MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING

EE463 TERM PROJECT

SIMULATION REPORT

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INTRODUCTION

In this project we are expected to make a driver circuit to drive a DC Motor. This driver will be fed via an AC grid that will be converted to a DC voltage. In this report, topology selection, analytical calculations, thermal calculations, component selection, simulation results and implementation process will be discussed.

TOPOLOGY SELECTION

For the term project, we consider and simulate different topologies. The very first topologies that we discussed are, simple dimmer circuit and alternistor triac driver for motors from littelfuse application note AN1003.
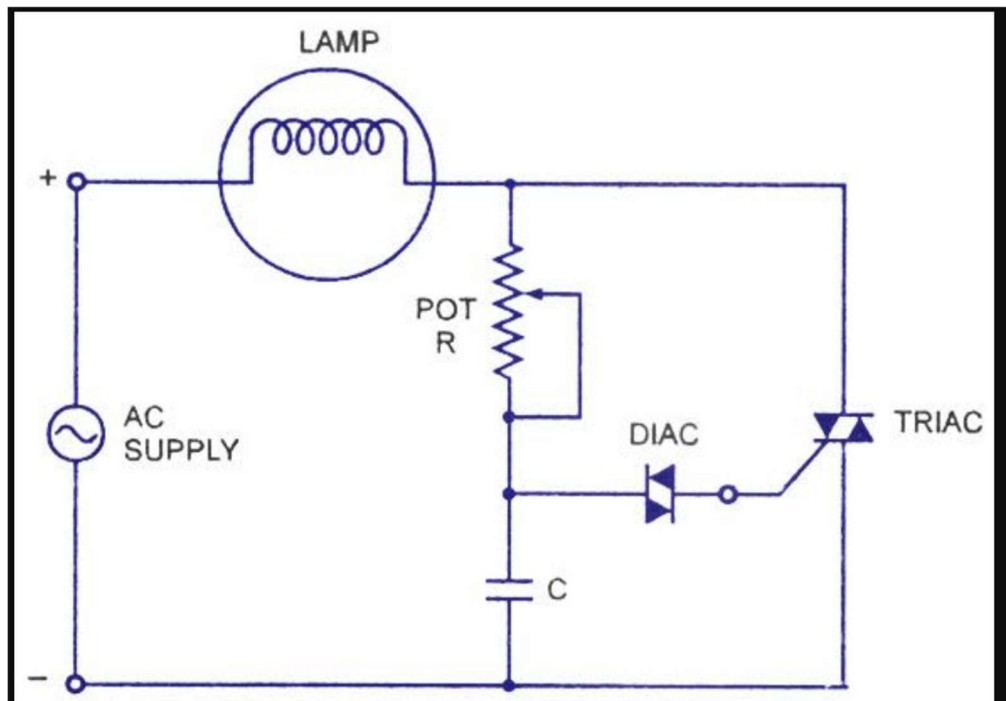
1. Simple Dimmer Circuit:

Figure 1. Simple Dimmer Circuit

Schematic of a simple dimmer circuit can be seen above. As can be seen from the figure, this circuit is mainly used for dimming lamps, however usage of it for inductive loads like motors can be found. So, we can assume that we connected the armature terminals of our motor rather than lamp as a load. When we do that, when the triac is not in conduction, capacitor c charges through resistor and load, when a certain capacitor voltage exceeded, triac is fired through diac, hence discharged the capacitor, and depending on the load current capacitor will be charged again, when triac is in cut-off region. This circuit is a very simple circuit; however, it works in open loop, moreover triac is a 2-way semiconductor, and it will actually apply both positive and negative cycles of the grid directly. Furthermore, there is also a small chance of taking bonuses with that circuit, we eliminated that circuit, but we again made more research on it and found a similar circuit in the application notes of littel fuse.

2. Alternistor Triac circuit:

This topology is actually a modified version of the topology given in the above, we found it in the application note AN1003 of littelfuse.
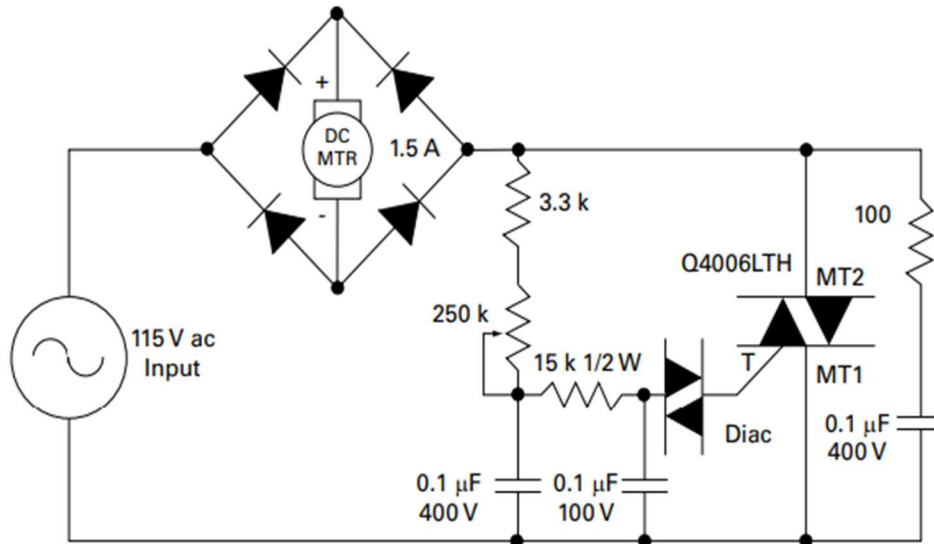

Figure 2. Alternistor Triac driver circuit

As can be seen above, the only big difference between this circuit is the bridge rectifier around the dc machine. With that rectifier, we can be sure that our machine always sees DC voltage. Fundamentals of the circuit are the same. But this circuit is giving us very little chance of taking bonuses and there will be high torque ripple. Hence, we also eliminate this circuit.

