MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

E463 – PROJECT #2

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I) INTRODUCTION

This report is prepared for the second software project of EE463 Fall2018 class in order to understand single phase controlled and three phase diode rectifiers operation and characteristics. Throughout the project Turkish grid system which has $400V_{ll}$ and 50Hz operation is used.

First question compares fully and half controlled single phase rectifiers. In the second question, a pulse modulated DC motor which is fed from a three-phase grid via a three-phase full bridge uncontrolled rectifier is observed. Plots of armature current, speed and torque of the motor, ripple characteristics of torque and the overall drive efficiency are discussed. Finally, in the last question alternative rectifier topologies for HVDC systems such as 12-pulse diode rectifier is explained.

II) QUESTIONS

QUESTION 1: Single Phase Thyristor Rectifiers

a) Hand calculations

For the calculation of the required firing angle α to acquire an average output current value of 40 A for fully controlled topology, average output voltage is given by (1)-(3).

$$Vavg = \int_{\alpha+u}^{\pi+\alpha} \frac{\sqrt{2}\,Vs\, sinwt\, dwt}{\pi} \quad (1)$$

$$V_{avg} = \frac{\sqrt{2}\,Vs\,[\cos(\alpha+u)-\cos(\pi+\alpha)]}{\pi} \quad (2)$$

$$V_{avg} = \frac{\sqrt{2}\,Vs\,[\cos(\alpha+u)+\cos(\alpha)]}{\pi} \quad (3)$$

Voltage drop due to commutation is found by (4)

$$V_{com} = \int_{\alpha}^{\alpha+u} \frac{\sqrt{2}\,Vs\, sinwt\, dwt}{\pi} = wLs \int_{Idmin}^{Idmax} d_{id} \quad (4)$$

Since Id is 40A, combining (3) and (4), we acquire (5) and (6)

$$\frac{\sqrt{2}\,Vs\,[\cos(\alpha)-\cos(u+\alpha)]}{\pi} = wLs * 40 \quad (5)$$

$$\cos(u+\alpha) = \cos(\alpha) - \frac{40\pi * wLs}{\sqrt{2}\,Vs} \quad (6)$$

Therefore; output average voltage Vd is (7).

$$V_d = \frac{2\sqrt{2}\, Vs \cos(\alpha)}{\pi} - 40 * wLs \quad (7)$$

Since output average current I_{av} is 40A and given by (8), combining (7) and (8) together we yield (9), therefore; α is (10).

$$\frac{V_d}{R_{load}} = I_{av} \quad (8)$$

$$40A = \frac{207.92 * \cos(\alpha) - 6.28}{4} \qquad (9)$$

$$\alpha = 36.89° \quad (10)$$

For half controlled topology, similar calculations are carried out in (10) and (11), yielding α in (12).

$$I_{av} * R_{load} = V_d = 160V \quad (10)$$

$$0.9Vs * \cos(\alpha) - wLs * I_{av} = 160V \quad (11)$$

$$\alpha = 56.55° \quad (12)$$

Output current simulation results of fully controlled and half controlled topologies can be observed in Figure 1 and 2, respectively.

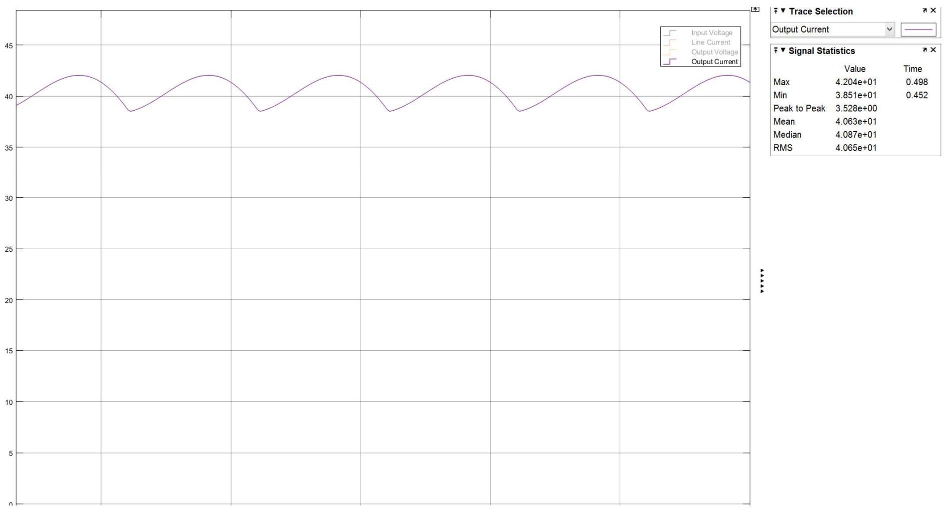


Figure 1: Output Current Simulation Result of Fully Controlled Topology

As can be seen from Figure 1, the calculations for fully controlled topology is consistent with simulation results. The simulated result is 40.6A. This little amount of discrepancy could be because we round numbers while calculating.

