MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE463

Project-2 Report

CONTROLLED RECTIFIERS

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1. Introduction

In this project, using the MATLAB Simulink we simulated different controlled rectifiers in order to observe their behaviours and differences. In part 1, fully and half controlled thyristor bridge rectifiers in single phase are examined. In part 2, a motor driver is constructed with 3 phase thyristor rectifiers. In part 3, an alternative rectifier topology is investigated. 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

In this part, a fully controlled rectifier and a half-controlled rectifier is constructed.

2.1. Part 2.a

It is needed that the average load current to be 40 Amperes. The firing angle that gives that average load current and corresponding voltage is calculated analytically.

<u>For fully-controlled rectifier</u>

Average output voltage when there is line inductance is equal to :

$$V_d = 0.9 \times V_s \times cos(\alpha) - \frac{2 \times w \times L_s \times I_d}{\pi}$$

Since the load inductance will have zero voltage at steady state :

$$V_d = R \times I_d$$

We want Id to be 40 A, hence ;

$$V_d = 4 \times 40 = 160\ V$$

$$160 = 0.9 \times 230 \times cos(\alpha) - 4 \times 50 \times 0.5 \times 10^{-3} \times 40$$

$$\alpha = 37.6\ degrees$$

<u>For half-controlled rectifier</u>

Average output voltage when there is line inductance is equal to :

$$V_d = 0.9 \times V_s \times (cos(\alpha) + 1) - \frac{2 \times w \times L_s \times I_d}{\pi}$$

$$V_d = R \times I_d$$

We want Id to be 40 A, hence ;

$$V_d = 4 \times 40 = 160\ V$$

$$160 = 0.9 \times 230 \times (cos(\alpha) + 1) - 4 \times 50 \times 0.5 \times 10^{-3} \times 40$$

$$\alpha = 54.22\ degrees$$

After calculating the necessary firing angle for an average load current of 40 A, some simulations are made. Firing angle that gives a mean current of 40A at the load is found for both of the cases.

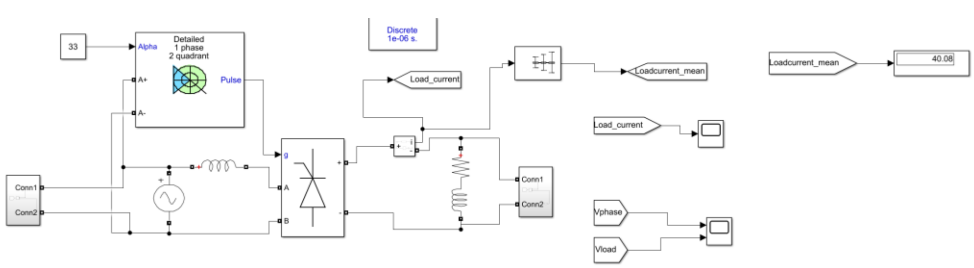


Figure 1 : Circuit schematic for fully controlled rectifier

As can be seen from Figure 1, a firing of 33 degrees, gives an average load current of 40.08, which is very similar to the firing angle found by theoretical calculations.

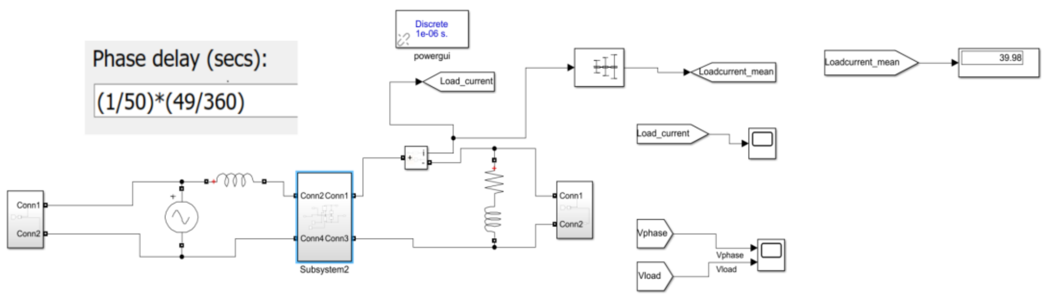


Figure 2 : Circuit schematic for half controlled rectifier

As can be seen from Figure 2, a firing of 49 degrees, gives an average load current of 39.98, which is very similar to the firing angle found by theoretical calculations.

2.2. Part 2.b

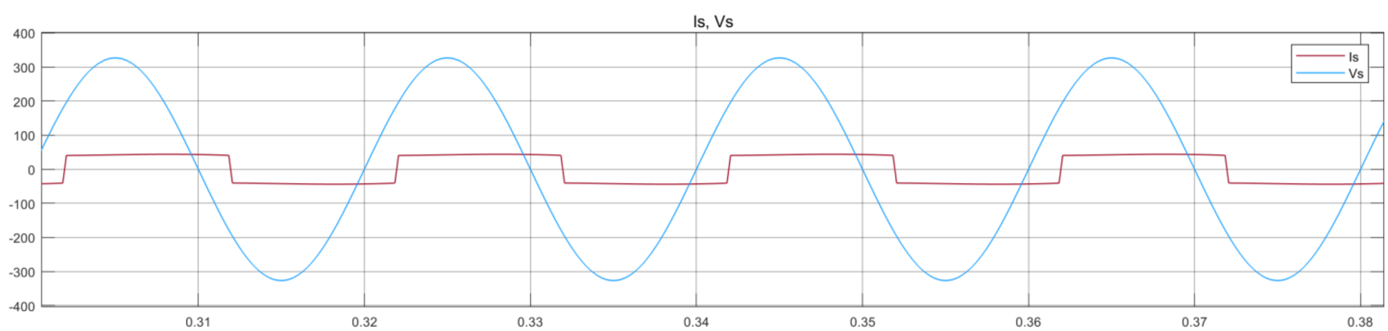


Figure 3 : V_s and I_s waveforms of fully controlled rectifier

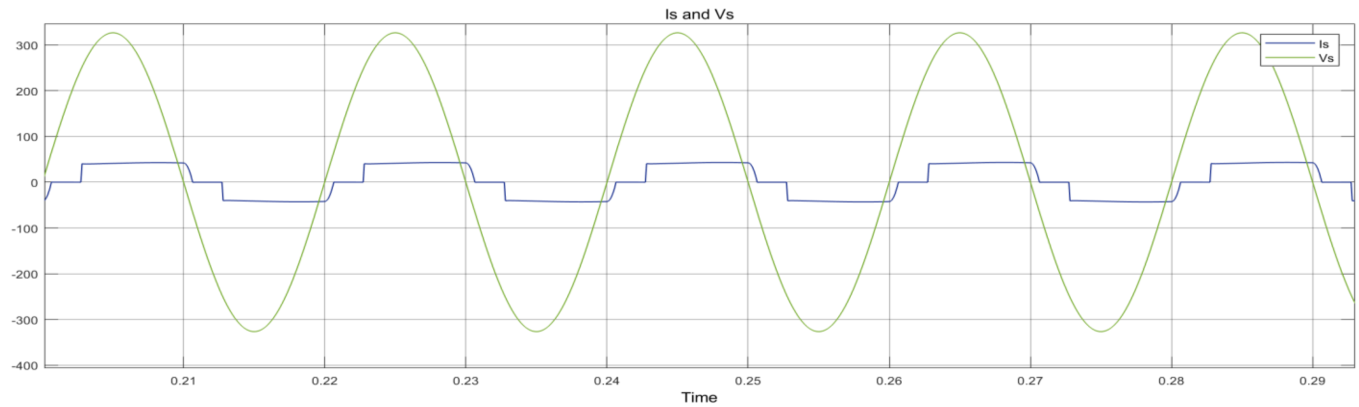


Figure 4: V_s and I_s waveforms of half controlled rectifier

V_s and I_s waveforms of fully and half controlled rectifiers can be seen in Figure 3 & 4, respectively.

