ECE 469
Lab Report - 1

Debojyoti Mazumdar[1] and Sebastian Armstrong[2]

[1]Electrical and Computer Engineering, UIUC
[2]Electrical and Computer Engineering, UIUC

***Abstract*—Overall this report discusses two labs conducted on the topic area of AC-to-DC conversion. Passive and active rectifier circuits are tested. Various load types includes R, RL, RC, and battery loads are tested. Power factor is measured.**

I. Introduction

THIS lab focuses on the topic of AC-to-DC conversion. The first section, on experiment 1, discusses a full bridge rectifier and SCR trigger circuit. The second section, on experiment 2, focuses on SCR-based controlled rectifiers including half-wave rectifiers and a 3-phase midpoint converter.

II. Discussion of Experiment-1

In the first experiment (lab 1), a passive full bridge rectifier was tested (part 1) followed by a controlled half-wave rectifier based on an SCR (part 2).

The following equipment and components were used in lab 1:

1) Agilent 3350B waveform generator
2) 25 V_{rms} three phase transformer
3) Yokogawa WT310 power meter
4) Tektronix Model MS04304B scope
5) current and voltage probes
6) diodes, part 1n4001
7) SCR, part 10RIA40 (or similar)
8) 500 Ω resistor box
9) load resistors, capacitor, and inductor ($C = 1$ μF, $R = 1$ $k\Omega$, 47 Ω, $L = 35$ mH)
10) 1:1 isolation transformer
11) 10k trimmer potentiometer
12) 1 μF cermaic capacitor
13) breadboard

A. lab-1 part-1 full bridge rectifier

In part 1 of lab 1, a full bridge rectifier was built using passive diodes. Figure 1 below shows the general circuit layout.

Note that this circuit uses a transformer for isolation in order to prevent the need for differential voltage probes. Also, a waveform generator was chosen as the source, rather than AC mains to ensure safety.

Three load types were considered: a purely resistive (R) load, a series resistor-inductor (RL) load, and a parallel

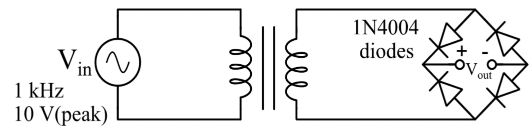

Fig. 1: Circuit diagram for part 1 of lab 1. A full bridge rectifier. Source: [1].

resistor-capacitor (RC) load. What follows is a brief discussion of the expected voltage waveforms for each load type. Note that for the R load, v_{load} is the voltage across the load resistor (see Fig. 3). For the RL case, v_{load} is taken across the resistor only (see Fig. 4). And for the RC load, v_{load} is taken across the capacitor. A small value 47 Ω resistor was also added in series with the RC load (see Fig. 5).

For these three cases, LTspice was used to model the circuit behavior. For the R load, we expect there to be zero filtering of the sinusoidal waveform, instead only the absolute value of the sinusoidal input is seen across the resistor.

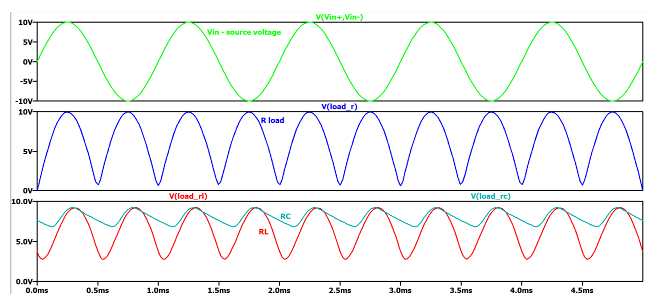

Fig. 2: Expected waveforms for part 1 of lab 1. Generated in LTspice.

For the RL load, we expect that the $v_{load-RL}(t)$ signal will be a DC value with ripple, since the inductor acts to filter the current. In addition, the peak output voltage will occur after the peak for the sinusoidal source, since current in an inductor generally lags the voltage. The expected load voltage for the RL load is shown as the red waveform in Fig. 2.

