Design and Implementation of an AC-DC Converter circuit to operate a DC Motor

Table of Contents

Objective:

The primary goal of this project is to design and implement a controlled AC-DC converter system that can transform a 220 V AC supply into a variable, regulated DC voltage, capable of powering a 12 V DC motor. A triggering circuit for controlled switching, a filter capacitor to reduce ripple voltage (≤4%), and a linear DC motor speed variation based on the adjustable output voltage should all be included in the converter. The goal of this project is to demonstrate how power electronics can be applied practically to control DC motor speed with enhanced stability and efficiency.

Apparatus:

Sl. No.	Component	Specification	Quantity

1	Transformer	220V / 12-0-12V	1
2	Diode	1N4007	2
3	Resistor	33 Ω	1
4	Resistor	3.9 kΩ	2
5	Resistor	330 Ω	6
6	Resistor	10 kΩ	1
7	Variable Resistor (Potentiometer)	5 kΩ	2
8	Capacitor	2.2 μF	2
9	Capacitor	100uf	1
10	SCR	2P4M	2
11	UJT	2N2646	2
12	Opto-coupler	PC101	2
13	Multimeter		1
14	Oscilloscope		1
15	DC Motor	12 V	1

Circuit Diagram

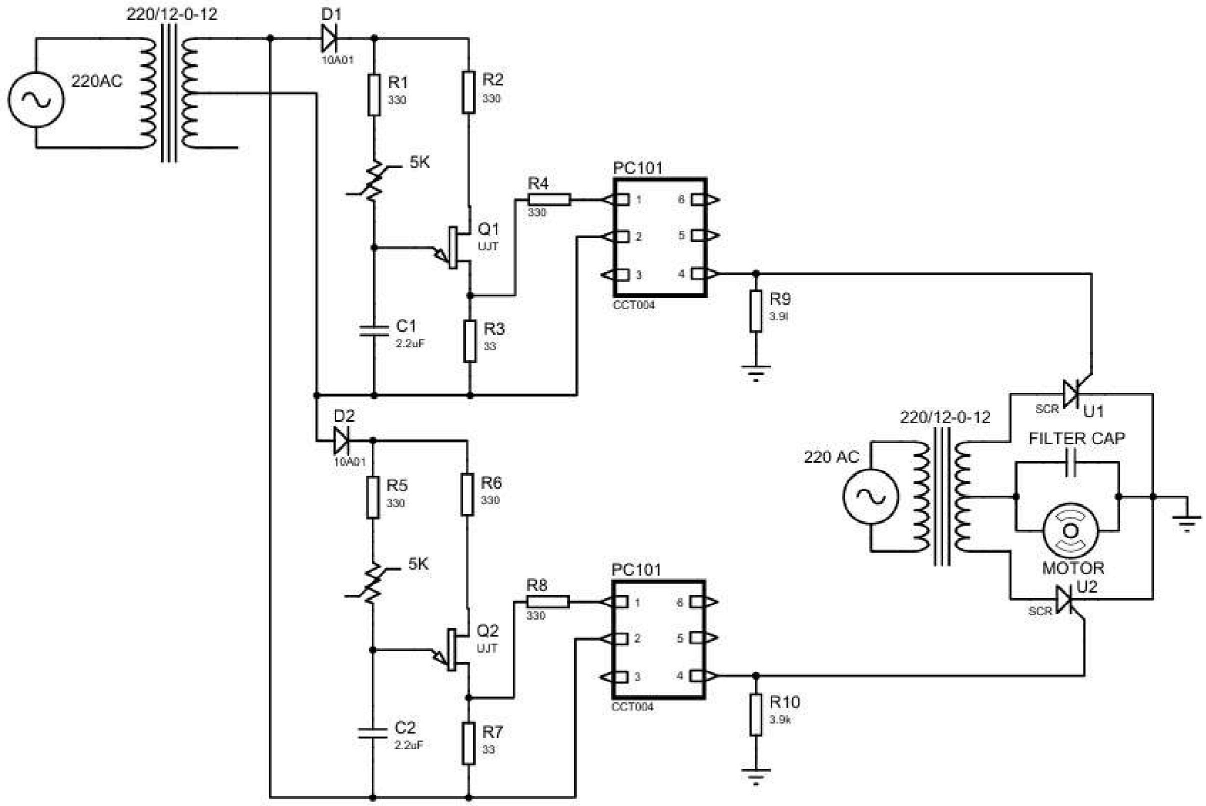

Figure: Circuit diagram of the controlled full-wave rectifier.

Theoretical Background:

A full-wave controlled rectifier typically consists of three main stages. The first stage is the pulse generator, which uses a Unijunction Transistor (UJT) at its core to generate triggering pulses for controlling the rectifier. The second stage is an isolation circuit, usually implemented with an optocoupler. This stage electrically isolates the low-power control circuitry from the high-power rectifier, ensuring that any fault on one side does not affect the other. The final stage is the controlled rectifier itself, which uses Silicon Controlled Rectifiers (SCRs) to convert AC to DC with a controllable output voltage. Below is a detailed theoretical discussion of each component and its operation.

Pulse Generator:

A thyristor will conduct current only under two main conditions: first, when a forward voltage is applied across its terminals, and second, when an appropriate gate pulse is provided (this process is called triggering or firing). To turn on a thyristor, a gate drive circuit is needed to supply this triggering pulse. One simple method is to use a voltage divider, consisting of resistors or capacitors, connected to the AC supply. If part of this divider is adjustable, the firing angle can be varied, which controls how long the thyristor conducts current; this is known as the conduction angle. However, these simple divider circuits have limitations: they can become unreliable due to temperature variations and generally lack efficiency and precision. For this reason, engineers often prefer using specialized components, such as Unijunction Transistors (UJT) or other negative resistance devices. These devices produce stable and predictable pulses, ensuring that the thyristor triggers correctly and consistently.

Figure: Symbol and 3D view of a UJT

Isolation:

In many electronic systems, signals need to go from one part of a circuit to another, or even from one device to another, without using a direct wire connection. This is really important when the two parts work at very different voltages. For example, one part might use small, low-voltage control signals, while the other part uses high power and high voltage. If they were connected directly, the high voltage could damage the control part or be dangerous. To solve this problem, we use isolation. Isolation means the two sides are not electrically connected, but they can still send signals to each other safely.

There are two main types of isolation:

- Galvanic isolation: There is no direct electrical link between the two parts.
- Optical isolation: Light is used to send the signal from one side to the other.

In circuits that use thyristors, isolation is very important. The power side of the circuit may operate at high voltages (such as over 100 V), while the gate control circuit requires low voltages (typically 12 V to 30 V). To keep the control side safe from the high voltage, an isolation circuit is used between the gate driver and the thyristor. This isolation can be done in two common ways: Firstly, by using Pulse transformers, which pass signals using magnetic fields. Secondly, by Opto-couplers, which pass signals using light. An opto-coupler is a small chip (usually with 6 or 8 pins). Inside, it has a tiny LED that shines light onto a photosensitive part (like a phototransistor). The light carries the signal across a small gap. This keeps the two sides completely separated and safe.