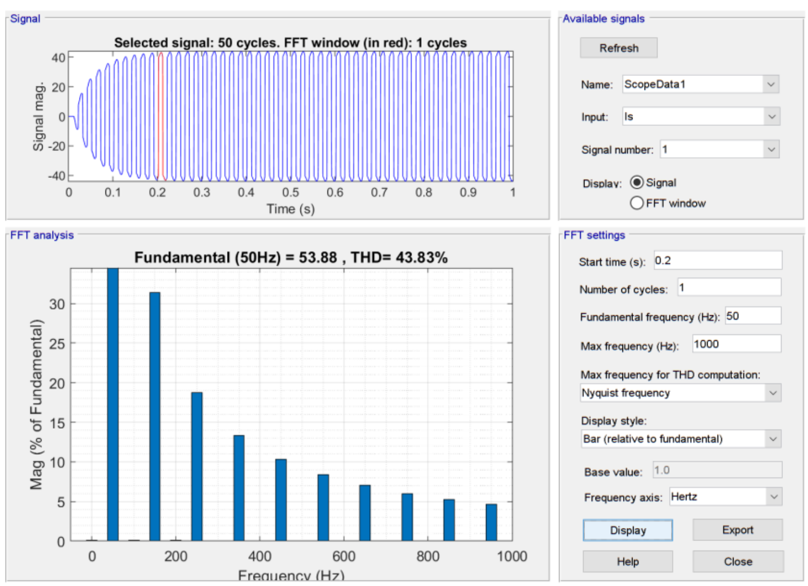


Figure 5 : FFT analysis of I_s for fully controlled rectifier

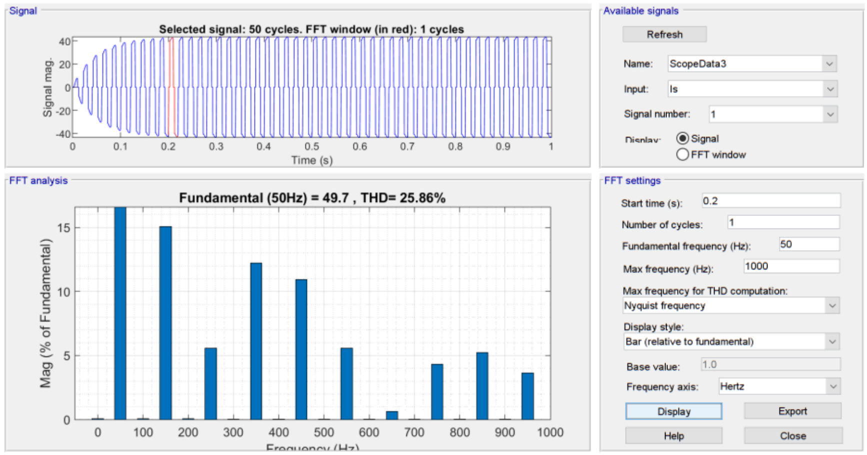


Figure 6 :FFT analysis of I_s for half controlled rectifier

FFT analysis of I_s for both of the topologies can be seen in Figure 5 & 6.

2.3. Part 2.c

The fully controlled rectifier let us produce output voltages with desired mean values by arranging the firing angle. The circuit can be operate in 2 quadrants and goes into negative region. However, output voltage ripple is bigger which is not desired. Moreover, THD value of source current is higher in the fully controlled case in comparison with the half controlled case.

On the other hand, the half controlled rectifier prevents output voltage to go into negative regions by providing a path for current to flow. In other words, the diodes in half controlled rectifier work as freewheeling diodes which keep voltage value at zero when it tries to be negative. With same firing angle, an increased output voltages are obtained since there are no negative currents in half controlled rectifiers. Moreover, there is less ripple at the output voltage which is preferable when we need to filter out with a capacitor. The disadvantage of half controlled rectifier is, now we can only operate in one quadrant and the circuit cannot give negative voltages in any case.

3. Part 2

In this part, a DC motor drive constructed by full-bridge diode rectifier is analyzed.

3.1. Part 2.a

A permanent magnet DC motor is fed from the full-bridge diode rectifier as shown in Figure 7.

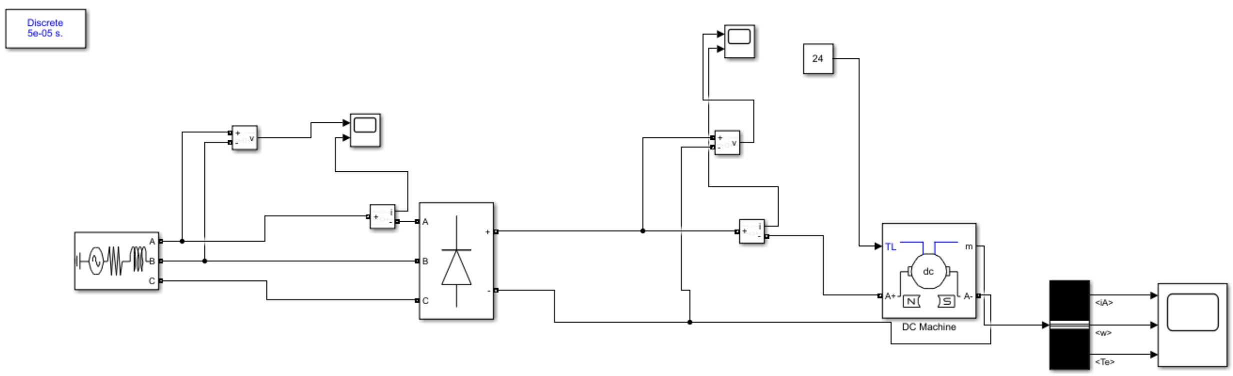


Figure 7: Circuit schematic for full-bridge diode rectifier

In this setup, DC motor's armature current, torque and speed will be simulated. The simulation results can be seen in figure 8 and 9. Figure 8 shows the initial values of the asked characteristics, but Figure 9 shows only the steady-state characteristics.

At the steady-state, RMS value of the armature current is 8.472, the shaft speed is 158 rad/s, and the torque is 24.6 Nm.

