Middle East Technical University
Electrical & Electronics Engineering

EE463 Hardware Project – AC to DC Motor Drive
Simulation Report
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Team Ree-Wired
Burak Yalçın – 2167534
Ayşe Beyhan Türkyılmaz-2232825
Mehmet Gürtekin-2166593

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Introduction

This simulation report is prepared for the hardware project of EE463 class for Fall 19-20 semester. This project requires the team to design and implement an AC to DC motor driver on hardware. In the following subsections, the expectations from the drive (a project definition in a sense) and the design options for such a motor drive are explained. A number of possible topologies will be investigated and compared by their advantages and disadvantages, in order to propose the topology to be used. Then this offered topology is to be examined thoroughly with simulations involved. Lastly, how to implement this topology will be discussed.

Project Definition

In this project, the team is expected to design an AC to DC converter topology and to drive a separately excited DC Machine. The driven machine is to be mechanically coupled to another DC Machine and is to be loaded with it.

The DC Machine specifications are given as follows.

Rated Voltage	220 V
Rated Current	23.4 A
RPM	1500
Armature Winding	0.8 Ohms, 12.5mH
Shunt Winding	210 Ohms, 23 H
Interpole Winding	0.27 Ohms, 12 mH

Overall, keeping the bonuses out of the equation, what is expected from the team is the design of an AC to DC Converter circuit.

AC to DC Converter – Options

As mentioned in the project definition part, the main purpose is to take a 3 or 1- phase AC signal and convert this to a DC voltage in order to drive the DC Machine. To achieve this, there exist two reasonable methods:

- Utilizing AC-to-DC controlled rectifiers. Directly converting an AC signal to a DC signal with adjustable magnitude.
- Rectifying the AC voltage into DC in an uncontrolled manner, then changing the level of this DC voltage with a DC to DC converter.

The topologies employing either of these two proposed methods are to be examined in the following subsections.

Discussions on the advantages and disadvantages of each topology are present.

Single-Phase Diode Rectifier & Buck Converter

In a single-phase diode rectifier, the output voltage cannot be adjusted by any signal applied externally, which is the case for any rectifier topology which does not enable controlled dc output.

Due to the fact that the output DC voltage level cannot be controlled, additional circuitry is needed to adjust the magnitude of the output voltage. For this purpose, a DC-to-DC converter topology is needed, probably a step-down type in our application.

As a disadvantage of this topology, using only one phase causes ripples in the output and makes the waveform at the output less DC like. When the single-phase full-bridge rectifier is fed with the purely sinusoidal grid voltage, the output is observed to be changing from zero volts to the peak value of the grid voltage. Ripple is very high in this case and that is definitely not desired. This situation can be overcome by filtering with capacitors. But the required capacitance values result in sizable components, which is a problem when aiming for compactness.

Single/Three-Phase Thyristor Rectifier

Thyristor rectifiers are used mostly in high power applications due to the fact that thyristors have high voltage and current handling capability. Although it is possible to use thyristor for our application, it comes with some complexity in the application.

When the controlled rectifier topologies are considered, the advantage of using such topologies would be to change the level of the output voltage with no need for additional configurations, so there is no need for extra components and corresponding selection process. However, driving the thyristors can be a little bit tricky. They should be synchronized with the grid voltage and that requires a transformer. Also, a driver IC comes with its own extensions. Complexity is something we tried to avoid for this project and thyristor rectifiers have that.

Additionally, the output of the thyristor rectifier configurations display higher ripples than that of the diode rectifier configurations which would probably require using larger filtering components. An additional bulky capacitor is again the case here and we do not want that.

Three-Phase Diode Rectifier & Buck Converter

Considering that both the single-phase and three-phase diode rectifiers utilize only diodes, the previously mentioned situation of not being able to control the output voltage level in the single-phase diode rectifier is also valid for the three-phase full-bridge diode rectifiers.

However, the three-phase diode rectifier, when compared to the single-phase diode rectifier, produces less ripple in the output. Therefore, the obtained dc voltage is observed to be much closer to an ideal dc. Filtering might not be needed at all for our means with a three-phase rectifier.

Buck converter extension is again inevitable here. However, it is not a problem since its topology is simple and easy to build. Only a pulse generator is to be added to the topology and it can be built by using a 555 Timer IC in astable mode.

This topology will be our choice.

