Laboratory-01: Design of Triac Regulator Circuit

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This report enlists the methodolgy employed to design the said circuit based on the specifications provided in the problem statement, and the results of the implementation of the said design in the laboratory.

1. Working

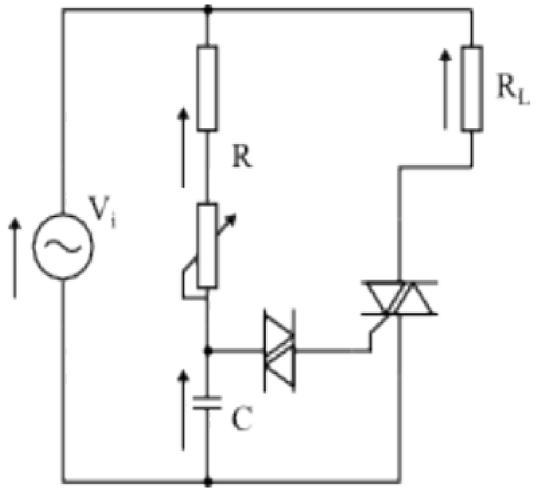

Figure 1. Triac Regulator circuit

The working of the circuit shown above is rather straightforward. The load, R_L, is connected to the load when the triac is conducting. The triac is turned ON when a gate voltage is applied to it and the current exceeds the latching current. It goes OFF when the current through the triac falls below the holding current. The diac triggers the gate of the triac when a voltage exceeding its breakover voltage is applied to it. This is achieved when the capacitor charges to the said voltage. The RC circuit provides the control over the firing angle. The greater the resistance, the lesser the capacitor charging current, the longer will it take the capacitor to charge to the breakover voltage, the greater will be the firing angle and the lower will be the rms voltage that appears across the load; and vice versa.

2. Design Equations

2.1 Constraints and assumptions:

The following constraints are assumed to be implicit for all cases of analysis:

1. Input voltage is a sine wave of frequency 50Hz and V_{rms} is 230V for the mains supply (although lower values of V_{rms} are used occasionally for analysing certain cases at low wattage loads here).

2. The diac used has a breakover voltage, V_{BO}, of 30V.

3. The triac used has a maximum gate current rating, $I_{G_{\max}} = 50$mA.

4. The wattage of the load is 60W resistive when connected to the mains supply. For analysis at lower voltages, a 5W, 1kΩ resistor is considered to be the load.

5. The voltage rating of all connected devices is assumed to be above the mains voltage.

6. The maximum range of phase angle control achievable is 0° to 180°.

2.2 Design equations

From the above, we know that

$$f = 50\,\text{Hz}, \;\; V_{\text{rms}} = 230\,V, \;\; V_{\text{BO}} = 30\,V$$

The supply voltage can thus be written as

$$v_i = V_{\text{rms}} \times \sqrt{2} \times \sin(\omega t), \;\; \text{where} \;\; \omega = 2\pi f$$

The capacitor is chosen to be

$$C = 0.1\mu F$$

The RC circuit can be analysed independently, and it is evident that the voltage across the capacitor will lag the the supply voltage by an angle,

$$\phi = \tan^{-1}\left(\frac{R}{X_C}\right), \qquad \text{where} \qquad X_C = \frac{1}{2\pi f \times C}$$
$$\phi = \tan^{-1}(\omega.R.C)$$

The instantaneous voltage drop across the capacitor can be written as

$$v_C = |v_i| \times \frac{X_C}{Z} \times \sin(\omega t + \phi), \;\; \text{where} \;\; Z = \sqrt{R^2 + X_C^2}$$

The instant of trigger of the triac can be found by substituting the breakover voltage of the diac as the voltage drop across the capacitor, thus giving:

$$\alpha = \sin^{-1}\left(\frac{V_{\text{BO}}}{|v_i|} \times \frac{Z}{X_C}\right) + \phi$$

The minimum firing angle, $\alpha_{\min}$, can be calculated by substituting $R = 0$ in the above equation.

$$Z = X_C, \qquad \text{since} \qquad R = 0$$
$$\alpha = \sin^{-1}\left(\frac{V_{\text{BO}}}{|v_i|}\right)$$

But the assumption for R above is reasonable only if the gate current is not limited by the available components. Practically, that is not the case. Since the gate current is limited by $I_{G_{\max}} = 50$mA, the actual value of $R_{\min}$ is not 0, but can be found as follows:

$$R_{\min} = \frac{\sqrt{|v_i|^2 - V_{\text{BO}}^2}}{I_{G_{\max}}}$$

Running these equations on the Python code as given in appendix A, the minimum resistance is found to be 6.48$k\Omega$ at a firing angle of 16.9 degrees.

