MIDDLE EAST TECHNICAL UNIVERSITY
Electrical & Electronics Engineering

Hardware Project

AC to DC Motor Drive

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1. Introduction

In this report, design, analysis, test and real-time implementation of a AC to DC Motor Drive, which is the Hardware Project of EE463 Static Power Conversion 1 Course, is presented. In Figure 1&2, the DC motor and its features are illustrated.

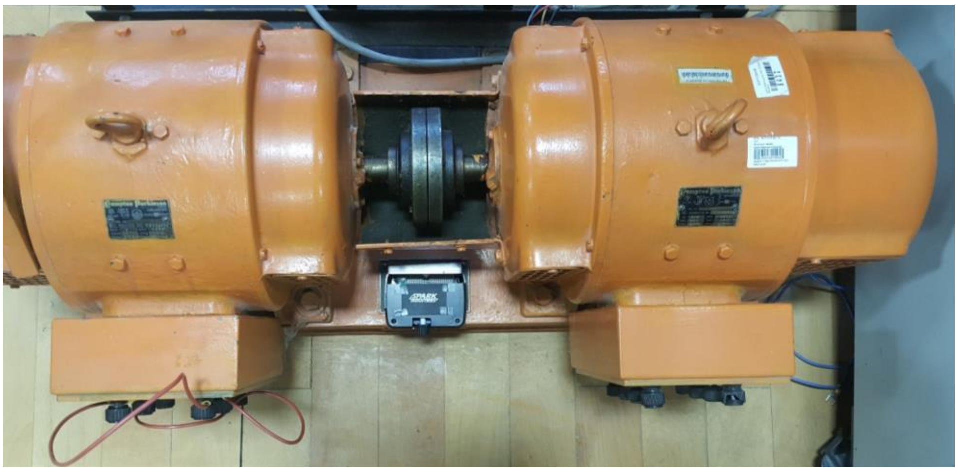

Figure 1:Series connected motor and our driver circuit

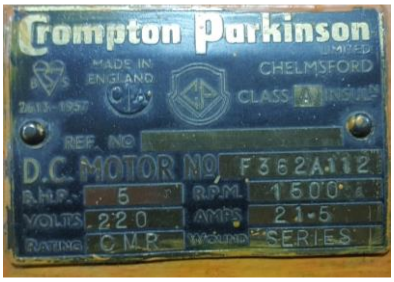

Figure 2: Features of DC motor

This project is implemented carefully in every step in order to obtain best result. Firstly, deep researches are conducted to choose the best option. It will help us to reduce the cost, energy and time we spent in every part of the project. Comparing different topologies, we have chosen the dimmer circuit topology which matches with demands perfectly. Then, project is simulated in digital environment and theoretical results are obtained. Having the required equipment and components, real-time implementations is completed. After that, some tests are performed with the R-L load which represents the motor. Later, a final test is performed on the motor with different loads.

2. Comparison of The Topologies

For AC to DC motor driver, there are four possible topologies. They can be listed as:

- Diode Rectifier + Buck Converter
- 3-Phase Thyristor Rectifier
- 1-Phase Thyristor Rectifier

- Dimmer Circuit

Each topology has some advantages and disadvantages. While comparing the topologies, easiness of implementation, simplicity, size of circuit, plenty of functionalities and cost are considered. According to these criteria, detailed analysis is following.

i. Diode Rectifier & Buck Converter

This topology consists of separately two part. Firstly, 220 Volt AC must be converted to DC voltage. Then, DC voltage varies by using buck converter. Up to design, ripple voltage in output can be very low. This topology can be used for all type of DC motor which are series, shunt and separately excited. Also, since this topology has a microcontroller, speed and armature current can be easily controlled by using this topology. Since this topology is very often used in industry, there is plenty of source and examples on the Internet.

