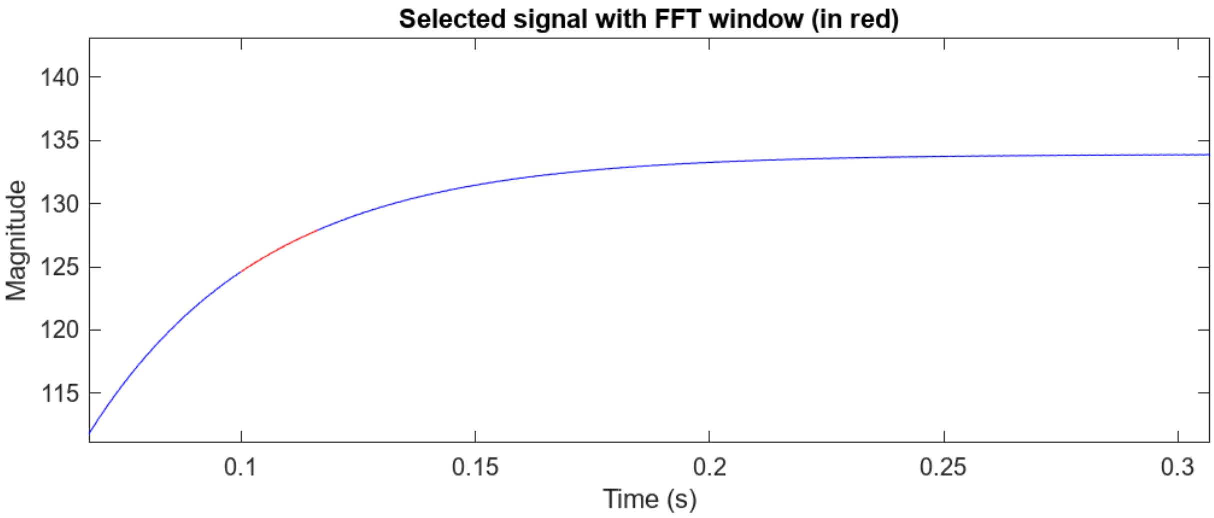

Figure 26. Signal with FFT Window of 12-Pulse Rectifier

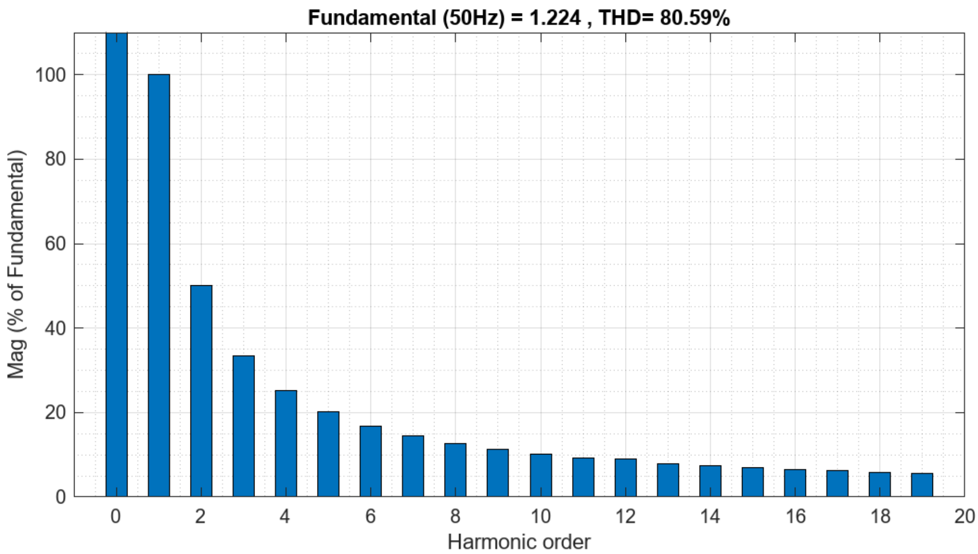

Figure 27. FFT of 12-Pulse Rectifier for Selected Signal

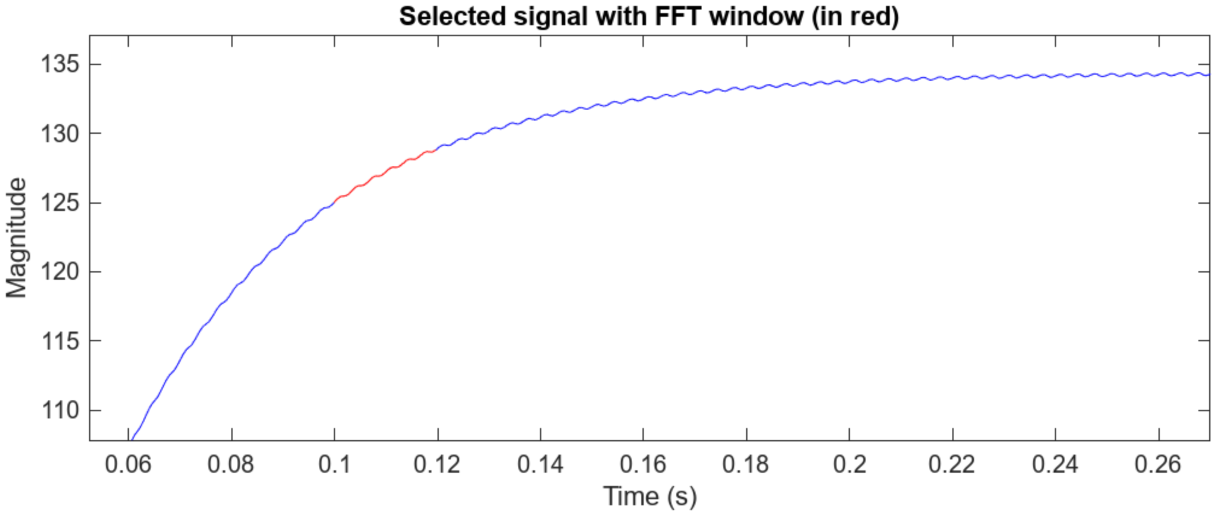

Figure 28. Signal with FFT Window of 6-Pulse Rectifier

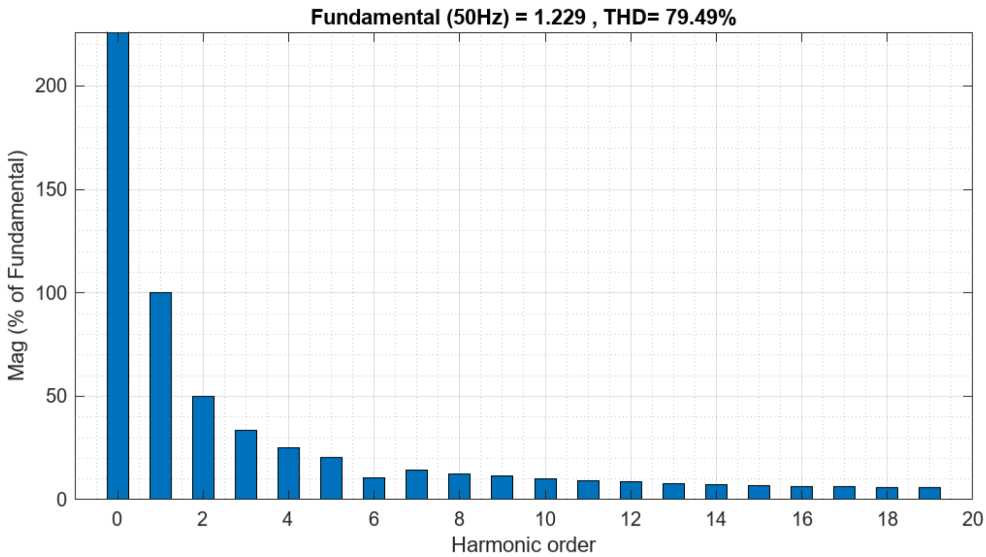

Figure 29. FFT of 6-Pulse Rectifier for Selected Signal

Here, as seen in the Figure's 26-29, THD analysis of the output currents can be seen. Ripple of the 6-pulse rectifier bigger than 12-pulse rectifier. For THD analysis, magnitudes of harmonics nearly same for both topologies. When we examine for the higher time intervals, THD of the 12-pulse rectifier is much lower than 6-pulse rectifier. So, 12-pulse rectifier has smaller harmonic distortion.

12-pulse rectifier requires additional transformers, phase-shifting circuit, and interphase reactors, so these make it more complex and expensive. Moreover, it requires more space due to the additional transformers and components. They are usually used for high-power applications.

Conclusion

In this report, we tried to explain our understanding of controlled rectifiers and power relations. We used basic relations to calculate power terms and controlled rectifier topologies. Different topologies for controlled rectifiers are being examined and compared between each other througout this report. We understand from Question 2 that, we can be flexible in terms of quadrants usage(Average output voltage) by using Fully Contolled Rectifier. For 12-pulse rectifier, we learned that the usage of this depends on where we want to use it. It will be more complex and costly with regard to 6-pulsed rectifier, but if we want a low ripple and low THD, we can consider to use 12-pulsed rectifier for usage. You can find our simulations, Simulink schematics and works in our GitHub repository by this.