

MIDDLE EAST TECHNICAL UNIVERSITY

Electrical & Electronics Engineering

Simulation Project #2

EE 463

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Introduction

In this project, we are asked to design and simulate controlled rectifiers and DC motor drive. The aim of the project is to observe the differences, advantages and disadvantages of half-controlled, fully controlled rectifiers and effects of the freewheeling diodes on each topology. In this document, related theoretical calculations are illustrated and the simulations are done in Simulink.

Q1)

a)

# Average Output Voltage:

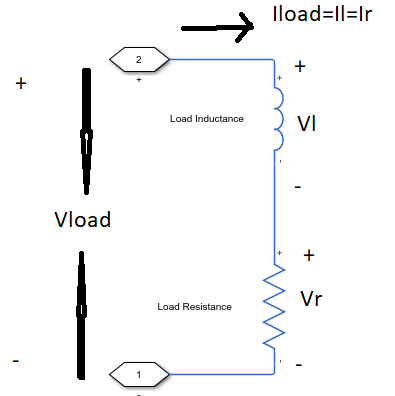


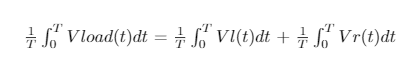
Figure 1 Load Voltage and Current Diagram

As can be seen at Figure X , Load voltage can be found with respect to Load current, inductance and resistance value. However, we can not know load current with respect to time. Only average value of current is given, ripple of load current is not known.So, Average voltage of load should be found by using only resistance value and average current of load. In addition, there is some assumption that voltage drop due to commutation is calculated average current, not minumum current.

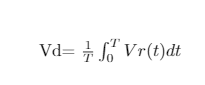
If required analytical explanation,



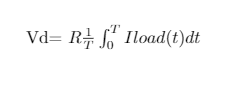
Equation 1



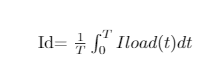
Equation 2



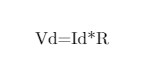
Equation 3



Equation 4



Equation 5



Equation 6

Equation 1 shows that KVL is valid for load. Series RL circuit has common current. For the time independent formulation, we take a mean value of each side of equation like Equation 2. For ındcutor, second voltage law says that mean value of inductor voltage must be zero. So, we can reduce the equation like Equation 3. Then, with property of integral, average value of voltage is written as kind of average current. Finally, Equation 6 is obtained and it indicates that average voltage of output is independent from inductance.

Average output voltage is 160 V for resistor with 4 ohm and this calculation is independent from source side.So, both of circuits, fully and half controlled, have same average voltage. Average current gives us the voltage drop from commutation and firing angle can be found by using output voltages and input voltages.

# Firing Angle Calculation of Fully Controlled Rectifier

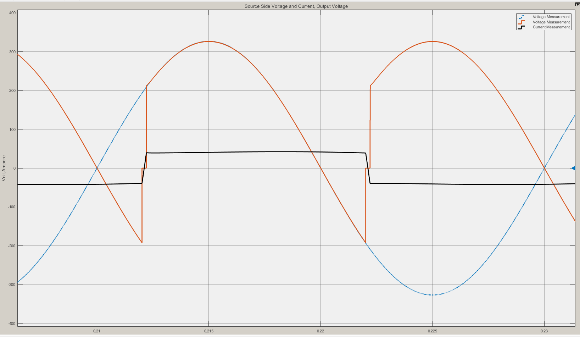
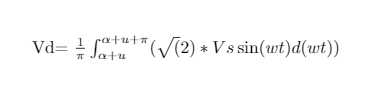


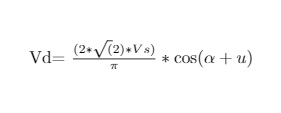
Figure 2

As can be seen Figure 2, there is a commutation at transition between thyristors. It reduces average voltage of rectifier. For the calculation of average voltage, it can not be ignored.



Equation 7

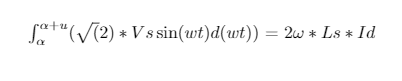
Equation 7 is used for calculate average output voltage of rectifier. The equation contains commutation time.



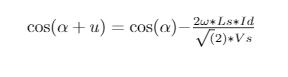
Equation 8

Equation 8 is deducted from equation 7. Average voltage depends on both firing angle and commutation time.

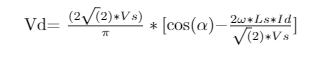
Commutation time depends on line inductance. It balances that current changes with respect to time. It is found by using voltage seconds law(Equation 9).



Equation 9



Equation 10



Equation 11

Then, average voltage is written with only firing angle dependency. It is not required commutation time to find firing angle

If numerical values are placed and firing angle that provides required average current is found 36.1 degree. Simulation are adjusted to 36.1 degree firing angle.

# Firing Angle Calculation of Half Controlled Rectifier

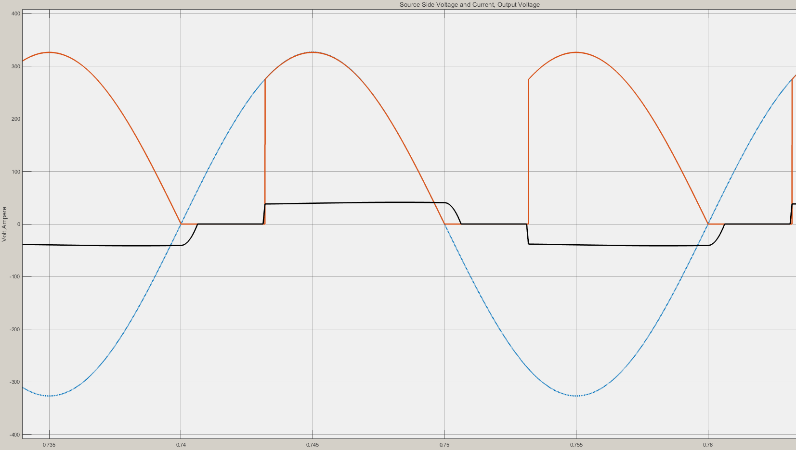
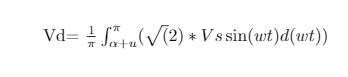


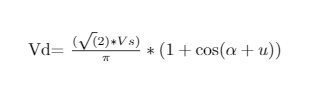
Figure 3

As can be seen Figure X output voltage can not passing negative cycle because of diodes. So, commutation occurs for transition between -Id and zero or zero and Id.



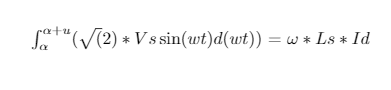
Equation 12

Equation11 shows that average output with respect to firing angle and commutation time. The equation is reduced to Equation 12.

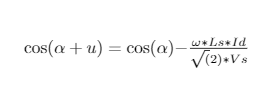


Equation 13

Commutation time is depends on line inductance, current and grid frequency. Then, Equation 13 is written to calculate commutation and it is written as Equaition 14.

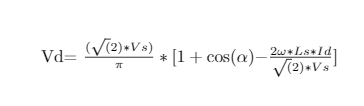


Equation 14



Equation 15

Then, average output voltage can be calculated as only firing agle varible if the circuit parameters and average current are known.



Equation 16

From equation 15, only unknown is firing angle. By placing other parameters numerical, firing angle is drawn as 56.06 degree. Simulation are adjusted to give 56.06 degree firing angle.

b)

# Simulation Results of Fully Controlled Rectifier

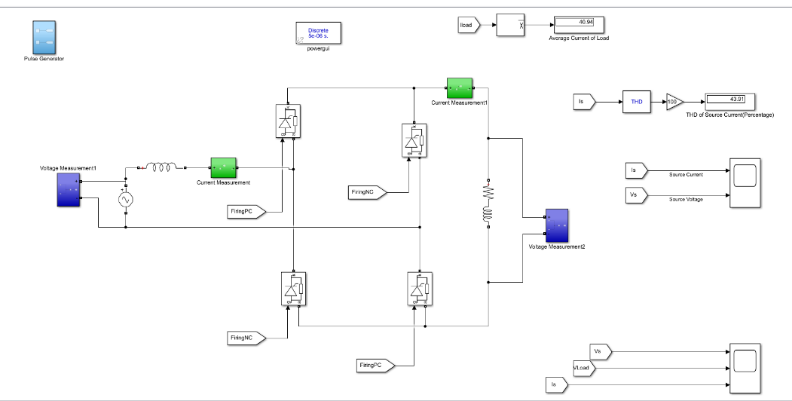


Figure 4

All circuit diagram shown Figure 3. The circuit has some subsystem that provides firing angles, measurement of currents,voltages and calculation of mean value and THD.