However, this topology has LC filter to get rid of harmonics. Since corner frequency is low, inductance and capacitance values are high and size of them are also big. Besides, since MOSFET and IGBT drives in the order of kHz, heat management may be problem. As power goes to higher values, components become expensive comparing to dimmer circuit. Because high frequency switching, inductance in the circuit usually cause problems.

ii. 3-Phase Thyristor Rectifier

This topology is used for high power application. This topology does not have to include DC link capacitor because ripple in the output is small. By using two 3-phase thyristor rectifiers, motor can be drive four- quadrant. However, there is synchronization problem for this topology. Thyristors must be fired according to grid. After this problem, thyristors must be fired a specific order and firing angle. This leads to use a microcontroller which makes works more complex comparing to dimmer circuit. Also, small ripple voltage is not must for AC to DC motor drive so, number of components is high for this application.

iii. 1-Phase Thyristor Rectifier

This topology has same advantages with the 3-phase thyristor rectifier. However, tis topology is simpler than previous one. Also, zero crossing of grid voltage has to be known to synchronize firing angle with grid for this topology. This problem can be solved by comparator circuit or a microcontroller with analog to digital comparator. However, there must be 180-degree delay between firing angles for functional operation. This operation is also more complex comparing to dimmer circuit. Since this topology has more components, it is also more expensive than dimmer.

iv. Dimmer Circuit

This topology has minimum number of components. Because of this, dimmer circuit has minimum size and cost. Also, it is very easy to implement. Besides, heat is not a big problem for this topology because switching frequency is not high. However, if using thyristor for switching purpose, input voltage must be 400-volt line to line voltage. With 400-volt line to line voltage, minimum desired output voltage (i.e. 180 volt) can be barely reached. If triac is used instead of thyristor, output waveform is similar to AC chopper circuit. Because of negative cycle, this topology with triac can be used for only series connected DC motors. Besides, since this topology is purely analog circuit, speed and armature current cannot be autonomously controlled.

To conclude, although dimmer circuit has some disadvantages, dimmer circuit is selected for AC to DC motor driver because simplicity, easiness of implementation, size and cost advantages.

3. Theory of The Dimmer Circuit

Circuit for this topology consists of only triac, diac, capacitor and resistor. Triac is a component which is composed of two thyristors connected in back to back however same gate connection. Triac has M1 and M2 connection instead of anode and cathode because it can be used for both directions. As in the thyristor, triac works with the gate current. However, triac can be opened with both negative and positive current although thyristor can be opened only positive current. After triggering to gate, triac is open until main current reduces below the threshold current which is close to 0. Triac is used in a lot of power application like dimmer, motor driver, AC chopper etc.

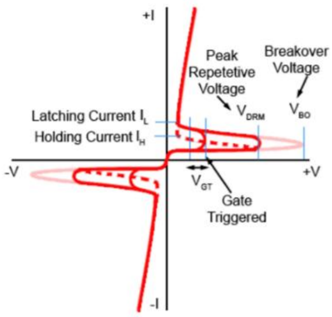

Figure 3: The Characteristic of the Triac

Diac [2] is a component which is composed of two diodes connected in back to back. Diac blocks the current flow if applied voltage is less than break over voltage like diode. However, in diac there is also negative break over voltage. That is when applied voltage is smaller than break over voltage (negative value), diac is open and it cannot block the current flow. Break over voltage is generally equal to 30 volts. Diac is also used in a lot of power application.

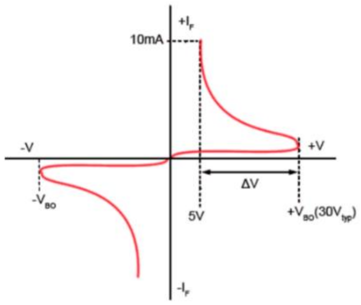

Figure 4:The characteristic of the Diac

Our motor driver circuit is shown in the figure 5.

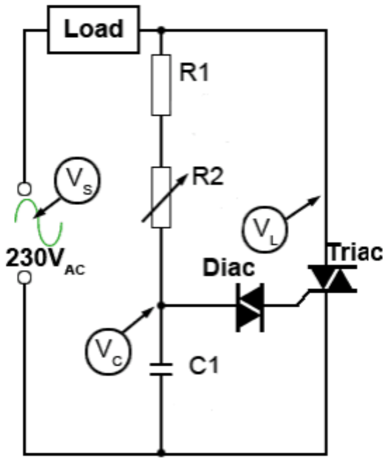

Figure 5: Dimmer circuit diagram

If triac is close, current is flow to the branch which includes resistances and capacitor. However, our resistance values are very high. Therefore, current passes through the load is very small. Moreover, in this condition, capacitor is charged.

