ECE 469
Lab Report - 3

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***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-6

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. Theory

1) PWM control: PWM control uses to different waveforms to produce a single waveform for the control of the switches of Voltage Source Inverters(VSI). The two waveforms are-carrier wave and modulating wave. Figure-1 shows Sine PWM in action.

The output of the PWM waveform is HIGH, if the carrier wave is higher than the modulating wave. It is LOW, if the carrier wave is less than the modulating wave. In case of Sine PWM, we use a triangle wave as our carrier wave and a Sine wave as our modulating wave. The ratio of the peak of the sine wave to the triangle wave is called amplitude modulation index (m_a). In case of the VSI shown in Figure- , the output would be either $+V_{dc}$ or $-V_{dc}$. Then we can write the output of the VSI with sine PWM control as follows.

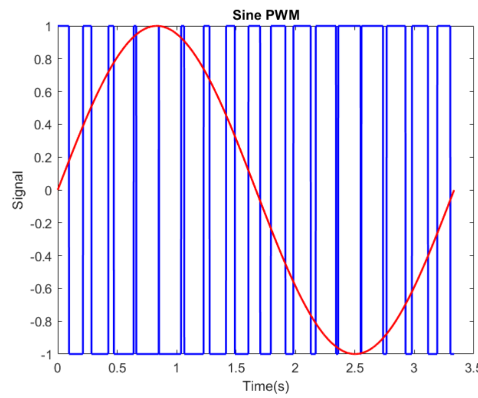

Fig. 1: Sine PWM

$$V_0 = \begin{cases} +V_{dc} & \text{When carrier wave } \geq \text{ modulating wave} \\ -V_{dc} & \text{When carrier wave } < \text{ modulating wave} \end{cases}$$

The fundamental component of the output of the VSI (V_0) would be a sine wave with the same frequency as the modulating wave.

$$(V_0)_1 = m_a V_{dc} \sin(\omega t)$$

[1] The advantage of Sine PWM control over the traditional square wave control is about reduced harmonics. The frequency spectrum of both the waves are shown in Figure-2. The Sine PWM wave used to generte the waveform has a carrier frequency of 5 KHz. As can be seen in Figure-2, the frequency spectrum of Sine PWM has peaks centered around multiples of the carrier wave frequency. So, by increasing the carrier wave frequency, we can increase the frequency up to which the filter can filter the output. This would result in reduction of the size of inductors and also lead to a much smoother output current as shown in Figure-5. This would result in

[1]Answer to Study Question-6

smoother motor operations and reduced losses in the motor due harmonic currents [2].

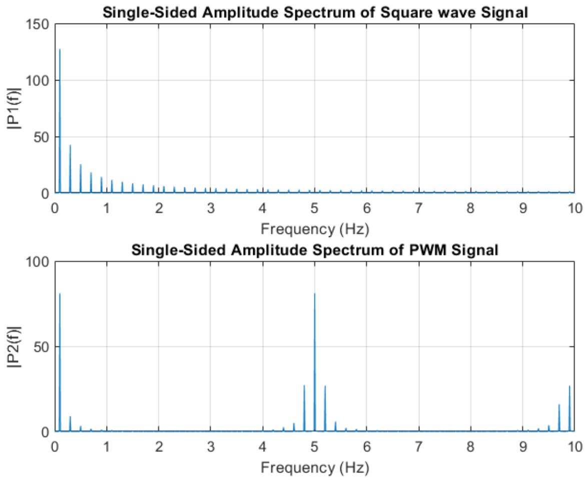

Fig. 2: Frequency spectrum of the output voltage (V_0) for (i) Traditional square wave control and (ii)Sine PWM control

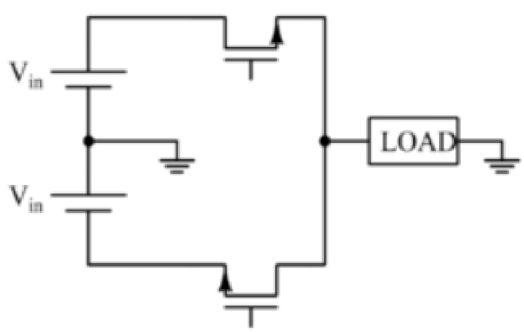

Fig. 3: Half Bridge Inverter

2) PWM VSI with an RL load: The output current(i_0) of in this kind of load can be found by solving the following differential equation.

$$V_0 = L\frac{di_0}{dt} + Ri_0$$

For an $R = 10\Omega$, $L = 0.1H$ and $V_{dc} = 100V$, and solving the differential equation through MATLAB, we get the output current waveform as shown in Figure-.

As can be seen from the waveforms, the RL load filters out the fundamental of the switching output voltage (V_0). The fundamental componentn of the ouput current (i_0) also has a phase shift from the fundamental component of the output voltage (V_0).