For the RC load, we also expect a filtered $v_{load-RC}(t)$ waveform, but it will look slightly different. The voltage across the capacitor will increase whenever the absolute value of the input voltage is greater than the capacitor voltage $|v_{in}(t)| > v_{cap}(t)$. When v_{in} drops below the capacitor voltage, the capacitor will begin to discharge with an approximately linear ramp (for RC time constant $\tau >> T$). The expected load voltage for the RC load is shown as the cyan waveform in Fig. 2. [1]

1) lab setup for part 1: For part 1, we first assembled a full bridge diode rectifier using four 1n4001 diodes on a breadboard. An isolation transformer was used to separate the common ground connections on the AC and DC sides of the rectifier. The initial connections and test points are shown in the sketch below (Fig. 3).

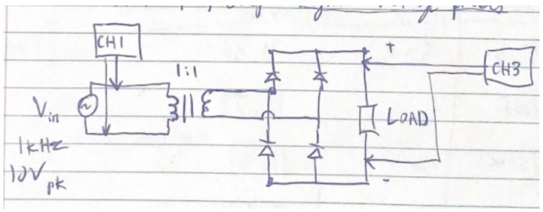

Fig. 3: Sketch of circuit and testpoints for R load case.

Note that the power rating for the 500 Ω resistor was found as:

$$P = \frac{V_{rms}^2}{R}$$

Using the fact that V_{rms} is equal to the source $V_{in(rms)}$, for the case of a full-bridge rectifier with purely resistive load, we get a power rating of $P = 0.1\ W$. Similarly, the RL and RC load cases were connected and probed as shown in figures 4 and 5 respectively.

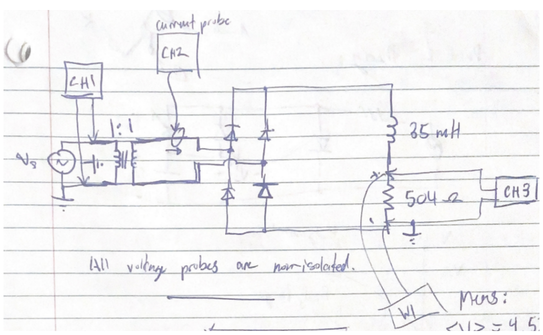

Fig. 4: Sketch of circuit and testpoints for RL load case.

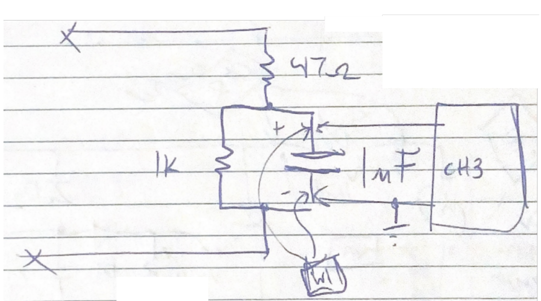

Fig. 5: Sketch of load circuit and testpoints for RC case. Rectifier output is connected to port with "x" terminals.

2) results from part 1: To begin, the oscilloscope measurements for the R-load case are shown in figure 6. Here, CH1 is $v_{in}(t)$, CH2 is the input current into the rectifier, and CH3 is the output voltage.

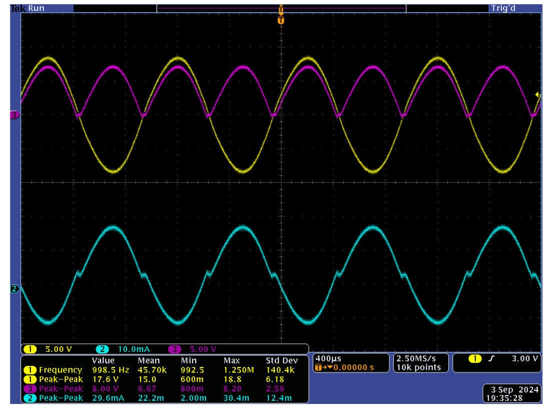

Fig. 6: Measured voltage and current for R load.

Note the diode drop of about 1V causes the actual output voltage (CH3, magenta) to fall slightly below the input voltage (C1, yellow).[2]

The RL circuit has a time constant $\tau = L/R$ equal to $\tau = 69.44\mu s$. In this case, $\tau << T$, so we therefore expect to see significant ripple with a non-constant slope. This is confirmed in both the simulation (Fig. 2) and the measured results shown in figure 7. In addition, the average load voltage was found to be $< v_{load} >= 4.073$ V in the case of the RL load.

Fig. 7: Measured voltage and current for RL load.