If triac is open, this means that load is connected to the grid directly, only difference voltage drops due to the triac voltage. Moreover, the branch which include resistances and capacitor is short that is capacitor is discharged.

We use the resistance-capacitive branch for triggering the triac. Moreover, diac is also used for triggering the triac. Firstly, capacitor is charged to positive/negative voltage. If capacitor voltage is equal to +/- V_{BO} which is opening voltage of the diac, then diac is open and triac is triggered. Afterwards, triac continues the conduction until triac current reduces below the threshold current. Generally, triac is closed when input voltage changes from positive to negative or vice versa if inductance of the load is small.

Moreover, potentiometer is used for changing time constant. That is, when resistance of the potentiometer is maximum value of POT, it takes a long time to charge the capacitor [3]. Therefore, triac does not conduct because of sign changes of input voltage. That is, capacitor voltage does not reach the V_{BO} volts. When resistance of the potentiometer is minimum value, capacitor is charged very fast. Therefore, triac is opened at approximately 0-degree. Existence of R1 resistor prevent the triac to open 0-degree.

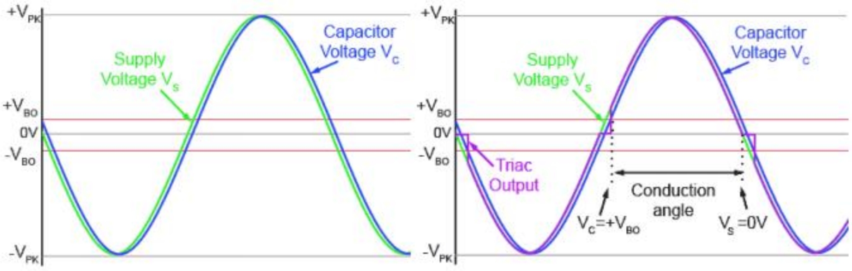

Figure 6:When POT at minimum value (VBO is opening voltage of diac)

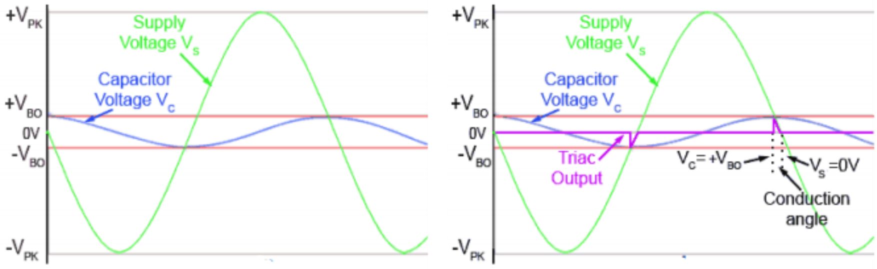

Figure 7:When POT at maximum value (VBO is opening voltage of diac)

In positive cycle, when total resistance is maximum, capacitor voltage is equal to V_{BO} at the end of the positive cycle to obtain 180-degree firing angle. After firing triac close 180-degree, triac conducts for short time. At the output small triangle ripple occurs (see figure 5). If we increase POT value further, triac does not conduct because capacitor voltage does not reach V_{BO}. That is, output voltage is zero.

4. Component Selection

To obtain 180-degree proper firing angle, there should be put a component whose opening voltage is high to trigger triac. If we use back to back two diodes for triggering, maximum firing angle becomes 90-degree because opening voltage of diode is very small comparing to diac. This problem can be solved by very high resistance which is not suitable. Because of this we use diac instead of back to back two diode. Selected diac's opening voltage is 30 V. To benefit from negative cycle of input voltage, triac is used instead of thyristor. However, there is drawback to use triac, which it can be used only series connected DC motor as explained above.

Voltage of capacitor depends on total impedance. When V_c reaches opening voltage of diac which is 30 volts, triac conducts. Calculations can be seen below.

$$V_c = \frac{V_{total}}{Z_{total}} x \frac{1}{wC}$$

$$V_c = \frac{220\ V}{\sqrt{R_{total}^2 + (\frac{1}{50 \times 2\pi\ \times C})^2}} \times \frac{1}{50 \times 2\pi\ \times C} = 30V$$

$$R_{total} \times C = 23{,}125 \times 10^{-3}$$

We select the capacitor value is 0,1 μF. Therefore, our total resistance is minimum 231,25 KΩ. Calculations are in the ideal case. Therefore, we put the error and select the 12 KΩ resistance and 500 KΩ.