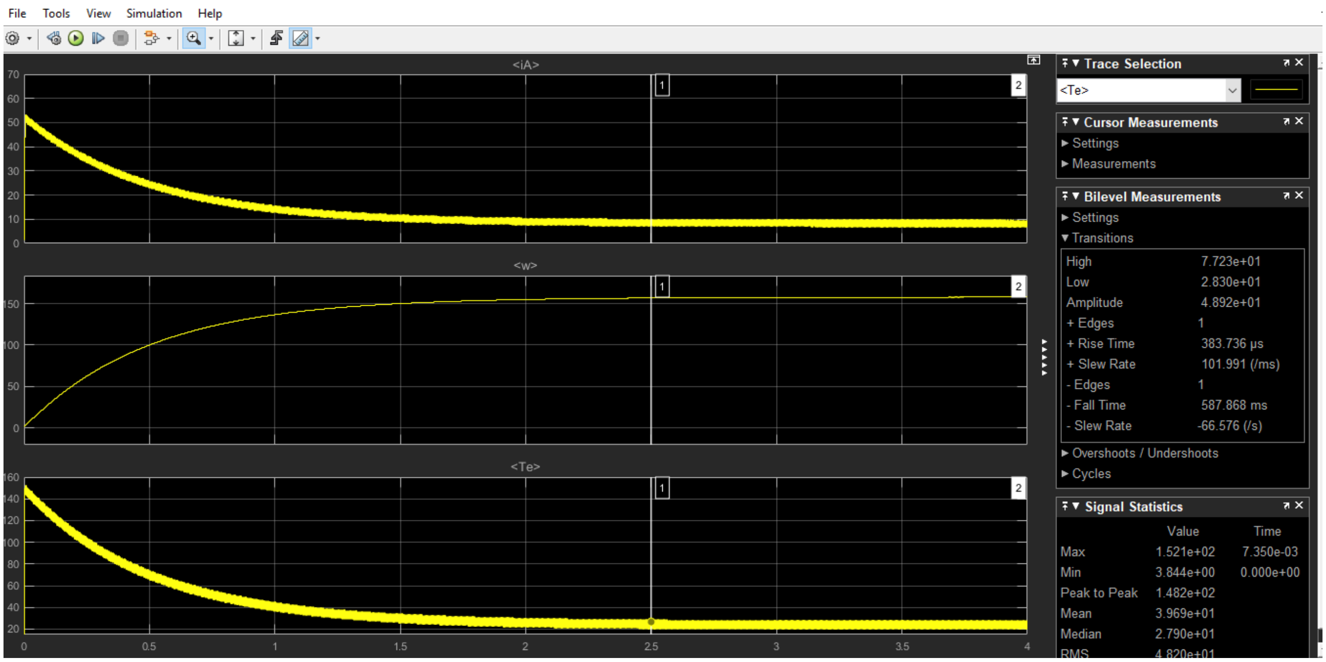


Figure 8: DC Motor characteristics from the zero-speed to full-speed

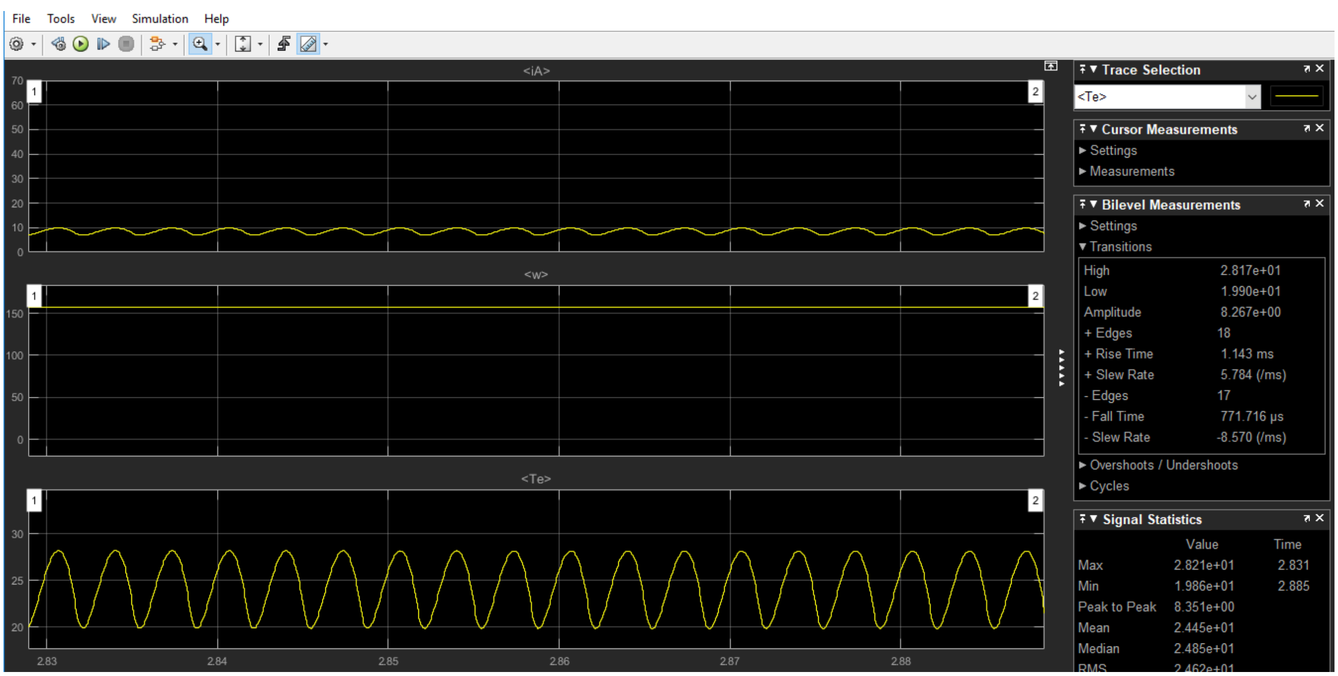


Figure 9: DC Motor characteristics at the steady state

3.2. Part 2.b

The torque ripple of the motor is 8.3 volts. This is about 35% of the average torque and very high for practical application. Some methods to reduce the torque ripple will mention the following part. The frequency of the torque ripple is 300 Hz because of the current frequency.

Torque is directly related with the current as seen in the following equation:

$$T = K_a I_a \Phi$$

K_a is a machine constant, I_a is armature current and Φ is flux generated by the permanent magnet. Full bridge rectifier's current has 300 Hz frequency.

When the machine starts to accelerate, the torque ripple is higher than the steady-state value, because armature current ripple is more than the steady-state value.

THD of the line current is seen from the Figure-10

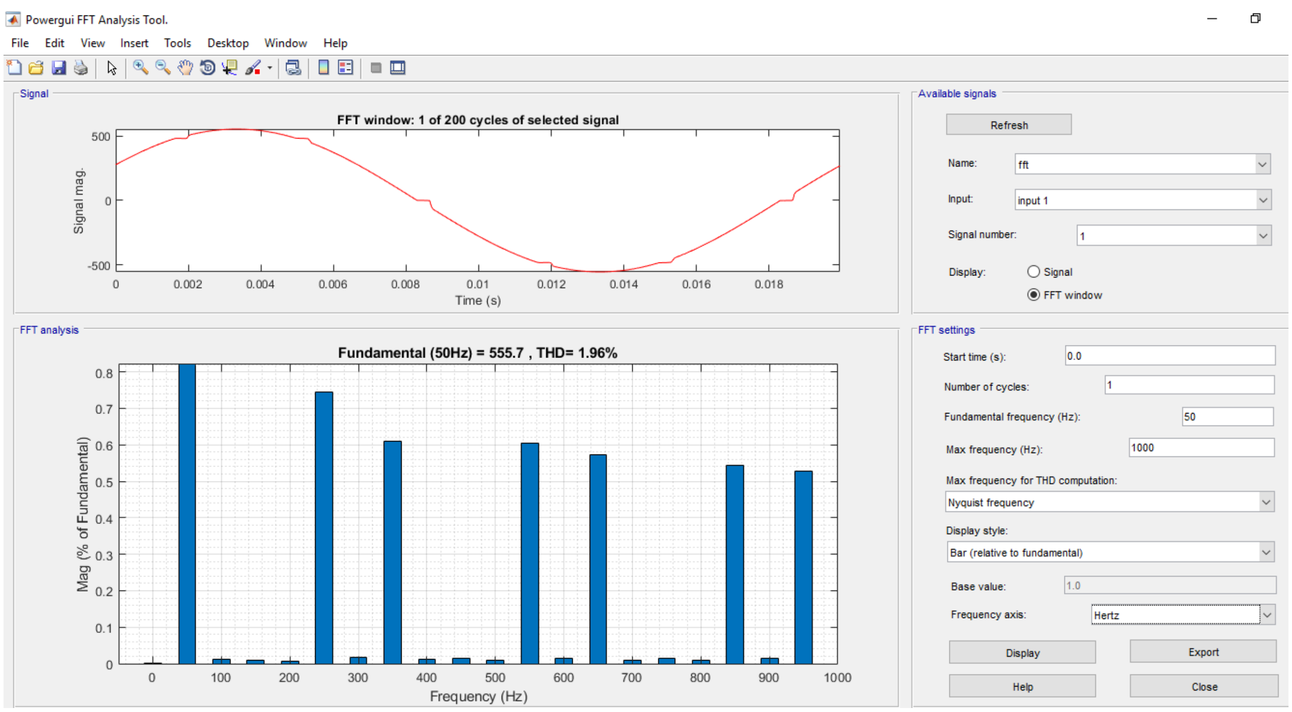


Figure 10: THD analysis of the line current

Line current THD percentage is very small, because the motor act like an ideal current source.

3.3. Part 2.c

In order to reduce to torque ripple, adding LC filter or using higher pulses rectifier will be studied. At the end of the diode bridge, series inductor with 100 μH and parallel capacitor with 1 mF can be added for the LC filter. Simulation results is seen in the Figure 11 and Figure 12.