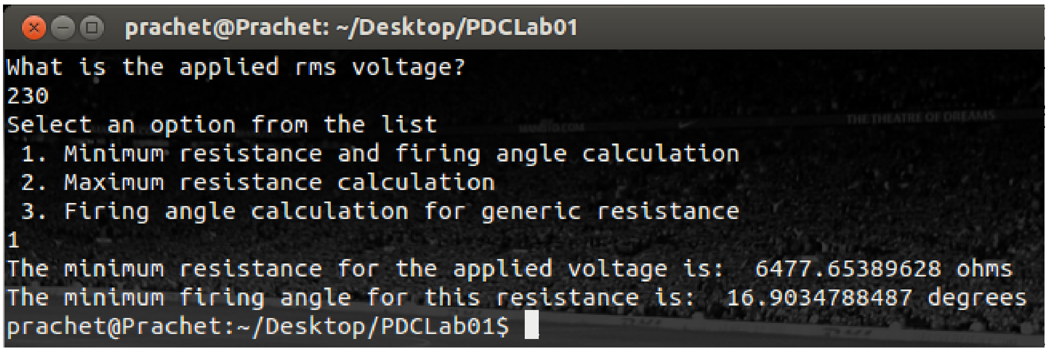

Figure 2. Python code output for minimum resistance calculation

The condition for the maximum resistance that can be applied is obtained by substituting the value of V_{BO} for $|v_C|$. The reason for this substitution is that for any v_C with amplitude below V_{BO}, the triac will not trigger at value of R and the load will be always OFF. Thus we obtain the expressions:

$$v_C = |v_i| \times \frac{X_C}{Z} \times \sin(\omega t + \phi)$$

$$|v_C| = |v_i| \times \frac{X_C}{Z_{\max}} = V_{\mathrm{BO}}$$

$$V_{\mathrm{BO}} = |v_i| \times \frac{X_C}{\sqrt{R_{\max}^2 + X_C^2}}$$

The solution to the above equation yields the value of the maximum resistance that can be connected in the RC network for the load to turn on. Executing this equation in the Python code appended in Appendix A, we find that for a supply voltage of rms 230V, the maximum resistance is around $343k\Omega$.

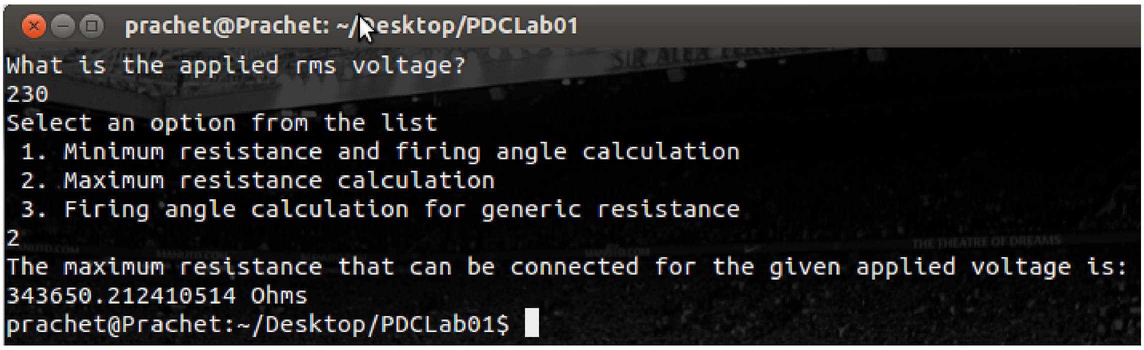

Figure 3. Python code output for maximum resistance calculation

Therefore, theoretically, the following can be inferred[1]:

	R	$\boldsymbol{\alpha}$
Min	6.48	16.9
Max	343.65	174.64

Table 1. Min and Max R for supply voltage rms 230V

The theoretical range of control can thus be found to be:

$$\Delta\alpha = 174.64 - 16.9 = 157.74\,\mathrm{degrees}$$

1. The value of α at $R_{\max}$ is obtained by executing the Python code for R=343.65k. Note that all values of resistances are in $k\Omega$ and angles in degrees.