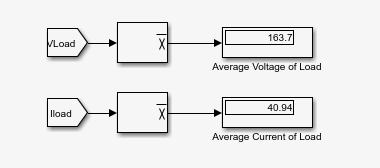


Figure 5

Average voltage and current at figure 4 is almost the same as analytical solution. In simulation, thyrisyors have snubber circuits and it can changes result in small size. In addition, we can solve analytically with assumption that commutation occurs ar average current.

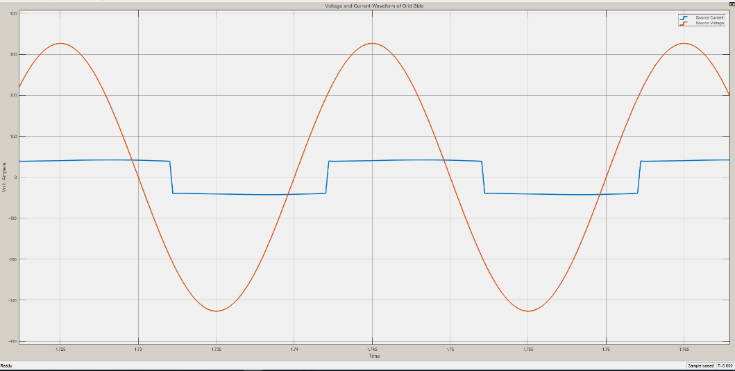


Figure 6

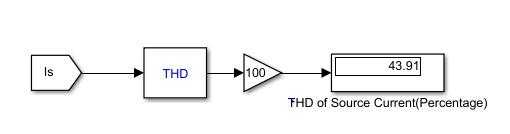


Figure 7

As expected, there is a phase difference at line current and line voltages. The circuit works on rectifier mode because of firing angle is smaller than 90 degree. The phase difference depends on firing angle and commutation time.



Equation 17

THD is smaller than 48% because commutation makes the current more smoother than square wave.

# Simulation Results of Half Controlled Rectifier

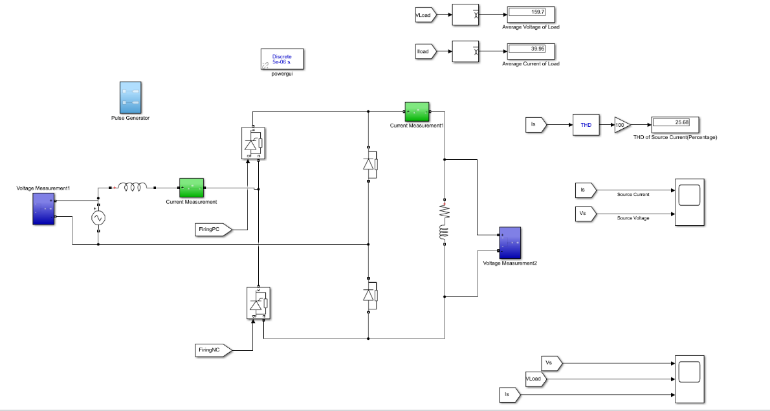


Figure 8

There is a half controlled rectifier at Figure 8. It is two ways to create these circuit. One of them is using one diodes and 4 thyristor. Other one is established by 2 diodes and 2 thyristors. Second one is used for this setup.

There is a sum subsytem to measure the reqiure voltage and current and calculation about them.

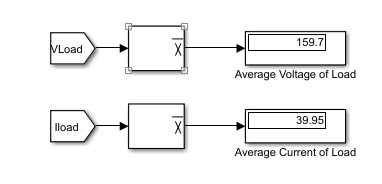


Figure 9

Figure 9 represents that our analytical calculation is true because as expected, the average current is like 40 ampers. Small changes are related to snubber circuit among diodes and thyristors. For the commutation, average current is taken to calculate analytically by assumption.

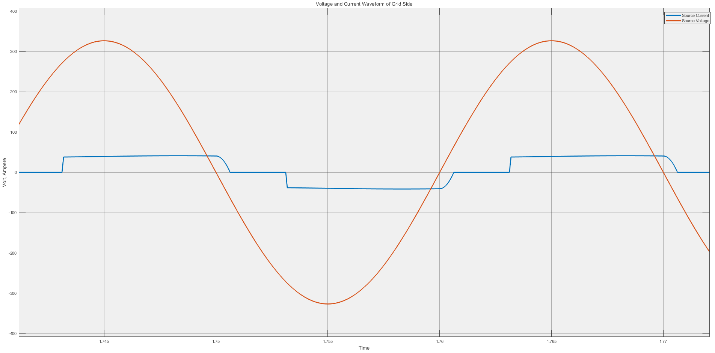


Figure 10

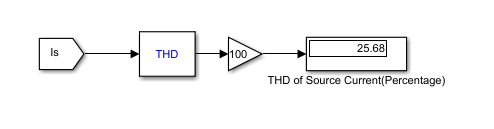


Figure 11

Current waveform is related to diodes. There is no negative current at output voltage and diodes provides that current is circulated. This behaviours reduces the THD of line current because the waveform is much smoother.

The phase difference between line current and line voltage depens on firing angle.( Equation 16)



Equation 18

c)

Fully controlled thyristor rectifier is used for one directional current at positive or negative polarity of voltage.Then, it can be used as rectifying or inverting mode by adjusting firing angle. However, it is not useful because of less average output voltage and worse power factor. The rectifier operates at inverting mode with the help of not firing thyristor. This causes at negative voltage is taken as output and decreases average output voltage. So, the circuit can be improved by connect free wheeling diode. This diodes does not let ouput negative. Then, it increases the avearage output. The rectifier is called as half controlled rectifier. The rectifier can not be used in inverting mode.

Q2) DC Motor Drive

a.

