Study of Basic OPAMP Configurations, Operations and Applications

Gayatri P
2nd year, Integrated M.Sc. Physics
Roll No.: 2211185
(Dated: January 25, 2024)

Operational Amplifiers, or Op-amps as they are more commonly called, are one of the basic building blocks of Analogue Electronic Circuits. In this, we demonstrate basic op-amp configurations and build summing and difference amplifiers. We also show the application op-amp as a comparator as well as a Schmitt trigger, which shows hysteresis. Additionally, we broadly discuss the design of a power supply system which can provide power to an op-amp as well as different types of grounding systems.

I. OBJECTIVE

1. Study of basic OPAMP configurations and simple mathematical operations.
2. Applications of OPAMP as comparator and Schmitt Trigger.

II. THEORY AND PROCEDURE

Introduction

One of the most versatile and widely used electronic devices in linear applications is the operational amplifier, most often referred to as the op-amp. Op amps are popular because they are low in cost and easy to use. Op amps have five basic terminals: two for supply power, two for input signals, and one for output. Inverting input marked with a negative sign, and the other a non-inverting input marked with a positive plus sign.

The ideal op amp (Fig. 1) has infinite gain which is frequency independent. The input terminals draw no current and exhibit infinite input resistance. Output impedance is 0 Ω, so that maximum voltage can be drawn by the load. The amplified output signal of an Operational Amplifier is the difference between the two signals being applied to the two inputs. Since an op-amp is an active device, power supply is provided to the op-amp using a bipolar supply and has typical values of ± 15 V.

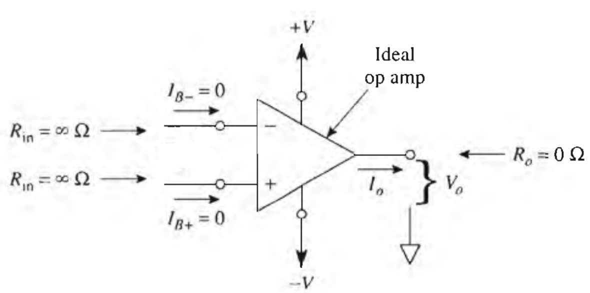

FIG. 1: Schematic of an ideal op-amp

The most commonly available and used of all operational amplifiers is the industry standard 741 type IC.

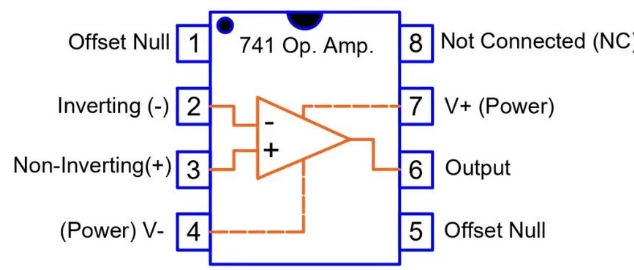

FIG. 2: IC 741 Pinout

The output voltage V_{out} is determined by the open loop gain (without any possible feedback connections), is given by

$$V_{\text{out}} = A_{OL}(V_1 - V_2) \tag{1}$$

Open loop gain or DC gain of an ideal Operational Amplifier can be very high, (around 10^6), making the amplifier hard to control as the smallest of input signals can cause the output to saturate and the input signal will lose its characterstics. Hence by losing some of this gain by connecting a suitable resistor across the amplifier from the output terminal back to the inverting input terminal, we can both reduce and control the overall gain of the amplifier. This then produces an effect called **Negative Feedback**, and thus produces a very stable Operational Amplifier system. The resulting gain is called its **closed loop gain**.

To separate the real input signal from the negative feedback voltage at the inverting terminal, we use the input resistor R_{in}. As we are not using the positive non-inverting input this is connected to a common ground. The effect of this closed loop feedback circuit results in the voltage at the inverting input equal to that at the non-inverting input producing a *Virtual Earth* summing point because it will be at the same potential as the grounded reference input.