RC time constant $\tau = RC = (1\ k\Omega)(1\ \mu F) = 1\ ms$ Note that the period is $T = 1ms$, so $\tau = T$ in this case. We may see some non-linearity in the discharge of the capacitor voltage through the parallel 1kΩ load resistor. In practice, the $v_{cap}(t)$ waveform still closely resembles a sawtooth shape. The measurements are shown in figure 8.[3] In addition, the average load voltage was found to be $< v_{load} >= 5.599$ V in the case of the RC load. This average load voltage is greater compared to the RL case.

An interesting result is demonstrated by comparing the RL and RC load cases. Inspecting the formulae for the filter time

[1] Answer to study question 1 from lab 1.

[2] Answer to study question 4 in lab 1.

[3] Answer to study question 2 from lab 1

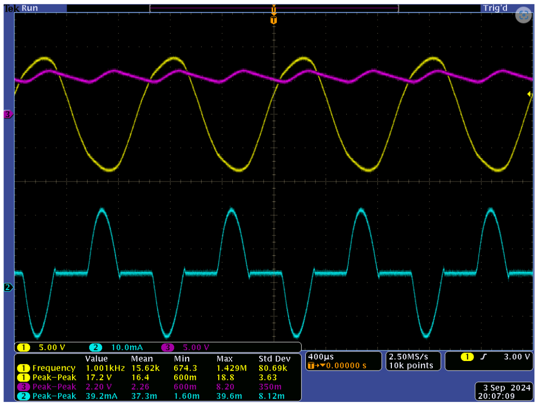

Fig. 8: Measured voltage and current for RC load.

constant τ, we find that for the RL case $\tau_{RL} \propto 1/R$ and for the RC caes $\tau_{RC} \propto R$. This means that the ripple for the RL filter will improve for a *lower* series load resistance. Meanwhile, the opposite occurs for the RC circuit: higher parallel load resistance increases τ_{RC} and reduces the ripple. In essence, the RC based filter works well when you want a DC voltage output and the RL filter works well when you want a DC *current* output. [4]

B. lab-1 part-2 discrete SCR circuit

In part 2 of lab 1, the following circuit was assembled as described in figure 9. This circuit uses a silicon controlled rectifier (SCR) as the main switch element in a controlled half-wave rectifier.

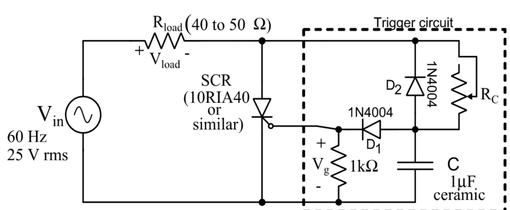

Fig. 9: Circuit diagram for part 2 of lab 1. An SCR half-wave rectifier with adjustable firing angle. Source: [1].

This kind of circuit is useful when you want to regulate the average power consumed by a load and the voltage ripple is less important. Resistive elements used in incandescent lights or space heaters are possible applications.[5].

Note that this circuit is not practical for a battery charging application, i.e., swapping R_{load} with a battery. A battery acts similar to a voltage source, and therefore should not be directly connected to another voltage source of varying potential. Although we can control the firing angle of the SCR, a filter (such as an indcutor) would be necessary to create a current source-like supply.[6]

[4]Answer to study question 3 in lab 1.
[5]Answer to study question 6
[6]Answer to study question 7 from lab 1.

TABLE I: Measured load voltage and firing delay for varying R_c potentiometer values.

R_c (Ω)	$< V_{load} >$ (V)	$V_{load(rms)}$ (V)	Firing delay (ms)
10k	8.62	16.67	≈ 3
406	11.62	19.14	1.28
0.3	12.18	19.34	≈ 0.2

1) lab setup for part 2: The circuit for part 2 was connected as shown in figure 10. The power meter was used to measure average and rms voltage across the load resistor, and the oscilloscope measured the following signals: CH1 source voltage, CH2 V_{load}, CH3 the SCR gate to cathode voltage V_g.

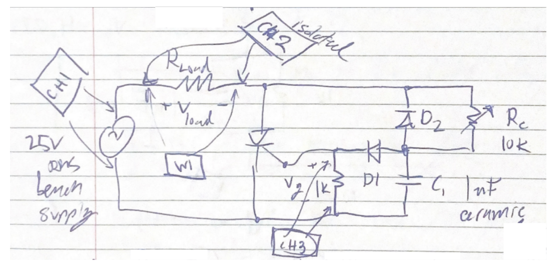

Fig. 10: Sketch of circuit and testpoints for part 2 of lab 1.