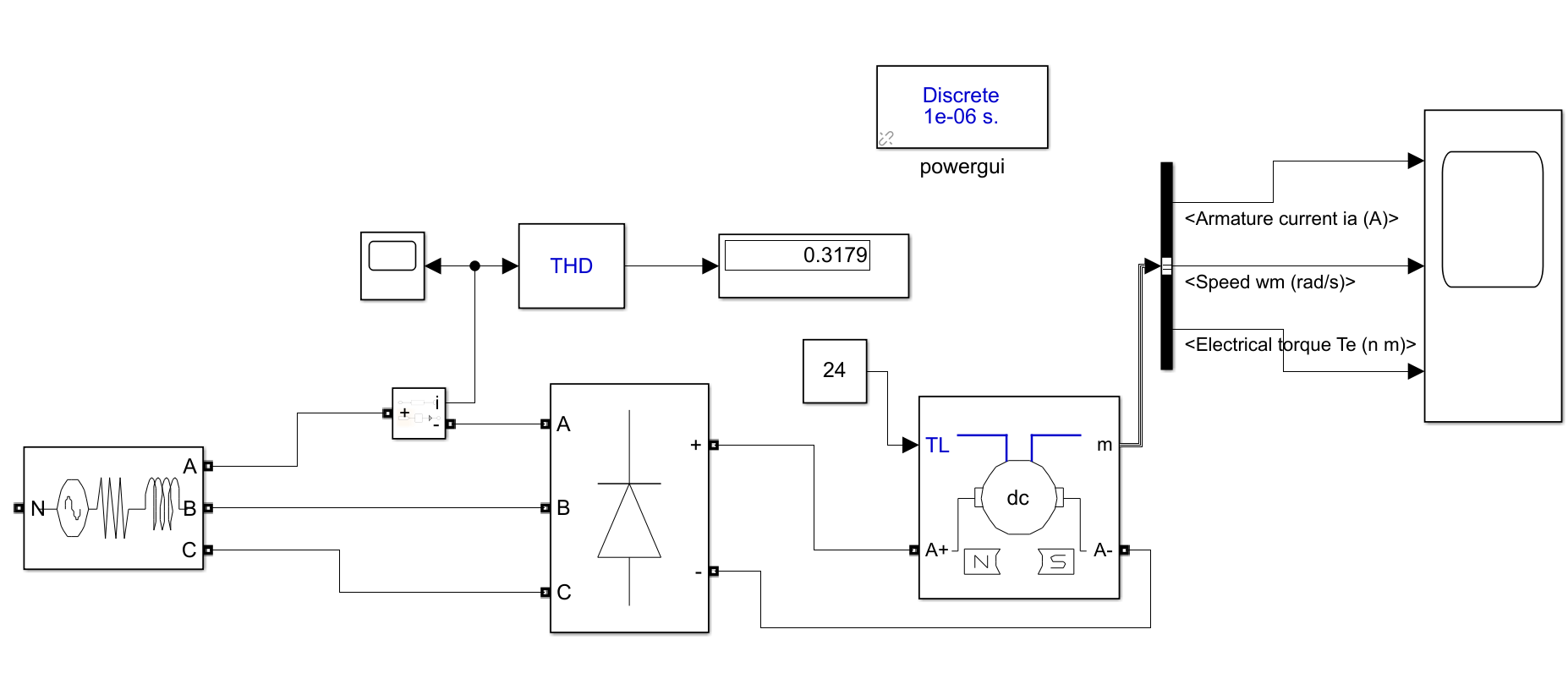


Figure : Circuit simulated DC motor drive

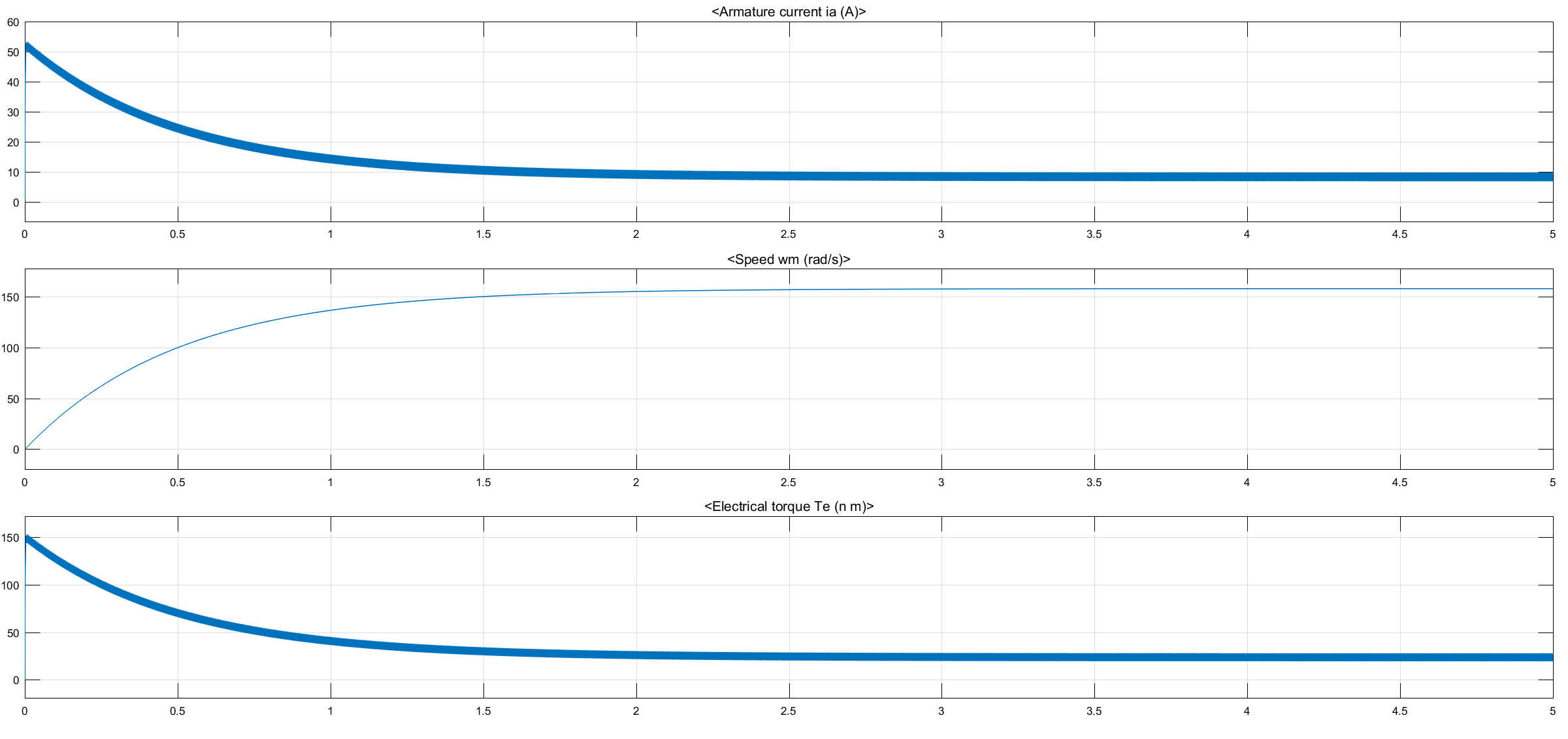


Figure : Armature Current, Speed and Electrical Torque waveforms

b. Note that THD is calculated and displayed on Figure ?? as %31.8

We want to drive our DC motor with a constant DC voltage. However, we have 3Ɵ full-bridge rectifier for DC rectification. As known, 3Ɵ full-bridge rectifier is the reason we have ripple at the output voltage, current and thus torque waveforms.

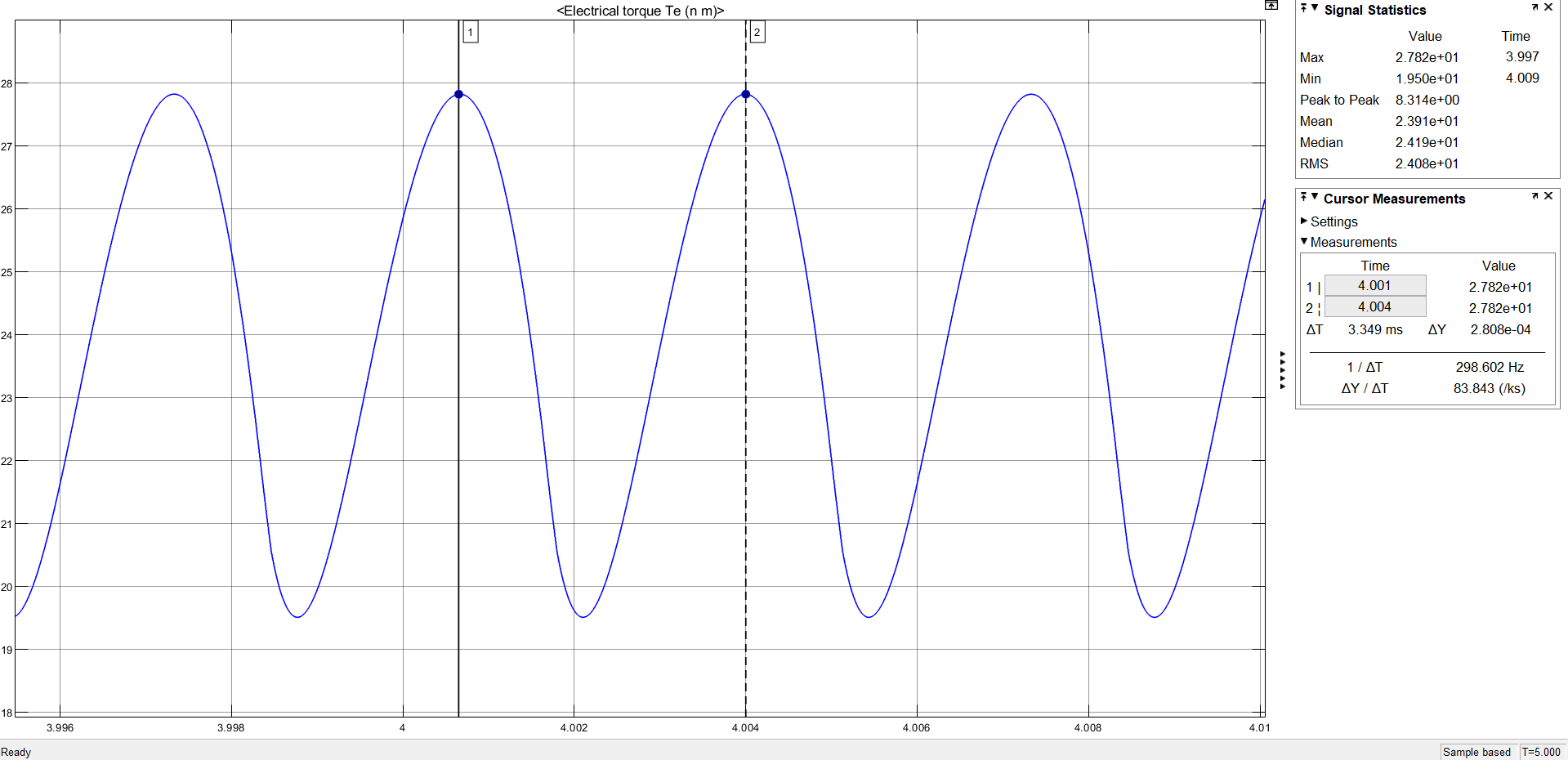


Figure : Electrical Torque waveform

In Figure ??, torque waveform is illustrated at steady state. When the cursor measurements are done, we see that torque waveform has 299Hz frequency. We expect it to be happen because at the output of 3Ɵ full-bridge rectifier, we have 6 pulses in each cycle which corresponds to 50Hz\*6=300Hz.