Proposed Design

As mentioned above, a three-phase diode rectifier combined with a buck converter will be our choice. How to implement the circuit and the components used will be mentioned in this section.

Diode Rectifier Design

Building a rectifier is not a complicated task but the important thing is to choose the proper components.

Diodes that will be used in our application should withstand at least 200 V, grid side peak voltage. Simulations show that this is the maximum voltage we will be drawing from the VARIAC. And considering that the motor has 23.4 A as rated current, their current capability should also be high. 35-40 A will keep us on the same side we assume.

A compact rectifier body can be our choice here. Datasheets of possible choices can be seen in the Appendix section.

Buck Converter Design

In the selected topology, after the three-phase full-bridge diode rectifier, there is a buck converter circuit which is used to change the motor speed by adjusting its output voltage. For the switching unit of this circuitry, there are options like MOSFETs and IGBTs. IGBTs have higher voltage and current ratings. On the other hand, MOSFETs are faster devices. IGBT is still an option for our topology but we are closer to use a MOSFET and used a MOSFET in our simulations, too. The input-output relation of the buck converter is given in the following equation:

$$V_O = V_{in} * D$$

In theory, obtaining an output voltage between V_{in} and zero is possible. However, in practical cases, the maximum value that is feasible to use for D is around 0.7. Therefore, in our simulations we tried to obtain the maximum speed of the motor for D is equal to 0.7. Moreover, in a buck converter circuit, switching frequency, inductor and capacitor values are needed to be selected. The relation between output voltage ripple and selected features are given in the following equation:

$$\frac{\Delta V_o}{V_o} = \frac{(1-D)}{8 * L * C * f_s^2}$$

From this equation, as the switching frequency increases, the output voltage ripple decreases. On the other hand, increasing switching frequency results in higher switching losses and increases the heat produced. Thinking in both ways and making some researches on the internet, we decided to select out switching frequency as 1kHz. The inductor and the capacitor in the buck converter are acting as a low pass filter. The purpose of this filter is to eliminate undesired components at the motor. Eliminated frequency components at the filter can be calculated from the equation given below:

$$f_{corner} = \frac{1}{2 * \pi * \sqrt{L * C}}$$

As the corner frequency decreases, the capacitance and inductance become larger. Considering this fact and available components on markets, we selected our corner frequency as 60 Hz and corresponding values are 470uF for the capacitor and 15mH for the inductor.

Pulse Generator for MOSFET

MOSFET in the buck converter needs a get current to open and to operate buck converter as desired, a repetitive and controllable gate current is required. Duty cycle of the pulse will determine the output voltage of the buck converter, therefore it is of utmost importance for our design.

Driving 555 Timer IC in astable mode provides us repetitive pulses as long as the circuit is powered. The duty cycle and the frequency of the pulses can be adjusted by externally connected resistances.

No feedback mechanisms to control the speed of the motor is included yet. If such an attempt is to be taken in the upcoming weeks, employing an Arduino board for our means would be a wiser choice. Switching from 555 to Arduino will not be a problem if need occurs.

Simulation Results

After designing our circuit completely, we created it in Simulink as indicated in Figure 1. Then we run a simulation to obtain rated speed in the motor at the practical full duty cycle and observe the needed current and voltage ratings for the components.