The rms value of the output voltage can be calculate by the expression:

$$V_{O_{\rm rms}} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} |v_i|^2 \sin^2\theta d\theta}$$

2.3 Practical design values

The practical design values that are selected to implement the circuit are:

$$C = 0.1\mu F$$
$$R_{\min} = 8.2k\Omega$$
$$R_{\rm pot} = 470k\Omega$$

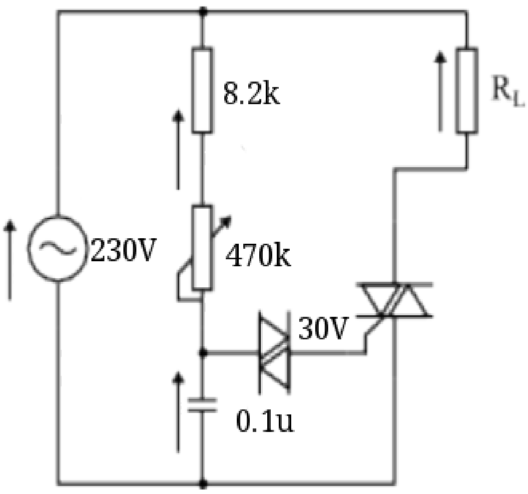

Figure 4. Circuit schematic

3. Simulation

3.1 Creating netlist and subcircuits

For the above designed values, the netlist of the circuit for execution in ngSPICE was made. The value of the load resistance for the simulation was calculated for the power rating of the load, as follows:

$$P = 60\,\text{Watts}$$
$$V_{i_{\rm rms}} = 230V$$
$$P = \frac{V_{i_{\rm rms}}^2}{R_L}$$
$$R_L = \frac{V_{i_{\rm rms}}^2}{P} = 881\Omega$$

The netlist thus made was:

```
V1 n1 0 sin (0 325 50Hz)
R1 n1 n2 100k [2]
C1 n2 0 .1uF
R2 n1 n3 881
X1 n3 n4 0 triac
X2 n2 0 diac
.end
```

The subcircuits for the diac and triac are included in Appendix B.

2. The value of this resistance is changed for different firing angles

3.2 Simulation results for R1=8.2kΩ

As is evident from the results, for low values of R1, the output voltage is high, as the firing angle is very low.