At a higher carrier wave frequency, the output current waveform becomes smoother. This can be seen by comparing Figure- and Figure-. In Figure - , the carrier wave has a frequency of 10 times that of in Figure-. This is because the PWM output changes more often in a cycle. This leads to a

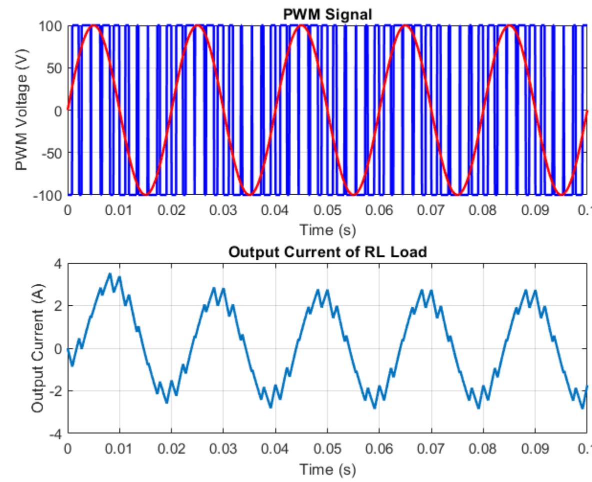

Fig. 4: Output current (i_0) waveform and output voltage (V_0) waveform.

more fine discrete steps in the current waveform. This leads to smoother waveform [3].

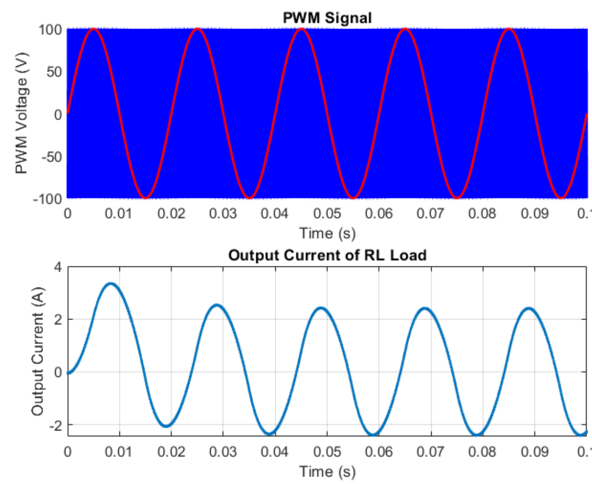

Fig. 5: Output current (i_0) and output voltage (V_0) waveforms for higher carrier frequency.

At a higher modulating frequency the frequency of the output current (i_0) waveform increases. This is because the RL load acts as a filter and filters out the fundamental component of the output voltage (V_0) [4].

3) Single phase full bridge PWM controlled VSI: The circuit diagram of the single phase full bridge VSI is as shown in Figure-7.

The only difference between the full bridge and half bridge VSI would be that signal going to the upper switch in Figure-3 would be the same as the signal going to both the switches S1 and S2 in Figure-7 and the signal going to the lower switch

[2]Answer to Study Question-2

[3]Answer to Study Question-1

[4]Answer to Study Question-1

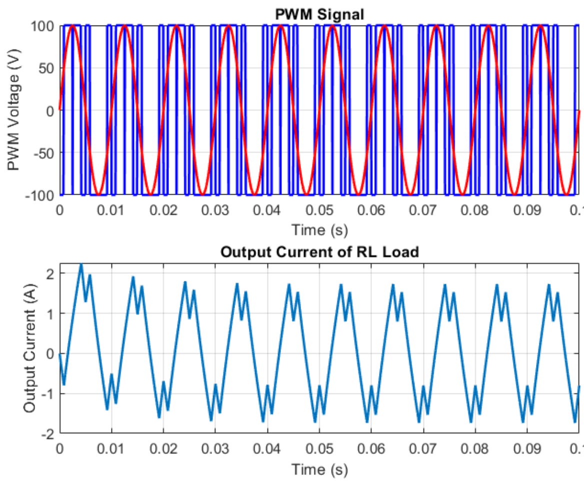

Fig. 6: Output current (i_0) and output voltage (V_0) waveforms at higher modulating frequency.

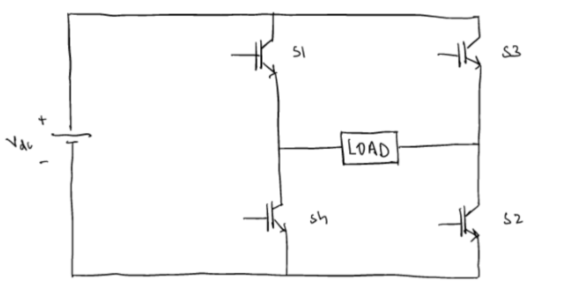

Fig. 7: Circuit diagram of a single phase full bridge VSI

in Figure-3 would be the same as the signal going to both the switches S3 and S4 in Figure-7 [5].