In magnitude case, the ripple is considerably high which oscillates between 19.5Nm to 27.5Nm where the average is 24Nm. The ripple is more than %10. In practice, it may cause problems and it should be decreased to a reasonable value.

c. To reduce the ripple, we can connect a parallel capacitor to load or connect a series inductor to load. By this way, we can reduce the output torque ripple by smoothing the current waveform and hence torque.

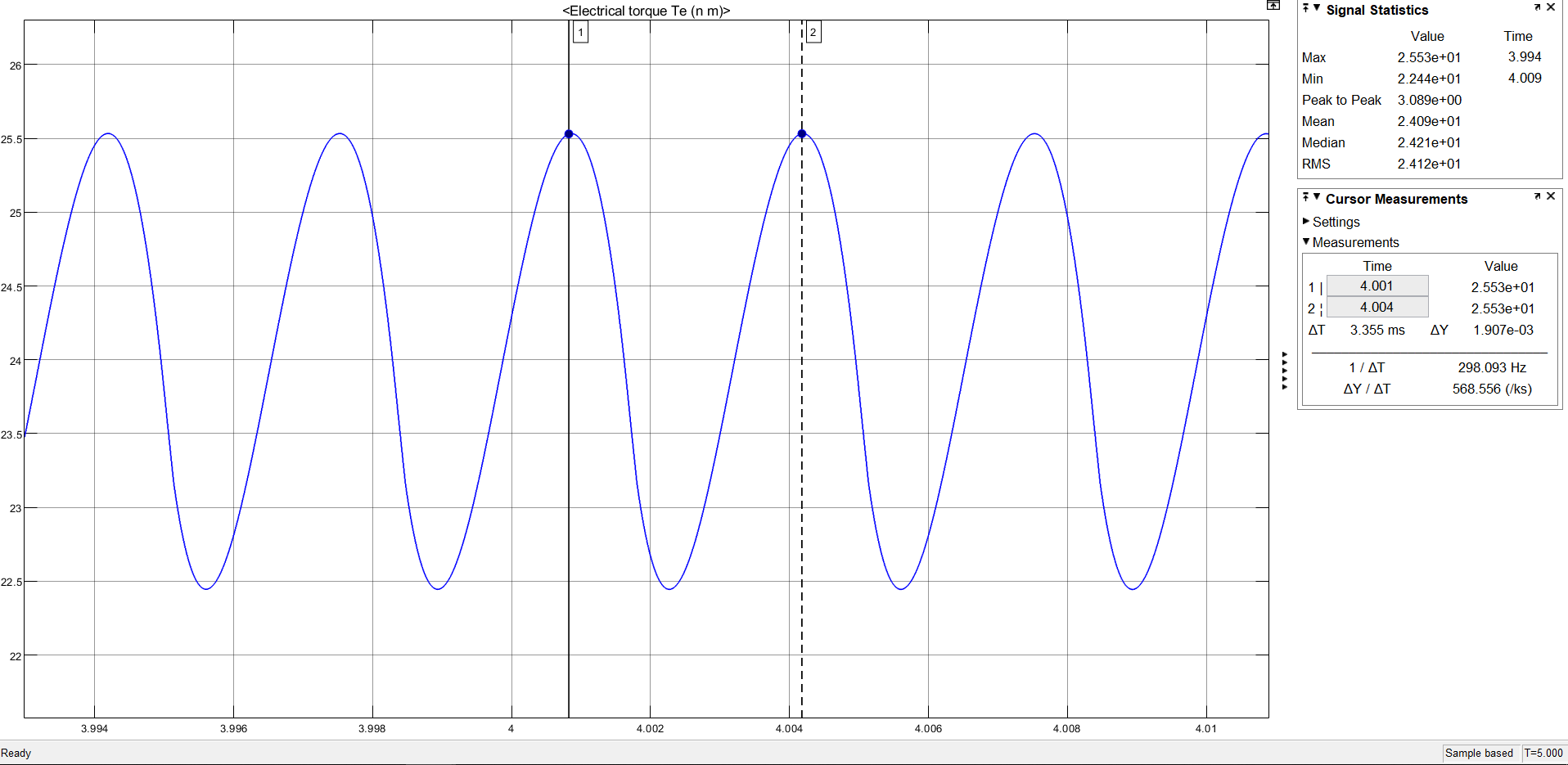


Figure : Electrical Torque waveform with L = 0.02H

As shown in Figure??, a series connection of L=0.02H reduces torque ripple about %6.