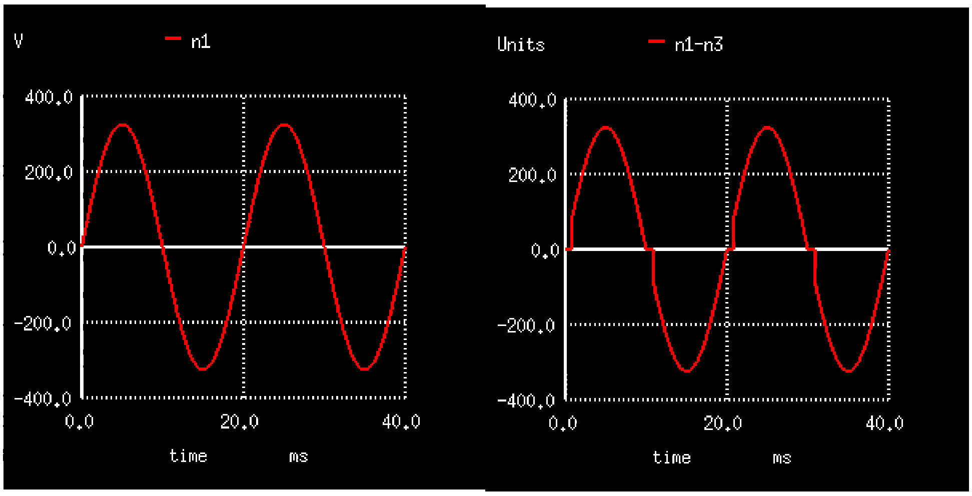

Figure 5. a. Input Voltage b. Output Voltage

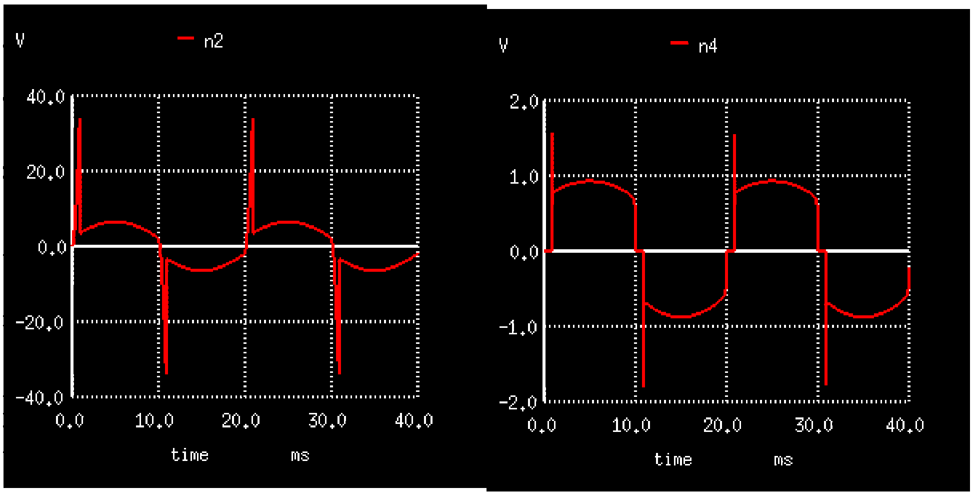

Figure 6. a. Capacitor Voltage b. Gate Voltage

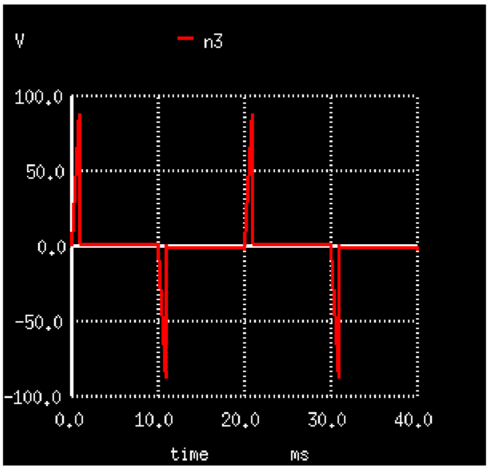

Figure 7. Triac Voltage

3.3 Simulation results for R1=300kΩ

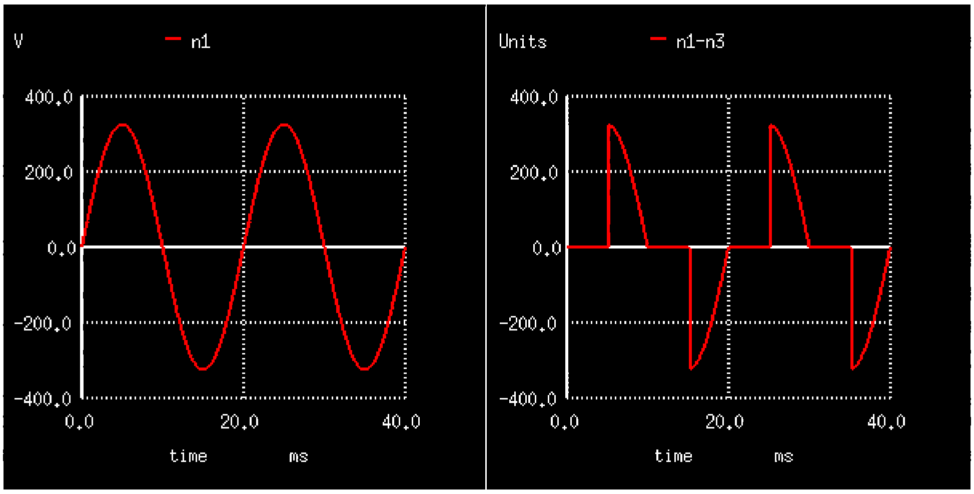

Figure 8. a. Input Voltage b. Output Voltage

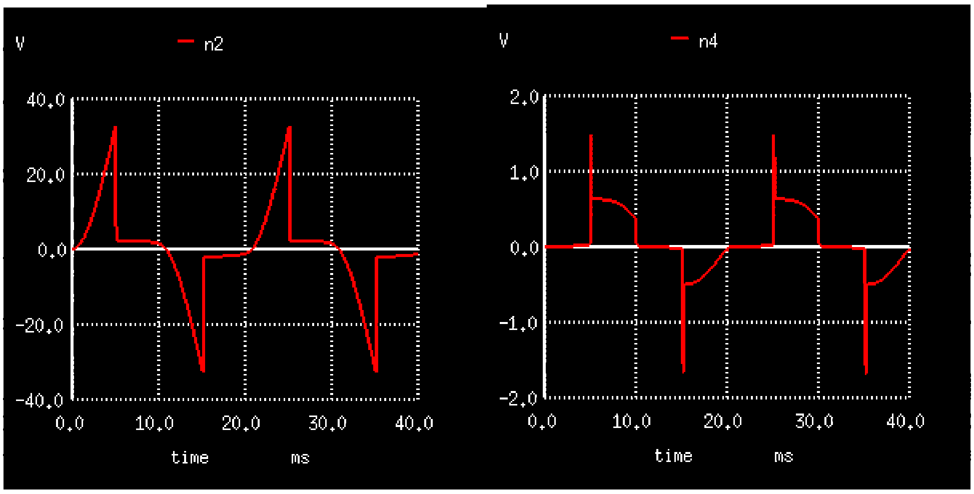

Figure 9. a. Capacitor Voltage b. Gate Voltage

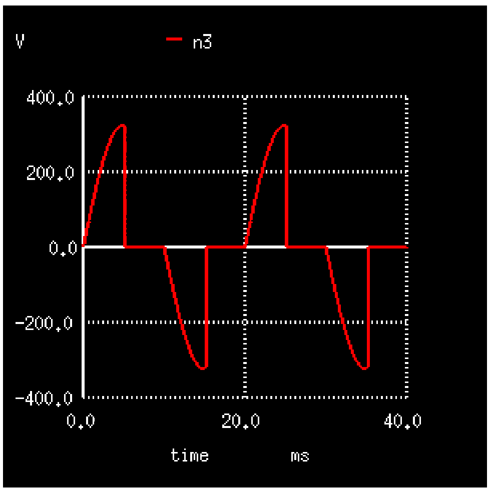

Figure 10. Triac Voltage