Full Wave Controlled Rectification:

A Silicon Controlled Rectifier (SCR) is a semiconductor device that allows current to flow in only one direction. It will only start conducting when a triggering pulse is sent to its gate terminal. In a full-wave controlled rectifier that uses a center-tapped transformer, two SCRs are used — one for each half-cycle of the AC input. Together, they convert the alternating current (AC) into a controllable direct current (DC) output.

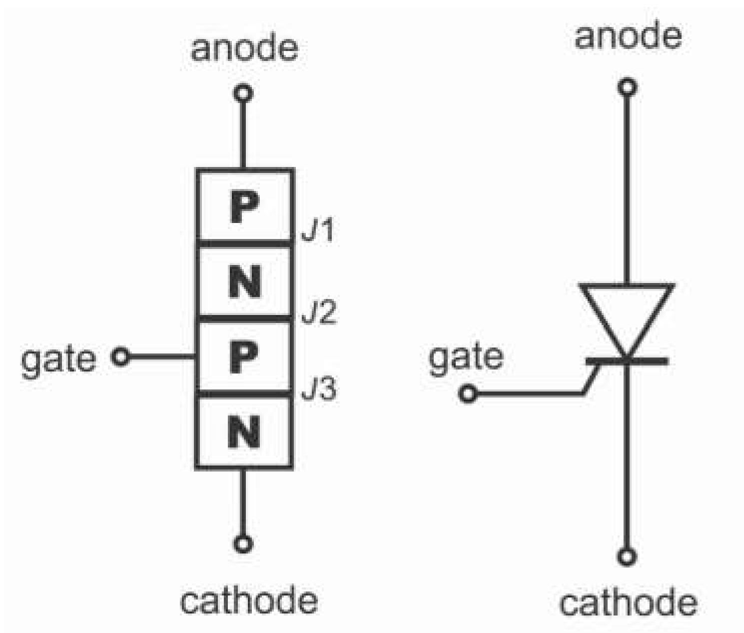

Figure: Construction and symbol of an SCR

Circuit Configuration:

The center-tapped transformer has three terminals: the two outer terminals are connected to the anodes of the SCRs (SCR1 and SCR2), while the center tap is connected to the load.

The load resistor is placed between the center tap and the cathodes of the SCRs, which are also connected to the DC ground. A gate triggering circuit — made up of a UJT and an optocoupler — sends triggering pulses to the gates of the SCRs. The delay of these pulses, called the firing angle (α), is adjusted using two potentiometers.

Working Principle:

1. During the positive half of the AC input cycle, the upper half of the transformer winding is at a positive potential concerning the center tap.
2. SCR1 becomes forward-biased.
3. When a gate pulse is sent to SCR1 after a delay (firing angle α), SCR1 turns on and current flows through the load.
4. During the negative half of the AC input cycle, the lower half of the transformer winding is at a positive potential concerning the center tap.
5. SCR2 becomes forward-biased.
6. When SCR2 receives a gate pulse (also delayed by the firing angle α), it turns on and conducts current through the load, in the same direction as SCR1.

As a result, the load always receives current flowing in one direction, producing a full-wave rectified output. By adjusting the firing angle α, the point at which each SCR starts conducting can be delayed, which controls how much of each AC half-cycle is used — this allows control of the average DC output voltage.

Advantages of Center-Tap Configuration with SCRs:

- Requires only two SCRs instead of four, making the circuit simpler and more cost-effective.
- Gate triggering circuitry is simpler and easier to design.
- The conduction intervals for each SCR are separated, making it easier to observe and understand the operation, especially for learning and experimentation.
- Provides good isolation and balanced waveform output due to the center-tapped transformer.
- This configuration is ideal for controlled rectification experiments, as it helps students and engineers easily understand how phase control works with SCRs and how the firing angle affects the average DC output voltage.

Design Considerations

- The input supply is **220 V AC**.
- A 220 V to 12-0-12 V center-tapped transformer is used to step down the voltage.

- A full-bridge controlled rectifier is implemented, requiring the design of a firing circuit for SCR triggering.
- The control objective is to achieve an adjustable DC output voltage so that the speed of the DC motor varies in a nearly linear manner.
- The ripple requirement is defined as: $\frac{V_{ripple,rms}}{V_{DC}} \leq 4\% = 0.04$
- The mains frequency is 50 Hz; therefore, the ripple frequency after full-wave rectification is 100 Hz.
- To maintain the ripple factor within the specified limit, an appropriate filter capacitor must be calculated and selected.

Calculations

- The ripple voltage requirement is **4%**.
- The formula for ripple voltage (Vripple) for a full-wave rectifier is approximately:

$$V_r = \frac{V_m}{2fRC}$$

  where V_m is the peak voltage, f is the frequency of the AC source (50Hz), R is the resistance,e, and C is the capacitance.
- We know that V_{ripple}=0.04×V_{DC_avg}. The average DC voltage (V_{DC_avg}) is approximately equal to the peak voltage for a full-wave rectifier with a large capacitor.

$$V_{ripple}=0.04\times V_m$$

- Rearranging the formula to find the capacitance: $C=\frac{1}{2fR\times 0.04}$
- So, if frequency **f** is 50 Hz, Resistance **R** is 450Ω, the Capacitance would be 555.56×10^{-6} approximately.