B. Simulations

1) Three phase inverter with PWM control: The circuit diagram of the simulation looks as shown in Figure-8.

[5]Answer to Study Question-3

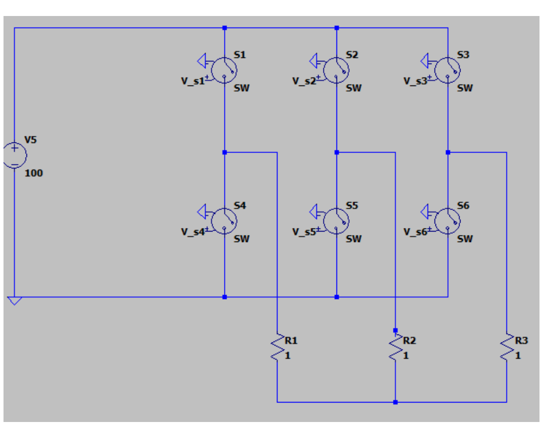

Fig. 8: Three phase inverter with PWM control.

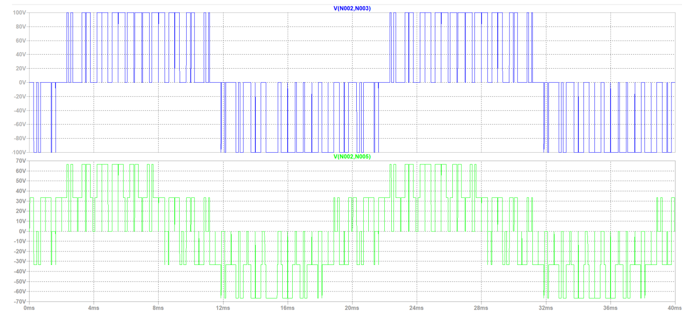

Fig. 9: Waveform of Phase-A voltage (Green) and Line-A to Line-B voltage (Blue)

The waveform of a single phase voltage and single line-to-line voltage is shown in Figure-9 [6].

C. Results

1) Part-1: PWM inverter, R-L load: We make the circuit connections as mentioned in Figure-10. We use 10 Ω resistor instead of 6 Ω at the output.

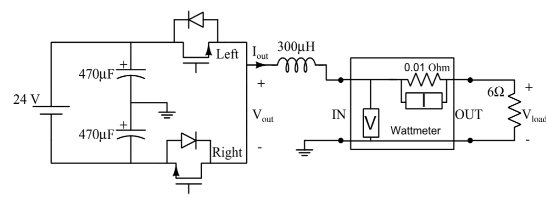

Fig. 10: Voltage-sourced inverter test circuit

Then we connect the probes for visualizing the waveforms with the channel numbers on the oscilloscope as mentioned in Figure-11. The Channel-4 of the oscilloscope is connected to the 'q' terminal of the FET box to measure the PWM signal and Channel-1 is connected to the function generator which produces the modulating sine wave.

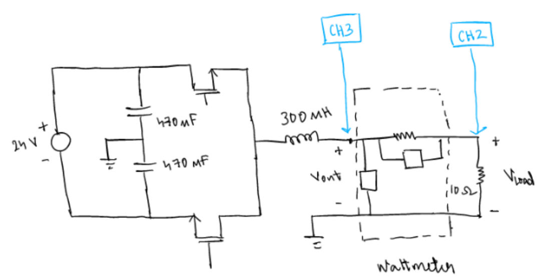

Fig. 11: VSI test circuit with probes.

We keep the amplitude modulation index at 0.75. We then observe the waveforms on the oscilloscope for two distinct switching frequencies, as illustrated in Figure-12 and Figure-13 (for f_{sw} = 20 KHz) and Figure-15 and Figure-14 (for $f_{sw} = 50$ KHz).