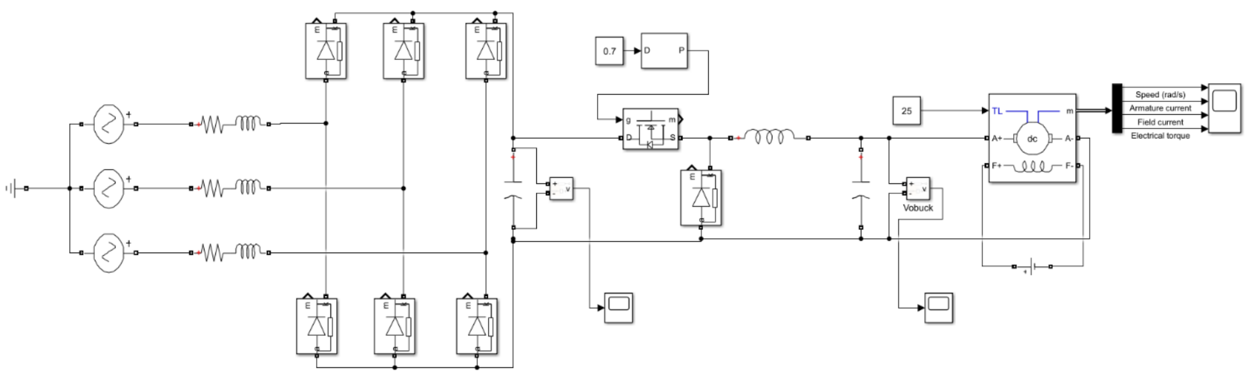

Figure 1. Complete schematic for SIMULINK

For the practical maximum duty cycle value (0.7), we wanted to have rated speed at the motor. After some simulations, we found out that the needed phase to neutral value for the input voltage is 165 V peak. Under these conditions, motor characteristics can be seen in Figure 2. At steady-state, motor speed is equal to 157 rad/s which corresponds to 1500 rpm (rated speed of the motor). We ran the simulation for different duty cycle values in order to observe the changes in the motor speed as indicated in Figures 3 and 4.

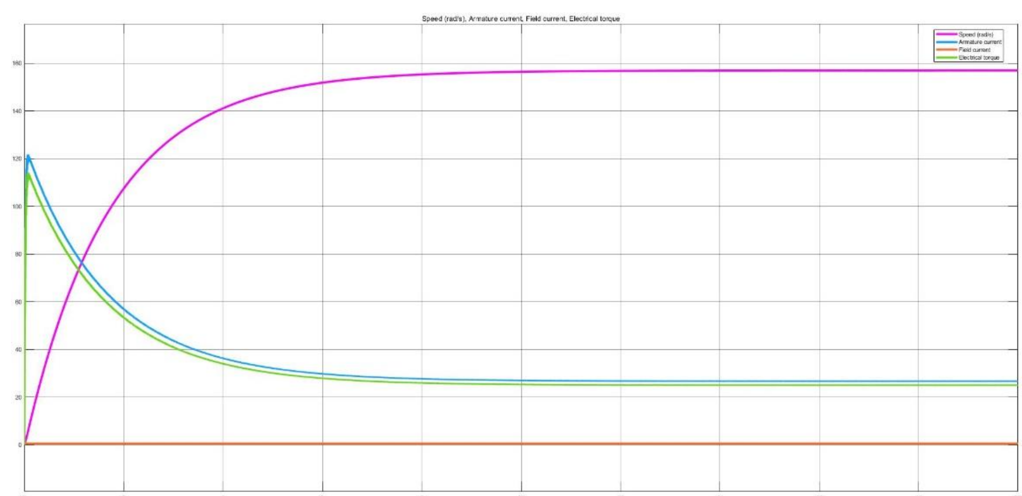

Figure 2. Motor features for D = 0.7

In order to find the ratings for our components, we observed the voltages and currents for different duty cycles on each component. For low duty cycles diode rectifier side has higher voltages and currents. Therefore, determining the needed ratings for rectifier side are done under low duty cycle condition. For the maximum voltage output for the rectifier, duty cycle is zero. Under this condition, the voltage on the output capacitor of the rectifier is indicated in Figure 5. Maximum voltage on this capacitor is 315 Volts in the simulations. Hence, we need a 470uF capacitor with voltage rating higher than 315 Volts. The MOSFET's voltage rating is also determined under this condition since it holds all of the voltage as it is in off mode. Therefore, we need a MOSFET with a voltage rating higher than 315 Volts. For the rest of the ratings, we need to apply the maximum duty cycle. In order to stay in the safe margin, we selected the duty cycle as 0.85.