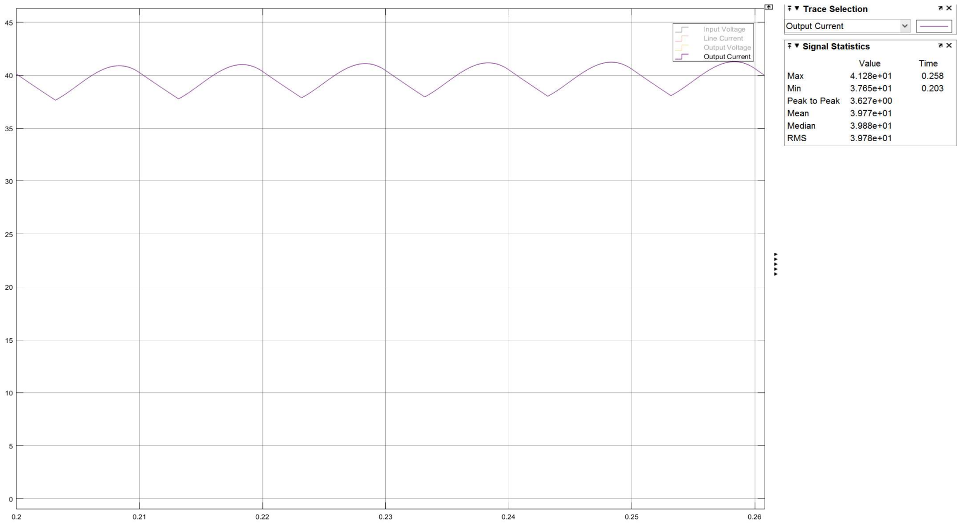


Figure 2: Output Current Simulation Result of Half Controlled Topology

As it can be seen from Figure 2 and the calculations of half controlled topology, they are also consistent with each other. The simulation result was 39.77A where the required value was 40A. The little discrepancy is because of the same reason.

b) <u>Graphical results of Vs and Is and THD values of Is</u>

Figure 3 shows the input current and voltage of fully controlled topology Figure 4 shows the input current and voltage of half controlled topology. Figure 5 shows the THD of input current for fully controlled topology. Figure 6 shows the THD of input current for half controlled topology.