3.4 Simulation results for R1=585kΩ

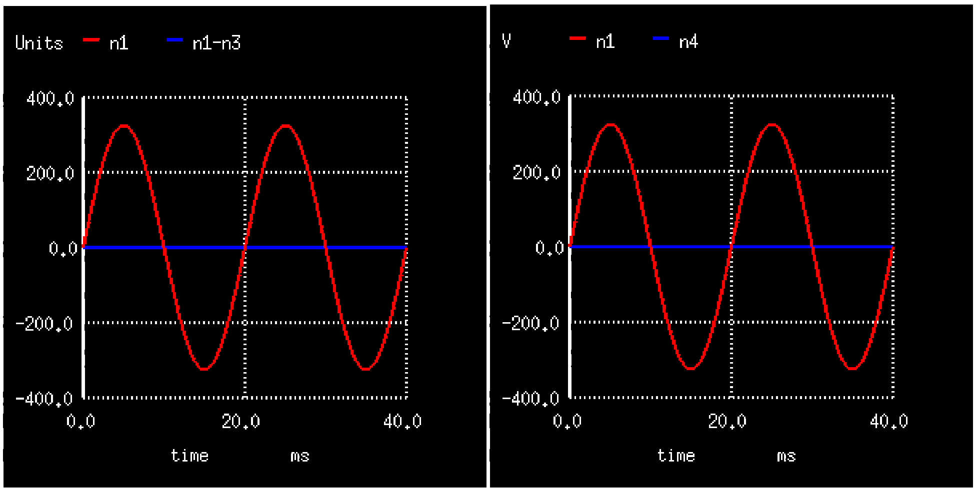

Figure 11. In red: Input Voltage. In blue: a. Output voltage b. Gate voltage

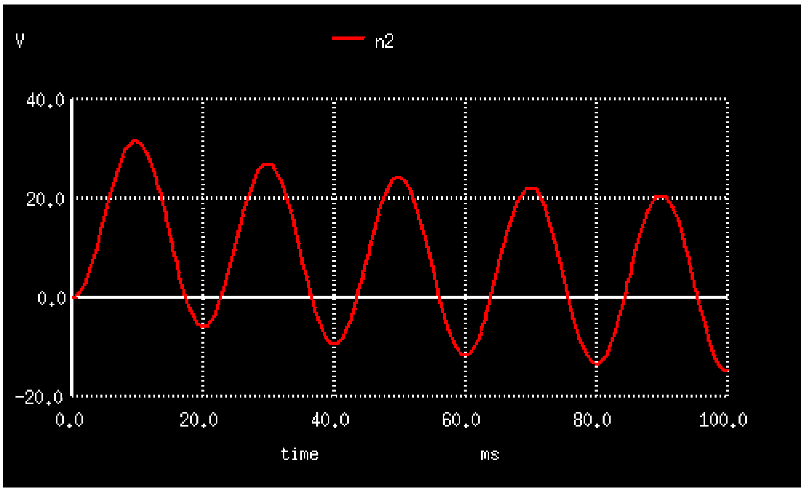

Figure 12. Capacitor voltage

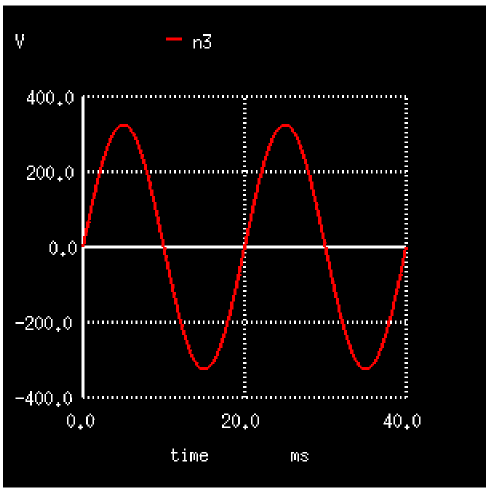

Figure 13. Triac voltage

3.5 Discrepancy in simulation results

As evident from the above waveforms, $R_{\max}$ does not occur at $343.65k\Omega$ as predicted by the design equations executed on Python. Instead, the triac continues to conduct at resistances much higher than that predicted.