2) results from part 2: Measurements from part 2 of lab 1 are described in table I. Figure 11 plots the average load voltage vs three R_c values.

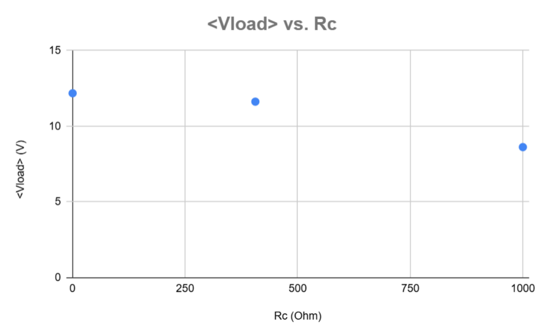

Fig. 11: Scatter plot of the average load voltage vs the potentiometer value, for lab 1 part 2.

According to Fig. 11, increasing potentiometer value decreases the average load voltage. This relationship makes sense, because we expect that the turn on delay for the SCR circuit depends on the RC time constant between R_c and C_1.

Consider the case of R_c = 406 Ω. Figures 12 and 13 show the measured $v_{in}(t)$ on CH1, $v_g(t)$ on CH3, and $v_{load}(t)$ on CH2 of the oscilloscope.

Fig. 13 uses a zoomed in horizontal axis in order to determine the turn on delay. Given that each horizontal division is 400 μs, the turn on delay can be found from the time delay between the rising edge in $v_g(t)$ and the firing of the SCR (indicated by 2nd rising edge on v_{load}). Here, the delay is equal to $T_d = 1.28$ ms. The RC time constant of the trigger circuit can be found as:

$$\tau = (R_{load} + R_c)C_1$$

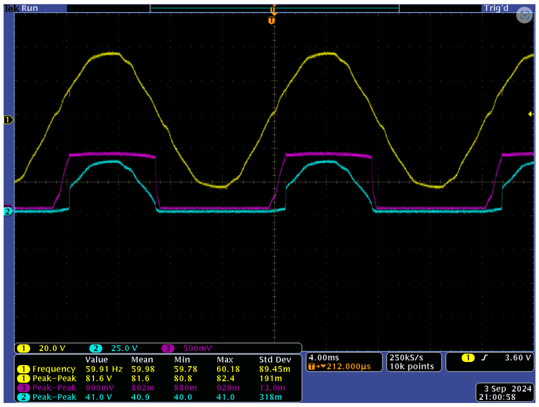

Fig. 12: Measurements on oscilloscope for part 2 of lab 1 for the case $R_c = 406\ \Omega$

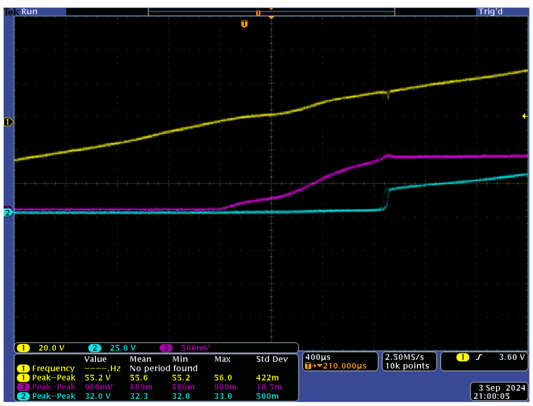

Fig. 13: Measurements on oscilloscope for part 2 of lab 1 for the case $R_c = 406\ \Omega$. Zoomed in view.

In the case of $R_{load} + R_c = 456\ \Omega$, we get $\tau = 0.456$ ms. Thus, since $\tau < T_d$, multiple time constants must elapse before the capacitor is sufficiently charged to trigger the SCR.

III. Discussion of Experiment-2

In this experiment, we are making a single phase AC-DC rectifier and a polyphase AC-DC rectifier.