3. **Single Phase Controlled Rectifier:**

In this topology for input voltage of 230Vrms, the output average voltage is about 207V. With a firing angle of about 30 degrees, we can achieve 180V output. To truly discuss it, rather than just giving numbers, we decided to simulate it in such a way that if we choose that topology we could build our circuit with that simulation. We know from previous homeworks that, without current control we will face really high inrush currents, to overcome that and get a close loop bonus, we decided to build with a close loop current control. In our simulations we used 4 Thyristors, however we can also use 2 thyristors and 2 diodes in implementation.
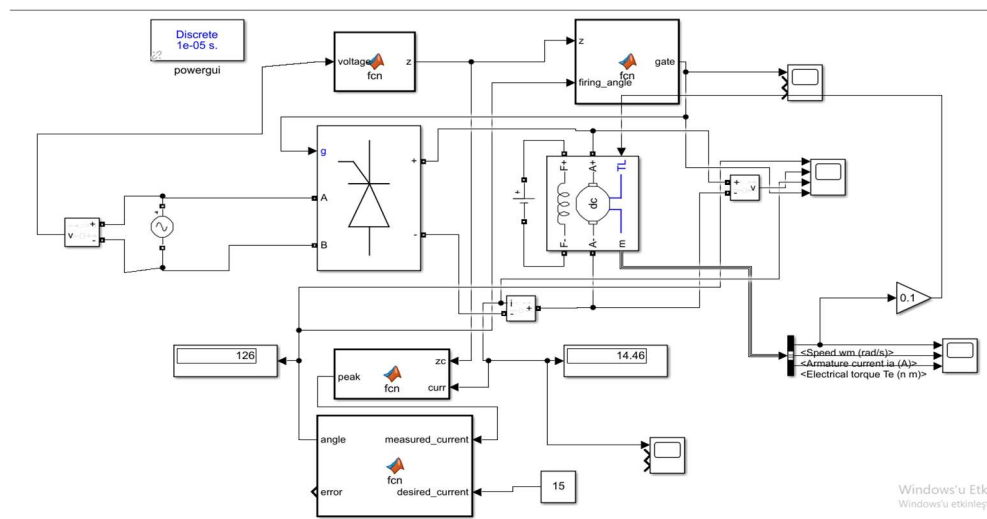
Figure 3. Single Phase controlled rectifier.

Since controlling the thyristors using analog controllers with jellybean controllers is really hard, we decided to use a microcontroller for that purpose. Even though work for microcontrollers in this application is quite lightweight, due to easy fondness of the evaluation boards and easiness of software development, we decided to use a STM32 microcontroller. We created 3 MATLAB functions to mimic the microcontroller and one MATLAB function to mimic the zero-crossing circuit. For the current control part, we used a simple i controller.
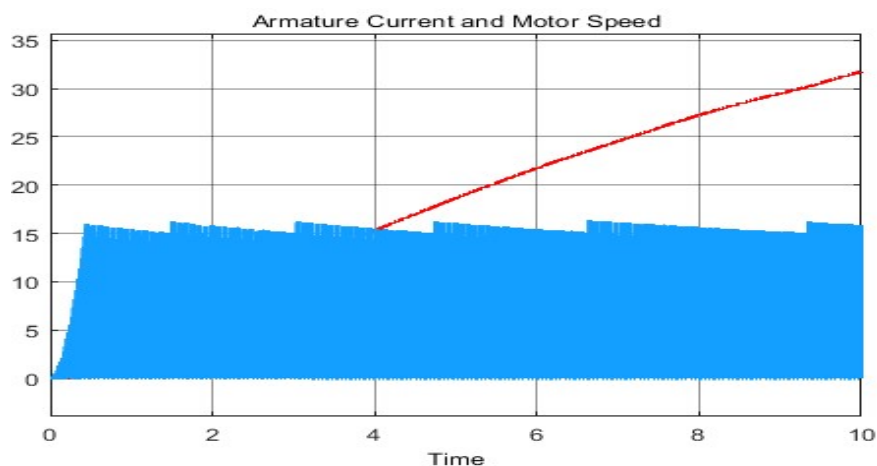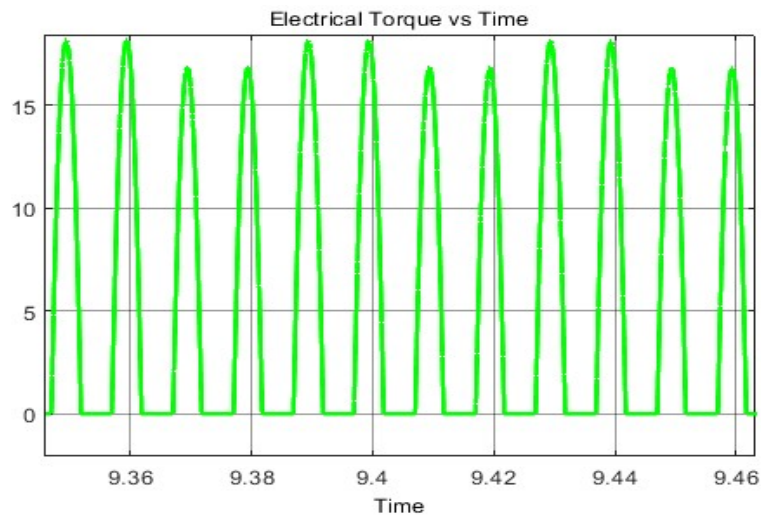
Figure 4. Armature current(Blue) and Motor Speed(Red, rad/sec) vs time

As can be seen from figure above, our current controller solves the inrush current problem but requires further tuning.


Figure 5. Electrical Torque vs time

The problematic situation about this configuration can be seen from the above figure, as can be seen from above, we have really high torque ripple at 100Hz, even though from an electrical perspective it is not a big problem, when we look from the mechanic side it creates problems. Due to high torque ripple bearing losses will possibly increase, life will be reduced, moreover the motor shaft life will be reduced. So, this driver can be chosen but can be better options. This driver's power stage can be implemented using 2 thyristors, 2 diodes, 2 drive circuits for thyristors, one shunt resistor or current sensor(like ACS781).