We want to 5 kW power through the circuit. Considering maximum output voltage 220 V_{rms}, maximum current flow through triac is 22.7 A. Therefore, triac must have capability of driving 23 A. 600 V polypropylene film capacitor is used because it is suitable for high power application. Datasheets of triac and capacitor can be reached from following links: Triac and Capacitor.

5. Simulation Results

Simulations are made by using LTSpice. RL load is used to simulate a DC motor. Circuitry can be seen below.

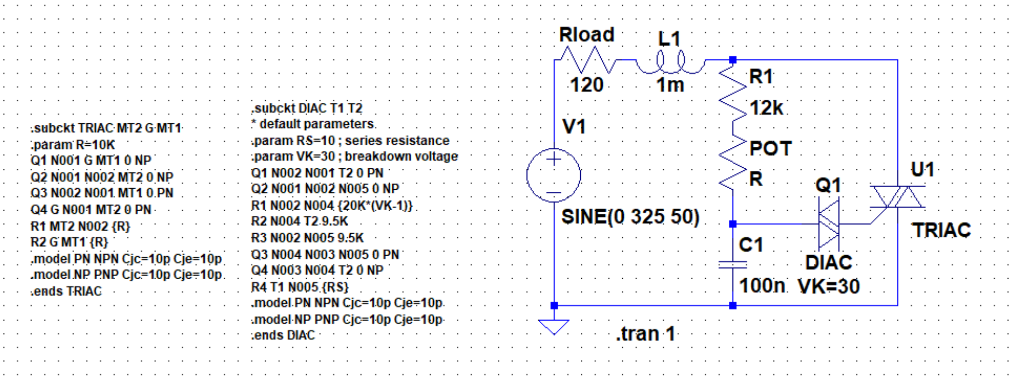

Figure 8: Circuit diagram of dimmer

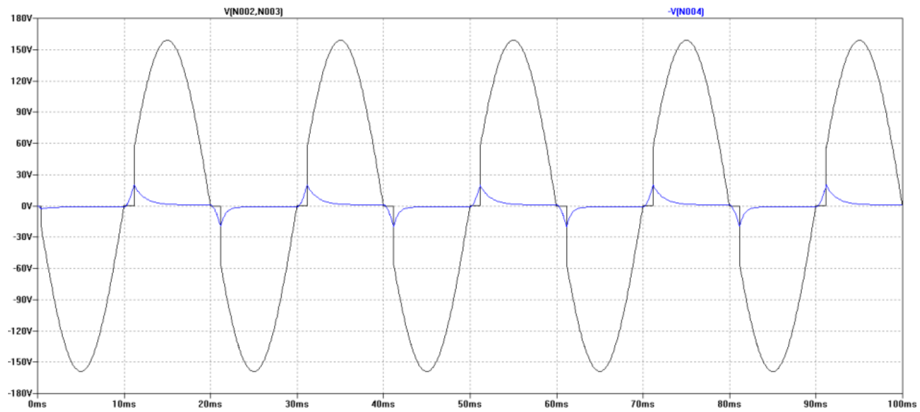

Figure 9: POT is at minimum value (Vc and output voltage)