A. Inverting Amplifier Circuit

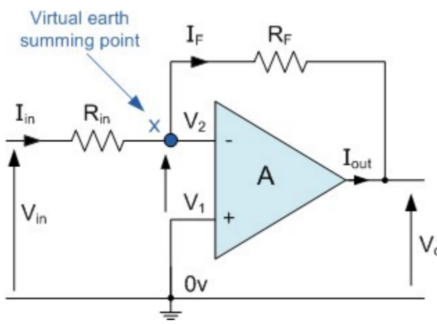

FIG. 3: Inverting Amplifier Circuit

In inverting amplifier circuit the operational amplifier is connected with feedback to produce a closed loop operation. Here, no current flows into the input terminal. Also, V_1 equals V_2 since the junction of the input and feedback signal is at the same potential as the positive (+) input which is at zero volts or ground and thus the junction is a *Virtual Earth*. Thus input resistance of the amplifier is equal to the value of the input resistor, R_{in}.

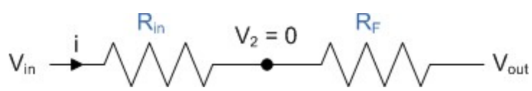

FIG. 4: Inverting Amplifier Equivalent Circuit

We can calculate the gain of this configuration by using the equivalent circuit (Fig. 4) the circuit to get,

$$i = \frac{V_{\text{in}}}{R_{\text{in}}} = -\frac{V_{\text{o}}}{R_f}$$
$$\implies \text{Gain, } A = \frac{V_{\text{o}}}{V_{\text{in}}} = -\frac{R_f}{R_{\text{in}}} \tag{2}$$

The negative sign indicates a phase difference of π of the output signal with respect to the input signal.

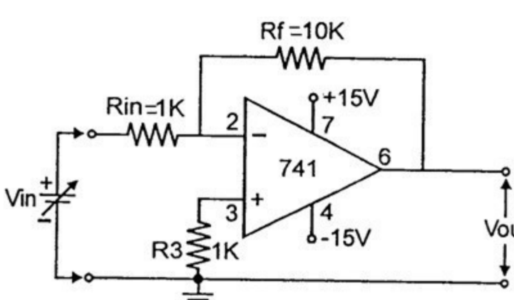

FIG. 5: Experimental Circuit Diagram for Inverting Amplifier

One of its undesirable feature is the low input impedance, particularly for amplifiers with large closed-loop voltage gain, where R_1 tends to be rather small. This is remedied in case of a non-inverting amplifier.

B. Non-Inverting Amplifier Circuit

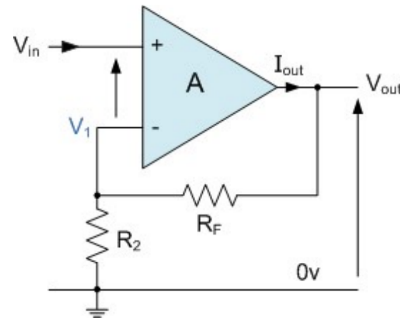

FIG. 6: Non-Inverting Amplifier Circuit

In this configuration, the input voltage signal, (V_{in}) is applied directly to the Non-inverting (+) input terminal. By applying a small part of the output voltage signal back to the inverting (-) input terminal via a $R_f - R_2$ voltage divider network, producing negative feedback, we can achieve very good stability, $R_{\text{in}} \to \infty$ (as no current flows into the positive input terminal) and a low output impedance, r_{out}.

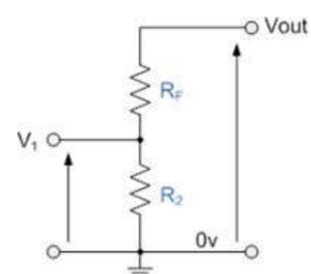

FIG. 7: Non-Inverting Amplifier Equivalent Voltage Divider Circuit

Since $V_1 = V_{\text{in}}$, the junction is a Virtual Earth summing point. R_f and R_2 form a voltage divider network across the amplifier. Using the equivalent circuit (7), we get,

$$V_{\text{out}} = V_{\text{in}} \left(1 + \frac{R_f}{R_2}\right)$$
$$A = \frac{V_{\text{o}}}{V_{\text{in}}} = 1 + \frac{R_f}{R_2} \tag{3}$$

Here, the gain is positive or the output signal is in-phase with the input signal.