4. **Three Phase Controlled Rectifier:**

We again simulated this circuit, such a way that we could implement using that simulation if we decide to build it. Our implementation can be found below.
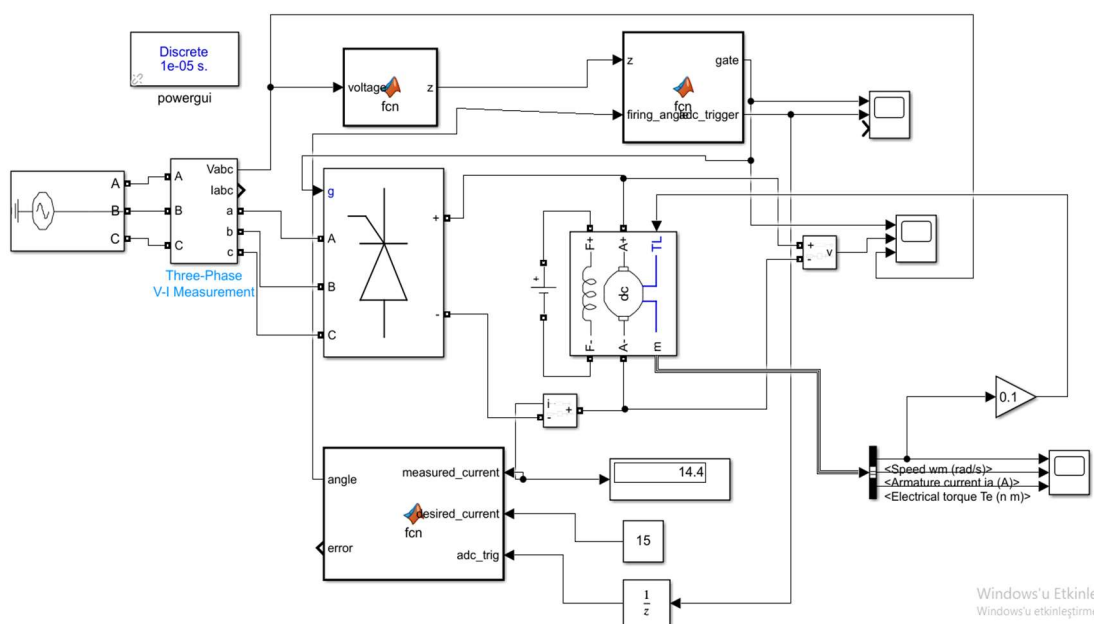

Figure 6. Three Phase controlled rectifier

In this rectifier, it is again possible to implement it using 4 thyristors and 2 diodes rather than 6 thyristors. But we decided to make simulations using 6 thyristors. In this simulation we used 1 MATLAB function as a zero-crossing circuit(it can be implemented in different types, but for our implementations it is actually just an optocoupler with small delay) and 2 MATLAB functions to mimic the microcontroller.
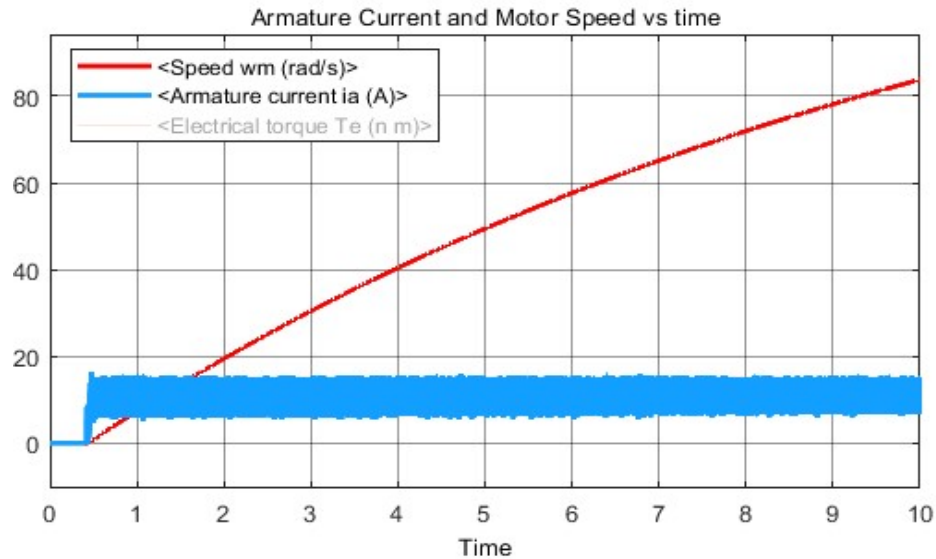
**Figure 7. Armature Current and Motor speed graph**

As can be seen from the figure above, again we don't have an inrush current problem, thanks to our current controller, and we can also say that we have a better tuned current controller in this simulation.
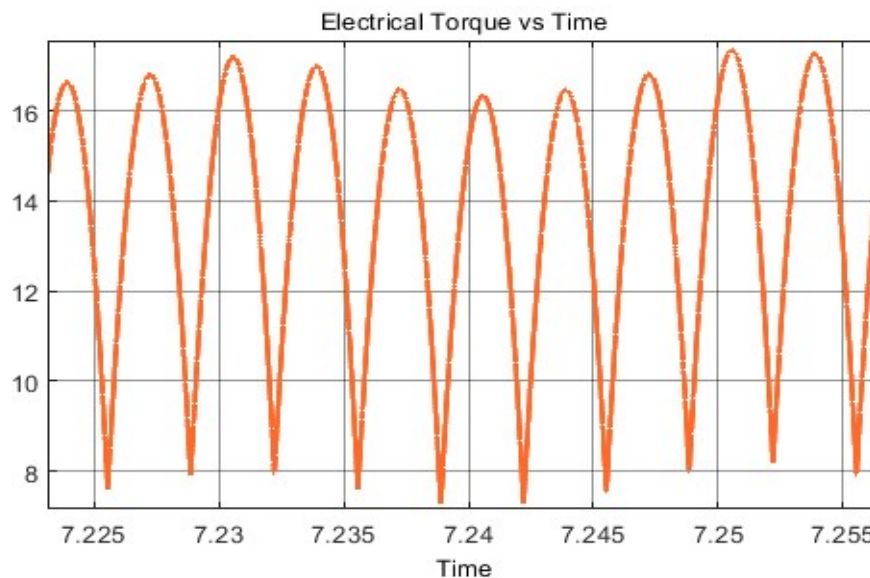
**Figure 8. Electrical torque vs Time graph**

It can be seen from the figure above, our torque ripple is reduced, which is better for our motor mechanic. We can clearly see that 3 phase is more stable than single phase rectifier case. While making those simulations, we decided to try 4quadrant operation, to check if it can be implemented easily.