We used the following equipments for our experiment :

1) Voltage source: Three-phase transformer set 120 V/25.2 V, using only two phases.
2) Scope: Tektronix Model MS04304B scope, 350 MHz 2.5 GS/s, 4 CH Analog and 16 CH Digital
3) Power meter: Yokogawa WT310 Power Meter
4) Current and voltage probes: Tektronix probes (current, voltage, and isolated voltage)
5) Diode: 1N4004
6) Polyphase SCR control unit
7) 50Ω load resistor
8) banana leads
9) breadboard with jumper wires

A. Theory

1) Single Phase AC-DC converter with resistive load: We get the equivalent circuit as shown in Fig. 14.

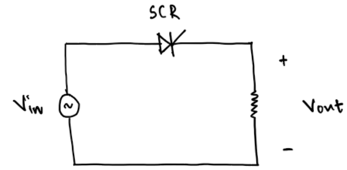

Fig. 14: Single Phase AC-DC converter with resistive load

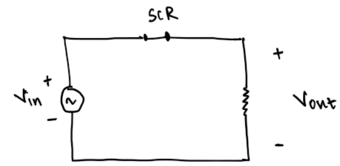

Fig. 15: Equivalent circuit when SCR is conducting

Here, there are only two states of operation, one when the SCR is ON and other when it is OFF. The SCR is ON when the input voltage $V_{in} \geq 0$. The equivalent circuit in this case is shown in Fig. 15. The SCR is OFF when ht einput voltage $V_{in} < 0$. The equivalent circuit in this case is shown in Fig. 16.

The voltage and current waveforms for this circuit are as shown in Fig. 17.

Let us say $V_{in} = V_m \sin(\omega t)$. Then we can write V_{out} and I_{out} as shown below.

$$V_{out} = \begin{cases} V_m \sin(\omega t) \text{ For } \alpha \leq \omega t \leq \pi \\ 0 \text{ For } 0 \leq \omega t \leq \alpha \text{ and } \pi \leq \omega t \leq 2\pi \end{cases}$$

$$I_{out} = \begin{cases} \frac{V_m}{R} \sin(\omega t) \text{ For } \alpha \leq \omega t \leq \pi \\ 0 \text{ For } 0 \leq \omega t \leq \alpha \text{ and } \pi \leq \omega t \leq 2\pi \end{cases}$$

We then calculate the $(V_{out})_{avg}$, input power factor and the efficiency.

1) $\underline{(V_{out})_{avg}:}$

$$\begin{aligned} (V_{out})_{avg} &= \frac{1}{2\pi}\int_0^{2\pi} V_{in}(t)d(\omega t) \\ &= \frac{1}{2\pi}\int_\alpha^{\pi} V_m \sin(\omega t)d(\omega t) \\ &= \frac{V_m}{2\pi}(1 + \cos(\alpha)) \end{aligned}$$

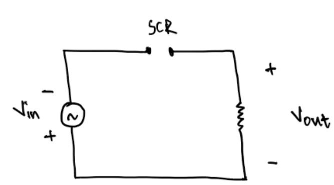

Fig. 16: Equivalent circuit when SCR is not conducting

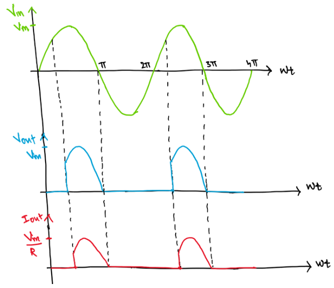

Fig. 17: Waveforms for the single phase AC-DC converter with resistive load.

2) $(V_{out})_{rms}$:

$$
\begin{aligned}
(V_{out})_{rms} &= \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_{out}^2(t)d(\omega t)} \\
&= \sqrt{\frac{V_m^2}{2\pi}\int_\alpha^{\pi} \sin{(\omega t)}^2 d(\omega t)} \\
&= V_m\sqrt{\frac{(\pi-\alpha+\frac{\sin{(2\alpha)}}{2})}{4\pi}}
\end{aligned}
$$

3) Input Power Factor :

$$
\begin{aligned}
(P_{in})_{avg} &= \frac{1}{2\pi}\int_0^{2\pi} V_{in}(t)I_{in}(t)d(\omega t) \\
&= \frac{1}{2\pi}\int_0^{2\pi} V_{in}(t)I_{out}(t)d(\omega t) \\
&\text{(Because } I_{in} = I_{out}) \\
&= \frac{V_m^2}{2\pi R}\int_\alpha^{\pi} \sin{(\omega t)}^2 d(\omega t) \\
&= \frac{V_m^2}{4\pi R}(\pi-\alpha+\sin{(2\alpha)}))
\end{aligned}
$$