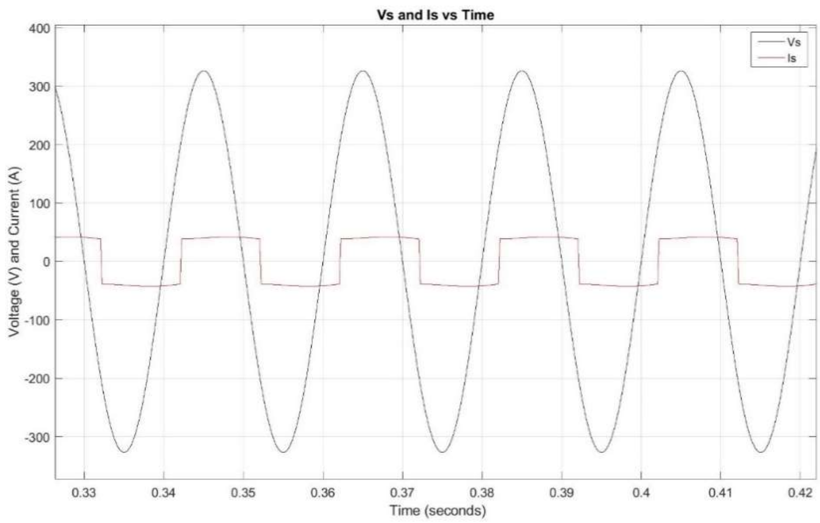


Figure 3: Vs and Is vs Time of Fully Controlled Topology

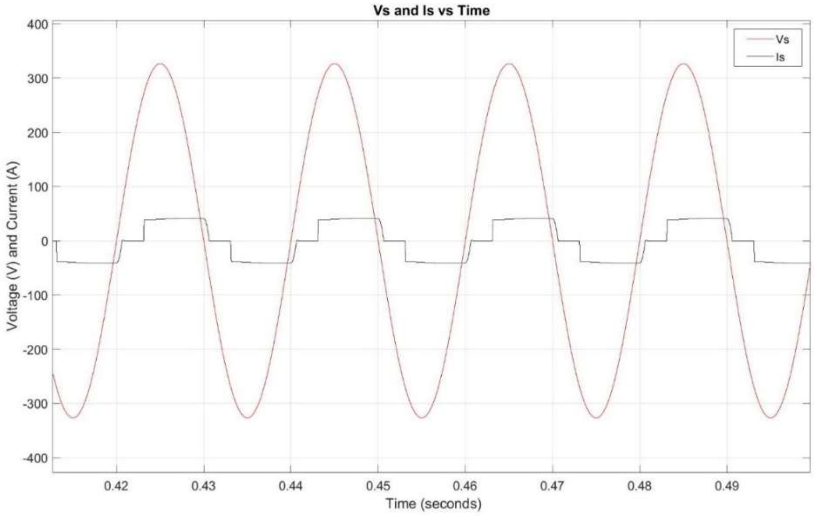


Figure 4 Vs and Is vs Time of Half Controlled Topology

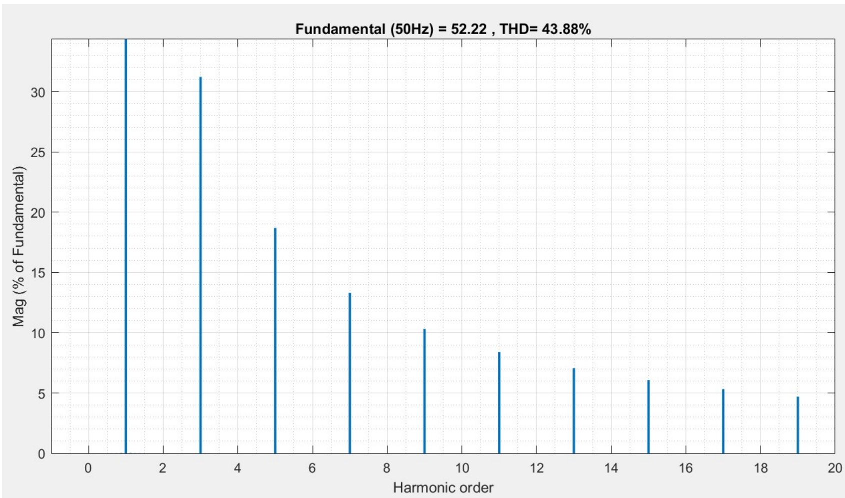


Figure 5 THD of Is for Fully Controlled Topology

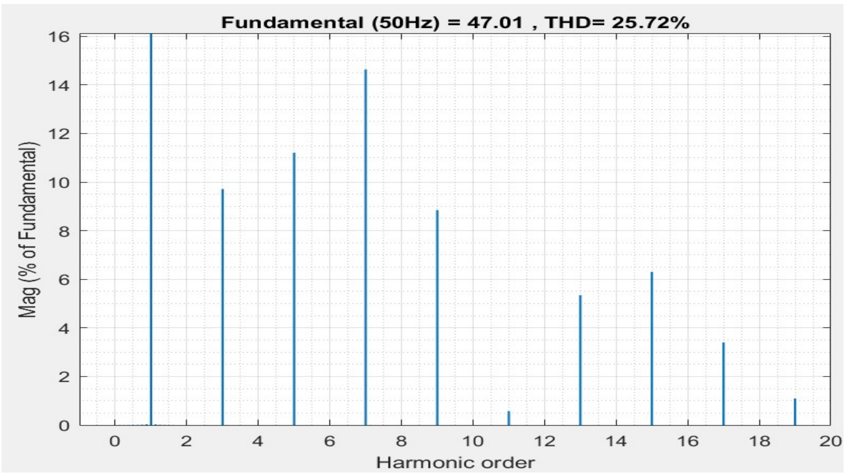


Figure 6 THD of Is for Half Controlled Topology

The fully controlled topology allows bidirectional power flow. By means of this, it can operate as a rectifier and an inverter. The output voltage can be negative. It has two more thyristors instead of two diodes as in the case of half controlled topology. This results more complex and expensive gate drive circuitry. It can be used any industrial application where utilization of the inverter mode operation is important. However, they have worse input power quality than half controlled topology. The half-controlled topology is also called unidirectional converter because of the fact that the voltage cannot be negative. This results that we only have control in the half of the wave. Also, since the voltage cannot be negative, the power flow is permitted only from AC to DC side. It cannot operate at inverter region. While the output is zero at negative cycle, the load current drawn is also zero. This results a more sinusoidal form than the fully controlled topology for input current and less THD. Its application areas include where inverter operation is unnecessary or not desirable.

QUESTION 2: PM DC Motor Drive

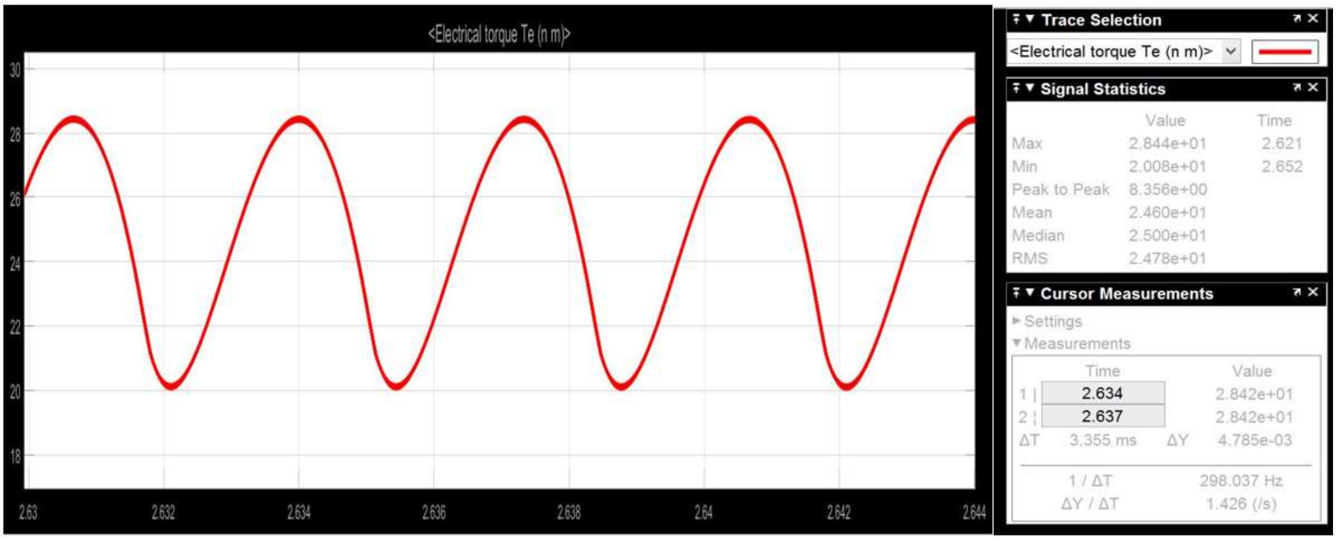
a) Armature curent, speed and torque of the current stand-still to steady-state graphs

Figure 7 shows armature current, speed and torque of the motor from stand-still (zero speed) to steady-state vs time.

Figure 7 Armature current, speed and torque of the motor from stand-still (zero speed) to steady-state

b) <u>Comments on the characteristics of torque ripple and THD of line current:</u>

Figure 8 shows the electrical torque in close up and the statistics of it. Figure 9 shows the THD of line current.