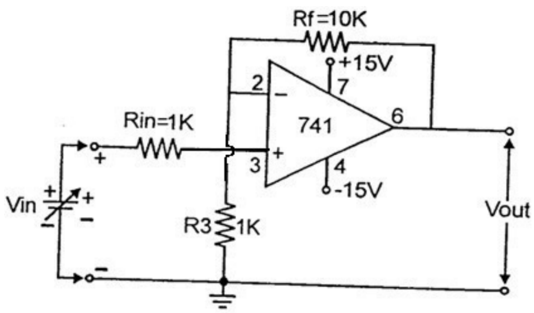

FIG. 8: Experimental Circuit Diagram for Non-Inverting Amplifier

C. OPAMP as a Summing Amplifier

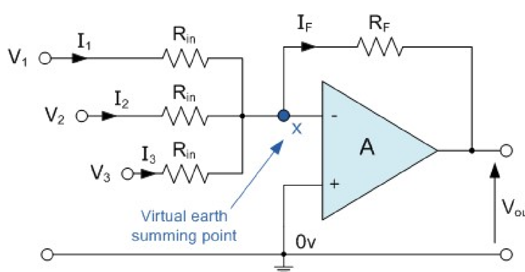

FIG. 9: Summing Amplifier Circuit

If we add another input resistor equal in value to the original input resistor, R_{in} in Fig. 3 we end up with another operational amplifier circuit called a Summing Amplifier or a *Voltage Adder* circuit (Fig. 9). The output voltage, (V_{out}) thus becomes proportional to the sum of the input voltages, $V_1, V_2, V_3, \ldots$. Using the original equation for the inverting amplifier (Eq. 2),

$$\begin{aligned} I_f &= I_1 + I_2 + I_3 \\ V_{\text{out}} &= -I_f R_f \\ &= -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right) \\ &= -\frac{R_f}{R_{\text{in}}} (V_1 + V_2 + V_3) \\ &= A_v (V_1 + V_2 + V_3) \end{aligned} \tag{4}$$

if $R_1 = R_2 = R_3 = R_{\text{in}}$, and thus $A_v = -R_f / R_{\text{in}}$.

Hence this enables us to effectively add together several individual input signals. Additionally, if the input resistors are of different values a *scaling summing amplifier* is produced which gives a weighted sum of the input signals.

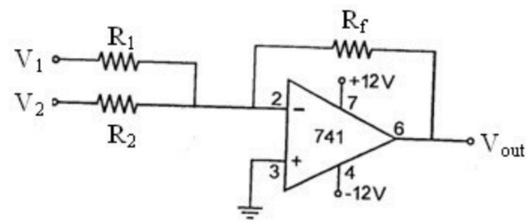

FIG. 10: Experimental Circuit Diagram for Summing Amplifier

D. OPAMP as a Difference Amplifier

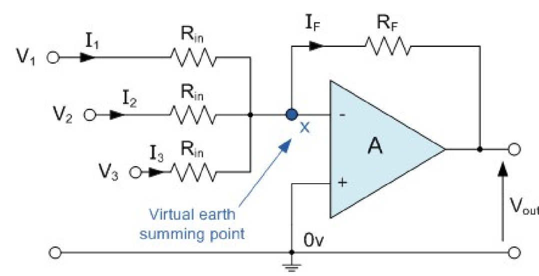

FIG. 11: Difference Amplifier Circuit

If we connect input signals to both inverting and non-inverting terminals simultaneously, the resultant output voltage will be proportional to the difference between the two input signals, V_1 and V_2. This type of circuit can be used as a subtractor.

$$\begin{aligned} V_o &= -\frac{R_1}{R_2} V_1 + \left(1 + \frac{R_1}{R_2}\right) \left(\frac{R_4}{R_3 + R_4}\right) V_2 \\ &= \frac{R_2}{R_1}(V_2 - V_1) \end{aligned} \tag{5}$$

if $R_1 = R_2$ and $R_3 = R_4$.

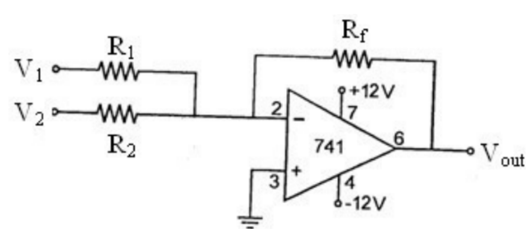

FIG. 12: Experimental Circuit Diagram for Difference Amplifier

E. OPAMP as a Comparator

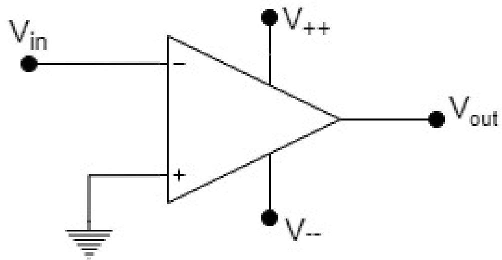

FIG. 13: Circuit Diagram for a Comparator Circuit

Without negative feedback, the op-amp goes into positive or negative saturation according to the difference of the input voltages, which can be used to design switching or non-linear circuits.