As predicted and seen from the oscilloscope readings, the output voltage (V_{load}) becomes smoother at higher switching

[6]Answer to Study Question-4

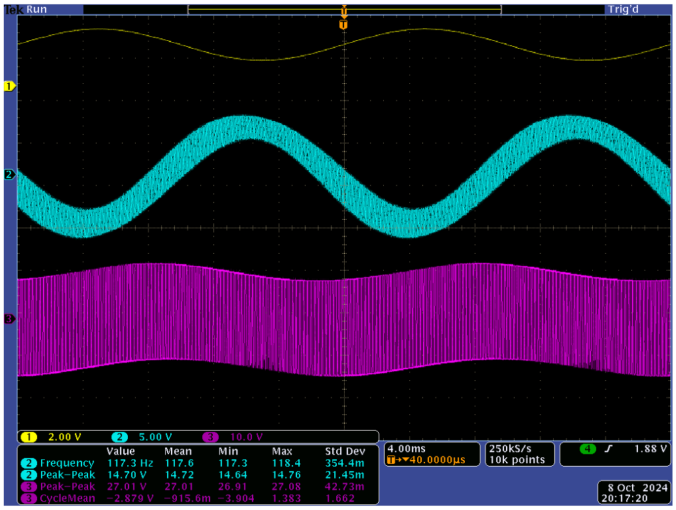

Fig. 12: Oscilloscope shot of the pwm signal ($q(t)$), load voltage ($V_{load}(t)$) and output voltage ($V_{out}(t)$) for $f_{sw} = 20$ KHz and $m_a = 0.75$.

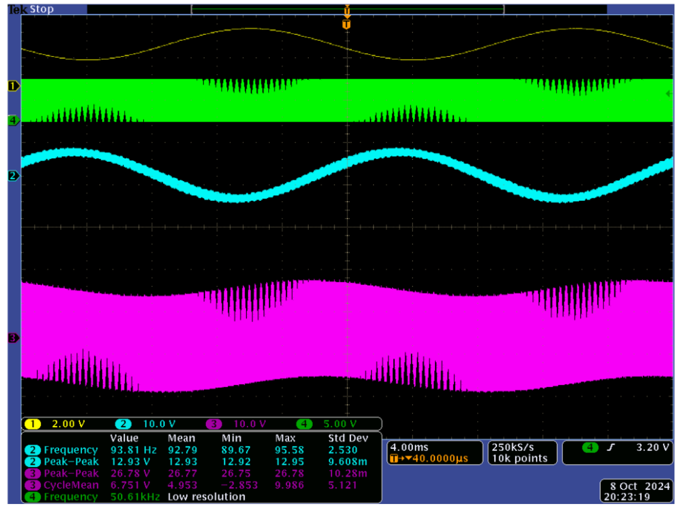

Fig. 14: Oscilloscope shot of the pwm signal ($q(t)$), load voltage ($V_{load}(t)$) and output voltage ($V_{out}(t)$) for $f_{sw} = 50$ KHz and $m_a = 0.75$.

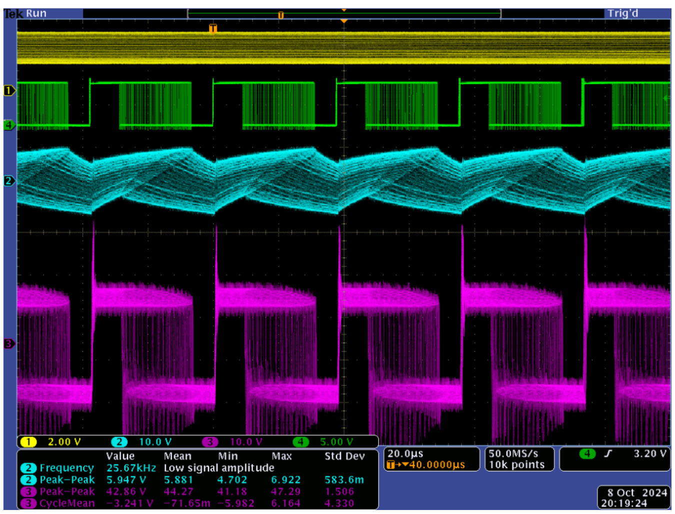

Fig. 13: Close up of oscilloscope shot of the pwm signal ($q(t)$), load voltage ($V_{load}(t)$) and output voltage ($V_{out}(t)$) for $f_{sw} = 20$ KHz and $m_a = 0.75$.

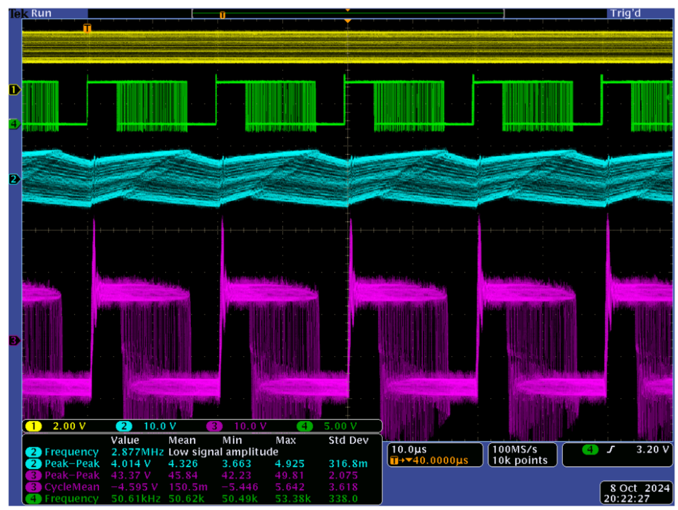

Fig. 15: Close up of oscilloscope shot of the pwm signal ($q(t)$), load voltage ($V_{load}(t)$) and output voltage ($V_{out}(t)$) for $f_{sw} = 50$ KHz and $m_a = 0.75$.

frequencies (f_{sw}). Then, we decrease the amplitude modulation index (m_a) to 0.375, keeping the switching frequency (f_{sw}) at 50 KHz.