Figurel 8 Electrical torque and its statistics

As can be seen from Figure 8, the output electrical torque frequency is 300 Hz. It is 6 times larger than the grid frequency which is 50 Hz. Since output voltage frequency of the rectifier is directed as armature voltage frequency, torque ripple frequency is 300Hz as well. Ripple is directly proportional to the ripple of armature current by (13)

$$T = k * \phi * I \quad (13)$$

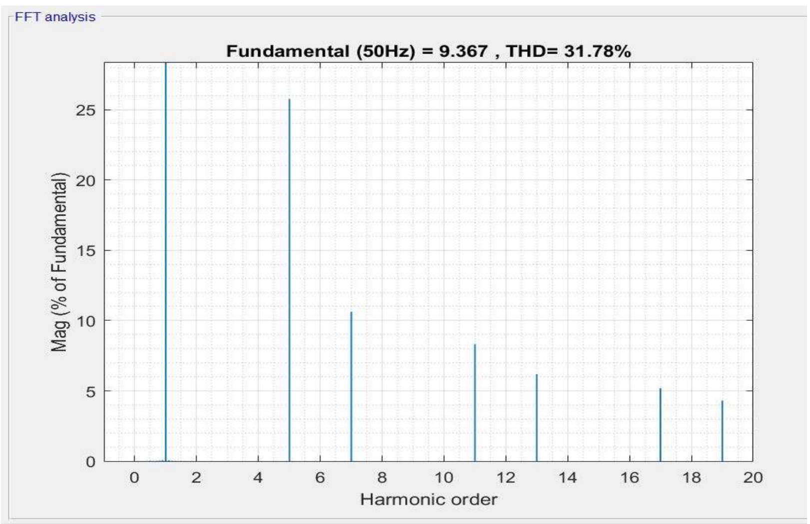


Figure 9: THD of line current

c) Proposed Methods for Reducing the Torque Ripple Below 10% of the Average Torque

- **LC Filter:**

The filter used for this method is called 'Choked Input L-section Filter'. The inductance in LC filter behaves as high impedance for AC component and as short circuit for DC components. For higher frequency components, the reactance increases even more. It is a good filter for higher frequency components. Also, by the energy charging and discharging, it smoothens the output. This filter reduces the ripple inversely proportional to capacitance and inductance values. Therefore, in order to get a narrow band filter, those values must be very high. Large inductors and capacitors are problems for this topology. However, LC filter suppresses the negative effects of shunt C filter and series L filter. All in all, an efficient output is obtained.

Figure 10 shows the LC filter topology. Figure 11 shows the graphs of armature current, electrical torque and rpm of dc machine at steady state. The ripple can be increased and decreased by varying the inductance and capacitance.

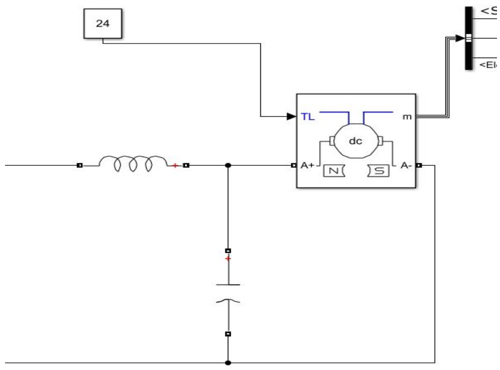


Figure 10 LC Filter

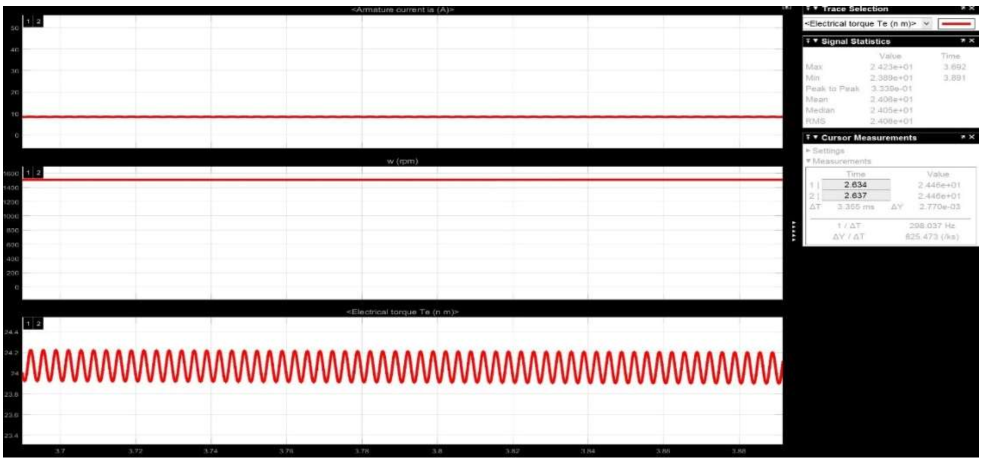


Figure 11 Armature current, electrical torque and rpm of dc machine at steady state

Figure 12 shows the THD of line current.

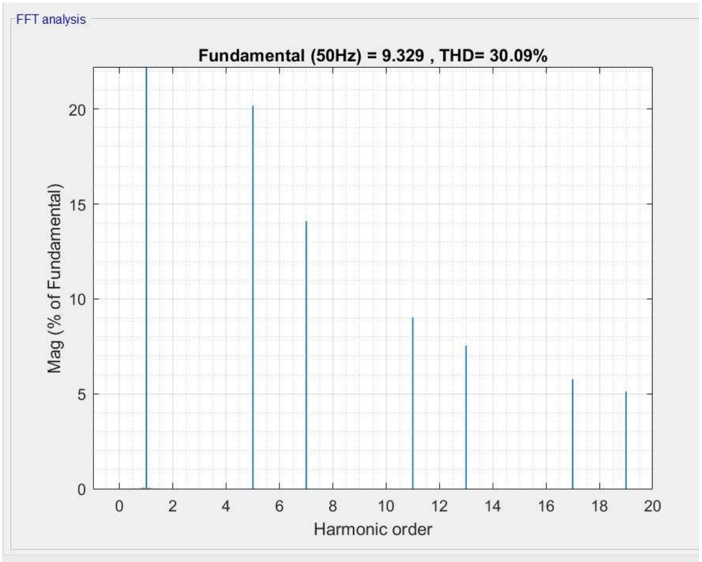
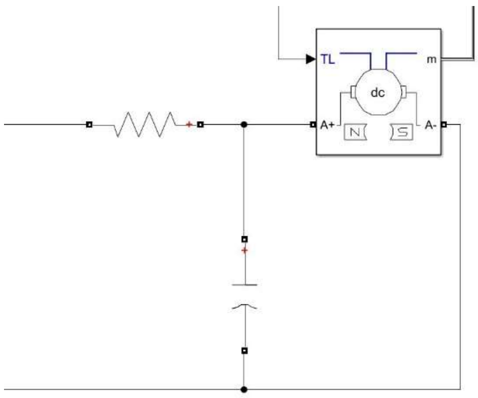