From the circuit diagram (Fig. 13) we can see that,

$$V_{\text{out}} \approx \begin{cases} V_{++} \text{ if } V_{+} > 0 \\ V_{--} \text{ if } V_{+} < 0 \end{cases} \tag{6}$$

Hence, the circuit can be used as a comparator.

If we modify the circuit a bit by connecting the non-inverting terminal to a any voltage source, V_{th} (Fig. 14), the circuit now switches when V_{in} crosses a the threshold value V_{th}.

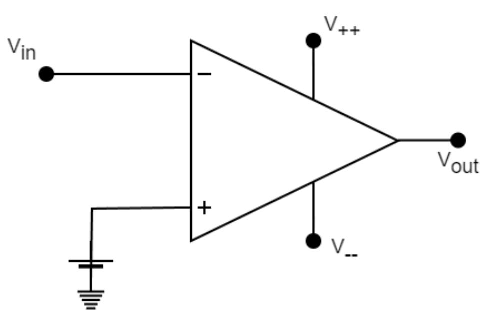

FIG. 14: Circuit Diagram for a Comparator Circuit with a certain threshold voltage

This simple comparator circuit is *not ideal* for practical use, i.e. if the input is noisy, the output may make several transitions as the input passes through the threshold point (Fig. 15). Also, for very slowly varying input, the output transitions can be rather slow. These can be remedied by using the *Schmitt trigger*.

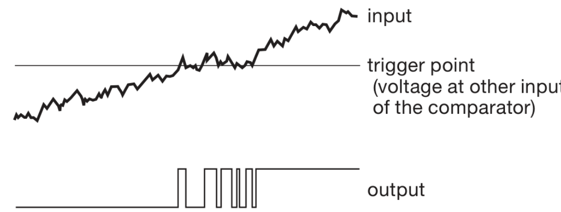

FIG. 15: Comparator output for the corresponding input signal

F. OPAMP as Schmitt trigger

The Schmitt Trigger is a modification on the comparator circuit with positive feedback. This causes the circuit to to have two threshold points — when the output is high, it makes the switching level higher than it is when the output is low. This causes the circuit to have hysteresis or toggle action. Thus, noisy inputs are less likely to output multiple triggering.

Let V_+ and V_- be the voltages at the non-inverting and inverting terminals respectively. Since V_{out} changes its state whenever V_+ crosses 0V, we need to find what value of V_{in} results in $V_+ = 0$. The two values of V_{in} for which the output switches are called the ***trip points***. $V_+ = 0$ acts as a voltage divider formed by R_1 and R_2 between V_{in} and V_{out}. Thus the trip points of a non-inverting Schmitt trigger are:

$$V_{\text{in}} = \begin{cases} -(R_1/R_2)V_{\text{out}} \text{ (Lower trip point, LTP)} \\ +(R_1/R_2)V_{\text{out}} \text{ (Upper trip point, UTP)} \end{cases} \tag{7}$$

Choosing suitable ratios of R_1 to R_2, enough hysteresis can be created in order to prevent unwanted noise triggers.