The Table - I shows the RMS load voltage ($(V_{load})_{RMS}$), RMS load current ($(I_{load})_{RMS}$), and average power into the load resistor ($< P_{load} >$) for two different amplitude modulation index (m_a), keeping the switching frequency (f_{sw}) at 50 KHz.

m_a	$< I_{in} >$**(A)**	$(V_{load})_{RMS}$**(V)**	$(I_{load})_{RMS}$**(A)**
0.75	0.085	3.95	0.38
0.375	0.035	2.13	0.206

TABLE I: Table for measurements for different values of amplitude modulation index (m_a)

As can be seen from the waveforms and the table, as the amplitude modulation index (m_a) decreases, the peak value of the load voltage (V_{load}) and current (I_{load}) decreases. This can be explained from the fact that the RL load filters out the fundamental component of the output voltage (V_{out}). The amplitude of the fundamental voltage is directly proportional to the amplitude modulation index as shown in the theory section. Therefore, the aimplitude of the voltage and current decreases across the resistor load.

The Table-II contains the efficiency values for the two different amplitude modulation index (m_a) [7].

We then reduce the switching frequency (f_{sw}) to 1 Hz and observe the pwm signal ($q(t)$) with time in the oscilloscope. Two snapshots of the video are shown in Figure-18 and Figure-19.

[7]Answer to Study Question-5

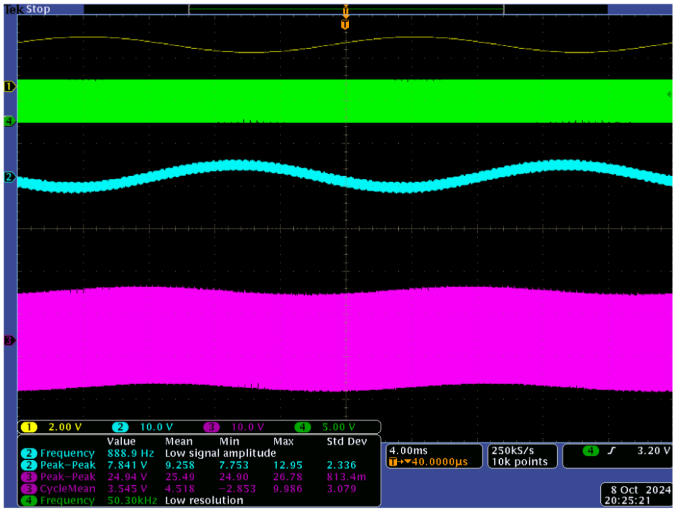

Fig. 16: Oscilloscope shot of the pwm signal ($q(t)$), load voltage ($V_{load}(t)$) and output voltage ($V_{out}(t)$) for $f_{sw} = 50$ KHz and $m_a = 0.375$.

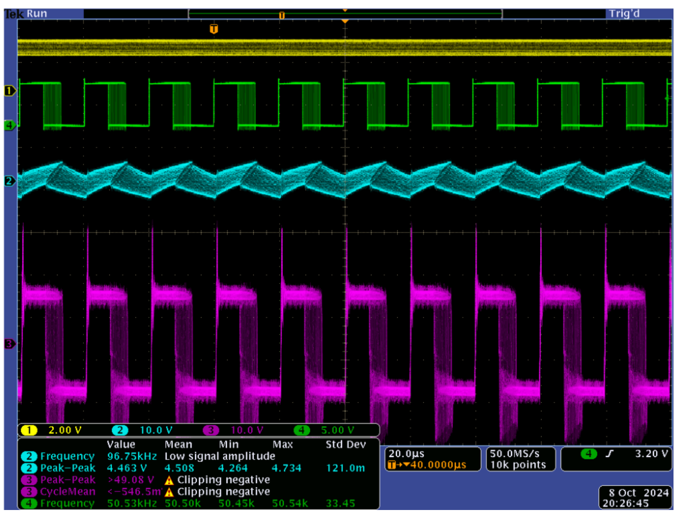

Fig. 17: Close up of oscilloscope shot of the pwm signal ($q(t)$), load voltage ($V_{load}(t)$) and output voltage ($V_{out}(t)$) for $f_{sw} = 50$ KHz and $m_a = 0.375$.

m_a	$< I_{in} >$(A)	$< P_{load} >$(W)	**Efficiency** (%)
0.75	0.085	1.52	74.5
0.375	0.035	0.43	51.2

TABLE II: Table for the measured average input current ($< I_{in} >$), average load power ($< P_{load} >$) and efficiency of the converter.