This is not an error in the calculations, as will be proved in the section to follow. It is here suggested that the cause of this discrepancy owes to non-conformity of the diac subcircuit to the practical apparatus. Suggested corrective measures for the same include modifying the diac subcircuit to better suit the practical properties of the diac, which the authors of this report have been incapable of accomplishing as of writing of this report.

An alternative, naive, way around the problem was found to be raising of the breakover voltage of the diac to 50V in the subcircuit (refer Appendix B for the subcircuit code). This solution circumvents the original problem and doesn't actually solve it and must, therefore, be avoided and a better solution devised.

4. Actual laboratory results

4.1 Soldering and testing

The components were soldered onto a standard printed PCB as per the design arrived at in section 2.3. The circuit was found to be working satisfactorily and the results are tabulated in subsections to follow. Initially, a load resistor of $1k\Omega$ was used, and voltages of rms 30V, 60V and 110V were applied. Following this, a bulb was connected to the load and a voltage of rms 230V applied and the output was observed.

4.2 Results versus expected values

The results at various supply voltages were tabulated and compared with calculated values obtained upon execution of Python codes (given in Appendix A).

This table lists the firing angles at $R_{\min}$ and $R_{\max}$ obtained at $V_{i_{\text{rms}}} = 60V$ and compares the observations with values obtained theoretically.

	$\boldsymbol{R_{\min}}$	$\boldsymbol{\alpha}$		$\boldsymbol{R_{\max}}$	$\boldsymbol{\alpha}$
Practical	8.2	43.2	**Practical**	82.2	144
Theoretical	“	35.9	**Theoretical**	84.2	158.2

Table 2. Comparison betweeen practical and theoretical values of a. Firing angle for $R_{\min}$ connected. b. $R_{\max}$ for applied voltage $V_{\text{rms}} = 60V$. (All values of R in $k\Omega$ and α in degrees)

The range of control achieved (in degrees) in the above case is $\Delta\alpha = 100.8$ practically and $\Delta\alpha = 122.3$ theoretically.

The next table lists the data obtained against that calculated theoretically for an applied voltage $V_{i_{\text{rms}}} = 110V$.

	$\boldsymbol{R_{\min}}$	$\boldsymbol{\alpha}$		$\boldsymbol{R_{\max}}$	$\boldsymbol{\alpha}$		$\boldsymbol{R}$	$\boldsymbol{\alpha}$
Practical	8.2	28.8	**Practical**	155	153	**Practical**	80.2	72
Theoretical	“	25.9	**Theoretical**	162	167.4	**Theoretical**	“	100

Table 3. Comparison betweeen practical and theoretical values of a. Firing angle for $R_{\min}$ connected. b. $R_{\max}$ c. Firing angle at an arbitrary $R_{\min} + R_{\text{pot}}$ for applied voltage $V_{\text{rms}} = 110V$ (All values of R in $k\Omega$ and α in degrees)

4.3 Specimen waveforms recorded from the DSO

The following waveforms were recorded from the DSO. The value of resistance of the potentiometer is varied to obtain waveforms at different conditions.

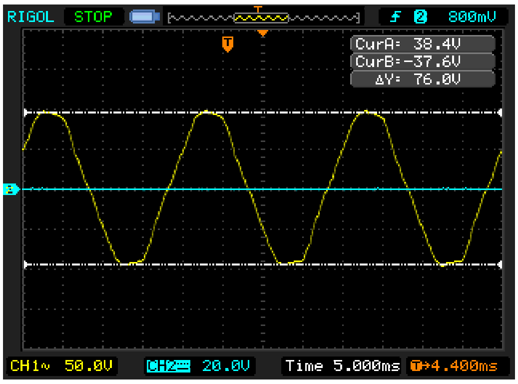

Figure 14. Input voltage

With the potentiometer at $63k\Omega$, the total applied resistance is $R = 71.2k\Omega$. The output waveform for this condition is shown below.