Figure 11 shows the initial values of the asked characteristics, but Figure 12 shows only the steady-state characteristics

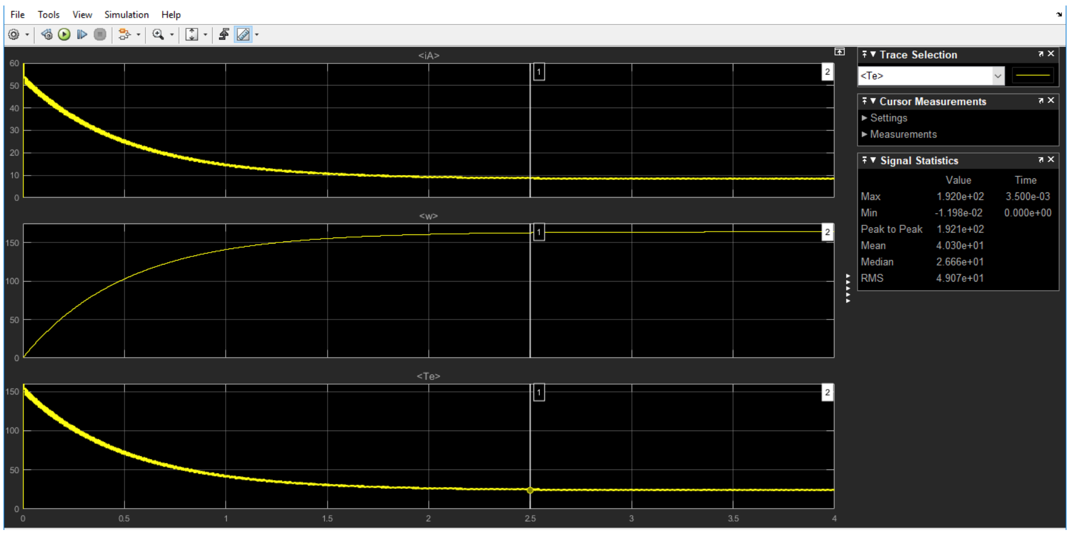


Figure 11: DC Motor characteristics from the zero-speed to full-speed when there is LC filter

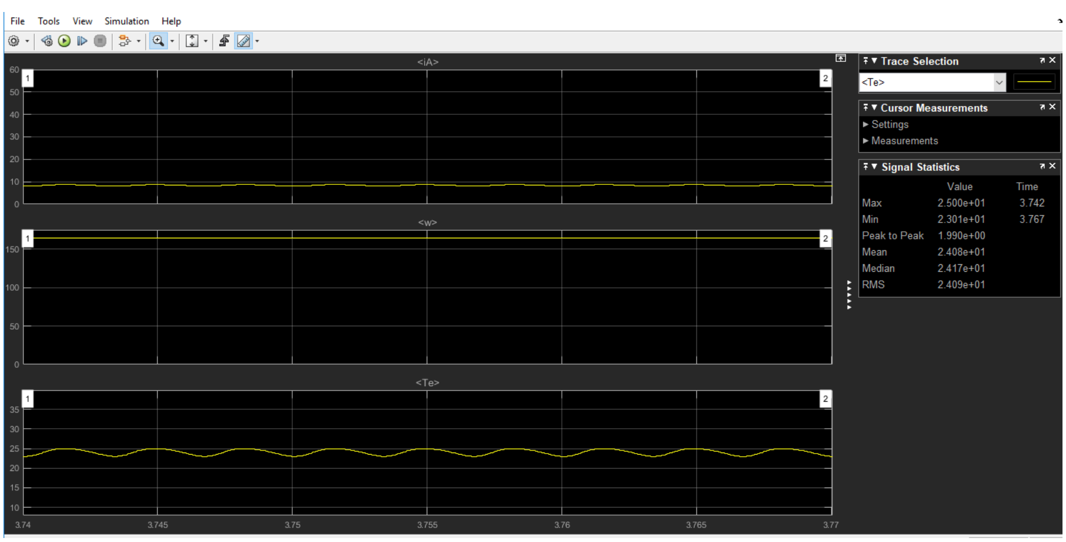


Figure 12: DC Motor characteristics at the steady state when there is LC filter

The average torque is still about 24 volts, but the torque ripple is only 2 volts. Again, it is dependent on the armature current. When there is LC filter, current ripple is less than the original circuit.

The second method to reduce to torque ripple is increase the pulse of the motor's input voltage. In this project, 12 pulse rectifier circuit is used, and the torque ripple is reduced enough. If 12 pulse is not enough, 24 or 48 pulse rectifier circuits can be used. The schematic of the 12-pulse rectifier is shown in Figure 13.

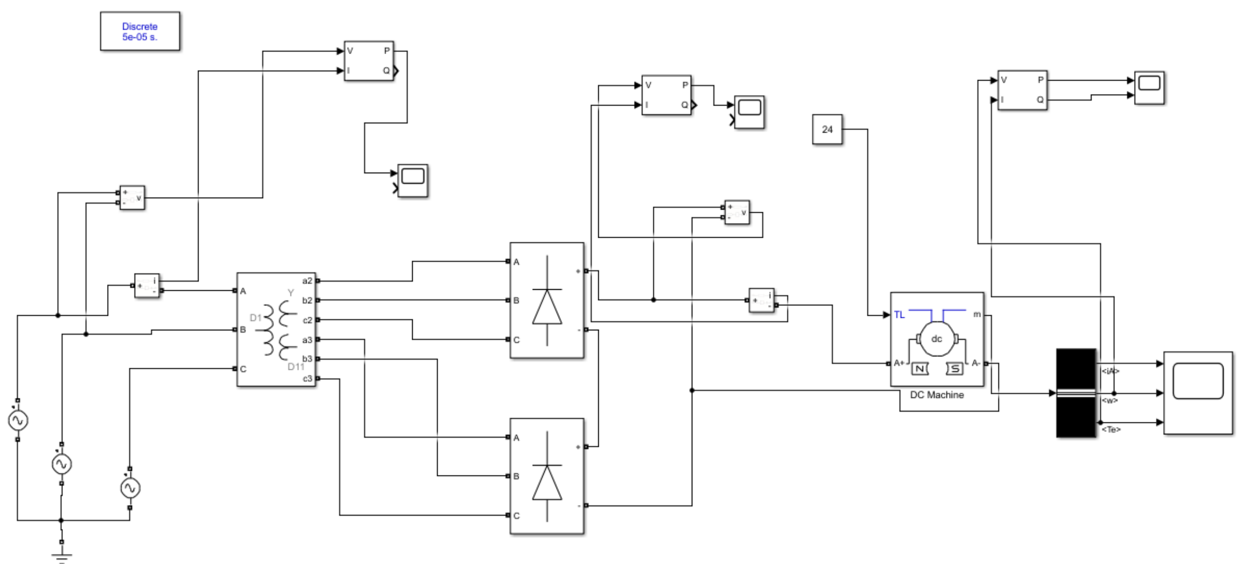


Figure 13: Schematic of the 12-Pulse rectifier circuit

For this circuit, two secondary winding transformers is used. One of the transformers is wye connected and the other one is delta connected. Simulation results is seen in the Figure 14 and Figure 15. Figure 14 shows the initial values of the asked characteristics, but Figure 15 shows only the steady-state characteristics.

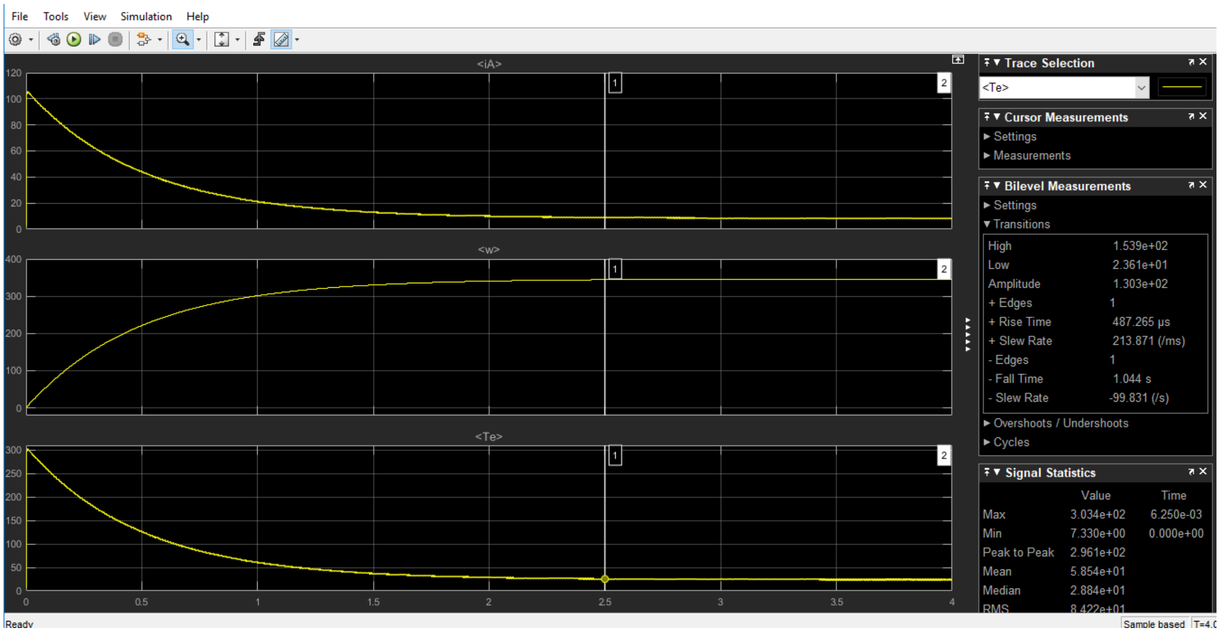


Figure 14: DC Motor characteristics from the zero-speed to full-speed when there is 12-Pulse rectifier