2) *Part-2: Induction motor drive:* We first make the circuit as shown in Figure-20. Here, a 1 KΩ is connected as a load across the secondary side of the transformer.

We then measure the average value of the load voltage ($< V_{load} >$) and the RMS value of the load voltage ($(V_{load})_{RMS}$) as shown in Table-III.

The oscilloscope shot of the waveform of load voltage (V_{load}) and resistor voltage (V_r) is shown in Figure-21.

Fig. 18: Oscilloscope shot of the pwm signal ($q(t)$), output voltage ($V_{out}(t)$) and load voltage ($V_{load}(t)$) for the modulating frequency of 1 Hz at one time instance.

Fig. 19: Oscilloscope shot of the pwm signal ($q(t)$), output voltage ($V_{out}(t)$) and load voltage ($V_{load}(t)$) for the modulating frequency of 1 Hz at one time instance.

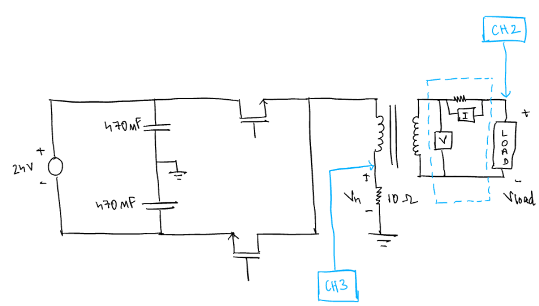

Fig. 20: Circuit diagram of PWM controlled half bridge VSI with a transformer and 1 kΩ load resistance with probe connections.

$< V_{load} >$(**V**)	$(V_{load})_{RMS}$(**V**)
0.75	0.085

TABLE III: Table for measurements for different values of amplitude modulation index (m_a)

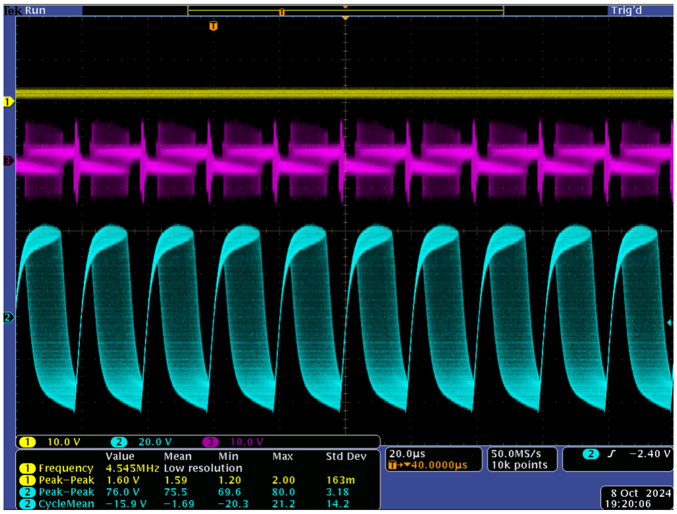

Fig. 21: Oscilloscope shot of the load voltage (V_{load}) of the 1 KΩ load resistance and resistor voltage (V_r) of the 10 Ω resistance.

We then reconnect the load side with the small quadrature motor as shown in Figure-22.

Then we observe the the waveforms of the voltage across the secondary side of the transformer (V_{out}) and the resistor voltage (V_r) for different values of the modulation frequency and amplitude modulation index (m_a).

3) Part-3: Audio amplifier application: We were shown a demo of the audio amplifier circuit. Here, as the amplitude of the modulating signal was increased, the audio amplifier became louder. The waveform of the modulating and carrier waves are shown in Figure-26.

4) Part-4: Commercial drive demonstration: We were shown a demo of a commercial PWM ac motor drive. Here, a three phase AC voltage was generated from an inverter using three PWM signals and fed into the windings of the AC motor. The waveform of a single phase voltage and current was observed for three different modulation frequencies are shown in Figure-27, Figure-28 and Figure-29.