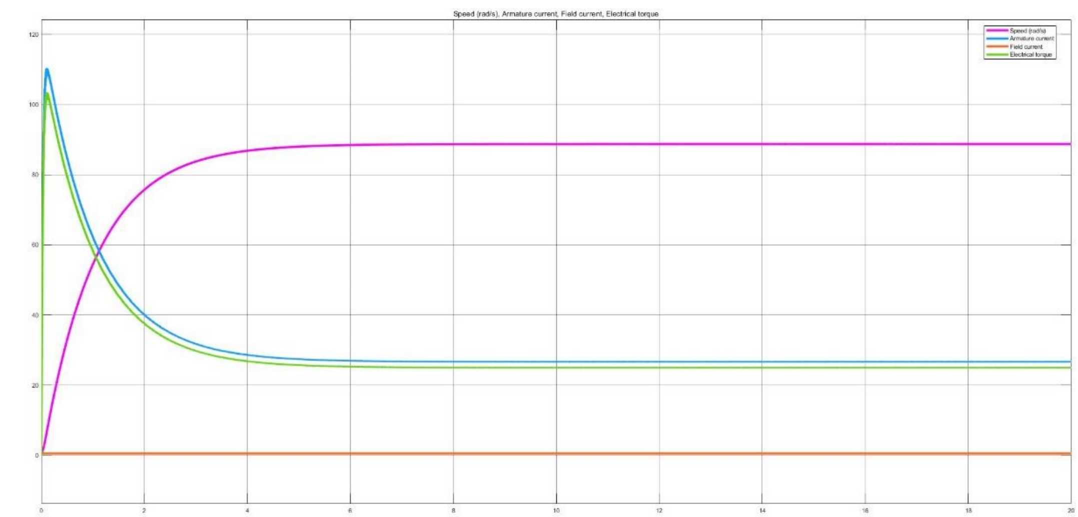

Figure 3. Motor features for D=0.4

Under the condition of duty cycle equals to 0.85, the current of the inductor in the converter is indicated in Figure 6. The current at the steady-state is 27 amps. However, at the start really high currents are passing through the inductor and these currents are important to work safely. Thus, the high starting currents should be controlled via feedback control and the current rating of the inductance should be higher than 35-40 amps. The MOSFET current is the same as the inductor current in this topology, so MOSFET's current rating should also be higher than 35-40 amps. The maximum output voltage of the converter is 192 Volts in simulations. In order to work safely, we need a capacitor with voltage rating higher than 200 Volts for the buck converter.

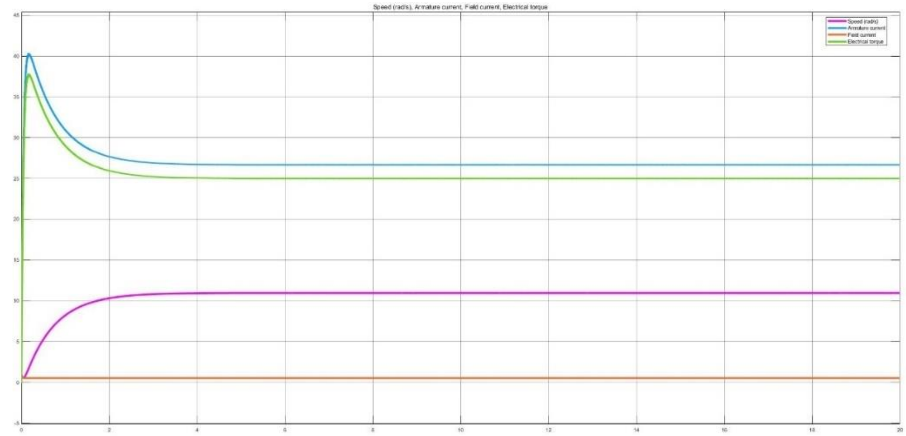

Figure 4. Motor features for D=0.1

Graphs related to some important components under different duty cycle percentages can be found in the following figures.