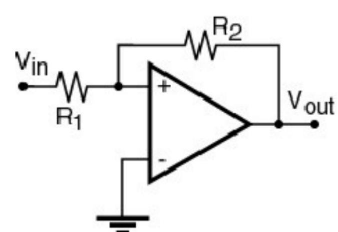

FIG. 16: Schmitt trigger circuit diagram

III. APPARATUS

1. OPAMP 741 Chip
2. Resistors
3. DC Power Supply
4. Breadboard
5. Connecting Wires
6. Multimeters

IV. OBSERVATION AND CALCULATIONS

A. Inverting Amplifier Setup

- $R_1 = 9.90$ kΩ
- $R_2 = 55.66$ kΩ
- $R_3 = 0.986$ kΩ

Input	$A = -R_1/R_3 = -10.04$			$A = -R_2/R_1 = -5.62$		
(V)	Output (V)	Gain	Avg. Gain	Output (V)	Gain	Avg. Gain
0.202	-2.021	-10.00		-1.11	-5.50	
0.411	-4.12	-10.02		-2.30	-5.60	
0.613	-6.16	-10.05		-3.44	-5.62	
0.809	-8.10	-10.01		-4.55	-5.64	
1.040	-10.43	-10.03	-10.02	-5.87	-5.64	
1.090	-10.69	-		-6.15	-5.63	-5.60
1.318	-10.72	-		-7.42	-5.63	
1.656	-10.72	-		-9.32	-5.63	
1.809	-10.72	-		-10.19	-5.63	
2.007	-10.72	-		-11.31	-5.64	
2.280	-10.72	-		-12.30	-5.39	

TABLE I: Measured input and output values for inverting amplifier setup.
Note: Gain for saturated values of V_o have not been considered.

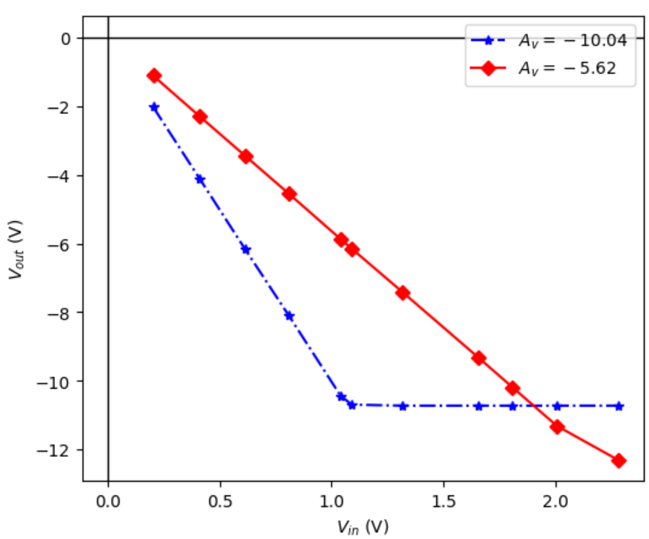

FIG. 17: V_{out} vs V_{in} for the inverting amplifier. Note how V_{out} saturates as it reaches around the value of $\pm V_{CC}$

B. Non-Inverting Amplifier Setup

- $R_1 = 9.73$ kΩ, $R_2 = 0.986$ kΩ
- $R_3 = 55.66$ kΩ, $R_4 = 9.90$ kΩ

Input	$A = 1 + R_1/R_2 = 10.87$			$A = 1 + R_3/R_4 = 6.62$		
(V)	Output (V)	Gain	Avg. Gain	Output (V)	Gain	Avg. Gain
0.220	2.40	10.93		1.49	6.75	
0.400	4.36	10.91		2.69	6.73	
0.600	6.54	10.90		4.03	6.72	
0.800	8.71	10.89		4.55	6.74	
1.000	10.91	10.91	10.91	5.39	6.72	
1.200	13.07	10.89		6.72	6.72	6.73
1.400	13.57	-		8.10	6.75	
1.600	13.57	-		9.40	6.71	
1.809	13.57	-		10.75	6.72	
1.800	13.57	-		12.12	6.73	
2.020	13.57	-		13.65	6.76	

TABLE II: Measured input and output values for non-inverting amplifier setup.
Note: Gain for saturated values of V_o have not been considered.

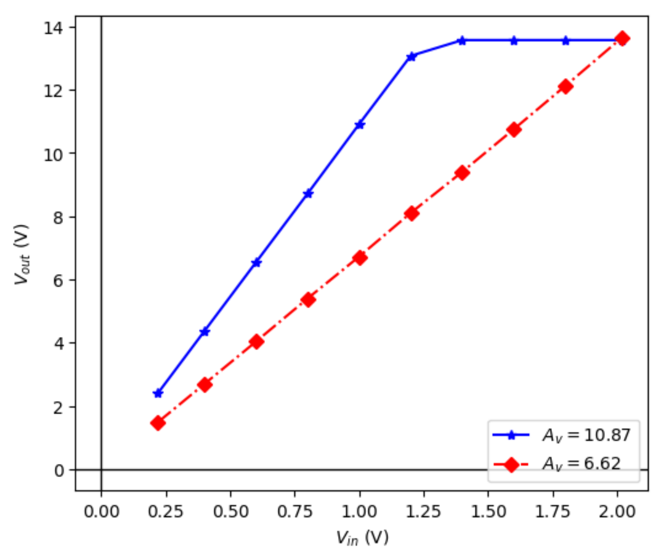

FIG. 18: V_{out} vs V_{in} for the non-inverting amplifier. Note how V_{out} saturates as it reaches around the value of $\pm V_{CC}$