We now find the RMS values of V_{in} and I_{in}.

$$
\begin{aligned}
(V_{in})_{rms} &= \frac{V_m}{\sqrt{2}} \text{ (Because sine wave)} \\
(I_{in})_{rms} &= \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_{in}^2(t)d(\omega t)} \\
&= \sqrt{\frac{V_m^2}{2\pi R^2}\int_\alpha^{\pi} \sin{(\omega t)}^2 d(\omega t)} \\
&= \frac{V_m}{R}\sqrt{\frac{(\pi-\alpha+\sin{(2\alpha)})}{2\pi}}
\end{aligned}
$$

Using this we can find out the input Power Factor.

$$
\begin{aligned}
\text{Input Power Factor} &= \frac{(P_{in})_{avg}}{(V_{in})_{rms}(I_{in})_{rms}} \\
&= \frac{\frac{V_m^2}{4\pi R}(\pi-\alpha+\sin{(2\alpha)}))}{\frac{V_m}{\sqrt{2}} \times \frac{V_m}{R}\sqrt{\frac{(\pi-\alpha+\sin{(2\alpha)})}{2\pi}}} \\
&= \sqrt{\frac{(\pi-\alpha+\sin{(2\alpha)})}{4\pi}}
\end{aligned}
$$

2) Single Phase AC-DC converter with inductive load: We consider the inductive load to be high enough, such that the current flowing through it can be assumed to be constant. This way we can get an approximate circuit as shown in Fig. 18.

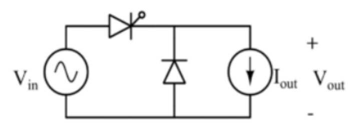

Fig. 18: A single-phase ac voltage to dc current converter.

In the circuit, we can easily see through KVL that when $V_{in}(t) > 0$ and the gate pulse of the SCR is high, then the SCR turns ON. When $V_{in} < 0$, the free-wheeling diode becomes forward biased and starts to conduct. When the free-wheeling diode turns ON, the current through the SCR becomes 0 and the SCR turns OFF. We can say that the equivalent circuits during the two modes of operations are shown in Fig. 19 and Fig. 20.

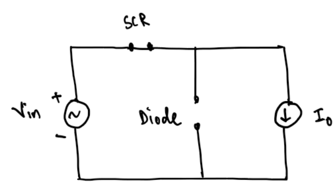

Fig. 19: Equivalent circuit when SCR conducting

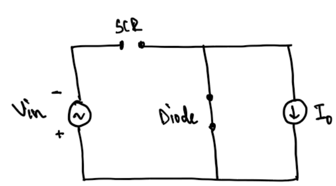

Fig. 20: Equivalent circuit when diode conducting

We will consider the input voltage to be

$$V_{in}(t) = V_m \sin{(\omega t)}$$

From the circuits we can find V_{out} in terms of the input voltage by applying KVL.

$$
V_{out} = \begin{cases} V_m \sin{(\omega t)} & \text{When the SCR is ON} \\ 0 & \text{When the SCR is OFF} \end{cases}
$$

From the circuits we can find input current (I_{in}) in terms of the inductor current by applying KCL.

$$I_{in} = \begin{cases} I_0 & \text{When the SCR is ON} \\ 0 & \text{When the SCR is OFF} \end{cases}$$

From this we get the waveforms as shown in Fig. 21.

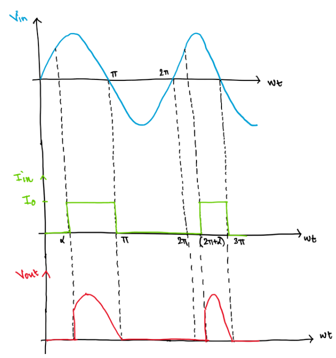

Fig. 21: Waveforms for the single phase AC-DC converter with inductive load.