For this purpose, we edited MATLAB functions, and copied one of them to control anti-parallel connected other thyristor bridges.
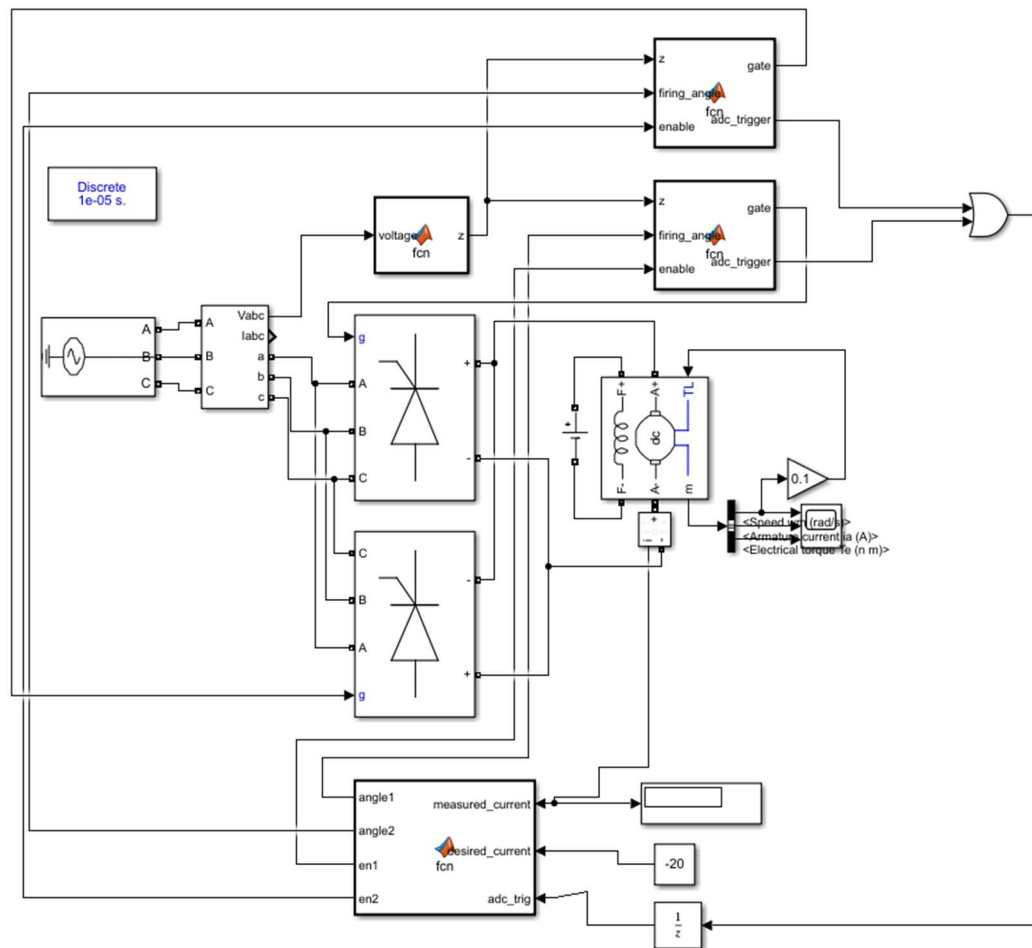
Figure 9. 3 phase-controlled rectifier for 4 quadrant operation

We can see from the figure below that, with that configuration we can work in all regions.
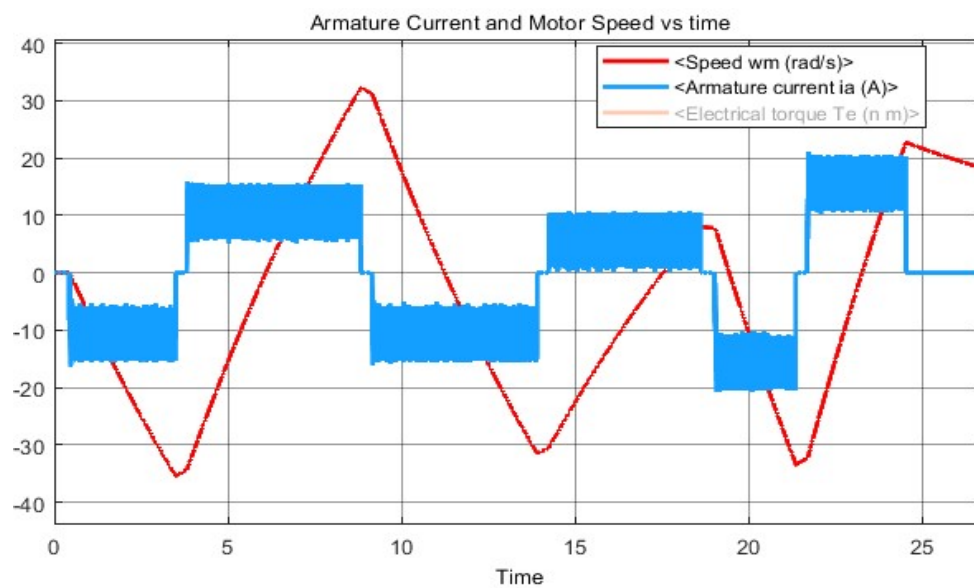
Figure 10. 4 Quadrant operation using three phase-controlled rectifiers

While taking into consideration the complexities of topologies and easiness of test and debug, increasing the number of phases is not good. To control a single 3 phase-controlled rectifier, we need 6 thyristor and 6 gate drive circuitry(4 voltage domain to supply those drivers), which causes very high cost and quite hard implementation. If we want to make 4 quadrant operation then this means that we need 12 thyristors, 12 gate drive circuitries(8 voltage domain). Implementation of that topology is hard and will not forgive any errors. So, we decided to look for different topologies before deciding.

5. **Diode Rectifier - Buck Converter**

This topology consists of two main parts which are the rectifier part and the converter part. In the rectifier part, a diode rectifier is used to convert AC signal to DC signal with ripple. The ripple voltage can be decreased by using a parallel capacitor at the output. However, when the ripple gets higher, larger capacitors are needed. Three-phase full-bridge rectifier is a good option for rectifier part since it gives the minimum voltage ripple among the diode rectifiers. Then, the output of this rectifier is connected to a buck converter. Buck converter is a pull DC-DC converter that uses a switch to regulate the output voltage. When the duty cycle of the switch decreases, the output voltage drops. In our simulation, we used IGBT as switch.

First advantage of this topology is, it is relatively easier than the thyristor topologies and the alternistor triac circuits, so it is easier to implement the circuit .Therefore, it is more suitable for obtaining more bonuses. Secondly, diodes are much cheaper than thyristors and using DC Motor at the output eliminates the necessity of using inductor and capacitor at the output of buck converter. Finally, it is easier to arrange the gate signal of the switch at buck converter than arranging six pulses that is going to the thyristors.