Figure 12 THD of line current

- **RC Filter**

Instead of series inductor in choke input LC filter, this topology has series resistor. One of the drawbacks is the voltage drop on the resistor. However, this depends on chosen resistance value and load resistance. Also, because of the resistor, heat dissipation is high. This leads to low efficiency and heat problems but the circuitry is very simple and cheap. It doesn't need to have large inductors, therefore cost and space issues can be solved.

Figure 13 shows the RC filter topology. Figure 14 shows the graphs of armature current, electrical torque and rpm of dc machine at steady state. The ripples can be changed by varying the R and C.



Şekil 13 RC filter topology

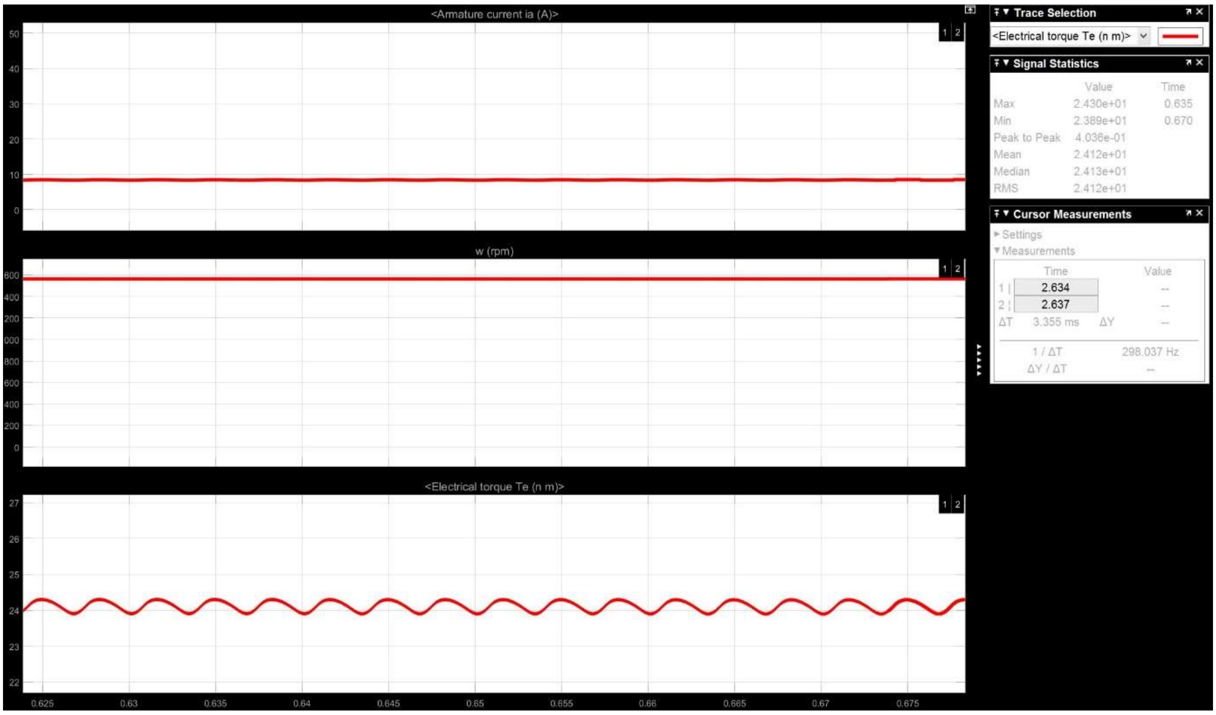


Figure 14 Armature current, electrical torque and rpm of dc machine at steady state

Figure 15 shows the THD of line current.

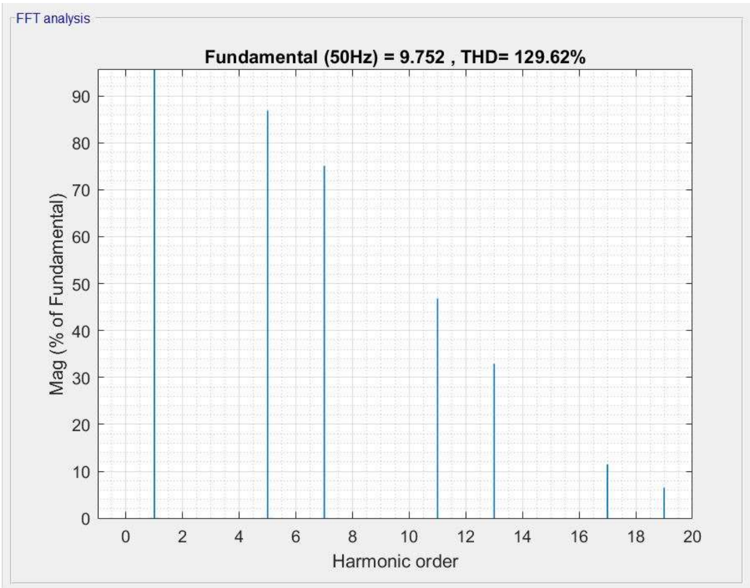


Figure 15 THD of line current

d) Overall Efficiency and Losses

At the steady state, because of the losses during the transmission of electrical power to mechanical power, it is known that there will occur some losses. These losses are because of

- Source side losses
- Diodes losses
- Motor losses

The electrical power will be converted to mechanical power, apart from these losses. Table 1 shows the losses and power flow values.