Then we calculate the formula for input power factor and efficiency. For this we

1) $\underline{(V_{out})_{avg}:}$

$$\begin{aligned}(V_{out})_{avg} &= \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t)d(\omega t) \\ &= \frac{V_m}{2\pi}(1+\cos(\alpha))\end{aligned}$$

2) $\underline{(V_{out})_{rms}:}$

$$\begin{aligned}(V_{out})_{rms} &= \sqrt{\frac{1}{2\pi}\int_{0}^{2\pi} V_{out}^2(t)d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi} \sin(\omega t)^2 d(\omega t)} \\ &= V_m\sqrt{\frac{1}{4\pi}(\omega t - \frac{\sin(2\omega t)}{2})_{\alpha}^{\pi}} \\ &= V_m\sqrt{\frac{(\pi - \alpha + \frac{\sin(2\alpha)}{2})}{4\pi}}\end{aligned}$$

3) Input Power Factor :

$$\begin{aligned}(P_{in})_{avg} &= \frac{1}{2\pi}\int_{0}^{2\pi} V_{in}(t)I_{in}(t)d(\omega t) \\ &= \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m\sin(\omega t)\times I_0 d(t) \\ &= \frac{V_m I_0}{2\pi}(1+\cos(\alpha))\end{aligned}$$

We then find $(V_{in})_{rms}$ and $(I_{in})_{rms}$.

$$(V_{in})_{rms} = \frac{V_m}{\sqrt{2}} \qquad \text{(Because it is a sine wave)}$$

$$\begin{aligned}(I_{in})_{rms} &= \sqrt{\frac{1}{2\pi}\int_{0}^{2\pi} I_{in}^2(t)d(\omega t)} \\ &= \sqrt{\frac{1}{2\pi}\times I_0^2 \times (\pi - \alpha)} \\ &= I_0\sqrt{\frac{(\pi-\alpha)}{2\pi}}\end{aligned}$$

$$\begin{aligned}\text{Input Power Factor} &= \frac{\text{Average Input Power}}{(V_{in})_{rms}(I_{in})_{rms}} \\ &= \frac{\frac{V_m I_0}{2\pi}(1+\cos(\alpha))}{(\frac{V_m}{\sqrt{2}})(I_0\sqrt{\frac{(\pi-\alpha)}{2\pi}})} \\ &= \frac{(1+\cos(\alpha))}{\sqrt{\pi(\pi-\alpha)}}\end{aligned}$$

3) *Single Phase AC-DC converter with Battery at the output:* A simple circuit diagram for this case is shown in Fig. 22.

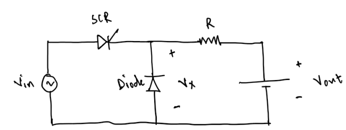

Fig. 22: Single phase AC-DC converter with battery at the output

For a given firing angle α we should get the waveform as shown in Fig. 23.

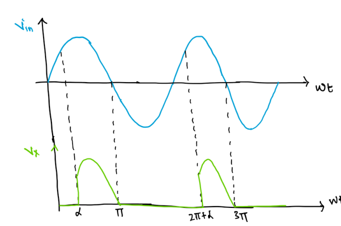

Fig. 23: Waveform for the single phase recitifer with battery at the output

We can find the $(I_{out})_{avg}$ by doing the following.

$$\begin{aligned}(V_X)_{avg} &= \frac{1}{2\pi}\int_{0}^{2\pi} V_X(t)d(\omega t) \\ &= \frac{V_m}{2\pi}(1+\cos(\alpha)) \\ (I_{out})_{avg} &= \frac{(V_X)_{avg} - V_{out}}{R} \\ &= \frac{\frac{V_m}{2\pi}(1+\cos(\alpha)) - V_{out}}{R}\end{aligned}$$

B. Results

We recorded that the RMS value of the input voltage using the scope to be $28.19V$.

1) Single Phase AC-DC converter with Resistive load :

We make the circuit connection as shown in Fig. 24.

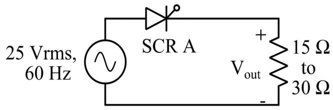

Fig. 24: Single Phase AC-DC converter with resistive load

TABLE II: Measurement of V_{out} with different firing angle.

Firing angle (ms)	$(V_{out})_{avg}$ (V)	$(V_{out})_{rms}$ (A)
0°	11.96	18.94
45°	10.36	18.15
90°	6.17	13.7
135°	2.19	6.78

TABLE III: Measurement of Power Factor (PF) with different firing angle.