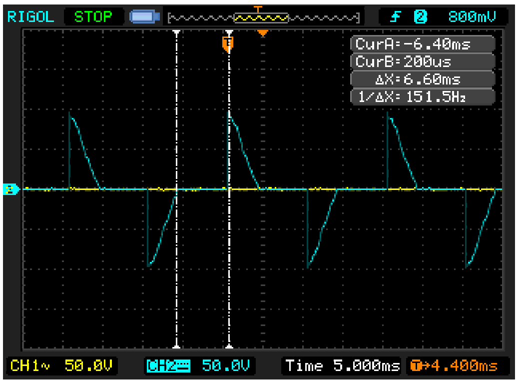

Figure 15. Output waveform

As can be seen, the firing instant of the output is 6.6ms. This translates to an angle as follows:

$$\alpha = \frac{t}{T} \times 360$$
$$\Rightarrow \alpha = \frac{6.6}{20} \times 360 = 118.8 \,\text{degrees}$$

The applied voltage is $V_{i_{\text{rms}}} = 72V$. Putting this in the Python code, for the above case, $\alpha_{\text{theoretical}} = 112$ degrees.

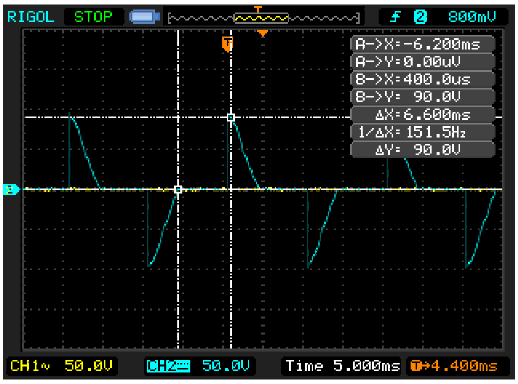

Figure 16. Output waveform

The waveform below shows the capacitor voltage. It can be clearly seen that when the voltage reaches 32V, the diac breaks down and triggers the gate of the triac.

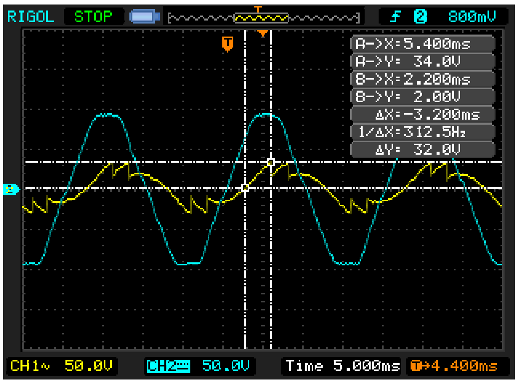

Figure 17. Capacitor voltage

The gate voltage is plotted below. Pulses are obtained everytime the capacitor voltage crosses the breakover voltage of the diac.

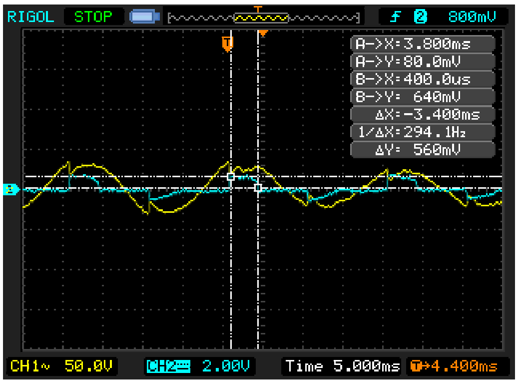

Figure 18. Gate voltage and Capacitor voltage

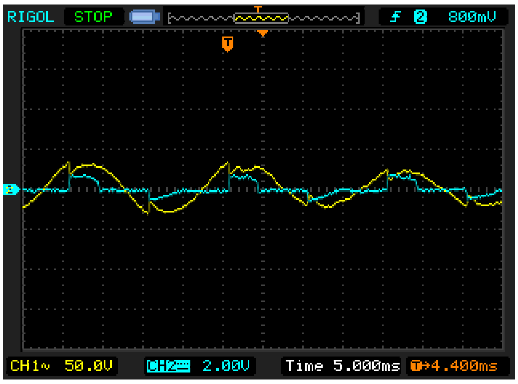

Figure 19. Gate and capacitor voltages

The minimum firing angle obtained practically for applied voltage of rms 72V is with the potentiometer at 0Ω, such that the resistance offered is only by the $R_{\min} = 8.2k\Omega$. The time of trigger, t=2.24ms. Therefore,

$$\alpha_{\min} = \frac{2.24}{20} \times 360 = 40.32\,\text{degrees}$$

The theoretical value of minimum firing angle is found to be $\alpha = 32.15$ degrees.