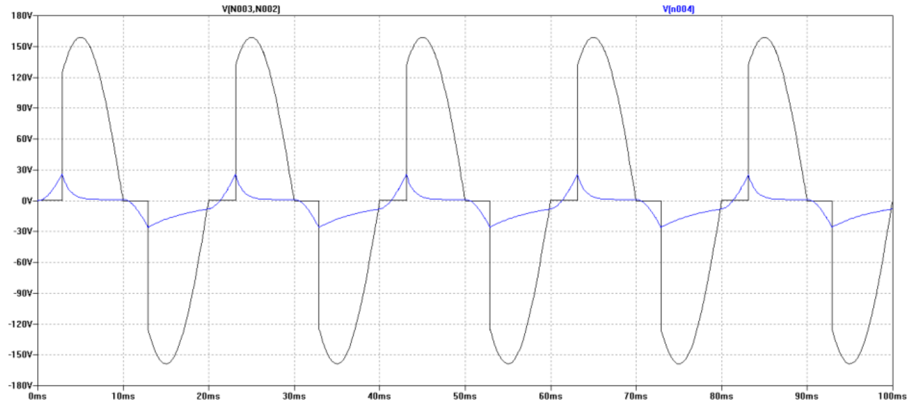

Figure 10: POT is at 50 Kohm (Vc and output voltage

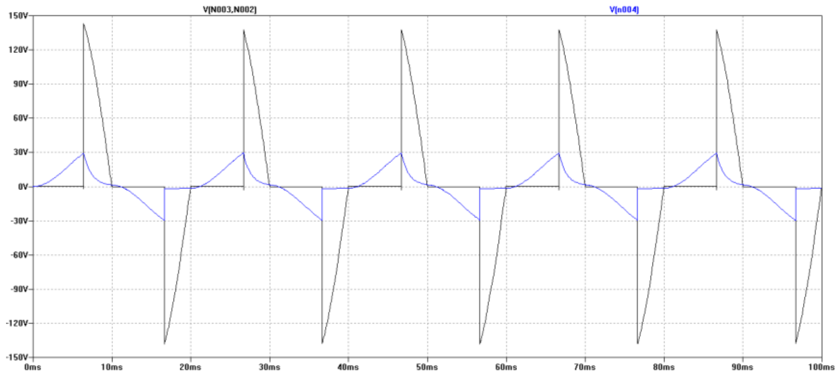

Figure 11: POT is at 200 Kohm(Vc and output voltage)

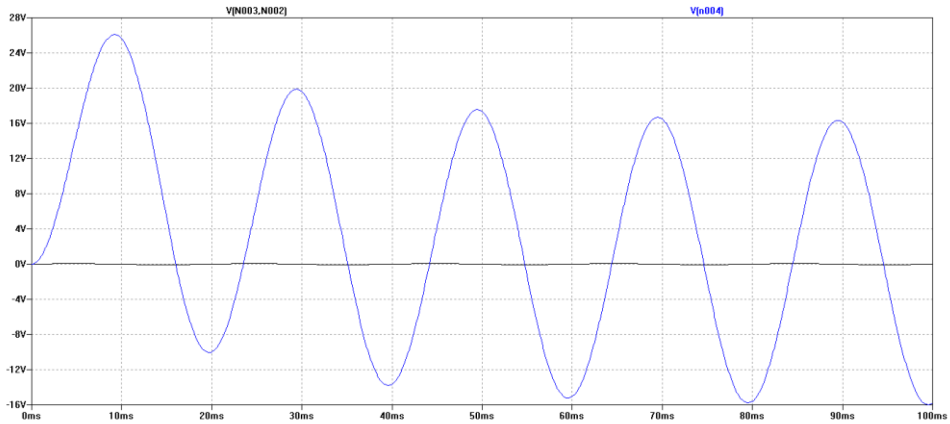

Figure 12:POT is at 300 Kohm(Vc and output voltage)

To conclude, as expected, when capacitor voltage reaches to opening voltage of diac, triac starts to conduct. When input voltage changes sign, triac becomes non-conductor. Even if triac never becomes to conduct for high value of POT, there is some voltage on the load via POT and capacitor as explained theory of the dimmer circuit part.

Hysteresis Problems

Although this topology widely used, there are some problems. The problem is that when capacitor is partially discharged into the diac, some charges remains on the capacitor. When input voltage cross zero-volt, remaining charges prevent the capacitor to charge up opposite polarity. Therefore, at next cycle firing angle is delayed. These leads to unequal conduction angles. Hence, AC wave at the triac output will not be centered on zero volt and it has a varying and unwanted DC component.