Firing angle (ms)	PF with Yokogawa	PF with Scope
0°	0.6952	0.690
45°	0.664	0.657
90°	0.498	0.497
135°	0.247	0.246

We will take firing angle of 45° to verify our theoretical calculations.

$$\begin{aligned}(V_{out})_{avg} &= \frac{V_m}{2\pi}(1+\cos(\alpha)) \\ &= \frac{28.19\sqrt{2}}{2\pi}(1+\cos(45^\circ)) \\ &= 10.83V\end{aligned}$$

This is close to the practical value of $(V_{out})_{avg} = 10.36V$.

$$\begin{aligned}(V_{out})_{rms} &= V_m\sqrt{\frac{(\pi-\alpha+\frac{\sin(2\alpha)}{2})}{4\pi}} \\ &= 28.19\sqrt{2}\sqrt{\frac{(\pi-\frac{\pi}{4}+\frac{1}{2})}{4\pi}} \\ &= 19V\end{aligned}$$

This is close to the practical value of $(V_{out})_{avg} = 18.15V$

$$\begin{aligned}\text{Input Power Factor} &= \sqrt{\frac{(\pi-\alpha+\frac{\sin(2\alpha)}{2})}{4\pi}} \\ &= \sqrt{\frac{(\pi-\frac{\pi}{4}+\frac{1}{2})}{4\pi}}\end{aligned}$$

Sketching the waveform for a firing angle of 45° is shown in Fig. 25.

2) Single Phase AC-DC converter with inductive load :

Fig. 25: Waveform for the single phase AC-DC converter with resistive load.

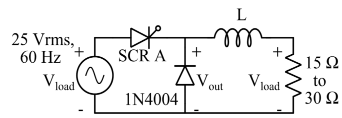

Fig. 26: Single phase AC-DC converter with inductive load

We use the circuit connection as shown in the Fig. 26.

$$\begin{aligned}(V_{out})_{avg} &= \frac{28.19\sqrt{2}}{2\pi}(1+\cos(45^\circ)) \\ &= 10.83V\end{aligned}$$

This is close to the practical value of $(V_{out})_{avg} = 9.7V$.

$$\begin{aligned}(V_{out})_{rms} &= V_m\sqrt{\frac{(\pi-\alpha+\frac{\sin(2\alpha)}{2})}{4\pi}} \\ &= 28.19\sqrt{2}\sqrt{\frac{(\pi-\frac{\pi}{4}+\frac{1}{2})}{4\pi}} \\ &= 19V\end{aligned}$$

This is close to the practical value of $(V_{out})_{rms} = 18.4V$.

$$\begin{aligned}\text{Input Power Factor} &= \frac{(1+\cos(\alpha))}{\sqrt{\pi(\pi-\alpha)}} \\ &= \frac{(1+\cos(45^\circ))}{\sqrt{\pi\times\frac{3\pi}{4}}} \\ &= 0.627\end{aligned}$$

This is close to the practical value of Input Power Factor = 0.58.

Sketch of the waveform for firing angle of 45° is shown in Fig. 27.

TABLE IV: Measurement of V_{out} with different firing angle for inductive load.

Firing angle (ms)	$(V_{out})_{avg}$ (V)	$(V_{out})_{rms}$ (A)	$(V_{load})_{rms}$
45°	9.7	18.4	14.6
90°	5.47	14	9.56
135°	1.9	7.05	3.57

TABLE V: Measurement of Power Factor (PF) with different firing angle for inductive load.

Firing angle (ms)	PF with Yokogawa	PF with Scope
45°	0.58	0.573
90°	0.4	0.428
135°	0.183	0.184

Fig. 27: Single phase AC-DC converter with inductive load

3) Single Phase AC-DC converter with battery at the output :

We make the circuit connection as shown in Fig. 28.

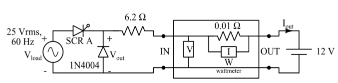

Fig. 28: Single Phase AC-DC converter with battery at the output

TABLE VI: Measurement of $(I_{out})_{avg}$ with different firing angle for inductive load.

Firing angle	$(I_{out})_{avg}$ (A)
45°	0.675
90°	0.388
135°	0.096

IV. Conclusion

Overall, we learned the effects of RL and RC loads on rectifiers, the control effect of adjusting the firing angle of an SCR, and how to measure power factor both with a power meter and from oscilloscope measurements.

References

[1] ECE 469 lab manual