Table 1: Power flow and losses

Input Electrical Power	Source Loss	Diodes Loss	Electrical output power	Motor Loss	Mechanical Output
4586 W	13,18 W	27,82 W	4545 W	737 W	3808 W

By using these simulated results, the efficiencies are calculated as can be seen from Table 2.

Table 2: Efficiencies

Efficiency Motor(%)	Efficiency Total (%)
83,78437844	83,0353249

The percentage shares of losses can be seen in Table 3 and Figure 16.

Table 3: Percentage shares of losses

Source Loss	Diodes Loss	Motor Loss
1,69%	3,58%	94,73%

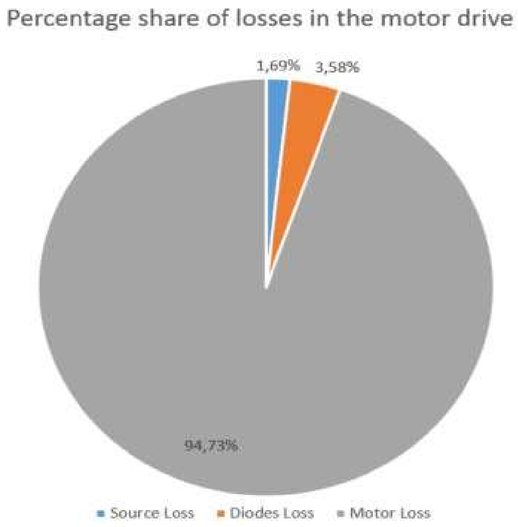


Figure 16 Percentage share of losses in the motor drive

QUESTION 3: 12-Pulse Uncontrolled Rectifier

a) Operation, application areas, and other variations

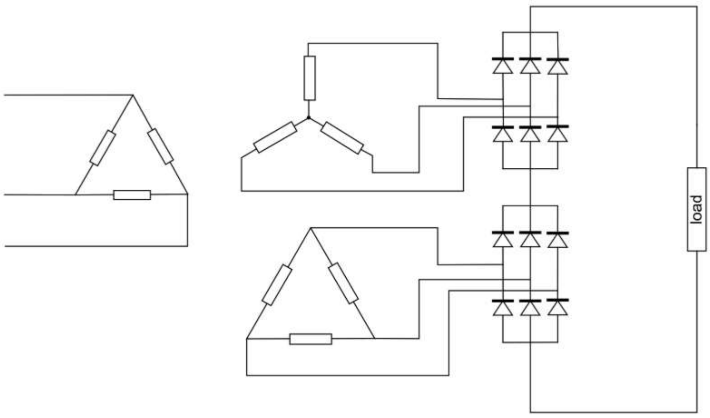


Figure 17: 12 pulse uncontrolled series connected bridge rectifier

Figure 17 shows a 12-pulse uncontrolled series connected bridge rectifier. Primary delta leads the secondary wye by 30^o, hence secondary delta leads secondary wye by 30^o as well. Therefore; the three-phase voltages supplying bridges are displaced by 30° resulting in 12 peaks per period of 20ms in the output voltage waveform.

12 pulse rectifiers can be obtained by half-wave (Figure 18) and parallel connected bridge (Figure 19) topologies. [1]

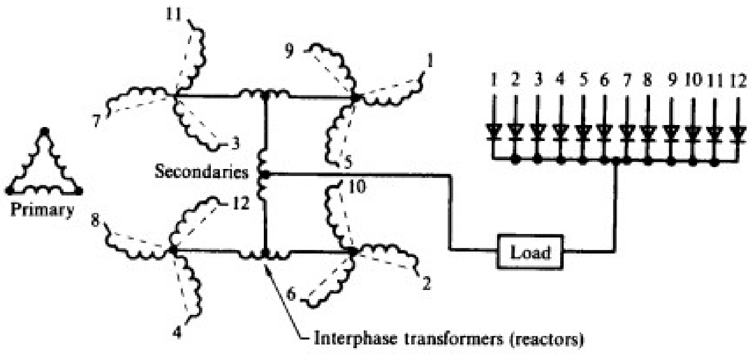


Figure 18: 12 pulse uncontrolled half-wave rectifier

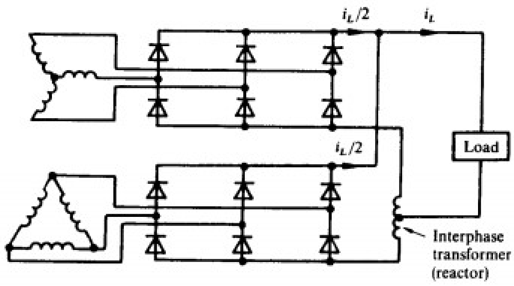


Figure 19: 12 pulse uncontrolled parallel connected bridge rectifier

In Figure 18, four wye connected secondary side windings are interconnected with reactors to give phases 30° apart from each other. 12 pulse uncontrolled parallel connected bridge rectifier works in the same fashion with its series version.