6. Thermal Analysis

Firstly, without heatsink circuit cannot be operated rated power. Calculations [2] can be seen below.

$$P_{Gate} = 1\,W\ (From\ Datasheet)$$

$$P_{Main} = V_{Triac} \times I_{Load} = (0.2V) \times (20A) = 4W\ (0.2V\ from\ datasheet, 20A\ from\ test\ result)$$

$$P_{Loss} = 5W$$

If there is no heatsink, $R_{j\text{-}a}$ is 60 °C/W. Therefore, temperature of the junction is

$$T_j = P_{loss} \times R_{j-a} + T_{ambient} = 5 \times 60 + 25 = 325$$

So, Junction temperature is 325°C. At this degree triac cannot operate. Temperature of the case need to below 125°C from datasheet. Therefore, we have to use the heatsink.

Maximum function temperature 125°C and ambient temperature is, suppose, 25°C. According to assumption, needed heatsink and calculations are below.

$$T_j = 125°\text{C} = P_{loss} \times R_{total} + T_{ambient} = 5 \times R_{total} + 25$$

$$R_{total} = 20°\text{C/W}$$

$$R_{total} = R_{j-c} + R_{heatsink} = 1.7 + R_{heatsink}$$

$$R_{heatsink} = 18.3\ °\text{C/W}$$

Therefore, $R_{heatsink}$ need to be smaller than 18.3 °C/W.

Since heatsink we use has not datasheet, from experimental data, $R_{heatsink}$ was calculated as 2°C/W. Calculation is below.

$$T_j = P_{loss} \times R_{total} + T_{ambient} = 5 \times 3.7 + 25 = 43.5°\text{C}$$

7. Test Results

Firstly, our circuit driver is presented. Then, voltage waveforms can be seen for different firing angles under RL load. After that, under 2 kW and 5 kW resistive load, output voltage, current and temperature of triac are presented.

Figure 13: Driver circuit

Figure 14: Connections and inside of driver

As expected, experimental results consistent with theoritical calculations and simulations. From 0° to 180°, firing angle can be changed. However, some parasitic effects has occurred. At the output, some peaky waveforms occurs. Despite of peaky voltage, motor did not affect from them because motor has large inertia to absorb them.

