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Nonideal Behavior of an Operational Amplifier

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Abstract

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The thesis is a an investigation of operational amplifiers (op-amps) from the rudiments of their explanation to how they are practically made into circuits by use of components, such as resistors and operational amplifier ICs like LT1498 or LM358, It also deals with different op-amp parameters including input offset voltage, bias current, slew rate, common-mode rejection ratio, gain bandwidth product and rail-to-rail operation. Additionally, it discusses both ideal and non-ideal features of op-amps along with their importance in electronic circuit design.

This thesis shows practical implementations of inverting operational amplifier circuits that employ LT1498 and LM358 which involve calculation of component values for desired gains. Furthermore, this thesis explores the behavior of these circuits using LTspice simulations and Altium design to demonstrate their functionality, performance characteristics and their such as voltage gain and cutoff frequency and their PCB design.

This thesis can be used as resource for learning about the theory and application of operational amplifiers in electronic circuit design. In particular this thesis unites theoretical concepts with real world circuit implementations that provide insights into designing and analyzing op-amp circuits for various applications.

Keywords : Operational Amplifier, key parameters, Analog device op- amp.

Contents

List of Abbreviations

A_{cm}: Common Mode Voltage Gain

A_d: Differential Voltage Gain

A_{vol}: Open-Loop Voltage Gain

A_v: Voltage Gain

BW: Bandwidth

CMRR: Common-Mode Rejection Ratio

F_t unity gain frequency of the amplifier.

IC: Integrated Circuit

I_B: Bias Current

I_{io}: Input Offset Current

I_l : Load current.

I_o : Output current

Op-Amp: Operational Amplifier

P_o: Output power

PCB: printed circuit board

RTR: Rail-to-Rail

R_f, R_2: Feedback Resistance

R_1: Input Side Resistance

SR: Slew Rate

V^-: Inverting Input Voltage

V^+: Noninverting Input Voltage

V_{cm}: Common-Mode Input Voltage

V_d: Differential Input Voltage

V_{io}: Input Offset Voltage

V_o: Output Voltage

$V_s +$: Positive Supply Voltage

$V_s -$: Negative Supply Voltage

V_{os}: Offset Voltage

Vpp: Peak to Peak Voltage

X_c: Capacitive Reactance

Z_l: Load Impedance

Z_n: Input Impedance

1 Introduction

In essence, an operational amplifier is a low output impedance, high gain differential amplifier that is directly coupled. An apparatus with several uses is the operational amplifier. The integrated circuit operational amplifier has evolved into a low-cost and efficient solution for solving circuit design issues. Despite being categorized as a linear integrated circuit, the operational amplifier finds application in non-linear and digital domains as well. Operational amplifiers make up about one-third of all integrated circuits; there are over 2000 different varieties that are sold commercially. Nearly majority of these are monolithic integrated circuits (ICs) with power dissipations of less than one watt at ambient temperature. The term "operational amplifier” (abbreviated "Op. Amp.") initially refers to an amplifier circuit that could do multiple mathematical operations, such as subtraction, differentiation, summation, and integration. Figure 1. shows the operational amplifier schematic.

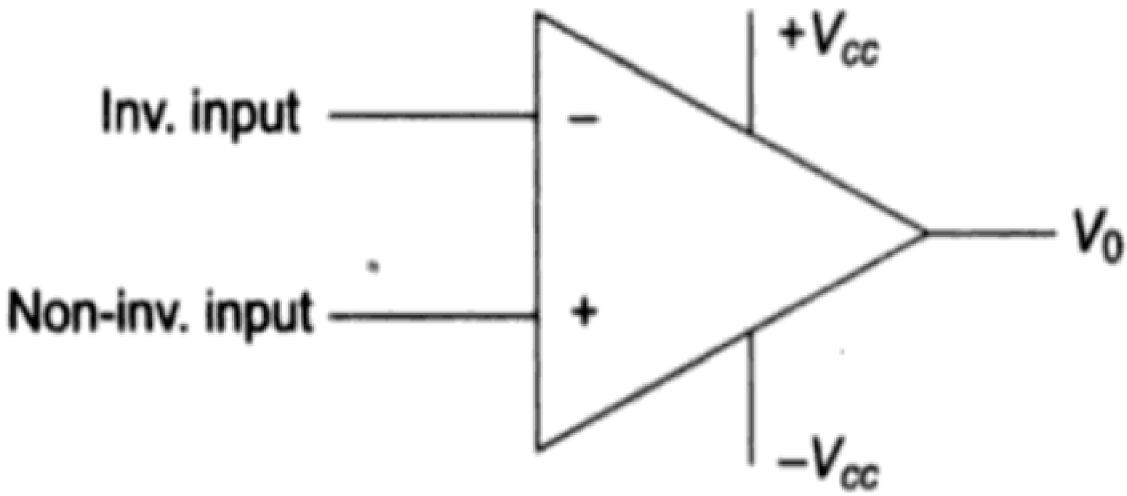


Figure 1. Operational amplifier schematic [2].