One disadvantage of this topology is it is not suitable for 4 quadrant operation like thyristor topology.

ANALYTICAL CALCULATIONS

In order to convert AC voltage to DC, we use a three-phase diode rectifier. Average output voltage of diode rectifier is calculated from Equation 1.

$$V_{av} = \frac{3\sqrt{2}}{\pi} \times V_{ll}$$

Equation 1

For the input voltage of the buck converter, we decided to use 225V so that for a duty cycle of 80% we will obtain 180V. Note that this calculation does not include the commutation effect. Therefore, the maximum duty cycle is decided as 80%.

$$D \times V_{in} = V_{out}$$

Equation 2

$$225V \times 0.8 = 180V$$

For the filter capacitor at the output of the rectifier, considering the availability of components we tried 470uF capacitor and we get peak to peak ripple voltage of about 30V.
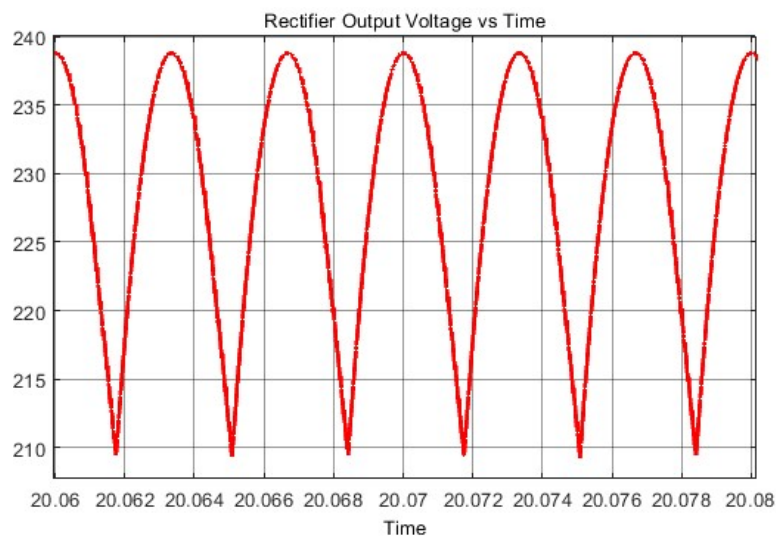
Simulation

We simulated the rectifier and buck converter stage together, while making those simulations, we loaded our machine with torque directly proportional to the speed of the machine. However, we tuned our current control and regulated the armature current to 15A. The reason why we choose 15A is actually quite simple, in the requirements maximum voltage of armature is said to be 180V. Assuming that the kettle in the laboratory is rated for 1.6kW and assuming that when we make the armature voltage 180V, our machine rotates at a certain speed that generator generates the rated voltage of the kettle. Up to that point we know our power output, if we assume both our generator and machine to be 60% efficient at total, we know that we need to supply approximately 2650W to our machine, this makes 14.8A at 180V. Because of that assumption, we tried to design our driver to supply at least 15A armature current. All presented figures below and more detailed versions of them can be reachable in our GitHub repo.
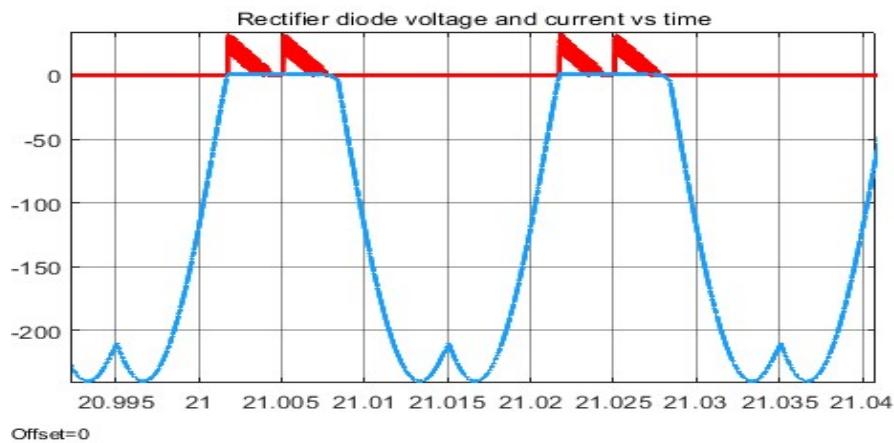
**Figure 11. Rectifier diode current(red) and voltage waveforms(blue)**

When we regulate the output current to 15A armature current and add a 470uF filter capacitor with 30mOhm ESR to the output of the rectifier. We observed that our rectifier diode has current peaks at about 30A and voltage peaks at about -250V. These values are quite informing about the component selection.

After bridge diode simulation, we moved on to the bridge output voltage waveform.


Figure 12. Rectifier output voltage vs time simulation

As can be seen from the figure above, we have quite high ripples in input voltage. But since we closed the loop, and we chose the filter capacitor so that even at the highest load, the rectifier output voltage never drops to the critical values. Assuming that we are working with 210V(this is the lowest value in the graph), we can still achieve 180V output voltage ripple condition by just increasing the maximum allowed duty cycle to 85%.
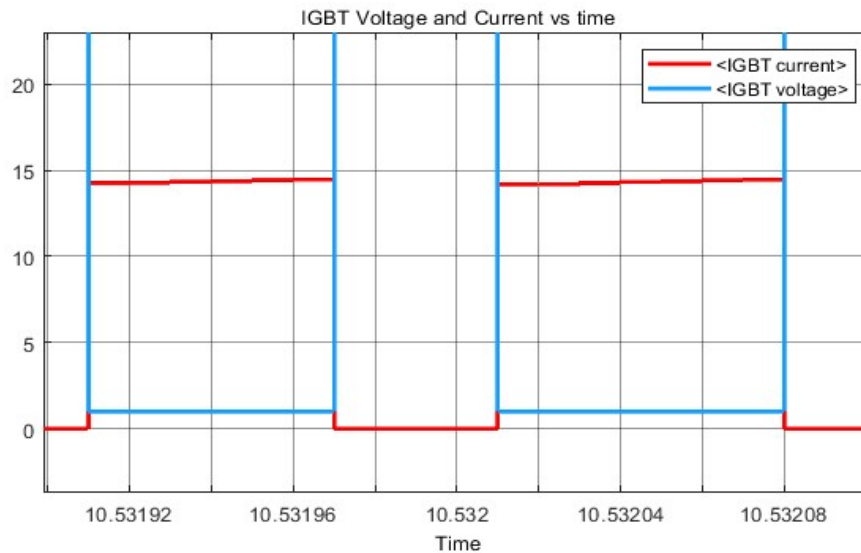
Figure 13. IGBT Voltage and Current