Experimental setup

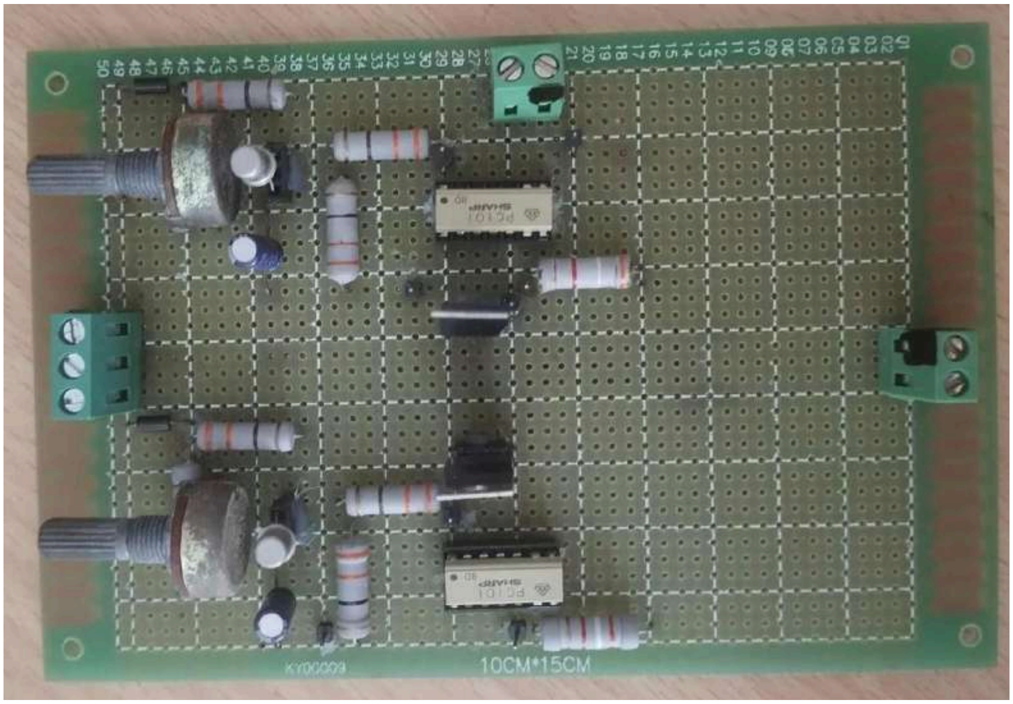

Figure: Vero Board Circuit

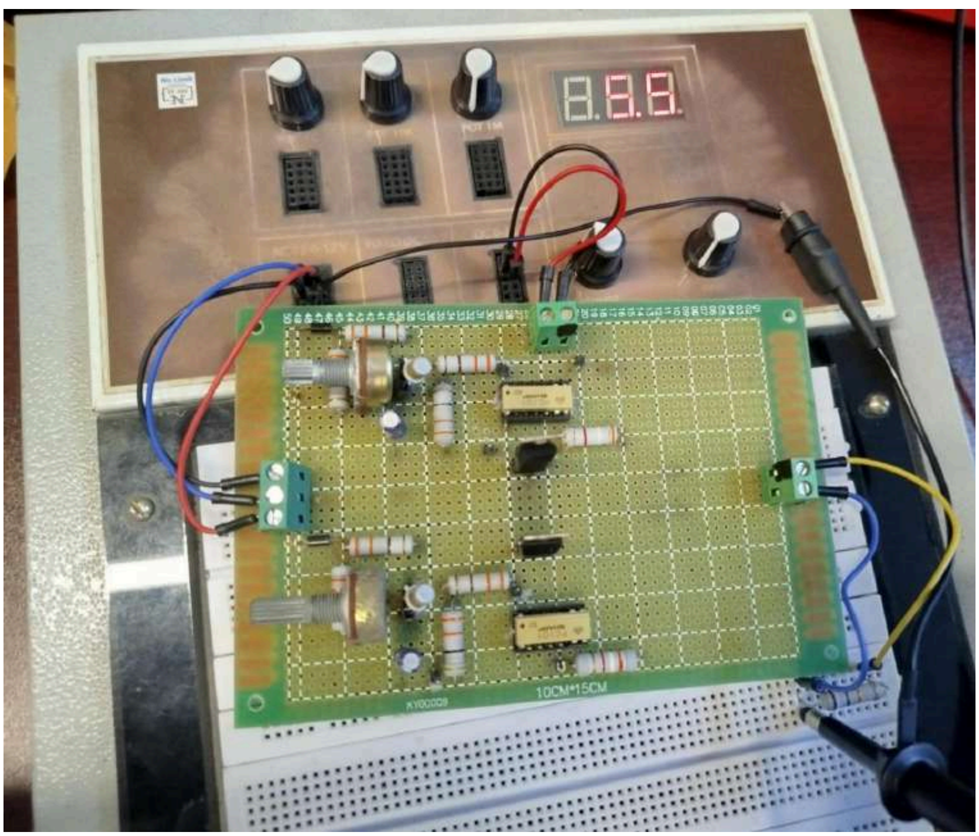

Figure: Experimental Setup.

Data collection:

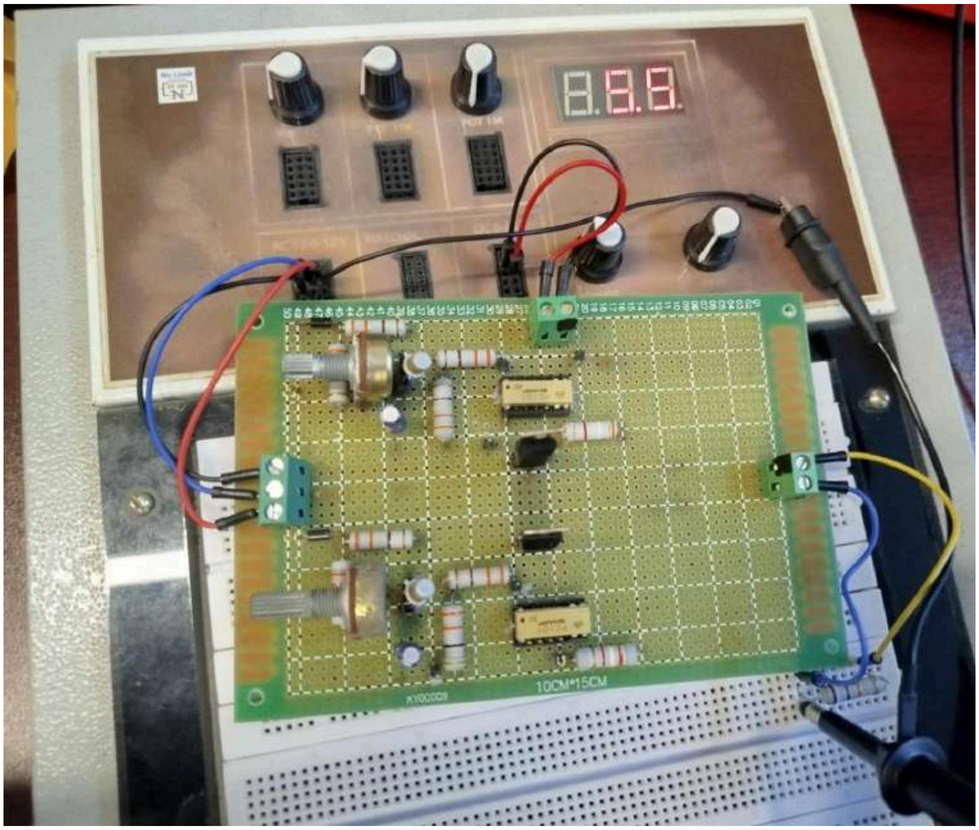

Figure: Circuit with 10K ohms Load

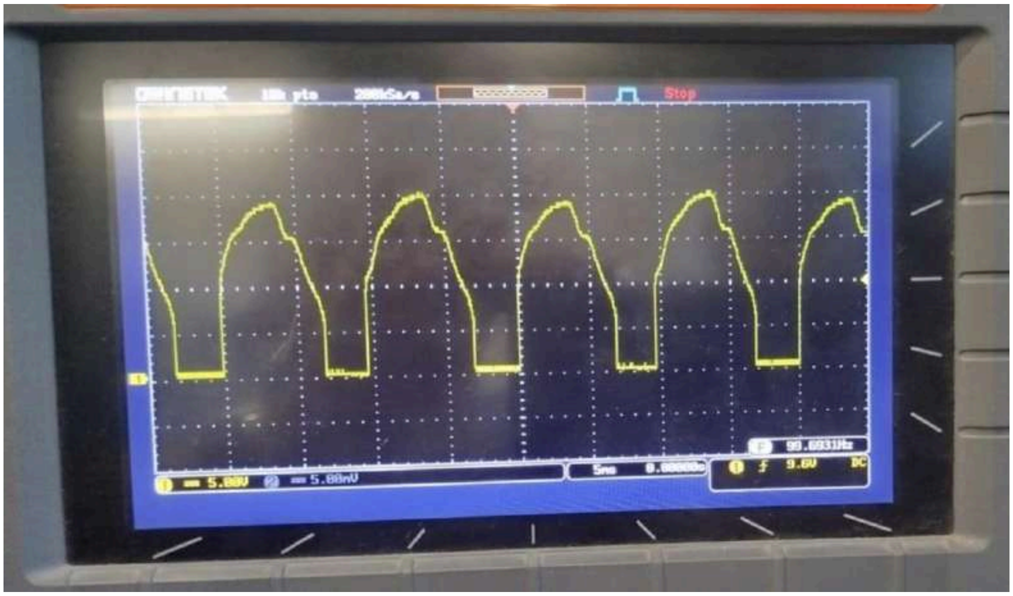

Figure: Waveform for 10K ohms Load

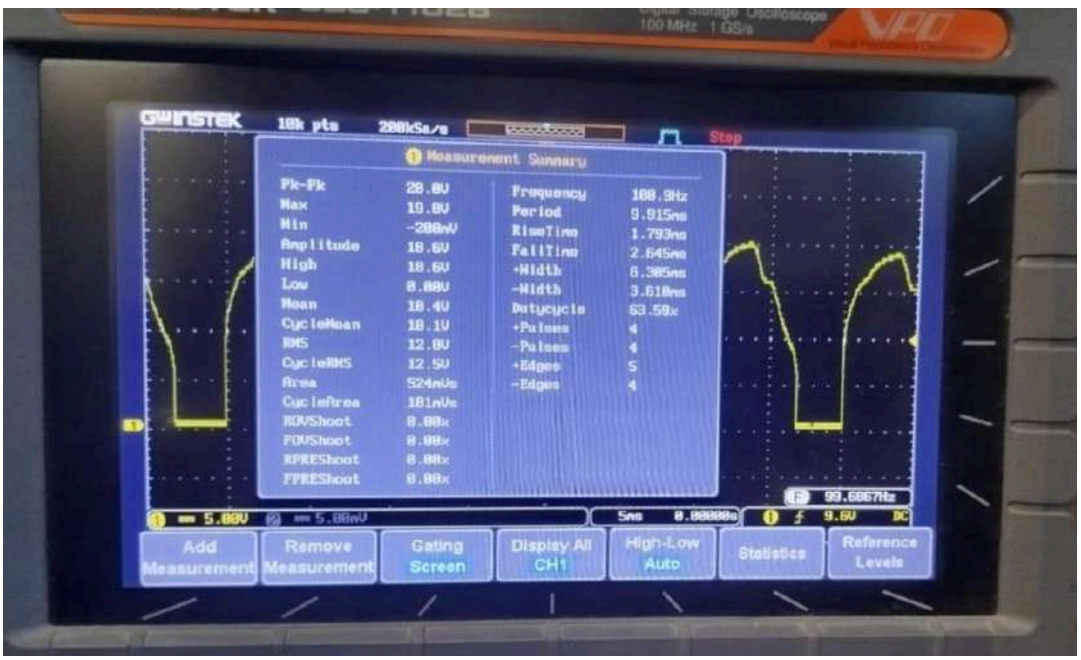

Figure: Measurement for 10K ohms Load

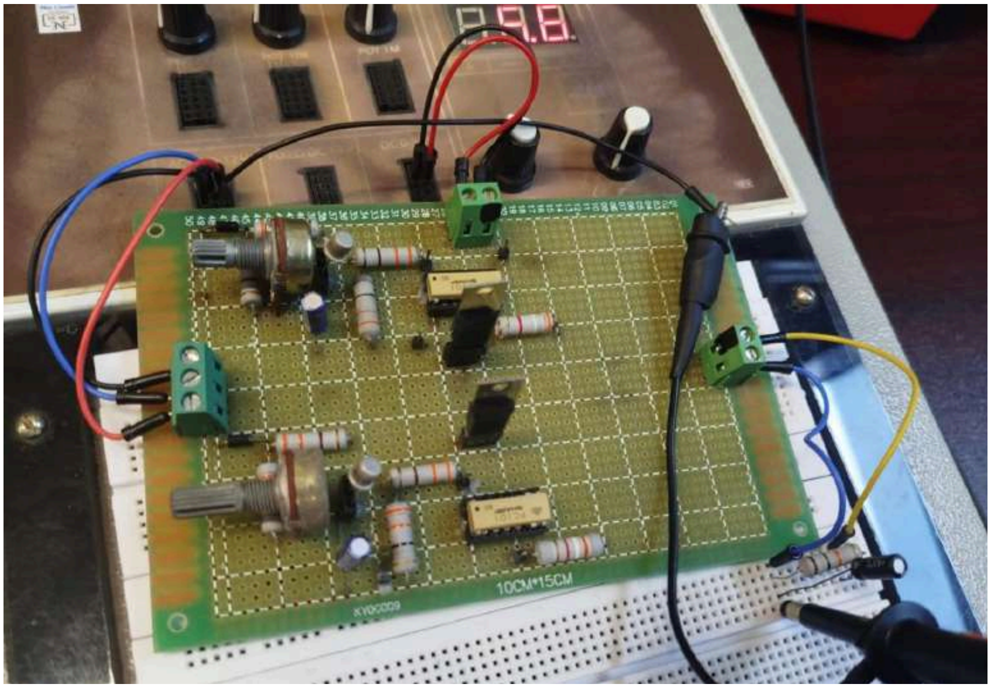

Figure: Circuit with 10K ohms Load and 22uF Capacitor

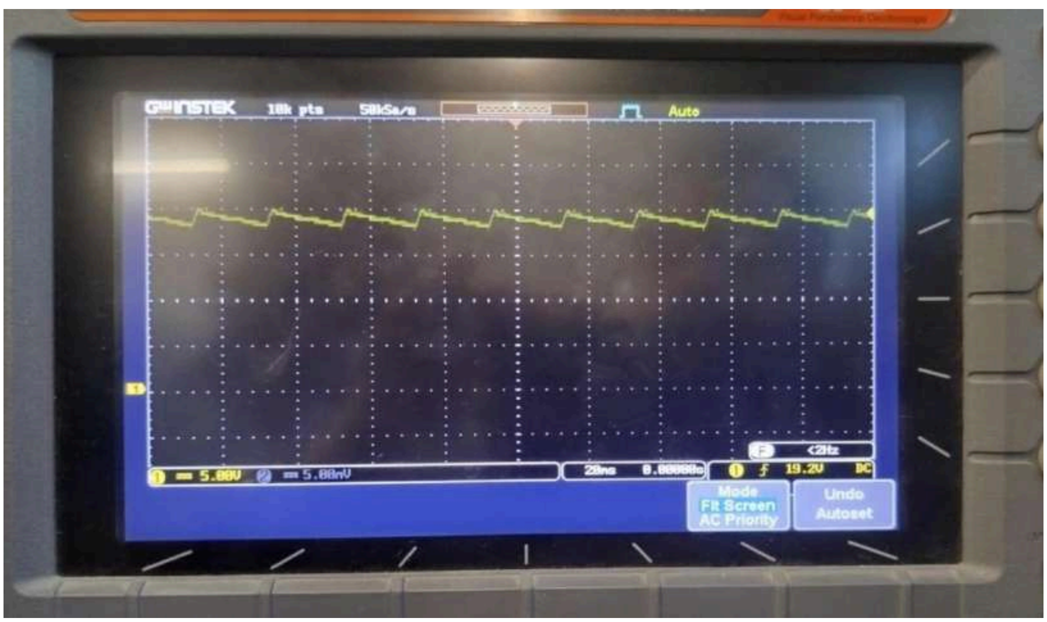

Figure: Waveform for 10K ohms Load and 22uF Capacitor

Figure: Measurement for 10K ohms Load and 22uF Capacitor

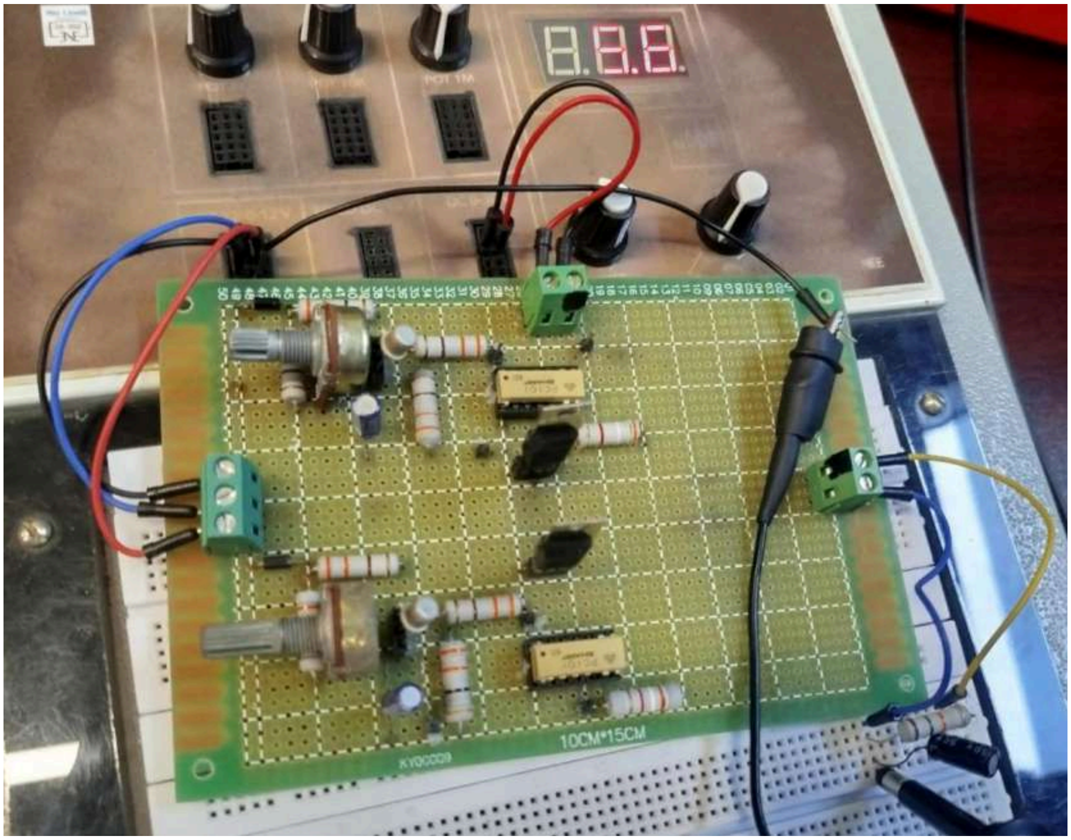

Figure: Circuit with 10K ohms Load and 47uF Capacitor

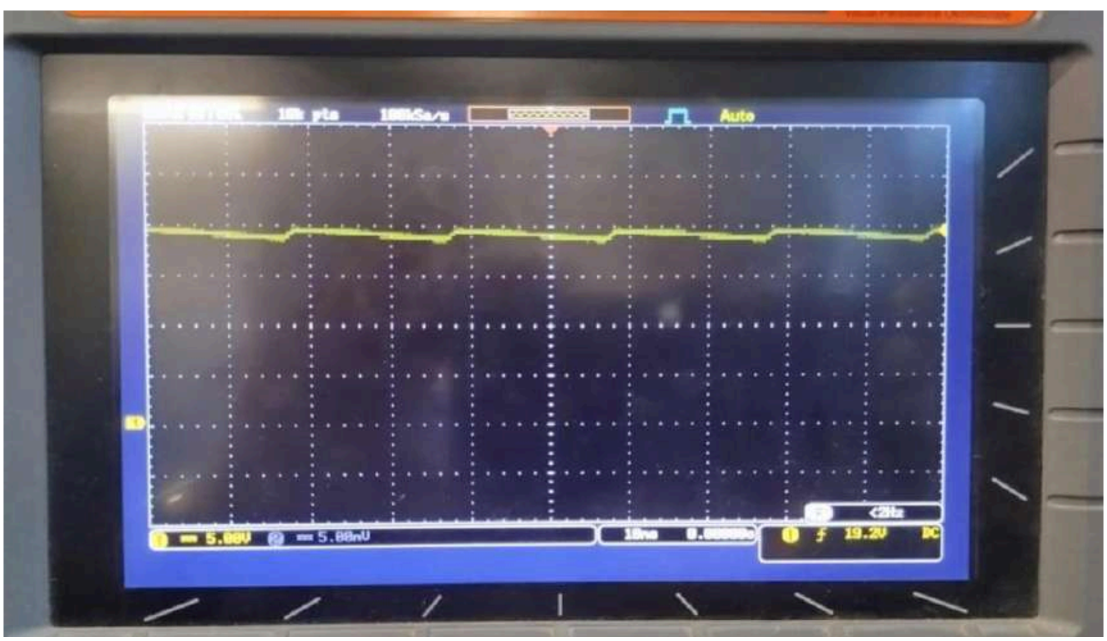

Figure: Waveform for 10K ohms Load and 47uF Capacitor

Figure: Measurement for 10K ohms Load and 47uF Capacitor

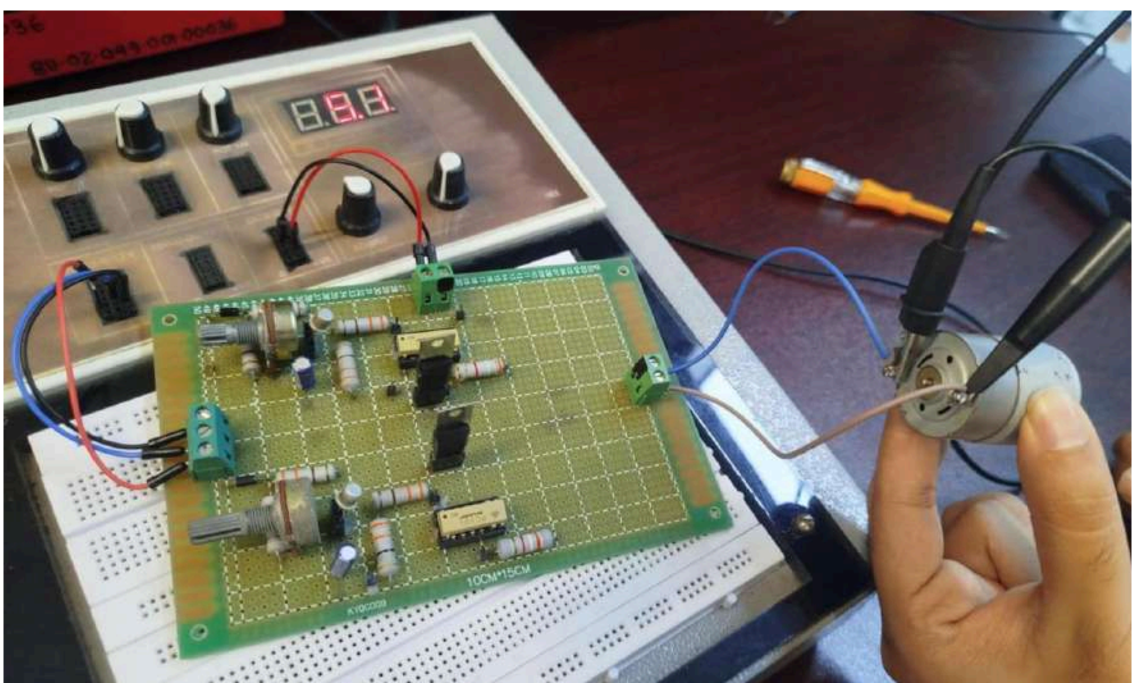