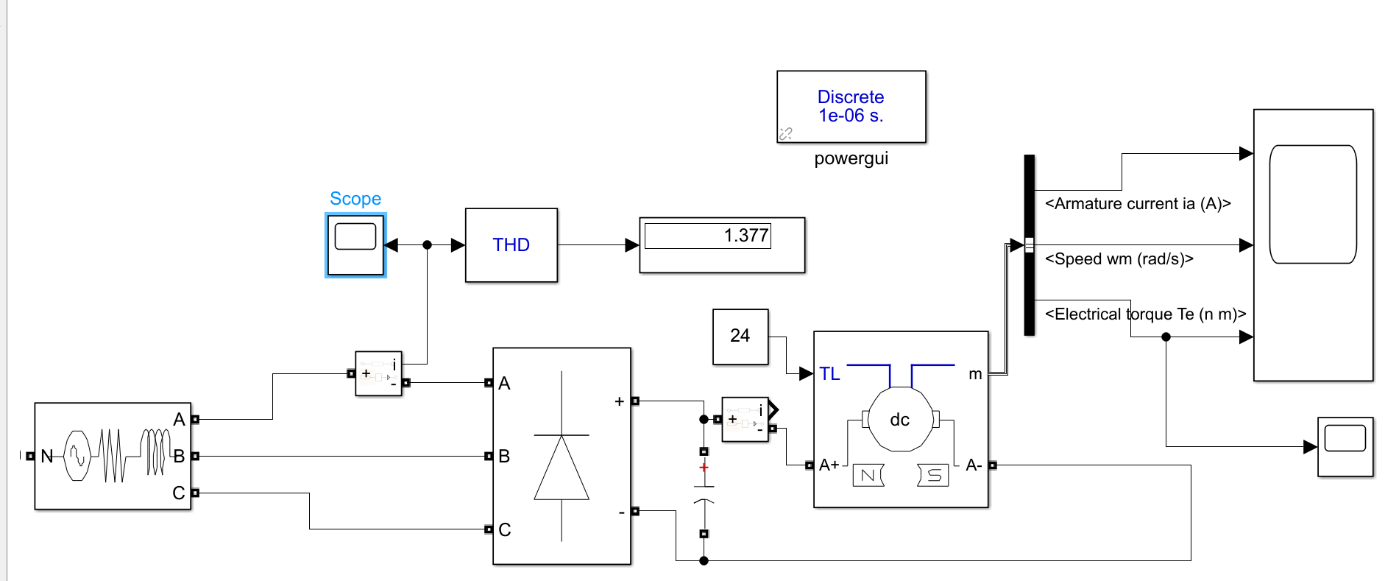


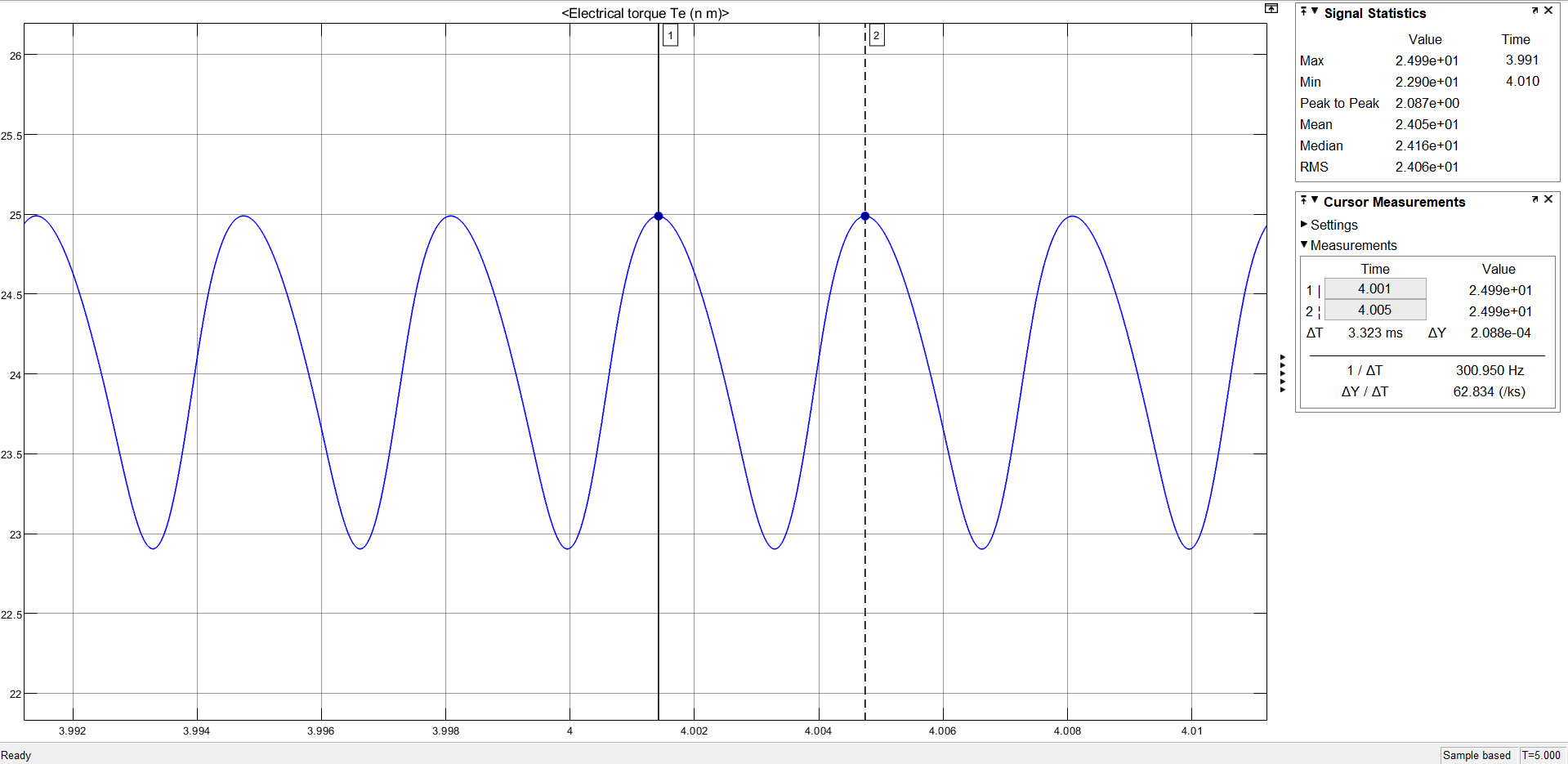
Figure ???: Circuit simulated with parallel capacitor of 1mF

Figure : Electrical Torque waveform with C = 1mF

As shown in Figure??, a parallel connection of C = 1mF reduces torque ripple about %4.

Although adding a parallel capacitor decreases the ripple at the output, it increases the THD to %137 which is shown in circuit schematic illustrated in Figure ???.

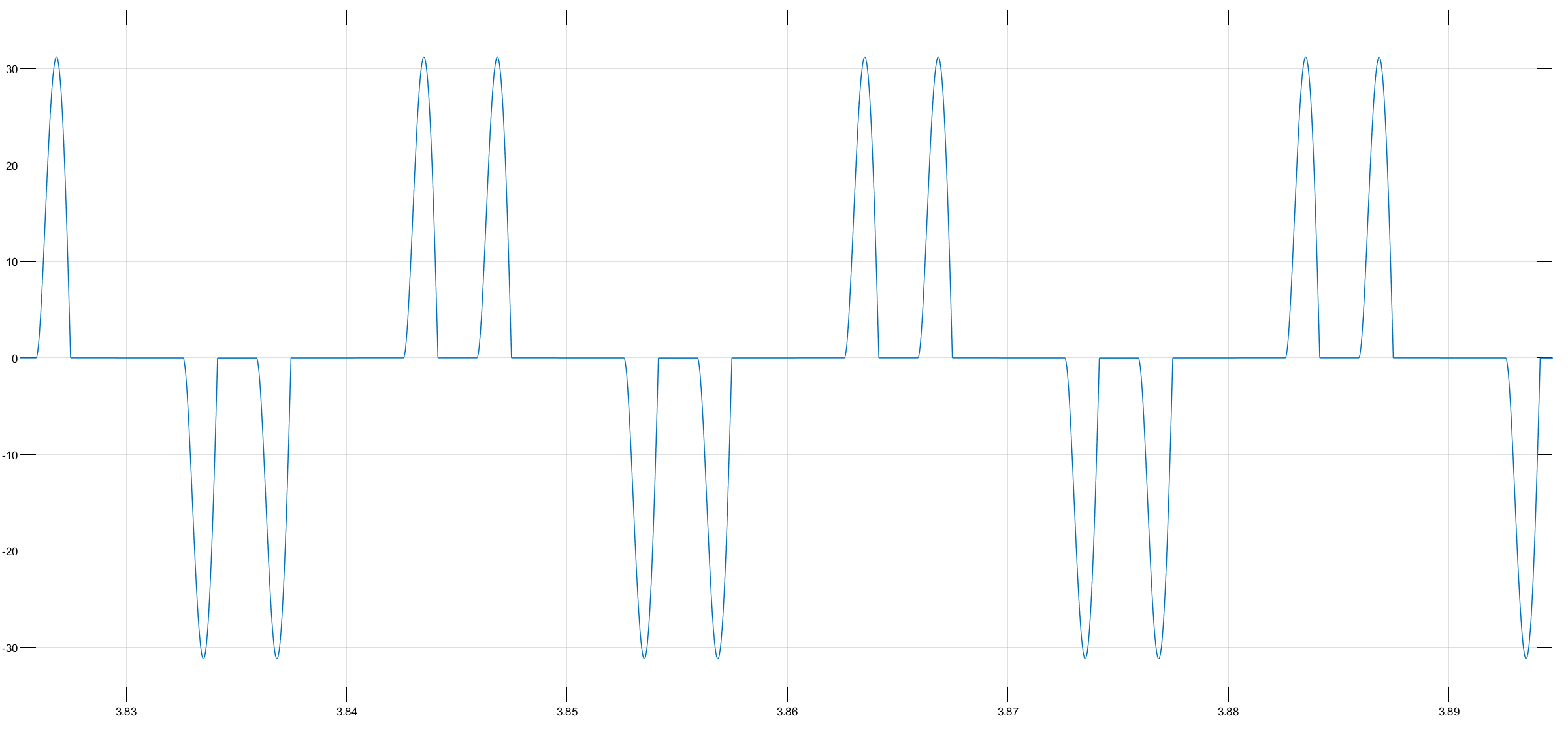


Figure ??: Current waveform when C=1mF is connected

Current waveform of the source side is illustrated in Figure ??. We do not prefer parallel capacitor connection because it increases the THD and current waveform is not desirable.

By connecting an extra circuit component, we can reduce the ripple torque which enables us to have more reliable torque characteristics for motor. Having smoother waveform is also important for mechanical concerns. If we have too much ripple at torque output, shaft of motor cannot be durable comparing with less ripple torque case.

What we trade-off here is adding an extra component to circuit. This increases the conduction losses. Also, for higher voltage values as in our case, we need to implement high voltage and current capacity elements which is directly related with the sizes of components. Having bigger components is hard for implementing circuit into board. Furthermore, it is harder to cool the system with bigger sized components. THD consideration and current waveforms are stated before.

d. Note that following values are calculated at steady state. Current, speed and voltage values are found from graphical analysis on Simulink. All values are approximated accordingly.