As can be seen from figure above, IGBT current is about 15A at peak, for the voltage part it is at rectifier output at max, and forward voltage of themselves at minimum. Since we didn't add parasitic elements due to the PCB(inductances etc.) to the simulation, we are not seeing any ringing at the waveforms. Moreover, without the snubber the components are working perfectly in that simulation. But with the further additions, we could see some non-idealities in our simulations.
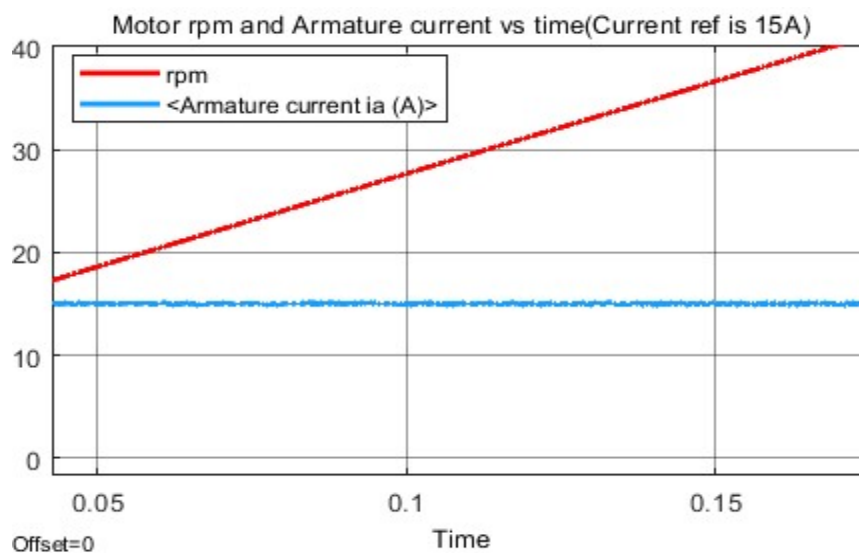
Figure 14. Motor rpm and armature current vs time

As can be seen from the above graph our current controller works perfectly and regulates the armature current with very little ripple. This means that we will see very little torque ripple.

COMPONENT SELECTION

When we check our simulation results, we obtained the following results

Maximum Current on IGBT : 15A

Maximum Current on Freewheeling Diode: 15A

Maximum Current on Rectifier: 32A

Maximum Voltage on Filter Capacitor: 225V

Maximum Voltage on IGBT: 225V

Maximum Voltage on Rectifier: 225V

Maximum Voltage on Freewheeling Diode: 225V

	Current Rating	Voltage Rating
IGBT	30A	600V
Diode	30A	600V
Rectifier	35A	1000V
Capacitor		400V

As it can be seen, we have enough safety margin for our topology.

As a PWM controller we used TL494. TL494 allows us to have control on maximum current, so that we will try to prevent inrush current which is very high. Also, by using this controller we will have closed loop control that controls the output voltage and adjusts the desired PWM accordingly.

In order to set the maximum current, the reference voltage of 5V provided by TL494 is divided to 3V and compared with voltage on the voltage sensing resistor. Resistor value is adjusted so that when the maximum current 15A flows through the resistor its voltage will equal to 3V. If it exceeds 3V, then the controller will reduce the PWM.
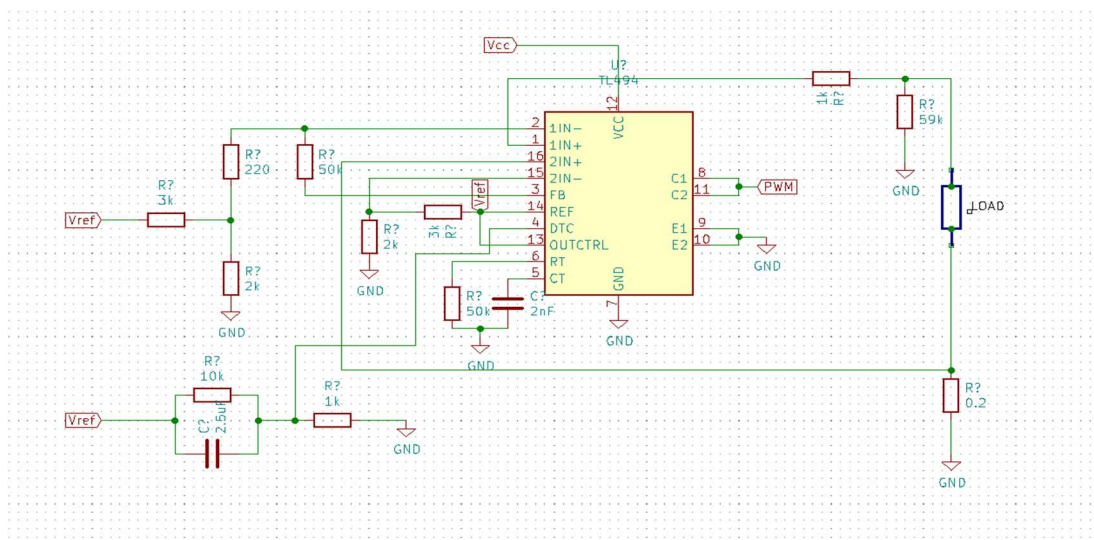
Figure 15: TL494 Controller Schematic

THERMAL CALCULATIONS

In this part of the report, the losses and the related thermal calculations are shown. In semiconductor materials, the main losses are switching losses and conduction losses. The equations related to these losses are shown in Equation 3,4 and 5.

$$P_{loss}=P_{conduction}+P_{switching}$$

Equation 3

$$P_{conduction}=V_f \times I_{on} \times (Duty\ Cycle)$$

Equation 4

$$P_{switching} = (E_{on} + E_{off}) \times f$$

Equation 5

For the bridge rectifier, the switching loss of the diodes are not indicated in the datasheet. Thus, only the conduction losses are considered. According to datasheet, V_f= 1.1V for each diode and the mean value of current on each diode is 11A . Since we are using 2 single-phase bridge rectifier blocks, 4 diodes are used in one component, whereas only 2 is used in the other one.