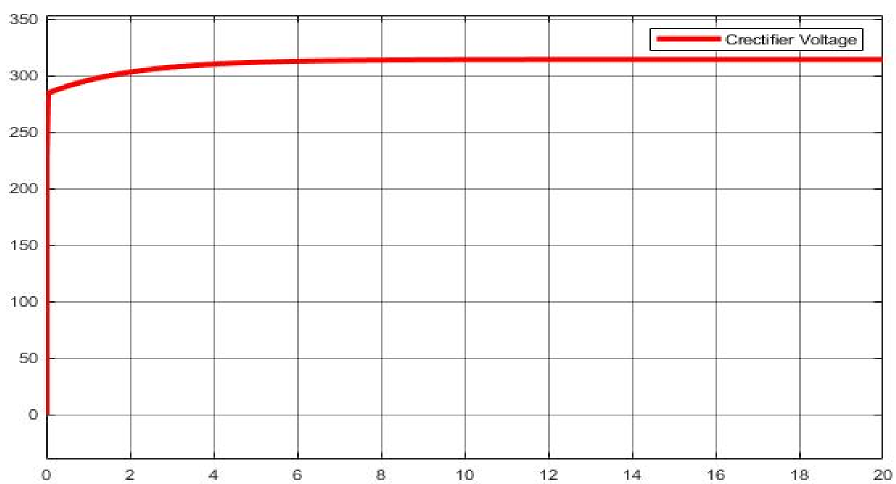

Figure 5. Rectifier capacitor voltage for D=0

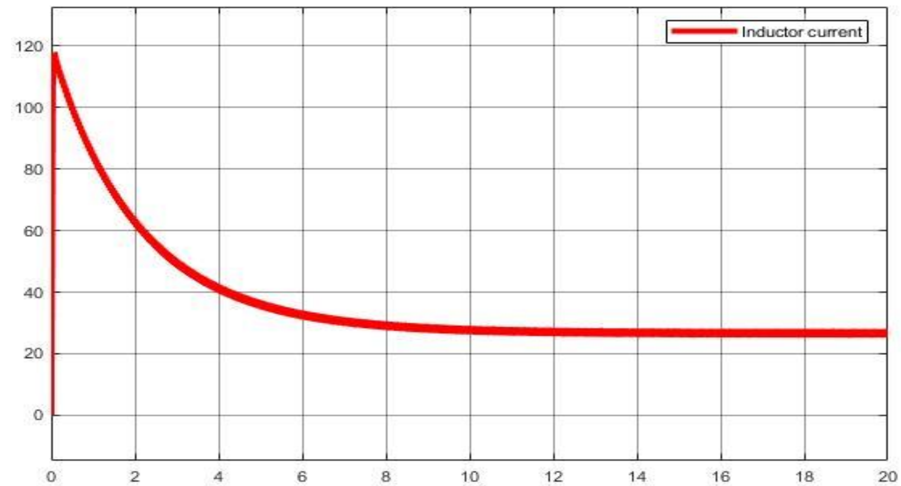

Figure 6. Inductor current for D=0.85

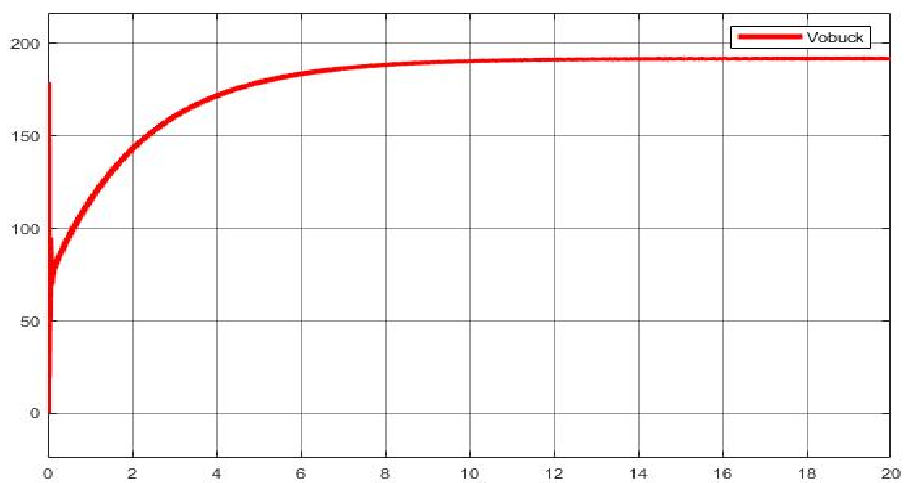

Figure 7. Output voltage of the buck converter for D=0.85

Conclusion

In this report, the aim of the project is specified and different solution methods are discussed. Comparison of advantages and disadvantages of 3 different solutions are presented. The proposed design by the team is the three-phase diode rectifier combined with a buck converter topology. The size of the circuit and the complexity of the design were two main reasons. The chosen topology fits the best for our aims. The simulation results are presented and the parameters are defined to be the closest as possible to the real life situations. Component selection is not thoroughly specified but the main expectations from the components are explained and some reasonable examples are provided.

Appendix – Diode Datasheets

3-Phase Rectifier Bridge: https://cdn.ozdisan.com/ETicaret_Dosya/582454_9707777.pdf

Single Phase Rectifier Bridge: https://cdn.ozdisan.com/ETicaret_Dosya/442977_845594.pdf