As the number of pulses increases output voltage waveform gets closer to dc form, whereas line current reaches to a sinusoidal form. Therefore, advantages of this rectifier are reduced THD level (Only 11th,13th harmonics) and voltage ripple output, increased output voltage. Thanks to these advantages high pulse rectifiers are used in HVDC transmission. The main disadvantage is the size of the equipment. [2] Also, frequency is doubled for 12 pulse rectifier so switching losses become larger.

There are 18-pulse, 24-pulse, 48-pulse and higher variations of this rectifier topology as well. Harmonics of these topologies can be found by (14) where n is the number of pulses.

$$h = 12n \pm 1 \quad (14)$$

18 pulse rectifier topology adds one more secondary windings and one rectifier in 12 pulse topology. Using phase shifting transformers 20^{o} shift is displaced between pulses. [3]. 24 pulse rectifier uses 15^{o} shifts between phases in Figure 20, whereas 48 pulse rectifiers has 7.5^{o} shifts.

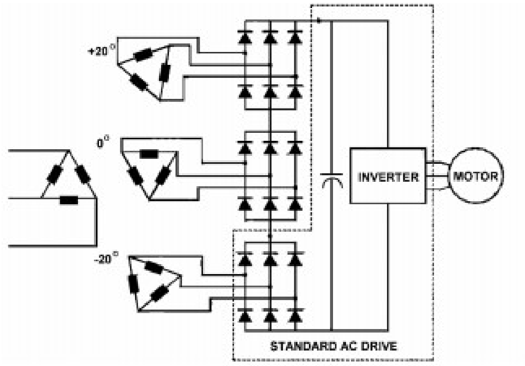


Figure 19: 18 pulse uncontrolled rectifier

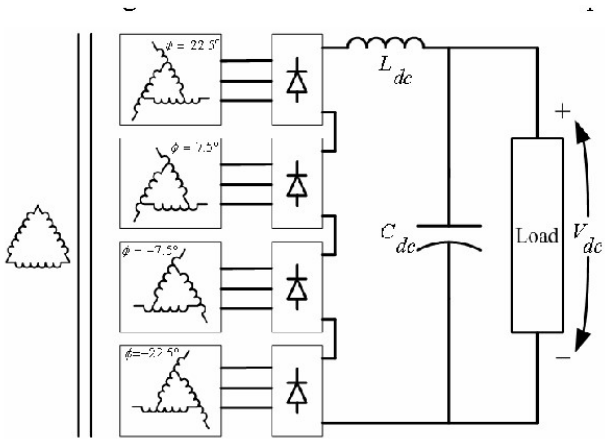


Figure 20: 24 pulse uncontrolled rectifier (Retrieved from www.semanticscholar.org)

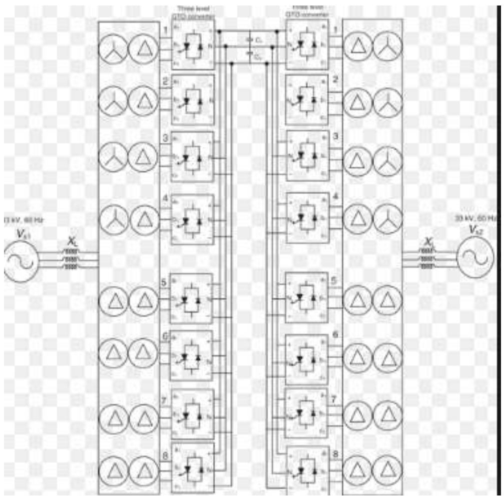


Figure 21: 48 pulse uncontrolled rectifier (Retrieved from www.degruyter.com)

b) Comparing between topologies

Peak values of the output voltage are given by (15) and mean of the output voltage is found by (16) and (17).

$$\sqrt{2}V_{ll} + \sqrt{2}V_{ll}e^{j30} = 1.931\sqrt{2}V_{ll} \quad (15)$$

$$V_d = \frac{1}{\frac{\pi}{6}} * \left(1.931\sqrt{2}V_{ll}\int_{-\frac{\pi}{12}}^{\frac{\pi}{12}}\cos(wt)\,d(wt)\right) \quad (16)$$

$$V_d = 2.7V_{ll} \quad (17)$$

We know that mean output voltage of a three-phase full bridge diode rectifier is given by (18) whereas 12-pulse rectifier's is (17).

$$V_d = 1.35V_{ll} \quad (18)$$

Therefore, we must choose 12 pulse bridge rectifier supply as **V_{ll} =200V** so that both topologies produce the same average output voltage and average load current. To simulate 12 pulse rectifier Simulink topology in Figure 22 is used. Unfortunately, with this simplified topology phase currents in the primary side windings cannot be observed. However, 3rd, 5th, and 7th harmonics of the line current is eliminated resulted in a lower input THD level. Figure 23 and 24 show load current and voltage waveforms of 12 pulse and 6 pulse rectifiers, respectively. FFT analysis of these output voltage waveforms suggests **540V** dc components. As it can be seen, another advantage of 12 pulse rectifier is reduced input voltage.

Output ripple is 19V for 12 pulse rectifier and 75V for 6 pulse rectifier. Also, frequency is doubled which means smaller time constants for capacitors. Therefore; capacitor sizes decrease as the number of pulses increases. As switching frequency is increased, so do switching losses.