C. Summing Amplifier Setup

V_1 (V)	V_2 (V)	$\lvert V_{\text{out}}\rvert$ (V)	$V_2 + V_1$ (V)
1.240	5.009	6.24	6.24
4.153	5.010	9.10	9.16
5.056	5.009	10.00	10.06
0.861	5.009	5.85	5.87
0.218	5.009	5.23	5.28
3.563	5.009	8.53	8.57

TABLE III: Observation table for V_1, V_2 and V_{out} values

D. Difference Amplifier Setup

V_1 (V)	V_2 (V)	V_{out} (V)	$V_2 - V_1$ (V)
8.440	5.009	-3.307	-3.431
5.306	5.009	-0.201	-0.297
4.712	5.009	0.385	0.297
2.051	5.009	3.013	2.958
1.460	5.010	3.604	3.549
0.540	5.009	4.504	4.469

TABLE IV: Observation table for V_1, V_2 and V_{out} values

E. Voltage Comparator Setup

$V_{\text{th}} = 0$ V		$V_{\text{th}} = 4.99$ V	
V_{in} (V)	V_{out} (V)	V_{in} (V)	V_{out} (V)
-8.00	-11.90	-9.00	-11.90
-6.00	-11.90	-5.00	-11.90
-4.00	-11.90	-4.00	-11.90
-2.00	-11.90	-2.00	-11.90
-1.00	-11.90	-1.00	-11.90
-0.10	-11.90	5.0 mV	-11.90
-6.3 mV	-11.82	0.50	-11.90
7.8 mV	13.34	1.00	-11.90
0.10	13.34	1.50	-11.90
1.00	13.34	2.00	-11.90
2.00	13.34	2.50	-11.90
3.00	13.34	4.00	-11.90
5.00	13.34	4.70	-11.90
7.00	13.34	4.98	-11.90
8.00	13.34	4.99	13.33
9.00	13.34	6.00	13.33
10.00	13.34	7.00	13.33

TABLE V: Observation table two sets of data for the voltage comparator circuit at different values of threshold voltage

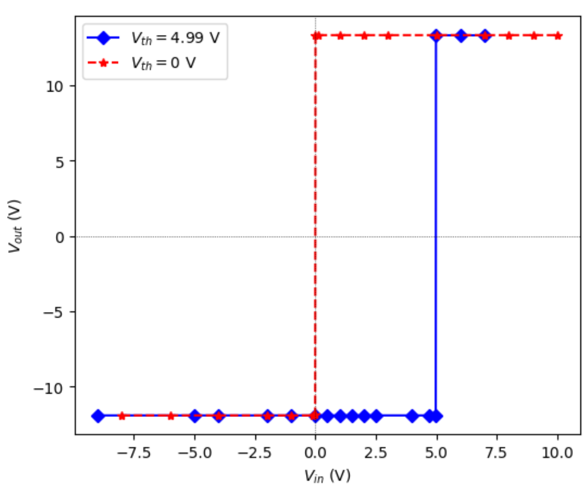

FIG. 19: V_{out} vs V_{in} for the voltage comparator circuit

F. Schmitt Trigger Setup

- Setup 1: $R_1 = 9.75$ kΩ, $R_2 = 9.89$ kΩ
- Setup 2: $R_1 = 0.987$ kΩ, $R_2 = 2.155$ kΩ

$(R_1/R_2)V_{\text{out}} = 12.70$ V		$(R_1/R_2)V_{\text{out}} = 5.92$ V	
V_{in} (V)	V_{out} (V)	V_{in} (V)	V_{out} (V)
15 mV	-11.85	0.10	-11.63
1.00	-11.85	1.00	-11.61
4.00	-11.85	2.00	-11.58
8.00	-11.85	3.00	-11.55
9.40	-11.81	4.00	-11.52
11.40	-11.81	5.00	-11.45
11.85	-11.81	5.80	-11.45
11.87	13.25	5.98	13.09
12.20	13.25	7.00	13.14
13.00	13.25	9.00	13.16
9.00	13.19	5.90	13.09
7.00	13.20	-0.10	13.01
3.00	13.18	-1.00	13.00
2.00	13.18	-2.00	12.99
-1.00	13.17	-3.00	12.95
-3.00	13.15	-4.00	12.96
-5.00	13.15	-5.00	12.95
-9.20	13.14	-5.70	12.93
-11.70	13.13	-5.80	12.93
-12.00	13.13	-5.94	-11.76
-13.24	-11.91	-8.00	-11.78
-13.40	-11.91	-10.00	-11.86
-9.00	-11.91	-6.00	-11.75
-5.00	-11.91	-5.30	-11.75
-1.00	-11.86	15 mV	-11.75