Figure: Circuit with Motor as Load

Figure: Waveform for Motor as Load

Figure: Measurement for Motor as Load

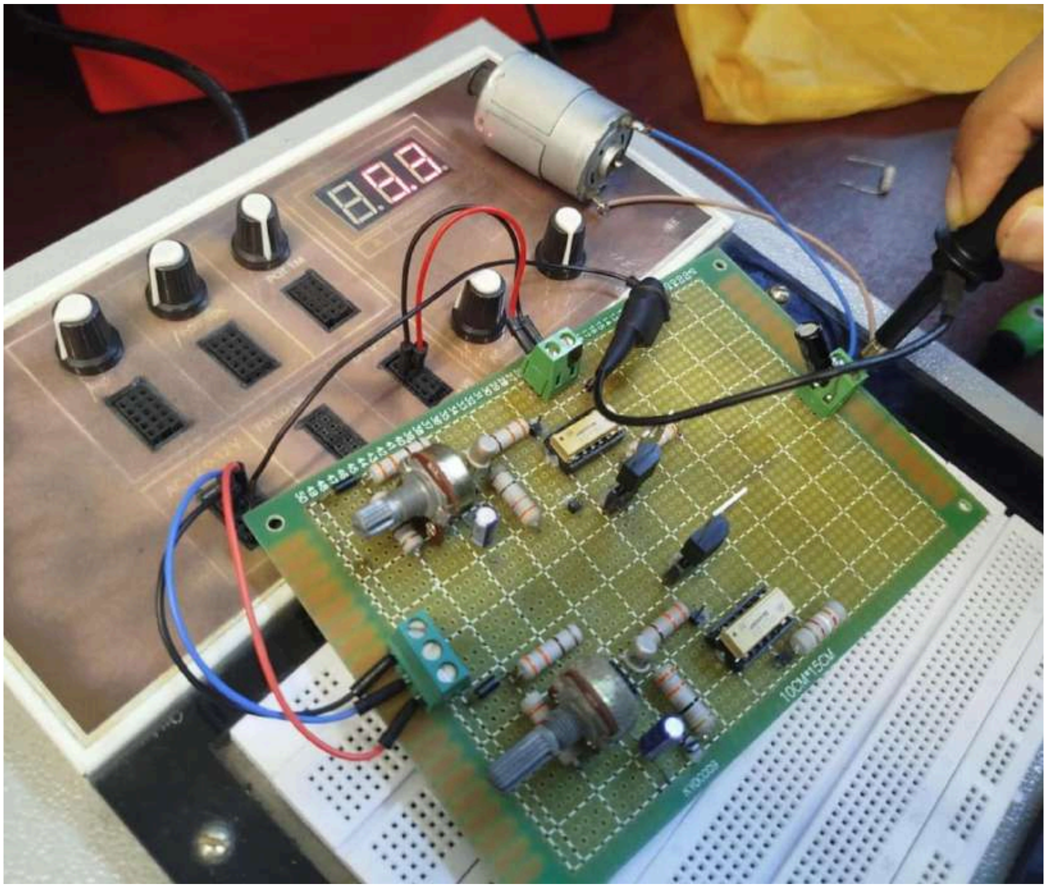

Figure: Circuit with Motor as Load with 100uF Capacitor

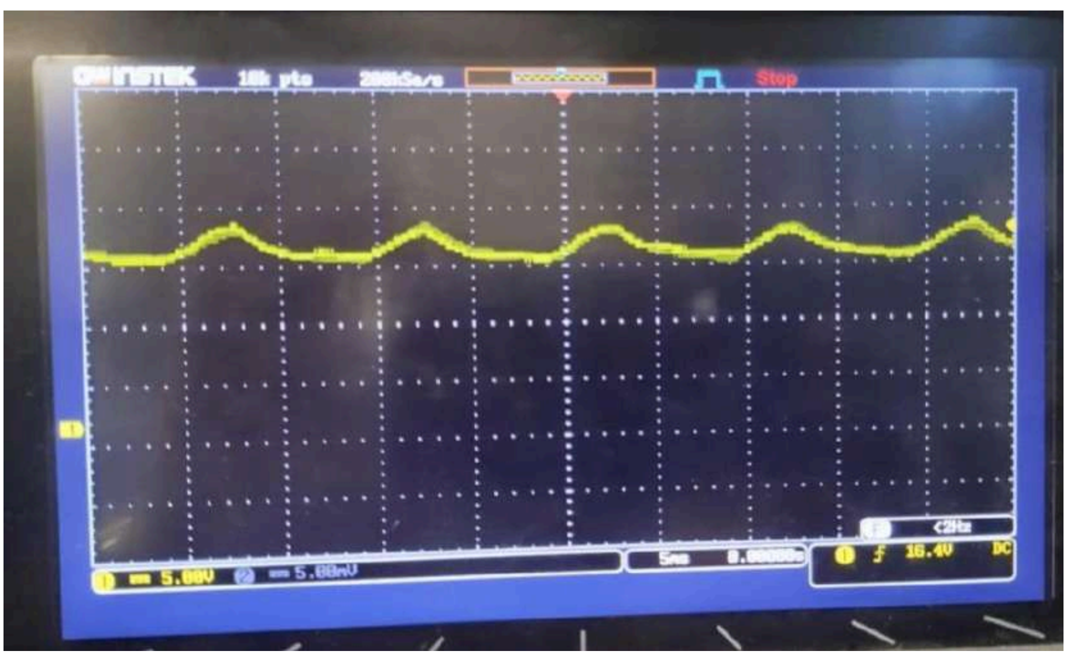

Figure: Waveform for Motor as Load with 100uF Capacitor

Figure: Measurement for Motor as Load with 100uF Capacitor

Motor with 235uf

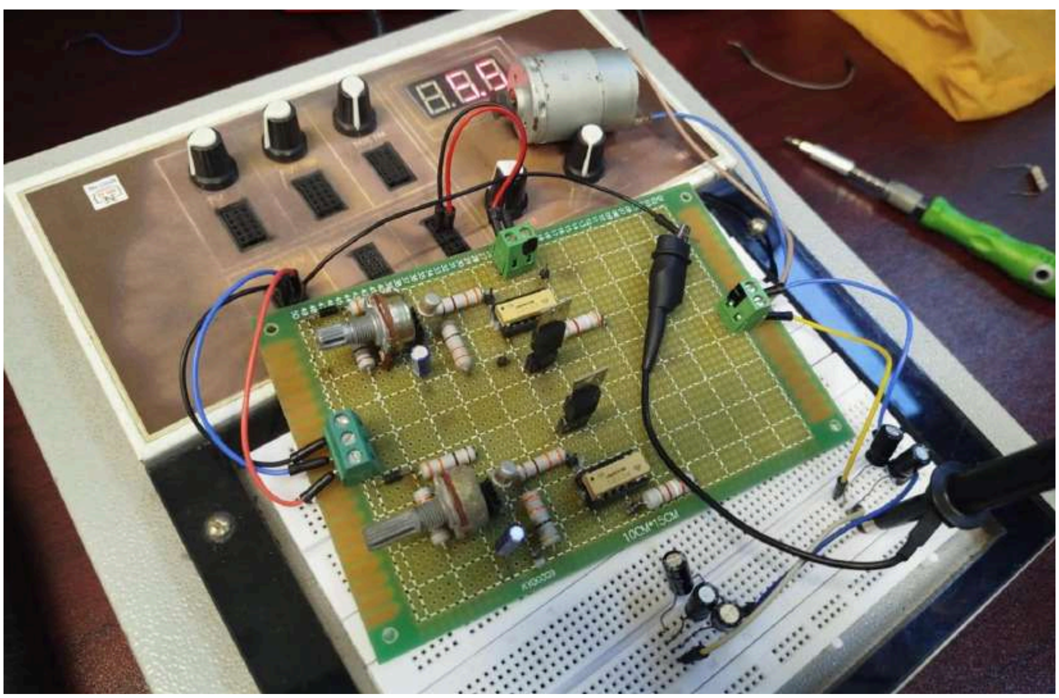

Figure: Circuit with Motor as Load with 235uF Capacitor

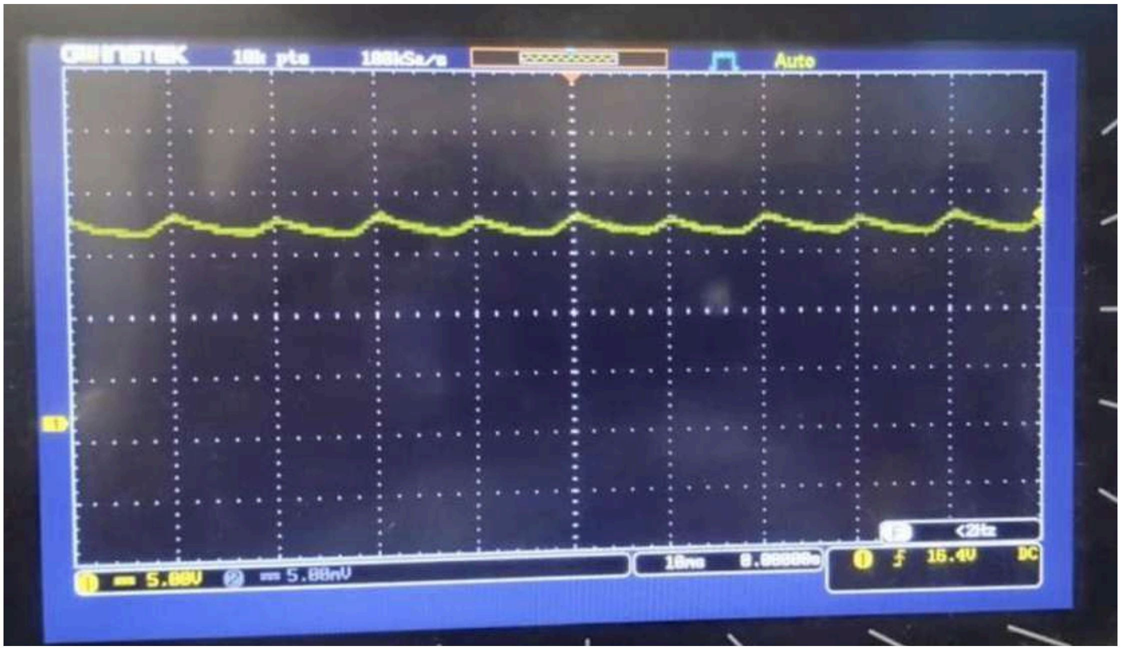

Figure: Waveform for Motor as Load with 235uF Capacitor

Figure: Measurement for Motor as Load with 235uF Capacitor

Result Analysis:

According to the question, our ripple voltage should be 4%

Resistive Load

We know, for a 10k resistive load
Ripple voltage