$$P_{loss-rectifier} = (1.1V) \times (11A) \times 4 = 48.4W$$

For the free-wheeling diode, since the switching losses are not given in the datasheet, the total switching loss is calculated by the linearized model. Since only the reverse recovery time is given in the datasheet (it is more dominant than the forward recovery time), forward recovery time is neglected.
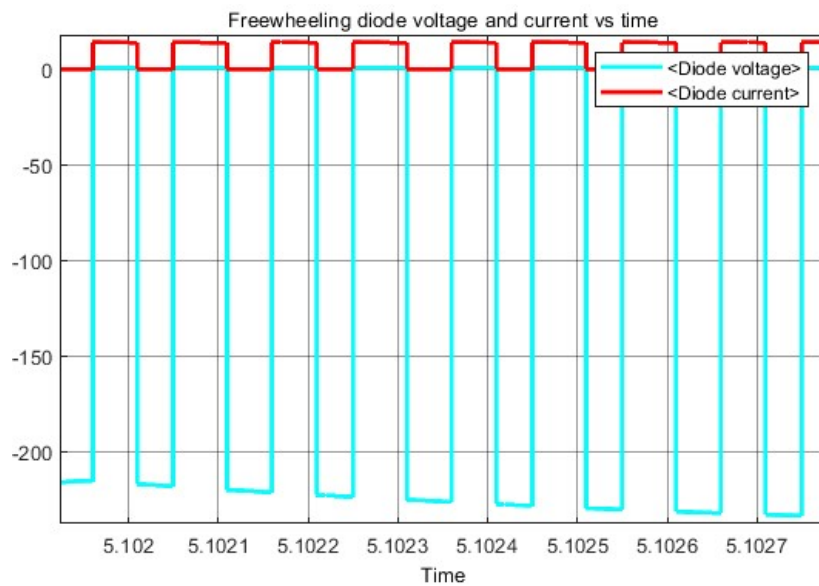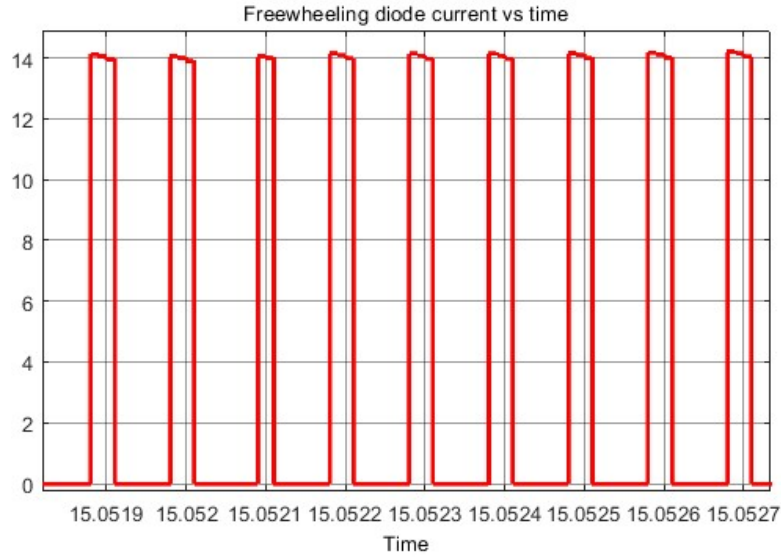

Figure 16: Current and Voltage Characteristics of Freewheeling Diode

Figure 17: Current Characteristic of Freewheeling Diode

As seen from Figure 4.1 and 4.2 ,I_{on}= 14 A and $V_{on} = 225\ V$. Reverse recovery time is found 40 ns from the datasheet. The duty cycle of the diode is 0.2 when the max duty cycle is applied to the IGBT(which is 0.8). The calculations are displayed below.
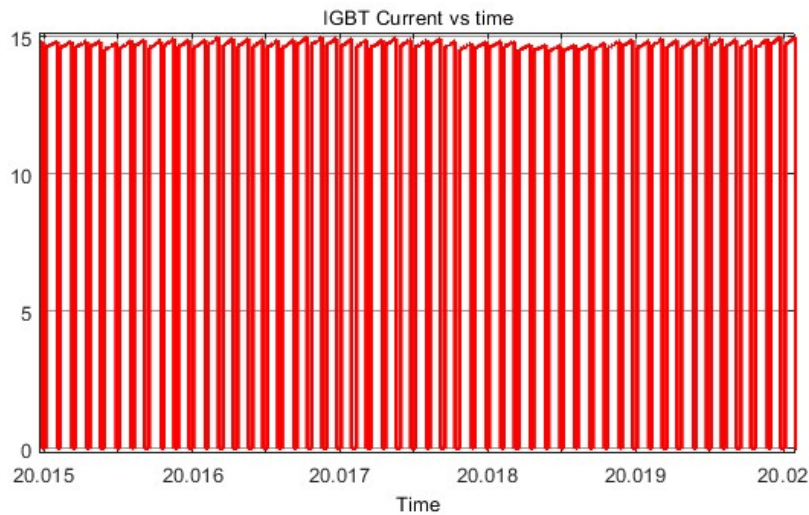
$$P_{loss-diode,switching} \simeq 0.5 \times I_{on} \times V_{on} \times t_{rr} \times f = 3{,}15mW$$

Equation 6

$$P_{loss-diode,conduction} = 2.27V \times 14A \times 0.2 = 6.36W$$

$$P_{loss-diode} \simeq 6.36W$$

Losses in IGBT are calculated below.

Figure 18: Current Characteristic of Freewheeling Diode

$$P_{loss-IGBT,switching} = (0.3mJ + 0.4mJ) \times (10kHz) = 7W$$

$$P_{loss-IGBT,conduction} = (2.28V) \times (15\ A) \times 0.8 = 27.36W$$

$$P_{loss-IGBT} = 34.36W$$

To find the thermal resistance of the heatsink for each element equation 7 and equation 8 is used. The ambient temperature is $40C^o$ and maximum junction temperature is $125C^o$ for the components.

$$R_{th-needed} = R_{th-needed} + R_{th-heatsin}$$

Equation 7

$$R_{th-needed} = (T_{max} - T_{ambient}) \div (P)$$

Equation 8

For rectifier;

$$R_{th-needed,rectifier} = (85\ C^o) \div (48.4) = 1.76\ C/W$$

Since the thermal resistance of the component is 2 C/W, we will cool this component with a fan.