TABLE VI: Observation table two sets of data for the Schmitt trigger circuit for two different values of R_1 and R_2 each

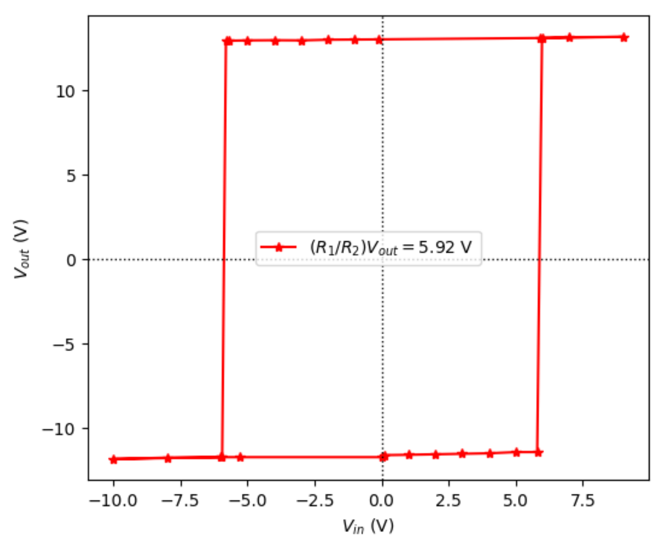

FIG. 20: V_{out} vs V_{in} for Schmitt trigger setup 1

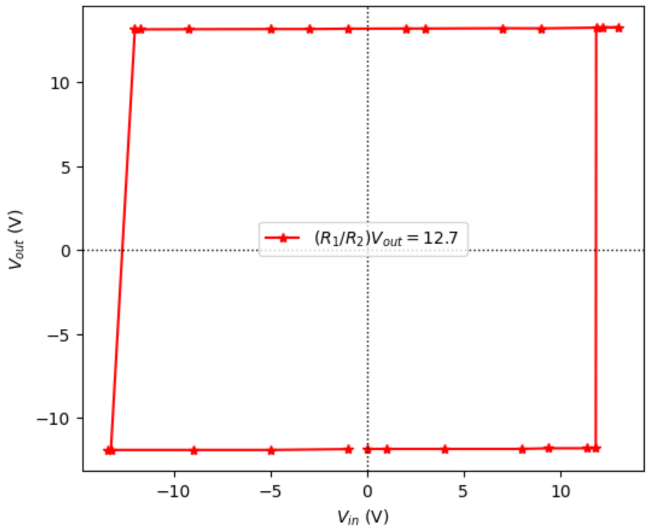

FIG. 21: V_{out} vs V_{in} for Schmitt trigger setup 2

V. DISCUSSION AND SOURCES OF ERROR

Using an IC 741 op-amp, we have successfully constructed inverting and non-inverting amplifier setups and measured their gain values. In case of an inverting amplifier, there is about 0.2% and 0.4% deviation of the experimental value from the theoretical value for each set of R_f and R_{in} respectively. For the non-inverting setup, the deviations were 0.4% and 1.7% respectively. These deviations could be due ito error in the measurement of resistance, error stemming from assumption of an ideal op-amp or due to small capacitances builing up at the metal junctions in the circuit.

Additionally, we have also demonstrated op-amp as a summing and difference amplifier. While the difference in theoretical and experimental values in the case of the summing amplifier was at most ± 0.06 V, the same for the difference amplifier was 0.035V to 0.194V. Since, there is no ideal op-amp in real life, the deviations could be due to a multitude of factors including common-mode gain, offset voltage, noise or due to supply voltage fluctuations.

We have also used the op-amp to build a comparator circuit with and without threshold voltage as demonstrated in Fig. 19. Similarly we have built a schmitt trigger circuit which was able to show hysteresis as shown in Fig. 20 and Fig. 21.