2 Operational Amplifier - Basics

Originally designed to execute linear mathematical calculations in analog computers, the operational amplifier is a multipurpose amplifying device. The internal circuit design of the operational amplifier, which has been developed over 40 years, largely mirrors the evolution of electronic components from vacuum tubes to monolithic integrated circuits. The focus of applications for operational amplifiers has migrated from laboratories to industries due to ongoing improvements in their qualities. In the field of analog electronic systems, the operational amplifier has become the industry standard due to its excellent performance, affordability, and versatility.

An operational amplifier is typically understood to be a direct-coupled amplifier that can operate steadily in a closed-feedback loop and has a high gain and low noise. It should be noted that the phrase "direct coupled" refers to an extension of the amplifier's operating range to zero frequency or infinitely long periods, rather than an upper limit on the frequency response of the amplifier.

The triangular shape of an operational amplifier's symbol in figure 2 indicates the direction of signal flow from input to output. The three signal terminals of a real operational amplifier are represented by three of the four terminals that are shown in figure 2 These are the output, noninverting input, and inverting input [1].

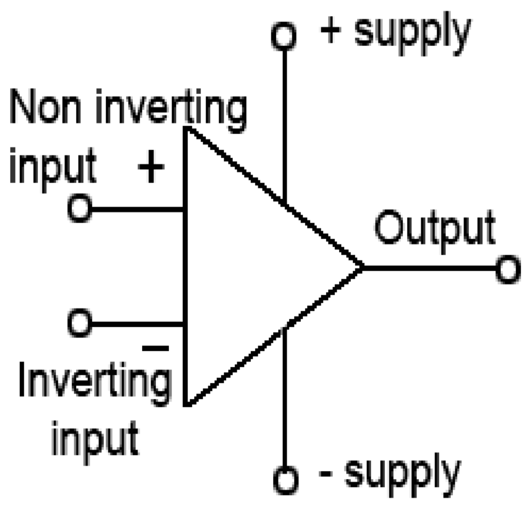
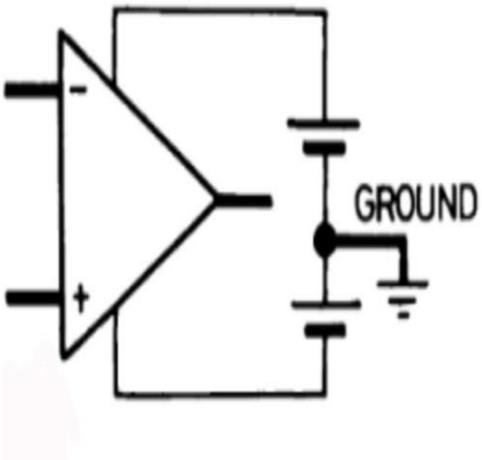


Figure 2. Symbol of an operational amplifier [7].

The ground which connected to the fourth signal terminal, might be virtual (figure 3 power supply common) or actual (figure 4). In either scenario, it symbolically denotes a collection of at least two terminals meant for energy delivery.



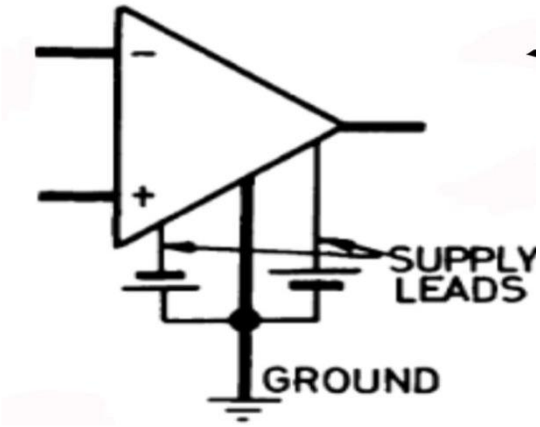
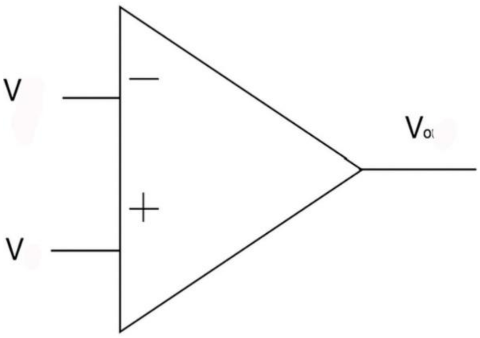


Figure 3. Figure 4.

Figures 3,4. Actual implementation of the ground terminal [1].