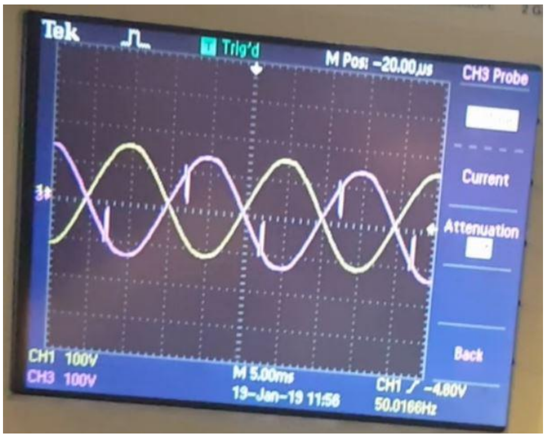

Figure 15: Zero firing angle under RL load

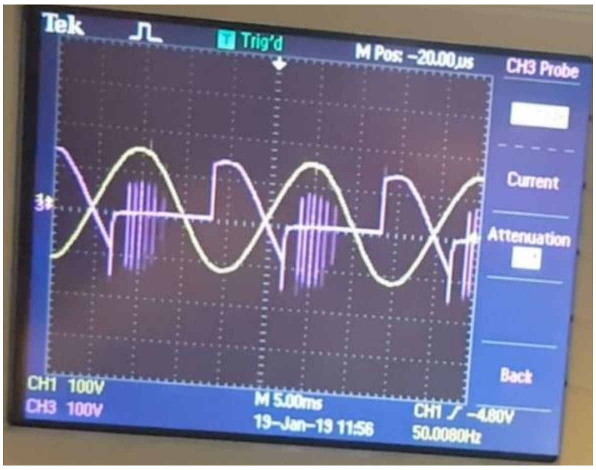

Figure 16: 60° firing angle under RL load

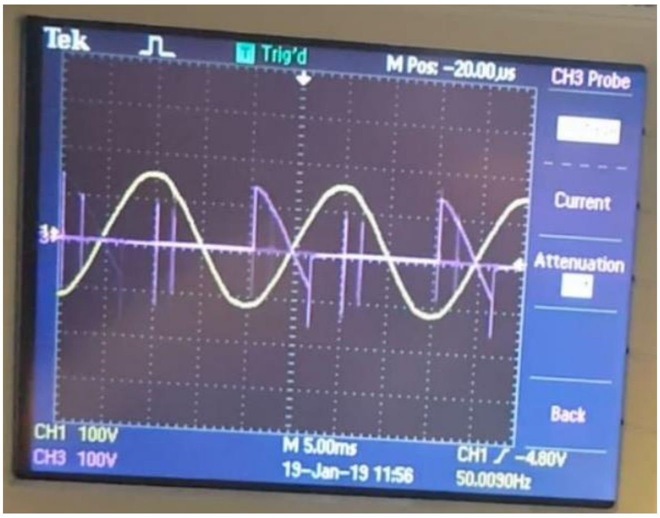

Figure 17: 120° firing angle under RL load

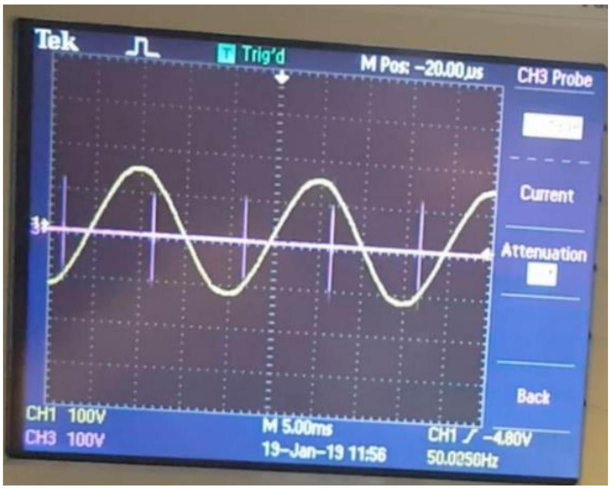

Figure 18: 180° firing angle under RL load(zero output voltage)

Figure 19: Output voltage and current under 2kW Resistive load

Figure 20:Output voltage and current under 5 kW Resistive load

Since switching frequency is not high, heat is not a big problem. Natural cooling is enough for this driver circuit. After 5 mins, temperature reaches 70° at steady state under 5 kW resistive load. Result can be seen from the following figures 21&22.

Figure 21:Temperature of triac under no load

Figure 22: Temperature of triac under 5 kW load after 5 mins

8. Video

Video link which is telling our story during the design process and project implementation. Also, demo of the working prototype can be seen in the video. Link are following:

https://www.youtube.com/watch?v=y3KiT9gIFnA&feature=youtu.be

https://drive.google.com/open?id=1T-X-PxqNw0keJ4RVch4P04yzUEBwR-IE

9. Conclusion

In this project, a controllable DC Series motor drive circuitry is build and tested. Starting with design, there exists different topologies for driving DC Motor. We have chosen the dimmer circuit topology. Firstly, theoretical analysis and designs are performed. Later on, simulations of designed circuit are analyzed on LTSpice. When the desired results are obtained, real-time application process has been started. Gathering the components and required materials, hardware implementation is finished. Finally, motor has been driven with different load values, i.e. no-load, 2KW and 5KW load. Results are satisfactory and they match with theoretical designs and expectations.

In conclusion, we have learned many things from the Hardware Project. Firstly, it is understood that comprehension of the problem and making a deep research on it is crucial for the rest of the project. Simpler and logical solutions can be found with this way and it results in reduce of the cost, energy and time in every aspect. Moreover, having different aims like small-box challenge, robustness, compactness etc. forced us to choose the best option in topology selection which requires being careful while designing and implementation process. Also, a real-time implementation is different than analyzing and designing a circuit on digital environment. Facing with different problems which can be experienced only in real-time applications helped us to consider putting more emphasis on this issue in our future projects and engineering career.

All in all, seeing the motor drive, which is designed and implemented from scratch by ourselves, is working properly and meets the requirements, we have the taste of success and it is worth to every effort we put on the project.

10. References

[1] Module 6.0 Thyristors. Retrieved from http://www.learnabout-electronics.org/Semiconductors/thyristors_60.php

[2] Mohan, N., Undeland, T. M., & Robbins, W. P. (2002). Power electronics: Converters, applications, and design. New York: John Wiley.

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