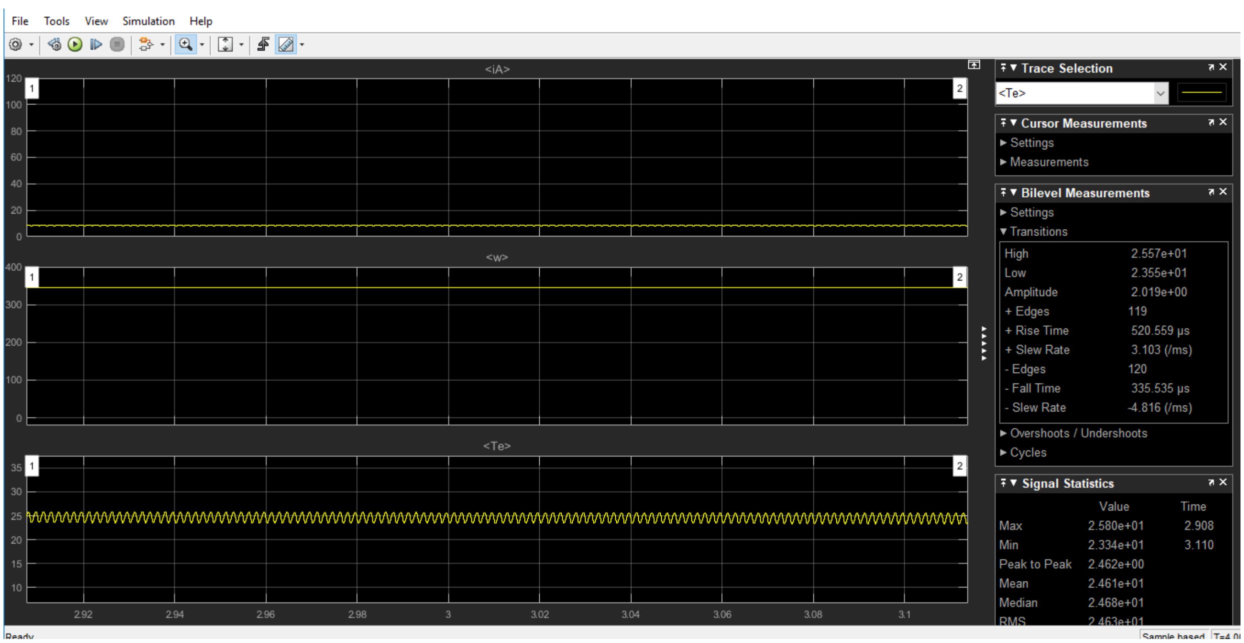


Figure 15: DC Motor characteristics at the steady state when there is 12-Pulse rectifier

As you can see, the torque ripple is below 10% of the average value. More pulses mean that less ripple in the output voltage of the rectifier circuit. More smooth voltage creates more smooth current and more smooth torque.

12 or more pulses rectifier circuit has better torque waveform, but there are expensive. For big machine or big loads 12-Pulse rectifier circuit is suitable. Also, input power of the machine can be adjusted by changing the transformer winding.

For small power-rated machine, using LC filter is enough. There are inexpensive. However, for high power application, there are expensive and not suitable for sizing due to increasing capacitance and inductance values.

3.4. Part 2.d

Drive efficiency will be calculated by using the following formula:

$$\eta = \frac{Output\ power\ of\ the\ rectifier}{Input\ power\ of\ the\ rectifier}$$

The following figures shows the power waveforms of the circuit. The input power is calculated for 1 phase only. In the calculation, we need to multiply them by 3. By using the data from the figures, drive efficiency is:

$$\eta_{drive} = \frac{2291}{1521 * 3} = 50.2\%$$

$$\eta_{system} = \frac{1915}{1521 * 3} = 41.97\%$$

The system has a lot of different losses due to diode resistances, diode forward voltage, armature resistance and the source resistance. Losses can be calculated by the following formula:

$$P = I^2 R$$

We can observe the source resistance loss by using the formula.

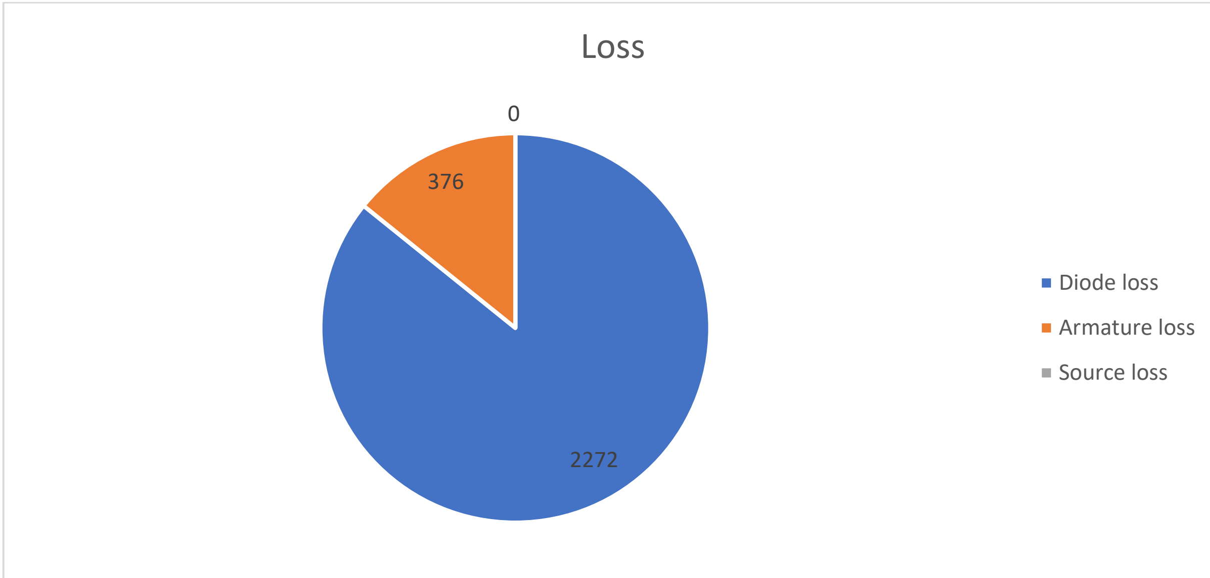
$$P = 3 * 6.95^2 * 0.1 = 14.49W$$

We can observe diode losses by subtracting the output power from the input power.

4563-2291=2272W

We can observe the motor armature loss by subtracting the mechanical output power from the output power.

2291-1915=376W



Source loss is so small, so it can be taken by 0. Diode motor drivers are very inefficient because of their losses.