For the other three terminals, the ground signal terminal serves as a point of reference. figure 5 and figure 6 shows the sign convention for the input voltages V^{-}, V^{+}, output voltage V_o, input currents i^{-}, i^{+}, and output current i_o. The ground is typically left out of the amplifier symbol and the terminal voltages are simply expressed by adding a letter when there is no chance of mistake.



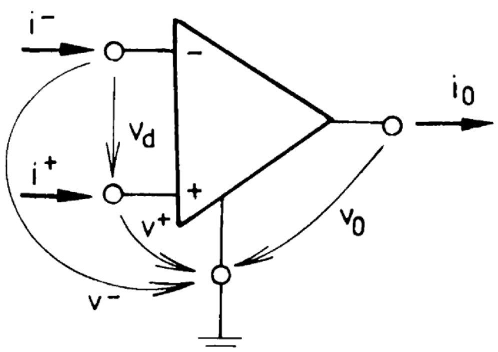


Figure 5. Figure 6.

Figures 5,6. Shows the sign convention for the input voltages. [1]

The supply voltages V_s^{+} and V_s^{-} typically provide a restriction on the absolute values of the signal voltages V^{-}, V^{+}, and V_o. In the absence of exceptional situations, the nominal values of $V_s^{+}$and V_s^{-} are + 15 V and -15 V, respectively. In both polarities, the corresponding signal swings of the output and input voltages are symmetrical and typically fall within ±10 V. Different supply voltages, symmetrical and asymmetrical (such as +5 V and 0 V), can also power a large number of operational amplifiers [2]

Operational amplifiers can handle various loads and so, they adjust their output current accordingly. They function with passive as well as active loads and operate at any point on the graph of the output voltage/current in relation to its four quadrants.

An important aspect of an operational amplifier is that it can amplify the difference between its two input voltages without taking into account what each value is. This definition yields us two essential concepts: first, a common-mode input voltage (V_{cm}) which is disregarded by the amplifier and based on the arithmetic mean of these two voltages; secondly, it provides differential input voltage (V_d), which is responsible for amplification in this amplifier and occurs when there are differences between both inputs.

$$V_d = V^- - V^+ \tag{1}$$

The definition of the common-mode input voltage is rather arbitrary.

$$V_{cm} = V^+ + Kv_d \tag{2}$$

because it is dependent on the constant K's value that is selected. In practice, there are two options: K = 1/2 and K = 0. The first option maintains symmetry.

$$V_{cm} = \frac{V^- + V^+}{2} \tag{3}$$

However, this causes formal issues when defining the parameters of the operational amplifier. Consequently, the second option where the noninverting input voltage V^+ is associated with the common-mode input voltage V_{cm} is favored.

$$V_{cm} = v^+ \tag{4}$$

Taking into account the closed-feedback loop function, where the noninverting input typically acts as a forced reference point with which the inverting input is compared, this second option is equally justified. Since the differential input voltage is typically minimal when compared to the common-mode input voltage range, the difference between the two definitions is essentially non-existent [2].

2.1 Open-Loop Gain

An op-amp in an open-loop arrangement, where the output terminal is unconnected from the input terminal, is seen in the circuit in figure 7. The feedback loop is hence open. The total voltage gains of the various stages inside the A_{VOL}. op-amp internal circuit is represented by the voltage gain in this design. A typical number is 10^5. ∞ is the ideal value.

A_{VOL}=Voltage gain in open-loop configuration

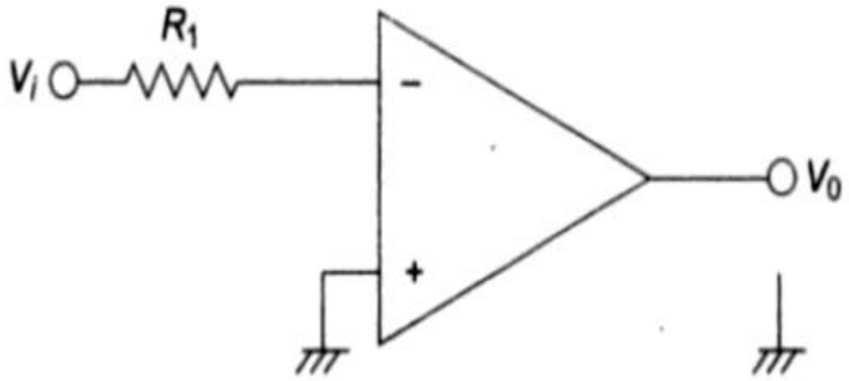


Figure 7. Open loop configuration [2].

2.2 Close-Loop Gain

An op-amp configured in a closed-loop is shown in figure 8 Since the input is sent to the inverting input terminal, the feedback in this case is negative. There is a 180° phase shift in the output. The relationship between R_f and R_1 sets a limit on the closed-loop voltage gain, or A_{VCL}, or just A_v.