For free-wheeling diode;

$$R_{th-needed,diode} = (85\ C^o) \div (6.36) = 13.36\ C/W$$

$$R_{th-heatsin\ ,diode} = 13.36\ C/W - 0.7\ C/W = 12.66\ C/W$$

This diode has a TO-220 package which is suitable for the heatsink provided by the department, but this component's datasheet is not provided. This heatsink will be tried first. If it doesn't satisfy the thermal needs of the component, another heatsink will be used.

For IGBT;

$$R_{th-needed,IGBT} = (85\ C^o) \div (34.36) = 2.47\ C/W$$

$$R_{th-heatsin\ ,IGBT} = 2.47\ C/W - 0.65\ C/W = 1.82\ C/W$$

530802B05100G heat sink will be used for cooling IGBT. It is suitable for TO-247 package, and it gives the necessary thermal resistance value with appropriate cooling.

IMPLEMENTATION

For the implementation part, we didn't set a lab meeting at school labs. We had meetings at our homes, and discussed the critical parts of the project. We choose our topology and implementation technique by making simulations together(this causes loss in time but we gained a lot of knowledge). So far, we decided on our critical components, we looked for a suitable heatsink. Since we know that we will have very high losses in our circuit we firstly looked for a suitable cooling method. Passive heatsink is actually a good method but since we have 100W loss(actually at that time, we also chose our components), it could not be enough. So, to overcome that problem we make research and found that most of the heatsinks at producing with cold rolling method, this method is quite simple and widely used in our country, we also learned that like "Seydişehir Alüminyum" shops in OSTIM,

sells heatsinks with kilogram. We decided to use one bulky heatsink at the bottom of our printed circuit board and by bending the legs of diodes and IGBT's, we will connect all components to the one heatsink by isolating their tabs. This method will introduce stray capacitances between tabs of the components and heatsink, and these stray capacitances actually need to be taken care of in an industrial application, however for our project these capacitances can be ignored. We are also planning to add a small fan to create forced air cooling.

Second decision we need to make, since we want to make a single supply bonus, we have to find a suitable way for it. If we didn't plan to add a small fan or if we know that our current consumption will be really small we learned that we can create that supply voltage with a series RC circuit with zener diodes. Since we want to have at least 2 or 3 watt supply, we eliminated that method for now. We also discussed adding a transformer at grid frequency for reducing voltage but then we saw that voltage modules like HiLink PM01, by looking from the cost perspective this method is more suitable, so we also ordered it.

For the driver circuit of the IGBT, we decided to use HCPL3120 since it is available at the laboratory, this driver needs at least 15V of supply voltage, we checked and saw that our IGBT is rated for maximum +-20V gate emitter voltage, so we choose +-12V as drive voltage. This will prevent false turn-ons. Schematic of the power stage without the rectifier part can be seen below. This schematic will be improved and will be used in the design PCB.
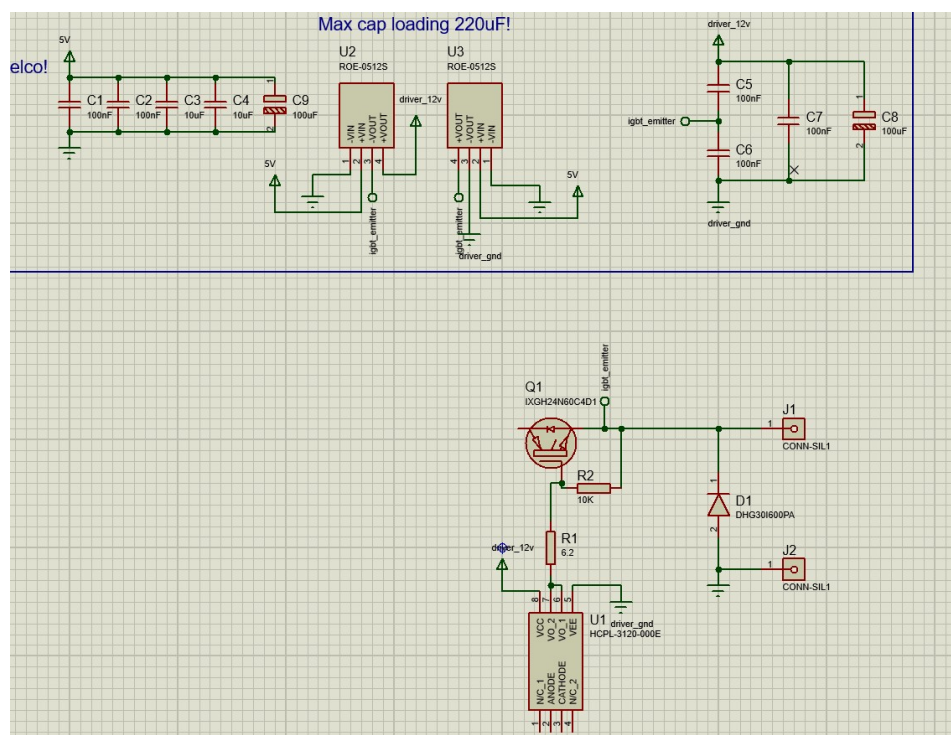
Figure 19: Schematic of Circuit

We also decided to make separate PCBs for control and power stage, so that we could change the controller. We will put a connector for the control PCB at the power stage PCB with all control pins, supply pins and feedback pins. We decided to mainly focus on TL494 as a controller, but we made two backup plans. First one is using NE555 at astable mode for PWM creation and second one is using a MCU for closed loop control.

CONCLUSION

In this report, the topology selection for the project is explained and the simulation results of the topology is investigated. The three-phase full bridge diode rectifier with a buck converter is selected to drive the DC motor since it is more advantageous than the other topologies. A closed loop feedback mechanism is used to limit the output current. The analytical calculations are satisfied in the simulation. Component are selected by the simulation results. Finally, the thermal calculations are made for the selected components.

Reference List

1) LittelFuse AN1003:
   https://www.littelfuse.com/~/media/electronics/application_notes/switching_thyristors/littelfuse_thyristor_phase_control_using_thyristors_application_note.pdf.pdf
2) TL494:
   https://www.ti.com/lit/ds/symlink/tl494.pdf?ts=1641056959661&ref_url=https%253A%252F%252Fwww.google.com%252F