VI. PRECAUTIONS

1. The power supply to the operational amplifier never becomes reversed in polarity.
2. Make sure the connections are proper before switching on the circuit.

VII. CONCLUSION

We have demonstrated basic op-amp configurations, including inverting and non-inverting amplifiers, and its application as a summing amplifier, a difference amplifier, a comparator and a Schmitt trigger.

VIII. APPLICATIONS

Op-amps have a broad range of usages, and as such are a key building block in many analog applications — including filter designs, voltage buffers, comparator circuits etc.

Early op-amps were used in circuits that could add, subtract, multiply, and even solve differential equations. General purpose op amps were redesigned to optimize or add certain features, and now can be found in communication ICs, radio ICs, audio/video ICs, instrumentation circuits which require high sensitivity etc.

Appendix A: Designing a DC Power Supply System

General purpose op-amps use bipolar power supply, typically ± 15 V. The common point between the +15V and -15V is the power supply common. This common is grounded and all voltage measurements are made with respect to this point.

Designing a power supply system which can give us such stable DC voltage outputs require multiple steps. Using a full-wave center tapped transformer, one can obtain +V, 0V and -V voltages. A typical power supply can have four major components:

1. **Step-down transformer** to convert 220V AC to the required voltage.
2. **Rectifier** to convert AC into DC.
3. **Filtering** to remove ripples from the pulsating DC signal.
4. **Voltage Regulator** (using a zener diode or otherwise) provides stability to the output voltage while load currents change.

Additionally, some filtering can be done at the output to further smoothen the DC output, and act as a low pass filter.

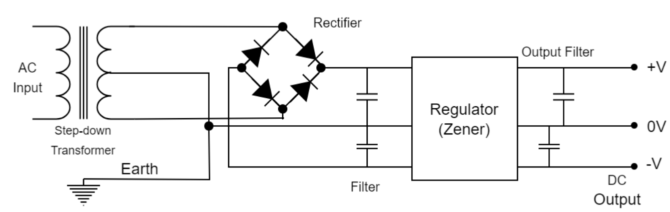

FIG. 22: Schematic diagram for a DC bipolar power supply system

Appendix B: Ground and Earthing

Ground is a reference point in an electrical circuit from which voltages are measured. It can be thought of as a common return path for electrical current. There are several types of grounds,

1. **Earth Ground:** Connecting the system to earth, i.e. a conductor buried in the ground usually using metal rods or wires, is called earthing. The ground pin on electrical outlets lead to this ground, and is intended to protect against insulation failure of the connected device.

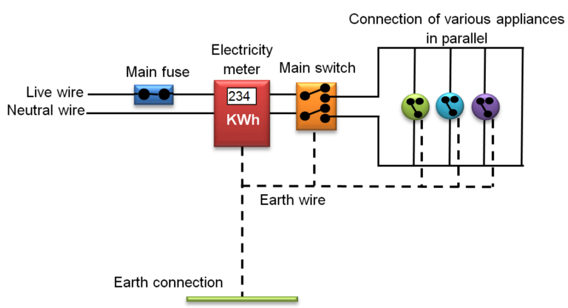

FIG. 23: Schematic of a domestic power supply system showing the live neutral and earth connections.

There are essentially two types of earthing systems: (i) Copper earthing for active devices and (ii) Galvanised iron for body earthing. These are regularly kept in check to ensure < 2V potential difference between the neutral and earth wires in the electricity outlet. Some real-world earthing systems are shown in Fig. 24.

2. **Floating Ground:** It is essentially a ground that isn't actually attached to the earth, but to some other entity for electrical isolation.

3. **Virtual Gound:** This is when a node of a circuit is maintained at a steady reference potential, without actually being connected directly to the reference potential. This is not an actual ground, but only a reference point.
In case of op-amps, when the non-inverting terminal is grounded then the inverting terminal will also act as ground, since they are at the same potential. Although the inverting terminal is not actually grounded, it acts as a virtual ground.

FIG. 24: Three types of earthing points near the SPS building, NISER

[1] SPS, *Operational Amplifiers (Supplementary note)*, NISER (2023).
[2] R. A. Gayakwad, *Op-Amps and Linear Integrated Circuits* (Pearson, 2015).
[3] P. Horowitz and W. Hill, *The art of electronics* (Cambridge University Press, 2015).