Input power = 3\*Single-Ɵ Power input = 3\*230V\*7A = 4830W

Output mechanical power = T\*w = 24Nm\*164.5rad/sec = 3948W

Drive efficiency = 3948W/4830W = %82

For loss calculations;

Power on Source Side = 4764W

Loss on Source Side = 4830W-4764W = 66W

Output Power of Rectifier = 4738W

Then, loss on Rectifier = 4764W- 4738W = 26W

Armature loss = Output Power of Rectifier – Output Mechanical Power

= 4738W-3948W =790W

Q3)

a)

It is called as ‘Twelve-Pulse Rectifier’. This topology is used for improving dc output over single phase rectifier. Output has less harmonics, the frequency of output is 6 times of input. In addition, there are two transformers, one of them Y-Delta, other one is Y-Y. Y-Delta is required to create a 30 degree phase shift. So, six phase is created by using only 2 transformers and three phase sources.

Dc output of the 12- pulse rectifier is the sum of 2 rectifying unit, one is 30 degree shifted.



Equation 1

For diode rectifier, firing angle is zero. Equation 1 shows that average output voltage is bigger than full bridge diode rectifier.

Kinds of this topology are used in the high voltage DC application. Output level is increasing and ripple is decreasing without using capacitance and inductance filter. For the HV DC rectifying, filtering to output requires more cost components like capacitor and inductor.

The multi phase converters like 12 pulse branch single-way and bridge rectifier. Some converters are 3 phase single way, 6 phase single phase, 6 pulse bridge, 24 pulse and 48 pulse bridge rectifier. These rectifiers can be compared in respect to average output level, output ripple frequency and output ripple. Number of phases increases the output voltage and decreases the ripple and ripple frequency. In addition, bridge rectifiers are better than single way rectifiers with respect to output voltage and ripple value if the phase numbers are equal.

b)