$$V_r = \frac{V_m}{2fRC}$$

$$0.04\times\ 19.4\ = \frac{19.4}{2\times50\times10\times10^3\times C}$$

$$C = \frac{19.4}{2\times50\times10\times10^3\times0.04\times19.4}$$

$$C = 25\times\ 10^{-6}\ \text{F}$$

Case 1:

In the practical, we have used 22µF at first
After connecting it to the circuit,
From measurement, we found that V_{p-p} = 1.88 V
V_m = 19.4 V

$$\text{Ripple factor} = \frac{V_{p-p}}{V_m}$$

$$= \frac{1.88}{19.4}$$

$$= 0.096\ \times\ 100$$

$$= 9.69\%\ \text{(more than 4\%)}$$

Case 2:

We used 47µF,
After connecting it to the circuit,
From measurement,
V_{p-p} = 1.28 V
V_m = 19.4 V

$$\text{Ripple factor} = \frac{V_{p-p}}{V_m}$$

$$= \frac{1.28}{19.4}$$

$= 0.065979 \times 100$
$= 6.59\%$ (more than 4%)

Case 3:

We used $100\mu F$,
After connecting it to the circuit,
From measurement,
$V_{p-p} = 0.78$ V
$V_m = 19.4$ V

$$\text{Ripple factor} = \frac{V_{p-p}}{V_m}$$
$$= \frac{0.78}{19.4}$$
$$= 0.04020 \times 100$$
$$= 4.02\%$$
$$\simeq 4\%$$

Our experimental results revealed different characteristics for the resistive. We initially used a 22 µF capacitor, which caused a high ripple of 9.69%. Increasing the capacitance to 47 µF reduced the ripple to 6.59%, which improved but still fell short of our goal. Using a 100 µF capacitor, we achieved the desired 4% ripple voltage reduction. This disparity between our theoretical and experimental findings emphasizes the importance of real-world testing, as factors such as component tolerances and the non-ideal properties of the DC motor load can have a significant impact on circuit performance.