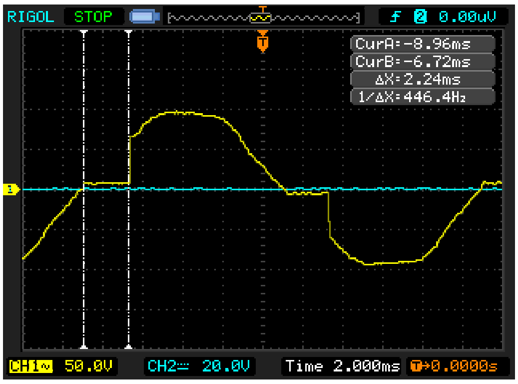

Figure 20. Minimum firing angle output waveform

The maximum firing angle for this case was found at a value of $R_{\text{pot}} = 100k\Omega \Rightarrow R = 108.2k\Omega$. The value of the firing angle is

$$\alpha = \frac{8.4}{20} \times 360 = 151.2\text{degrees}$$

The theoretical value of $R_{\text{pot}} = 103.24k\Omega$ at an angle of 162.5 degrees, as found from the Python code.

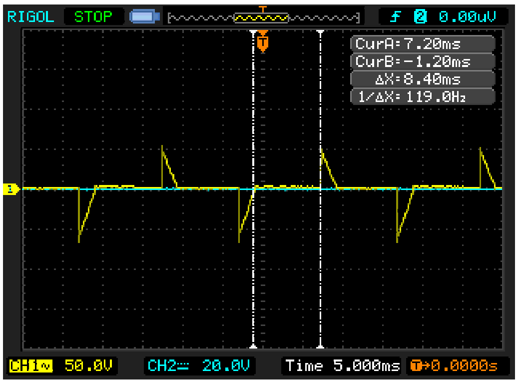

Figure 21. Maximum firing angle output waveform

The range of phase control achievable for this case can be noted as follows:

$$\Delta\alpha_{\text{theoretical}} = 162.5 - 32.15 = 130.35\text{degrees}$$
$$\Delta\alpha_{\text{practical}} = 151.2 - 40.32 = 110.88\text{degrees}$$

APPENDIX A

File: Lab01Design.py

Refer attachments.

APPENDIX B

File: Lab.net

```
* gnetlist -g spice-sdb Lab.sch
V1 n1 0 sin (0 325 50Hz)
R1 n1 n2 585k
C1 n2 0 .1uF
R2 n1 n3 881
X1 n3 n4 0 triac
X2 n2 n4 diac
.end

*============= TRIAC Subcircuit =================
.SUBCKT triac 1 2 3
* TERMINALS: MT2 G MT1
Qnpn1 5 4 3 NoutF OFF
Qpnp1 4 5 7 PoutF OFF
Qnpn2 11 6 7 NoutR OFF
Qpnp2 6 11 3 PoutR OFF
Dfor 4 5 DZ OFF
Drev 6 11 DZ OFF
Rfor 4 6 12MEG
Ron 1 7 300m
Rhold 7 6 250
RGP 8 3 350
RG 2 8 150
RS 8 4 250
DN 9 2 DIN OFF
RN 9 3 6.0
GNN 6 7 9 3 0.2
GNP 4 5 9 3 2.0
DP 2 10 DIP OFF
RP 10 3 4.0
GP 7 6 10 3 0.5
.MODEL DIN D (IS=382F)
.MODEL DIP D (IS=382F N=1.19)
.MODEL DZ D (IS=382F N=1.5 IBV=50U BV=400)
.MODEL PoutF PNP (IS=382F BF=1 CJE=190p TF=0.3U)
.MODEL NoutF NPN (IS=382F BF=3 CJE=190p CJC=38p TF=0.3U)
.MODEL PoutR PNP (IS=382F BF=5 CJE=190p TF=0.3U)
.MODEL NoutR NPN (IS=382F BF=0.5 CJE=190p CJC=38p TF=0.3U)
.ENDS triac

*================= DIAC Subcircuit =====================
.SUBCKT diac 1 2
* TERMINALS: MT2 MT1
QN1 5 4 2 NOUT; OFF
QN2 8 6 7 NOUT; OFF
QP1 6 8 10 POUT; OFF
QP2 4 5 9 POUT; OFF
D1 7 9 DZ
D2 2 10 DZ
DF 4 3 DZ; OFF
DR 6 3 DZ; OFF
RF 4 3 1.13E+7
RR 6 3 1.13E+7
RT2 1 7 0.755
RH 7 6 10k
RH2 4 2 10k
```

```
.MODEL DZ D (IS=321F RS=100 N=1.5 IBV=10N BV=30.3)
.MODEL POUT PNP (IS=321F BF=100 CJE=134p TF=25.5U)
.MODEL NOUT NPN (IS=321F BF=200 CJE=134p CJC=26.8p TF=1.7U)
.ENDS diac
```