III. 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.

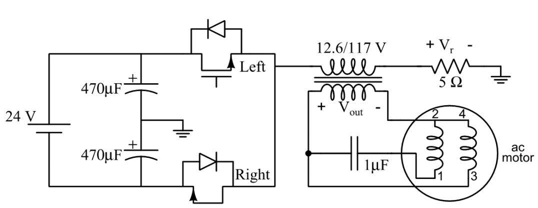

Fig. 22: Single phase Ac motor drive test circuit

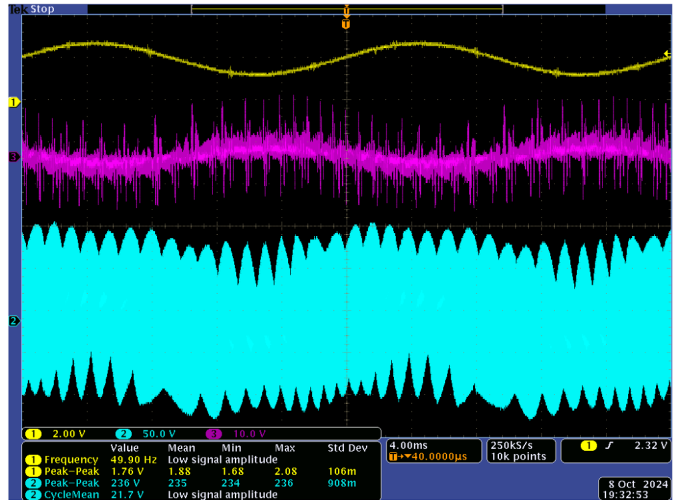

Fig. 23: Oscilloscope shot of the output voltage (V_{out}), resistor voltage (V_r) for modulation frequency of 50 Hz and $m_a = 0.75$.

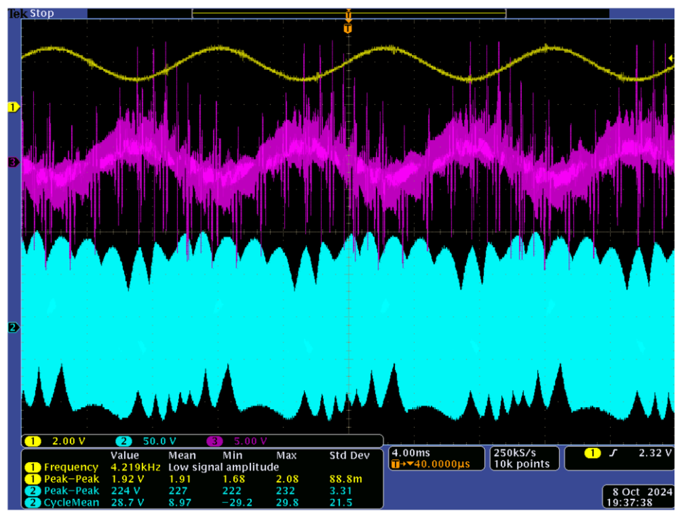

Fig. 24: Oscilloscope shot of the output voltage (V_{out}), resistor voltage (V_r) for modulation frequency of 98 Hz and $m_a = 0.75$.

References

[1] ECE 469 lab manual

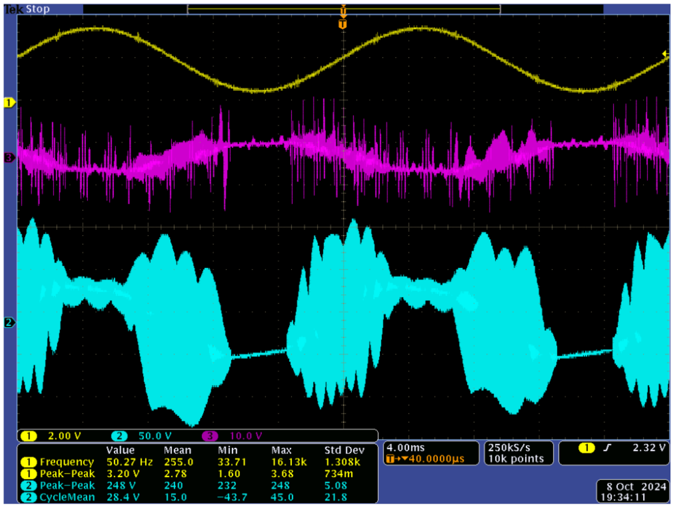

Fig. 25: Oscilloscope shot of the output voltage (V_{out}), resistor voltage (V_r) for modulation frequency of 50 Hz and $m_a = 1.5$.