Resistive Inductive Load (Motor)

To find the Resistor value, we attached an Ammeter to the motor in series, and from there, we found that the Current drawn is around 33×10^{-3} A. And from the oscilloscope, we have found out that the V_m is 22.6V

So,

$$R_L = \frac{22.6}{33 \times 10^{-3}} = 684.5\Omega$$

Now,

$$V_r = \frac{V_m}{2fRC}$$

$0.04\times 19.8 = \frac{19.4}{2\times50\times10\times10^{3}\times C}$

$C = \frac{22.6}{2\times50\times684.85\times0.04\times22.6}$

$C = 365.043\times 10^{-6}$ F

Case 1:

At first, we used **100**μF**,**

From measurement,

$V_{p-p} = 3.2$ V

$V_m = 17.8$ V

Ripple factor $= \frac{V_{p-p}}{V_m}$

$= \frac{3.2}{17.8}$

$= 0.179 \times 100$

= 17.97% (more than 4%)

Case 2:

Again, we have used 235μF,

From measurement,

$V_{p-p} = 1.88$ V

$V_m = 16.66$ V

Ripple factor $= \frac{V_{p-p}}{V_m}$

$= \frac{1.88}{16.66}$

$= 0.112 \times 100$

= 11.2% (more than 4%)

Our laboratory did not have the necessary capacitance (365.04 μF) to achieve a low ripple voltage due to practical constraints. We connected five 47 μF capacitors in parallel, achieving a total capacitance of 235 μF. This configuration reduced ripple voltage from 17.97% (measured with a 100 μF capacitor) to 11.2%, but it still did not meet our target of 4% ripple. Our experimental results, however, clearly demonstrate the fundamental principle that increasing filter capacitance directly reduces ripple voltage, resulting in a more stable DC output for the motor.

Observations:

Load	Capacitance	Vr_{p-p} (measured)	V_m	Ripple Factor	Target Achieved?
10 kΩ	22 µF	1.88 V	19.4 V	9.69%	No
10 kΩ	47 µF	1.28 V	19.4 V	6.59%	No
10 kΩ	100 µF	0.78 V	19.4 V	4.02%	**Yes**
Motor	100 µF	3.2 V	17.8 V	17.97%	No
Motor	235 µF	1.88 V	16.66 V	11.2%	No

Discussion

The primary objective of this project was to design a controlled AC–DC converter with filtering, such that the ripple factor of the output voltage remains below 4% when driving a DC motor.

To validate the design method, a resistive load (10 kΩ) was initially used for comparison. Theoretical calculations indicate that achieving the ripple factor target requires only about 25 µF. The experimental results revealed higher ripple factors than expected: 9.69% at 22 µF and 6.59%

at 47 μF. Using a larger capacitor of 100 μF reduced the ripple factor to approximately 4.02%. This discrepancy demonstrates that theoretical formulas that assume ideal conditions do not fully capture the behavior of real-world circuits with capacitor ESR, diode/SCR voltage drops, and measurement limitations. Thus, the resistive load experiment was primarily used as a comparison to highlight the disparity between theory and practice.

The real target was the motor load, which is a resistive-inductive load with distinct characteristics. The motor's effective resistance was estimated to be 684.5 Ω based on measured current. A 4% ripple factor requires approximately 365 μF of capacitance, according to theoretical calculations. The laboratory's maximum capacitance was 235 μF, which was achieved by connecting five 47 μF capacitors in parallel. At 100 μF, the ripple factor was 17.97%; at 235 μF, it decreased to 11.2%. Although this represents a significant improvement, it falls short of the 4% target. The result indicates that inductive loads demand much higher filtering capacity than purely resistive loads.

The difficulty of filtering the output is directly related to the behavior of the controlled rectifier circuit. A standard, uncontrolled rectifier with only diodes generates a continuous, pulsating DC waveform with a consistent shape. The output voltage is the full half-sinusoid of each half-cycle, producing a relatively smooth waveform that a capacitor can effectively filter.

The UJT-based triggering circuit creates a variable firing angle (α) for the SCRs. This means that the SCRs are not turned on until a certain delay has passed in each half-cycle. As a result, the output waveform is no longer a continuous pulsating DC, but rather a series of cut down voltage pulses. This discontinuity results in significant "gaps" or periods of zero voltage between pulses, which are especially noticeable at low motor speeds (i.e., high firing angles). During these gaps, the capacitor must supply all of the load current, resulting in a much larger voltage drop and, consequently, a higher ripple voltage than in an uncontrolled rectifier. As a result, the controlled waveform's inherent design for speed variation makes effective filtering more difficult.

In conclusion, the resistive load was useful in demonstrating the gap between theory and practice, whereas the motor load results revealed the practical limitations of achieving low ripple in real-world applications. Larger filter capacitors or additional filtering stages (such as LC filters) would be required to bring the ripple factor closer to the motor's design goal of 4%.

Importance of this power electronic circuit

This AC-DC converter circuit is a fundamental power electronic application. Its importance lies in:

- Variable Speed Control: It enables precise control over the speed of DC motors, which are commonly used in industrial applications, electric vehicles, and home appliances.
- Energy Efficiency: By providing the exact voltage required for a specific task, it helps to optimize energy consumption.
- Versatility: Controlled rectification principles are fundamental to modern power electronics, with applications ranging from battery chargers to power supplies to inverters.

Future Work

- **Closed-Loop Control:** Set up a feedback loop with a sensor (such as a tachometer) that measures the motor's speed and automatically adjusts the firing angle to keep the speed constant despite changes in load. This is a more advanced and practical option.
- **Microcontroller-based Control:** Replace the analog triggering circuit with a microcontroller (such as Arduino). This would enable more precise and complex control algorithms, as well as the creation of a user interface.
- **Power Factor Correction:** Look into ways to improve the input power factor of the circuit, which is typically low in controlled rectifiers.

References:

1. *Power Electronics: Circuits, Devices and Applications* by Muhammad H. Rashid, Third Edition, Prentice-Hall of India Private Limited.

2. *Power Electronics: Converters, Applications and Design* by Ned Mohan, Tore M. Undeland & William P. Robbins, Second Edition, John Wiley & Sons Inc.