# Simulation Setup and results for 12-Pulse Rectifier

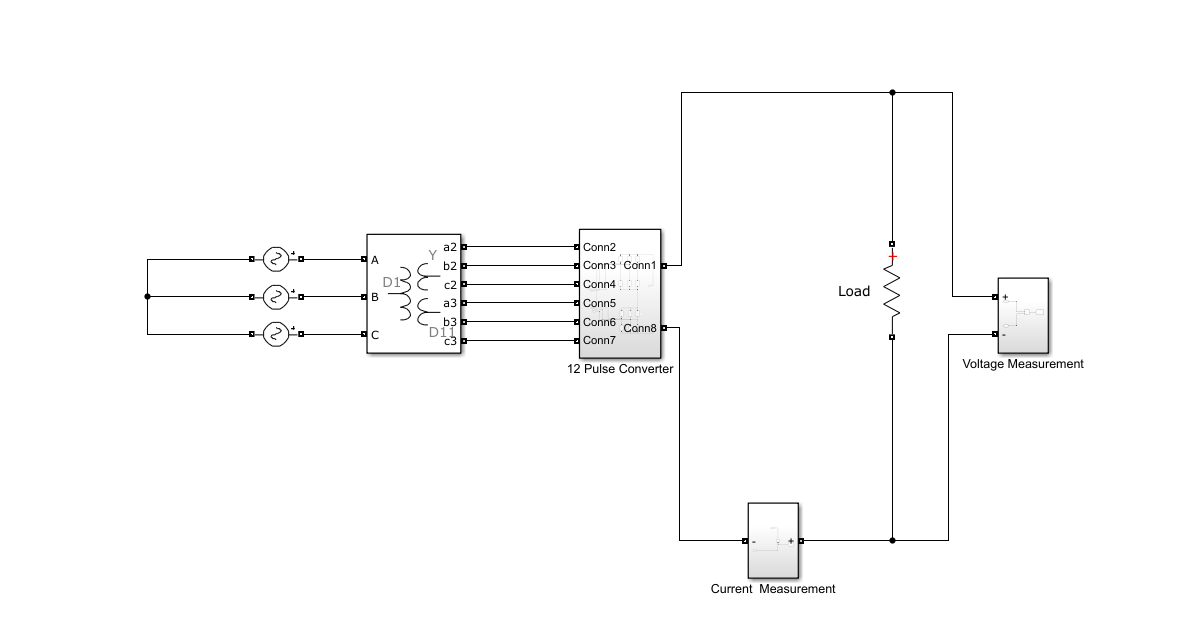


Figure 12

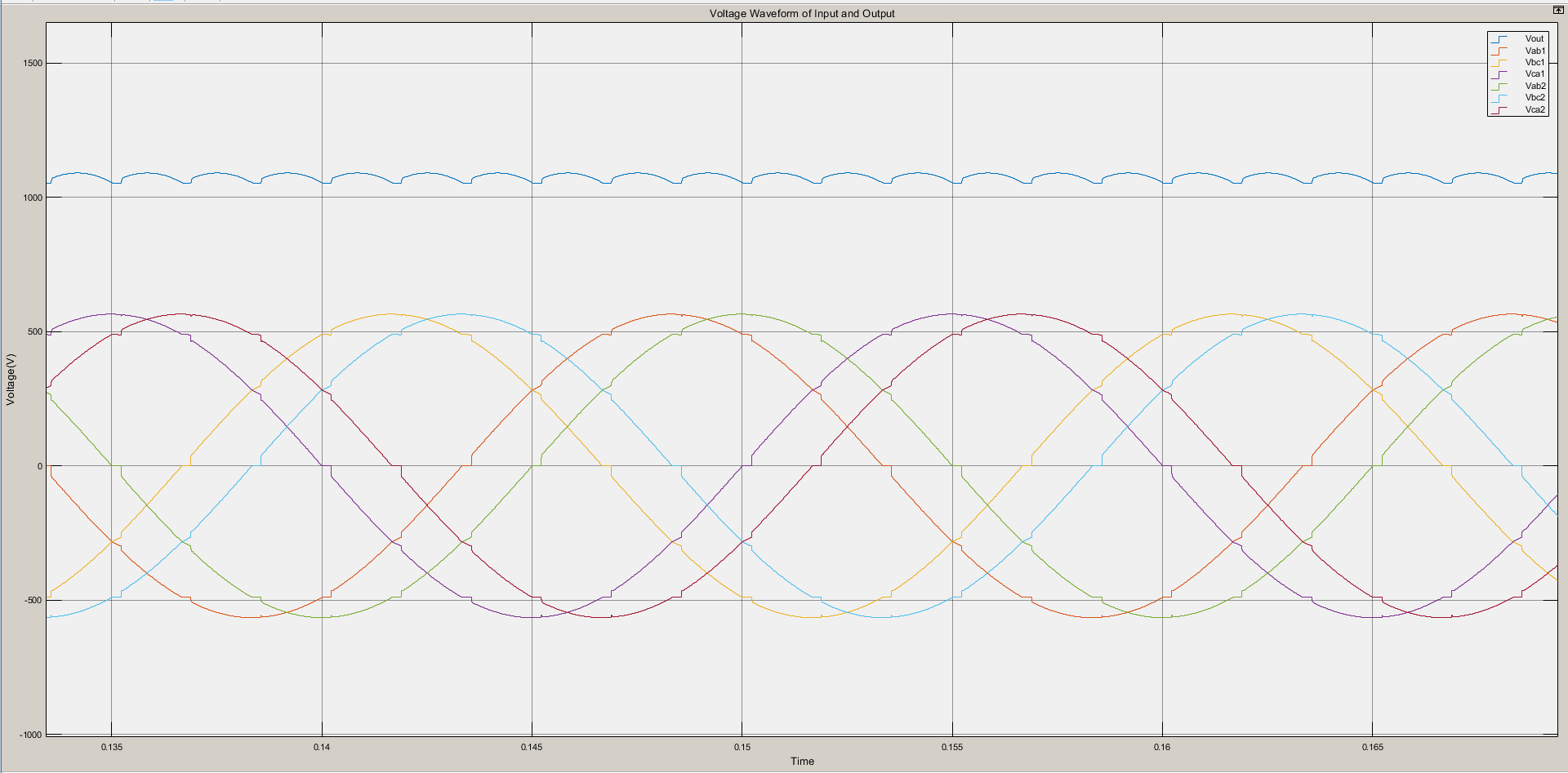


Figure 13

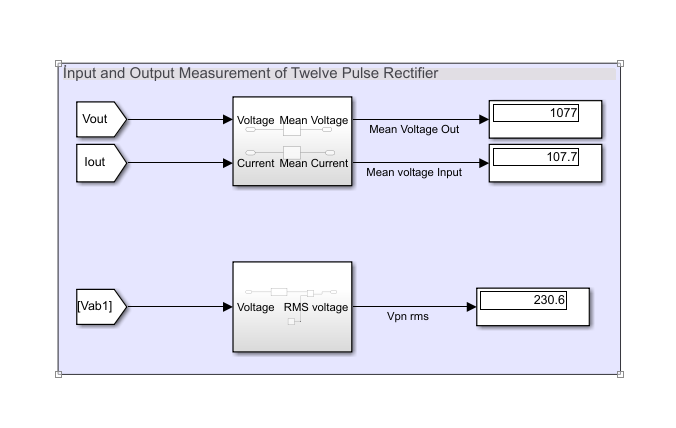


Figure 14

# Simulation Setup and results for Full Bridge Rectifier

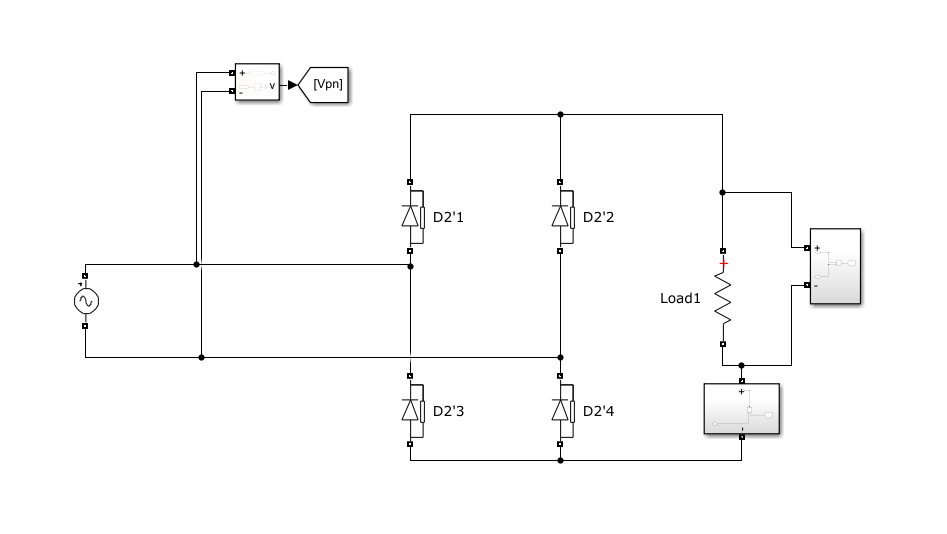


Figure 15

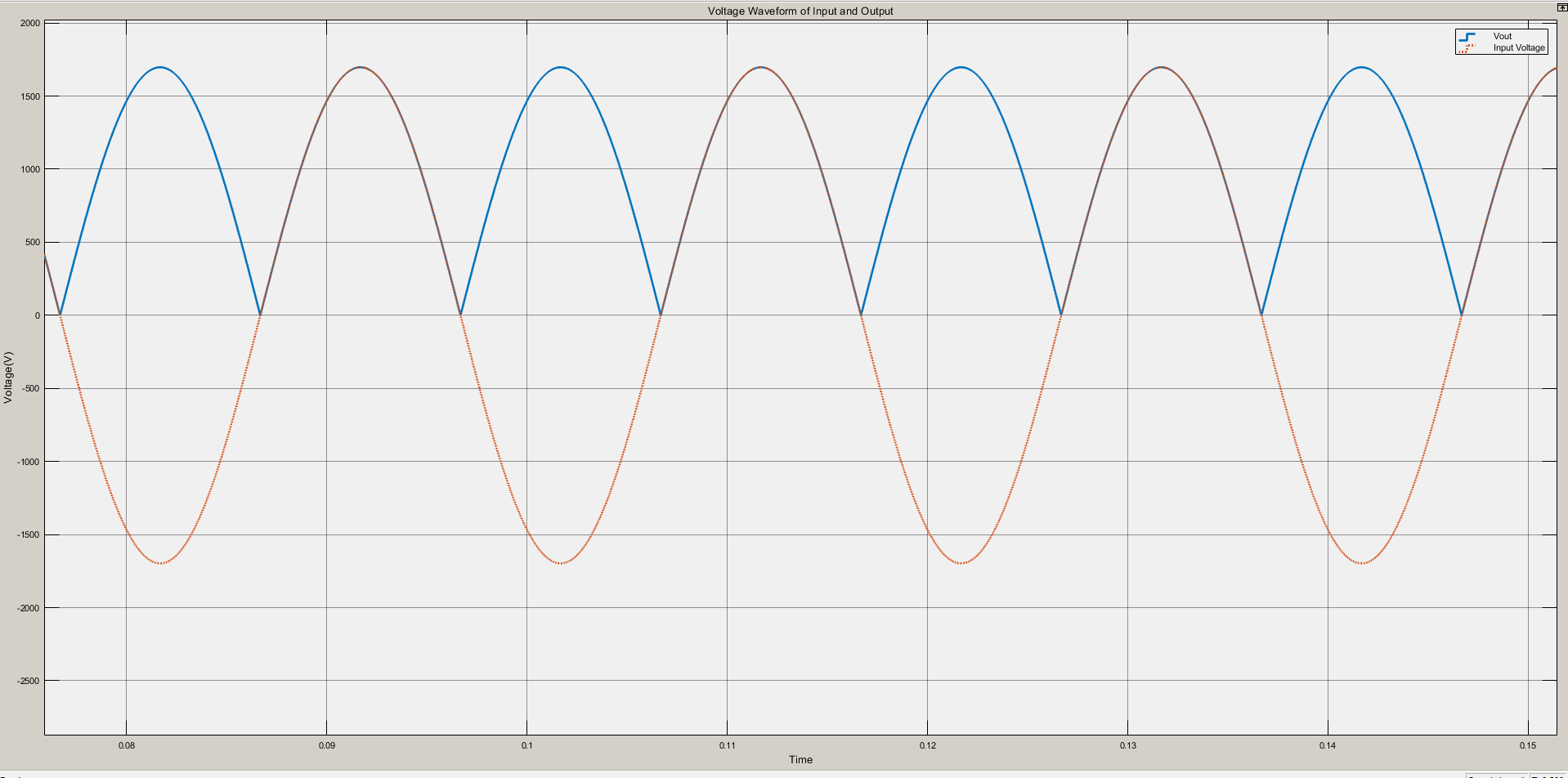


Figure 16

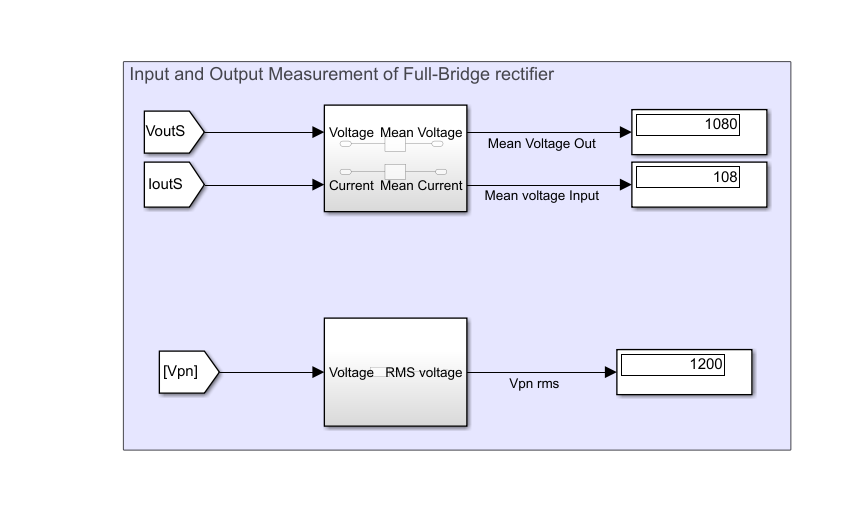


Figure 17

# Comparison

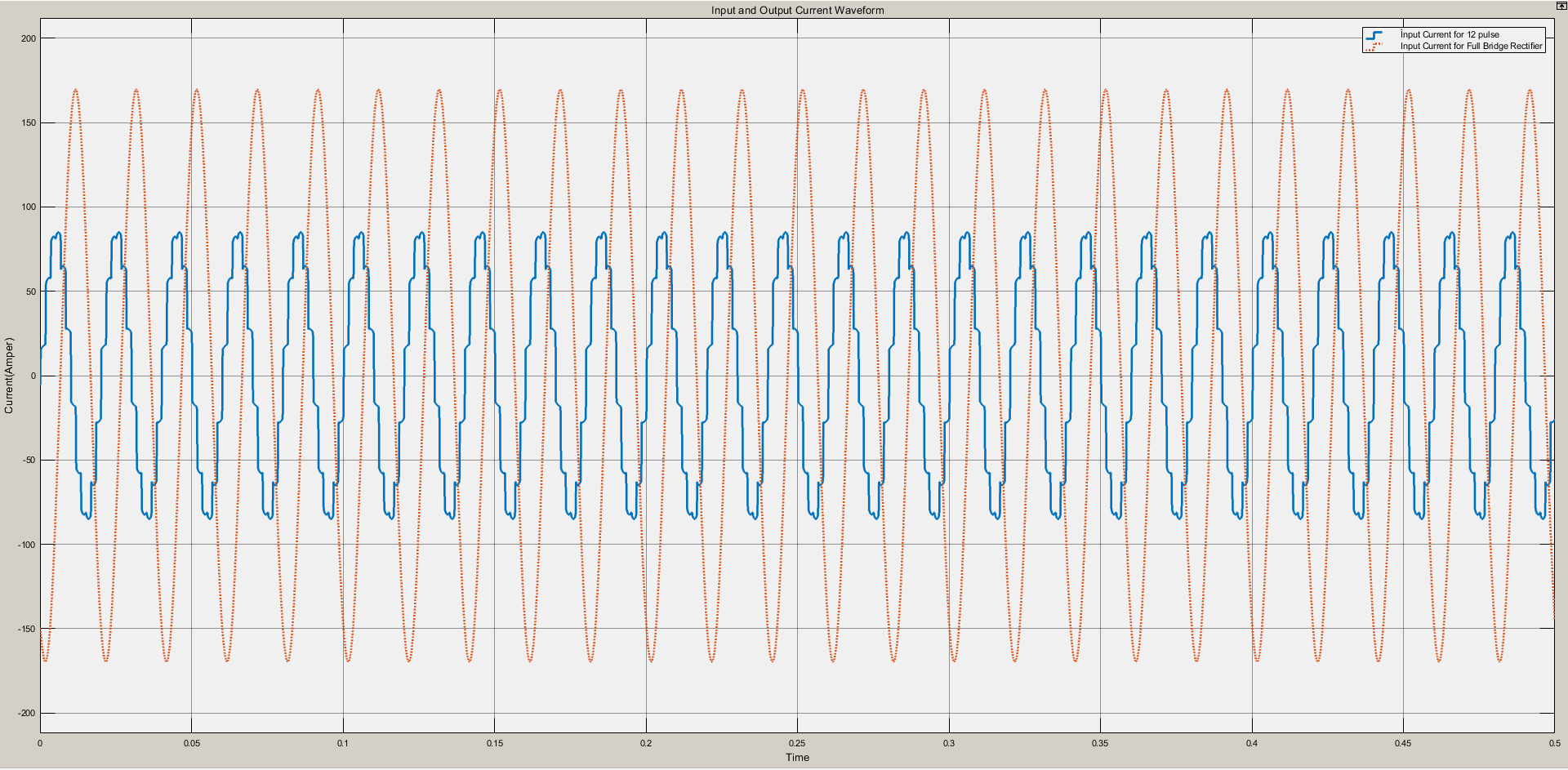


Figure 18

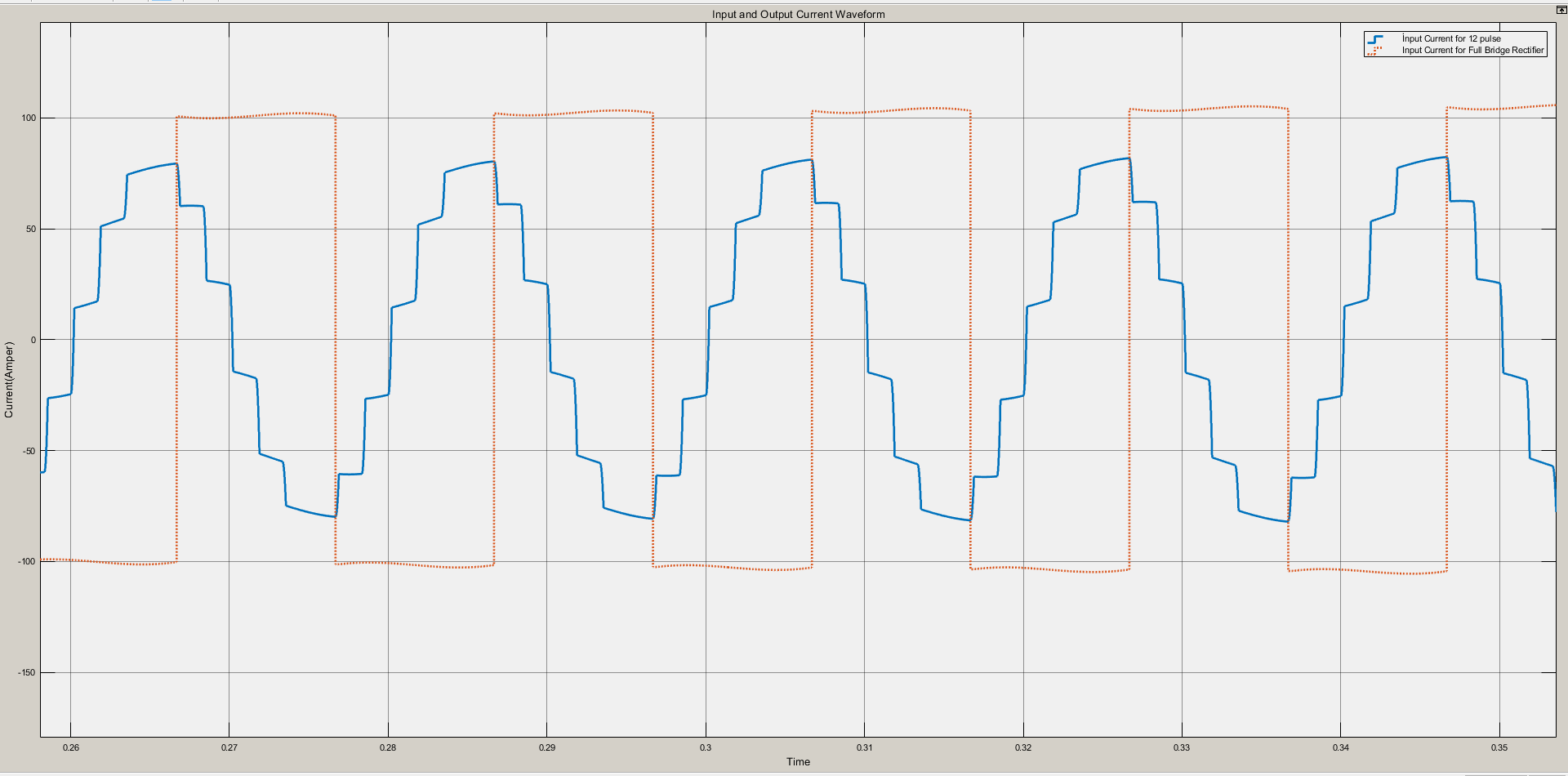


Figure 19

There are some topics that is compared to rectifiers. One of them is output voltage level. 12 pulse rectifiers have more average output level with respect to full-bridge rectifier. 12 pulse rectifiers can be used HV DC converters for this characteristic. In addition, output ripple is important for the converter’s quality. 12 pulse rectifiers have lower ripple than full bridge rectifier and it is not required to use filters. Source side current THD is another topic. For comparing THD of line current, the circuit is installed as constant current load. Figure 18 and Figure 19 shows that line current of 12 pulse rectifiers draws like sinusoidal current while full-bridge rectifier draws square waveform current. These topics shows that 12 pulse is more advantageous than full- bridge rectifier. However, for the 12 pulse generation from 3 phase sources, there is a required two transformers. It increases the cost of rectifier. Until the voltage is very high, 12 pulse rectifiers are not sensible.

Conclusion

In this document, controlled rectifiers with different topologies are analysed. The effect of firing angles onto output voltage and currents and the resultant effect of THDs and effects are examined. Characteristics for each topology is mathematically derived and explained respectively.

DC motor drive which is fed by 3-phase AC grid, rectified with full-bridge rectifier, is analysed. Output waveforms are illustrated such as speed, back emf voltage and armature current etc. Two methods, combining capacitor and inductors accordingly, are proposed to reduce the ripple at the output torque which is related with the output current. Power and efficiency calculations are done. They are illustrated in the pie chart.

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.

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