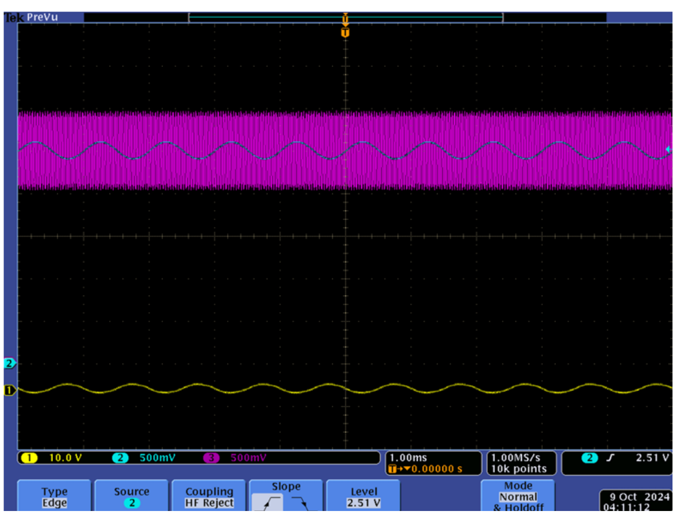

Fig. 26: Waveforms of triangle carrier wave (Purple), modulating function (blue) and switching function (yellow).

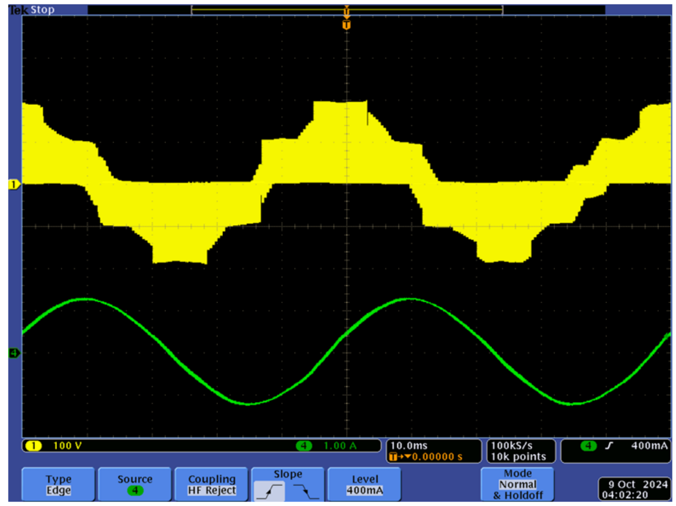

Fig. 27: Waveform of a phase voltage (yellow) and same phase current (green) for a modulation frequency of 20 Hz.

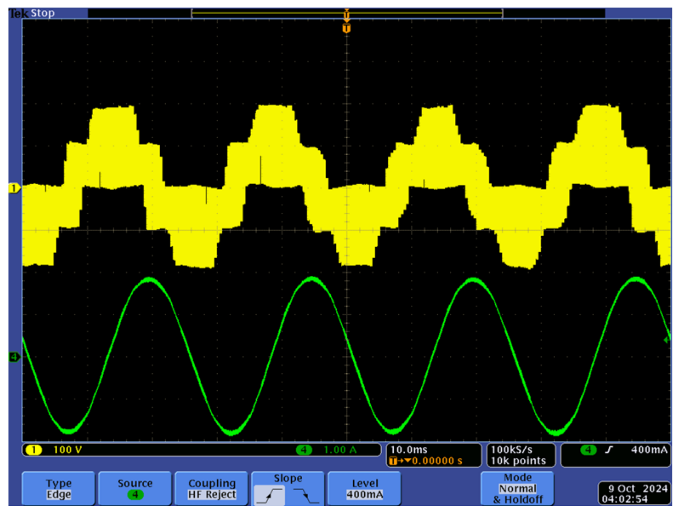

Fig. 28: Waveform of a phase voltage (yellow) and same phase current (green) for a modulation frequency of 40 Hz.

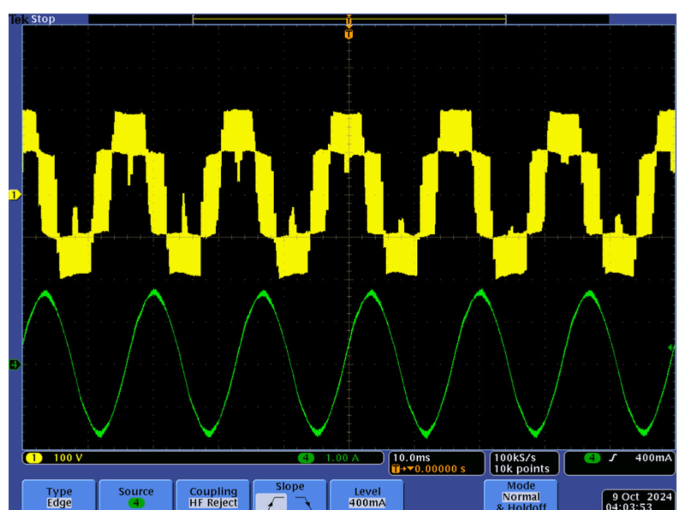

Fig. 29: Waveform of a phase voltage (yellow) and same phase current (green) for a modulation frequency of 60 Hz.