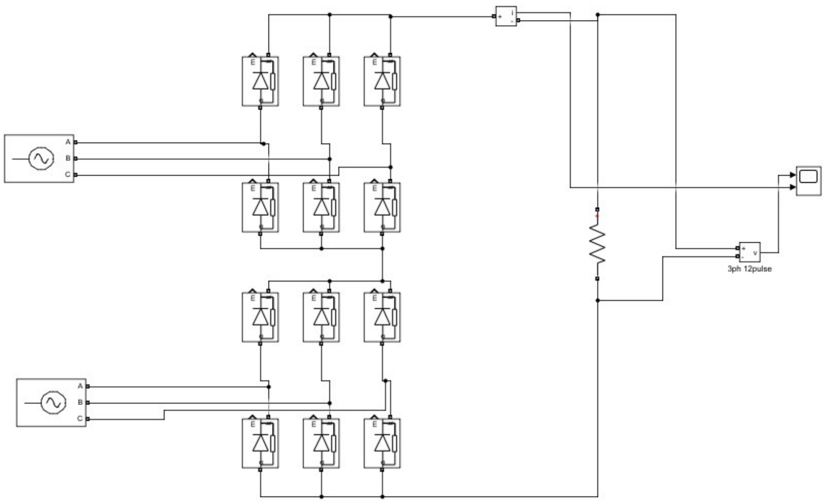


Figure 22: Simulink topology of 12 pulse uncontrolled series connected bridge rectifier

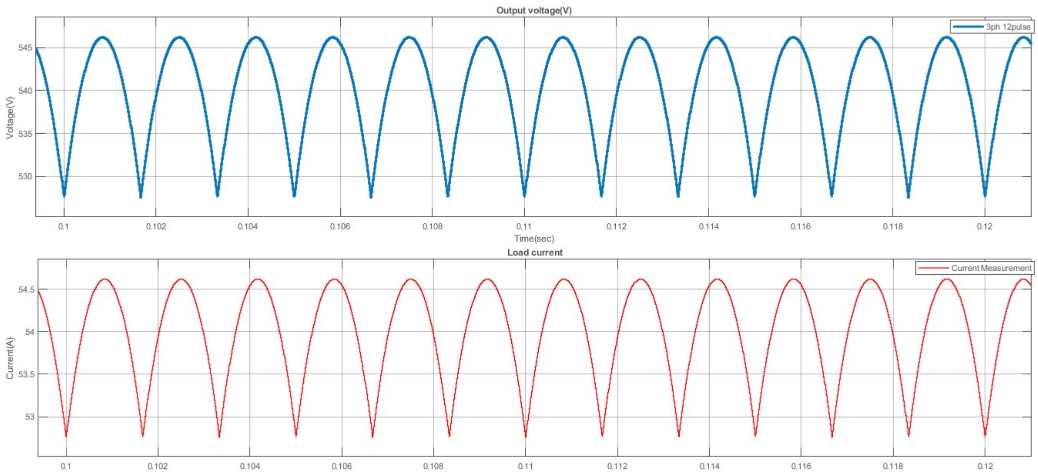


Figure 23: :Output waveforms of 12 pulse uncontrolled series connected bridge rectifier

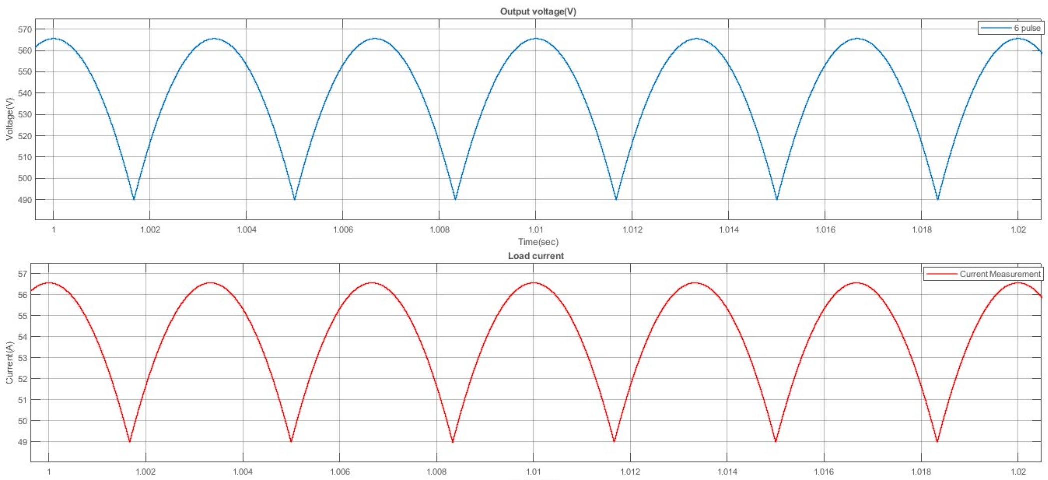


Figure 24: Output waveforms of 6 pulse uncontrolled series connected bridge rectifier

III) CONCLUSION

In this project, fully and half controlled single phase rectifiers are investigated in the first question. Fully controlled topology allows bidirectional power flow and it can be used as inverter. To improve input power quality a half-controlled model can be used instead, however this only allows unidirectional power flow from the grid side.

A pulse modulated DC motor which is fed from a three-phase grid via a three-phase full bridge uncontrolled rectifier and its plots of armature current, speed and torque of the motor, ripple characteristics of torque and the overall drive efficiency are discussed. It turns out torque ripple frequency is the same as output voltage frequency. To decrease percentage of the torque ripple RC and LC filters can be used. Source side, diode, and motor losses affect overall efficiency.

Finally, in the last question alternative rectifier topologies for HVDC systems such as 12-pulse diode rectifier is explained. As number of pulses increase dc characteristics of output voltage increases and THD of the current drawn from line improves.

IV) REFERENCES

[1] LANDER C., Power Electronics, 3rd Edition, Page 71-72

[2]Siemens, Industry Machines, Retrieving date: 15.12.2018
https://w3.siemens.no/home/no/no/sector/industry/marine/pages/12_pulse_system_configuration.aspx

[3]PERSONS J., Comparing Harmonic Mitigation Techniques, 2014.04.08