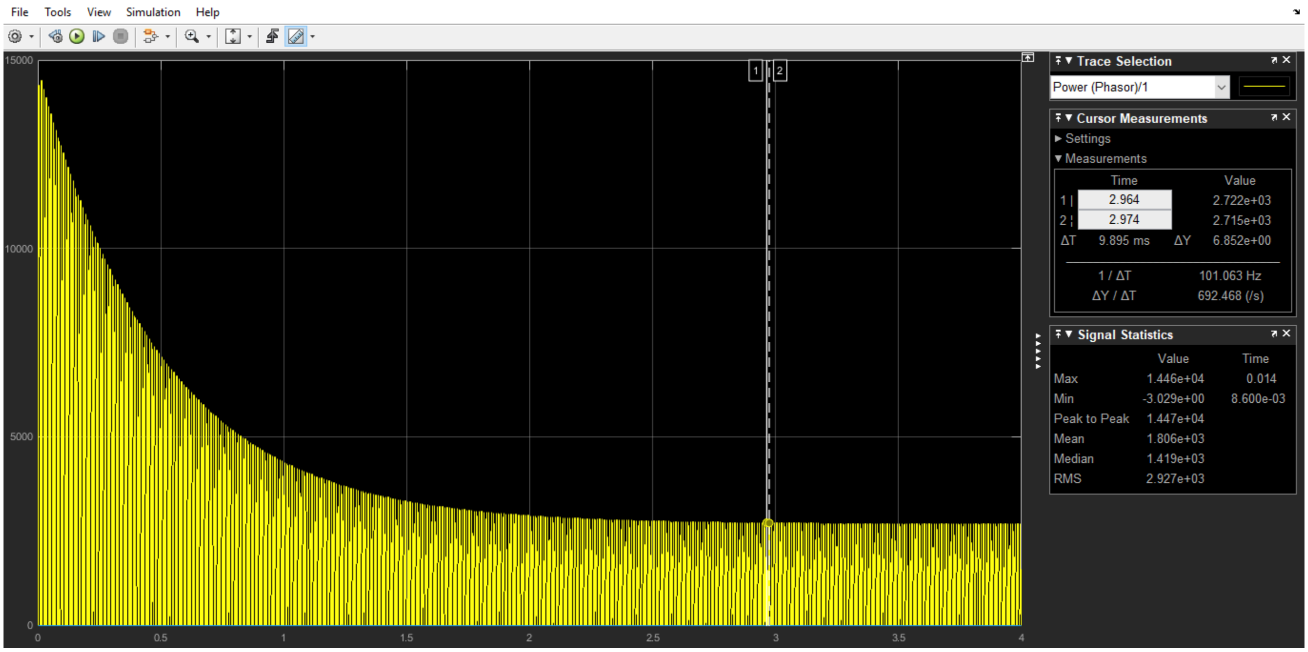


Figure 16: Input power from the zero-speed to full-speed of the motor

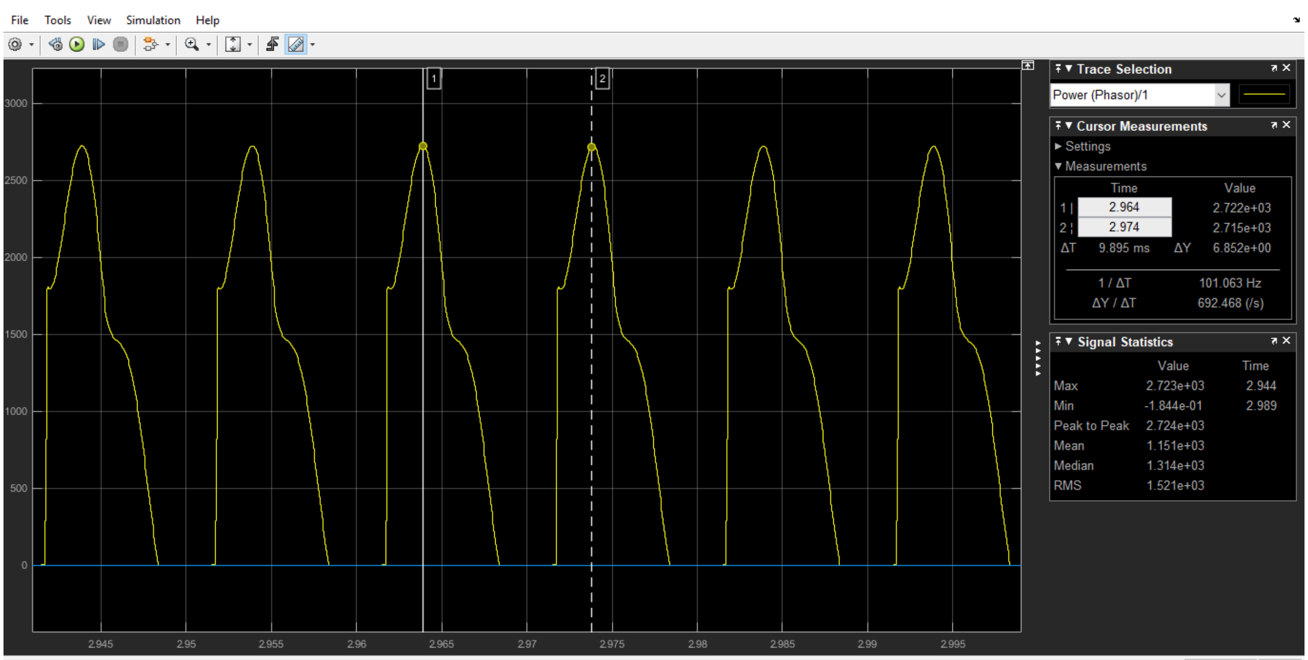


Figure 17: Input power at the steady state

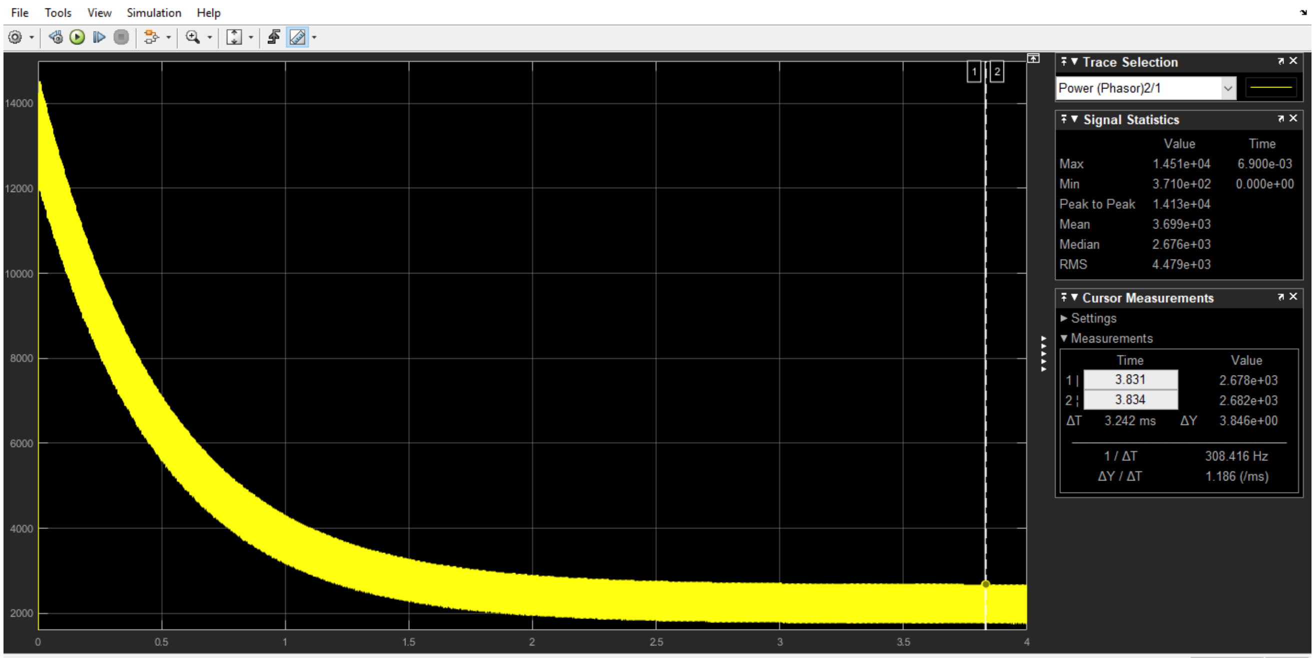


Figure 18: Output power from the zero-speed to full-speed of the motor

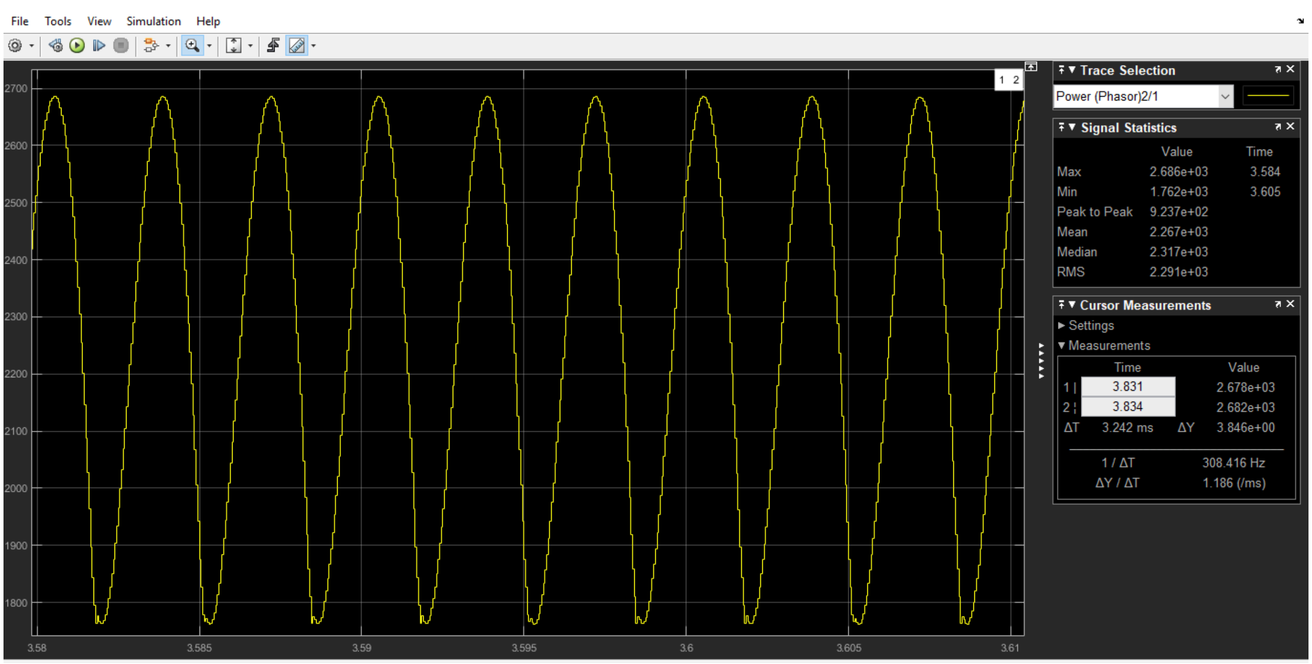


Figure 19: Output power at the steady state

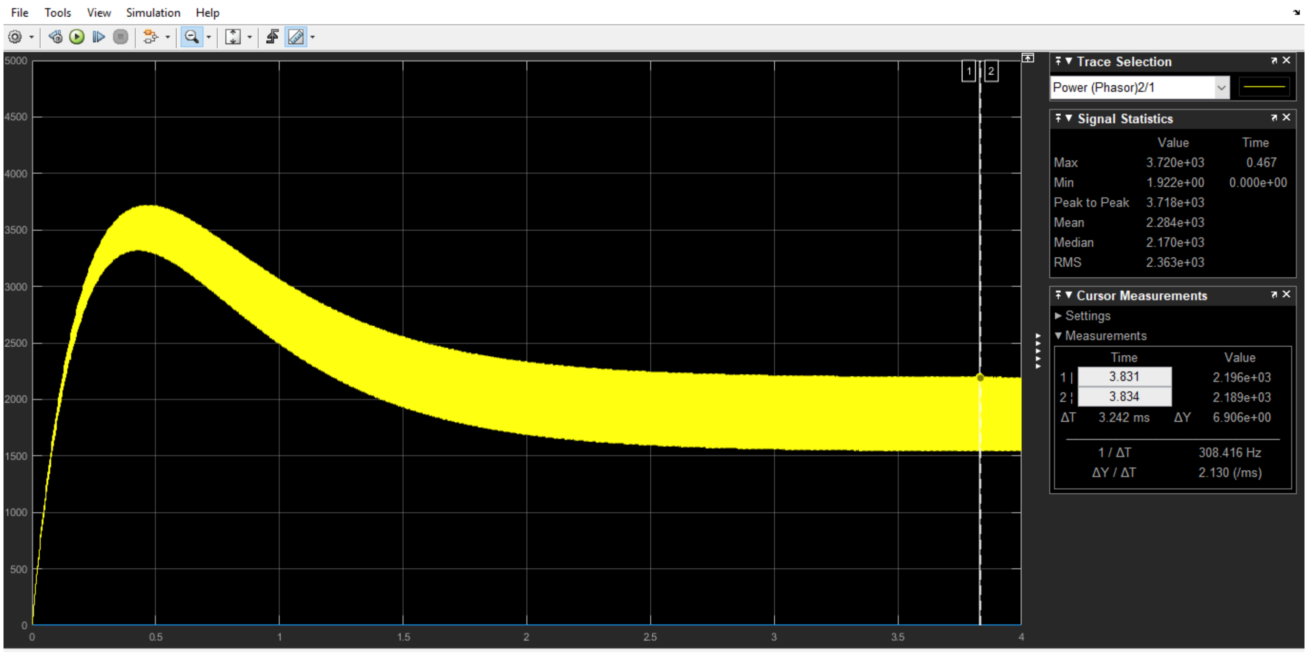


Figure 20: Electromechanical output power from the zero-speed to full-speed of the motor

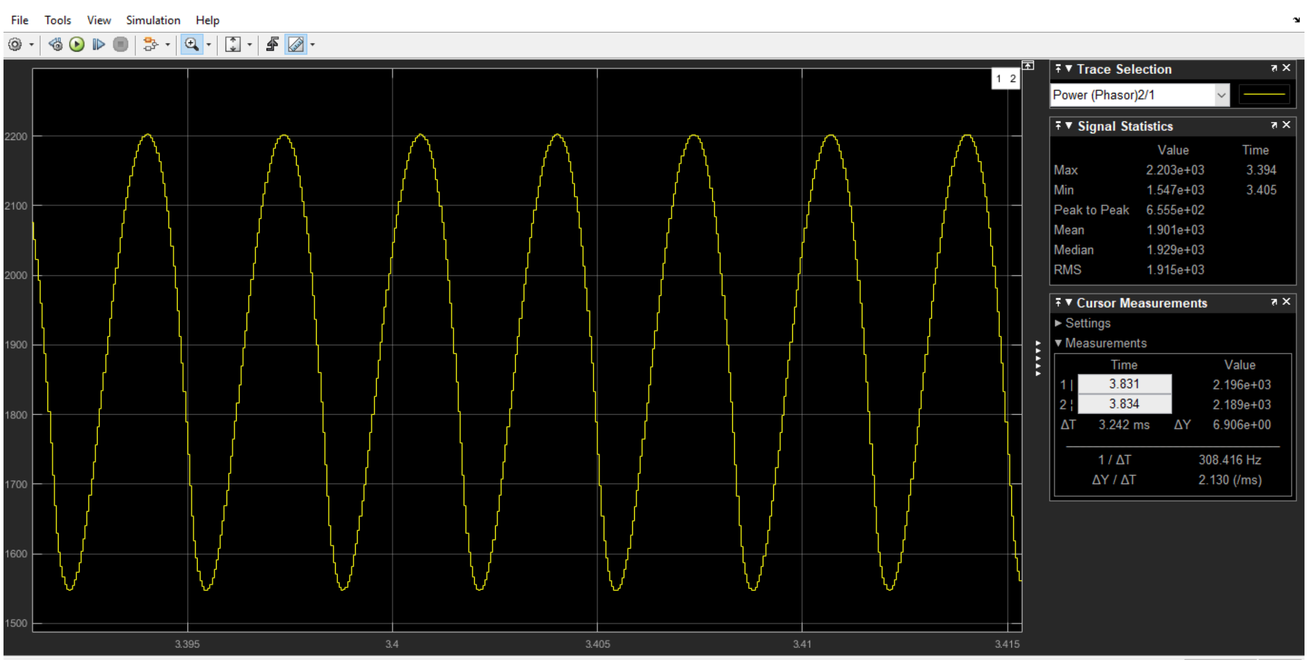


Figure 21: Electromechanical output at the steady state

4. Part 3

In this part, an alternative rectifier topology is investigated and compared with the full-bridge diode rectifier with the conditions that they produce the same average voltage and current.

4.1. Part 3.a

The topology given in Part 3.a is a 12-pulse rectifier with series connected bridges and the simulink schematic can be seen in Figure 7. It is composed of two 6-pulse rectifiers connected in series and their AC supply is from a transformer with two secondary windings, one is delta and one is wye connected. Hence, a 30 degrees phase shift is produced between the two bridges. Which leads a symmetrically displaced 12 pulse in overall.

The 12-pulse rectifier is usually used in high voltage DC (HVDC) systems. It has less harmonics than 6-pulse rectifier, hence a lower THD.

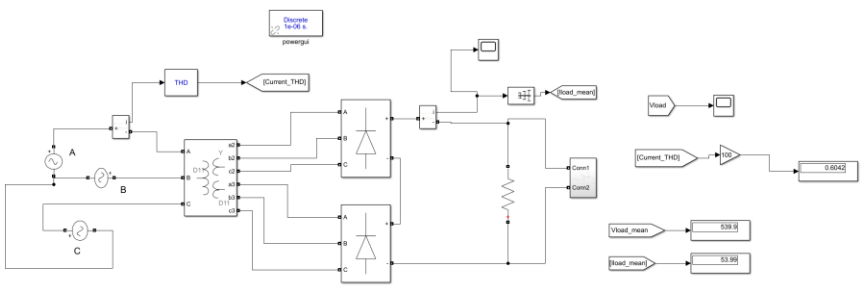


Figure 7: The simulink schematic of 12-pulse rectifier

There are two more variations of 12 pulse rectifiers. These are; 12-pulse rectifier with parallel connected bridges and half-wave 12 pulse rectifier.

The one with the parallel connected bridges are very similar to the one in Figure 7. It also consists of an transformer with two secondary windings.

The half-wave 12 pulse rectifier consists of four Y-connected interphase transformers at its secondary side and they are connected to the load side via reactors.[1]

4.2. Part 3.b

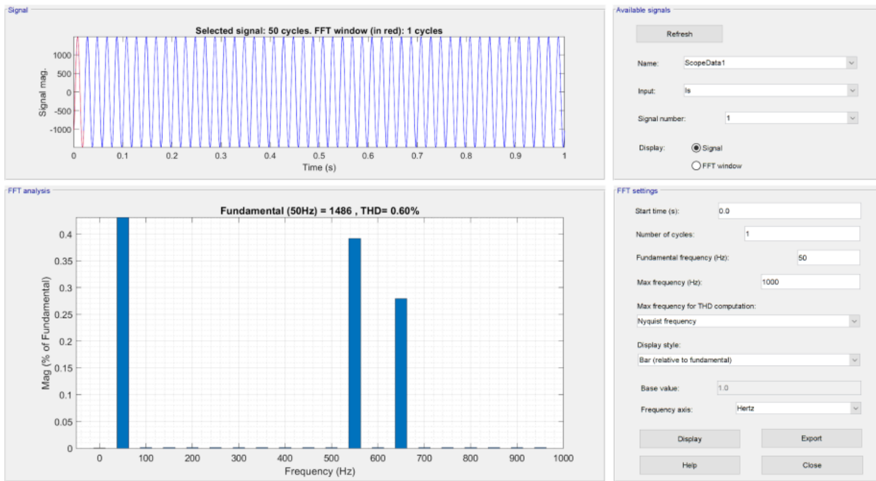


Figure 8 : FFT Analysis of $I_s$in 12-Pulse rectifier

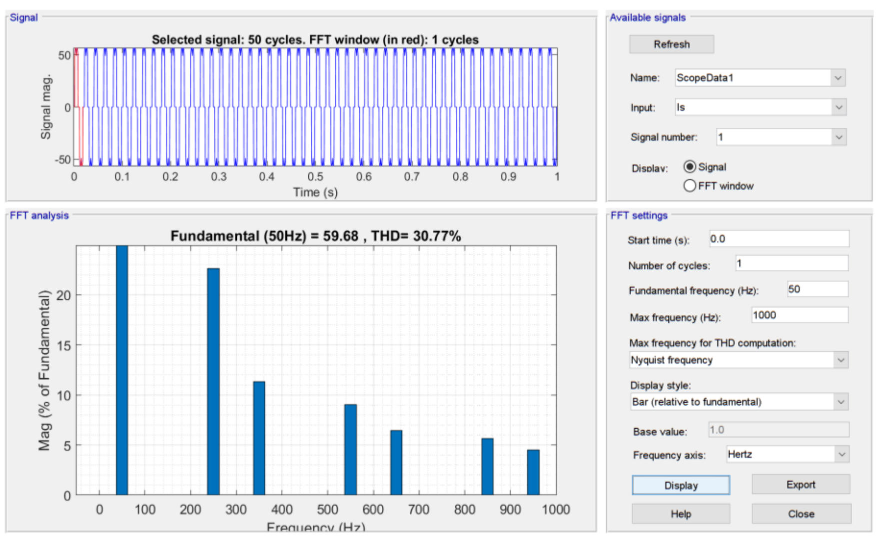


Figure 9: FFT Analysis of $I_s$in bridge rectifier

As can be seen from Figures 8 & 9, the THD of I_s is much more higher in bridge rectifier in comparison with the 12-pulse rectifier. This is because, 12-pulse rectifier eliminates the 11th and 13th harmonics as well as the 5th and 7th ones.

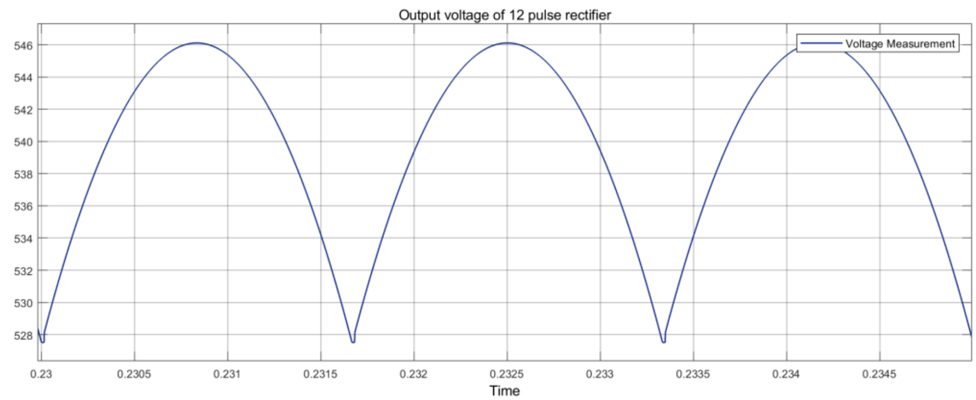


Figure 10: Output voltage of 12-Pulse rectifier

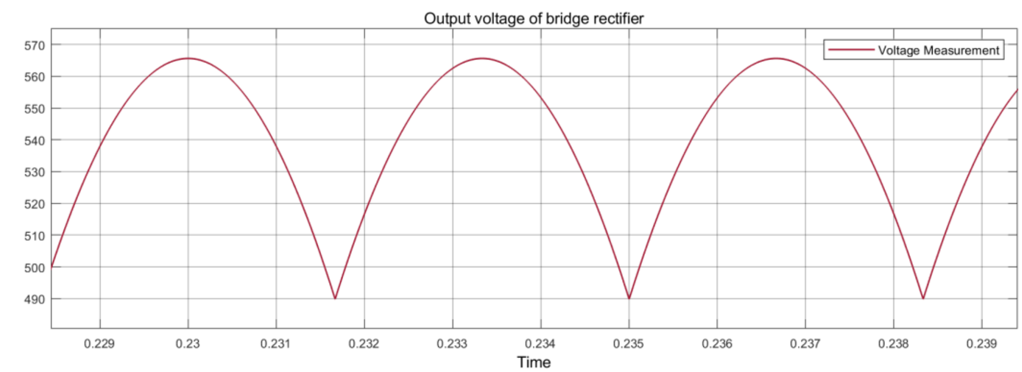


Figure 11 : Output voltage of Bridge Rectifier

As one can see from Figures 10 & 11, although the average voltage values are the same for 12-Pulse and full bridge cases, the voltage ripple is different. The voltage ripple in 12-Pulse rectifier is about 18 V, whereas it is approximately 75 V in full bridge rectifier. Since our purpose is rectification, a smaller ripple is better because it resembles more to a DC voltage.

Moreover, the frequency of the output voltage ripple is higher in the 12-Pulse case. Hence, 12-Pulse rectifier is more advantageous because when one want to filter out the output voltage the needed capacitor value is smaller with 12-pulse case. This is because the corner frequency of 12-Pulse rectifier is at a higher frequency than the full bridge rectifier.

5. Conclusion

In this report, we represented the results of Project-2 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 compared a fully controlled rectifier with a half controlled one and saw advantages of both. We saw that with the same firing angle it is possible to obtain a higher average voltage in half-controlled case. However, only one quadrant operation is possible in half controlled rectifier unlike the fully controlled one in which two quadrant operation is possible.

In part 2, we observed a motor drive by using full-bridge diode. Machine characteristics and power calculations are obtained. Also, we learned how to decrease the torque ripple.

In part 3, we constructed a 12-pulse rectifier. We saw that, compared with the full bridge diode rectifier, it produces an output voltage with a smaller ripple and higher ripple frequency which are both advantageous properties for an rectifier.

6. References

[1] Lander, C. W. (1993). *Power electronics*. London: McGraw-Hill.