R_f = Feedback resistance.

R_1 is the resistance that is connected to the circuit's input side [3].

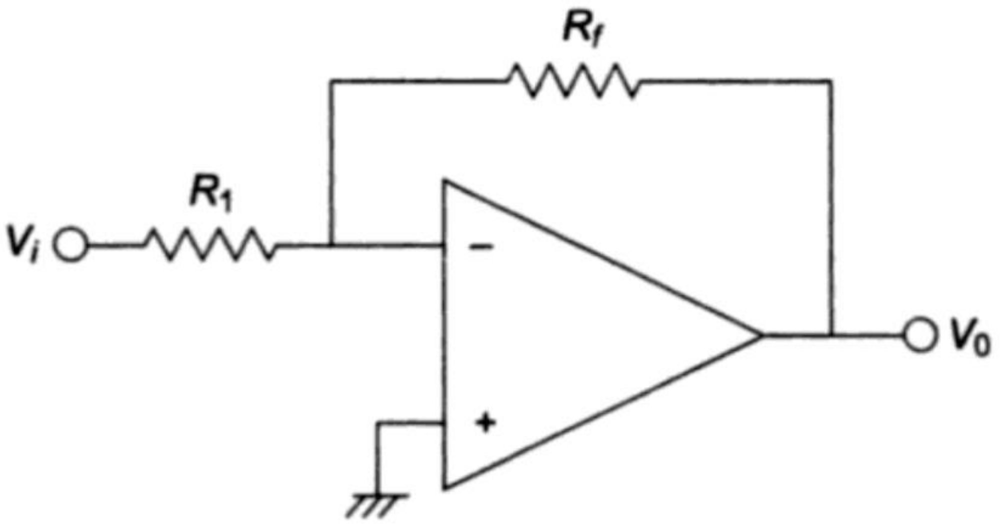


Figure 8. Close loop configuration [2].

3 Operational Amplifier Circuit

3.1 Inverting Operational Amplifier Circuit

An inverting operational amplifier consistently produces an output voltage that is the opposite sign of the input voltage, with the magnitude of the output determined by a fixed gain factor. Figure 9 shows the circuit configuration of inverting operation amplifier.

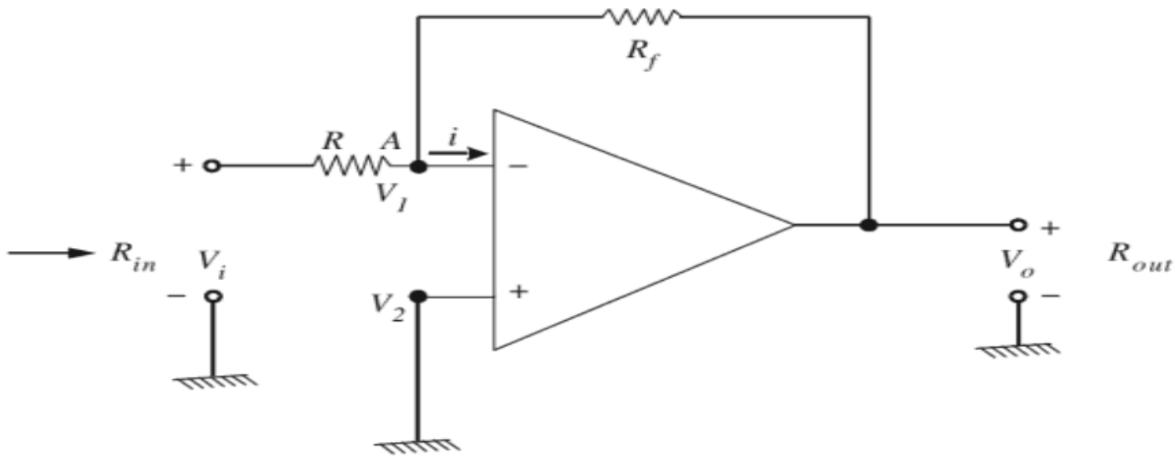


Figure 9. Inverting operational amplifier [3]

The gain in an inverting operational amplifier circuit is determined by the input and feedback resistors. This means that the current flowing through the input resistor is equal to the current flowing through the feedback resistor as far as the inverting input being at a virtual ground. Consequently, we can obtain an equation that connects the input and output voltages.

$$\frac{(V_{in}-0)}{R_i} - \frac{(0-V_{out})}{R_f} = 0 \quad (5)$$

or

$$\frac{V_{in}}{R_i} = -\frac{V_{out}}{R_f} \quad (6)$$

Now we will determine the relationship between our input and output, denoted by the gain or amplification term "A," where A = V_{out}/V_{in}. After rearranging the equation, the following becomes apparent:

$$A = -\frac{R_f}{R_i} \quad (7)$$

As a result, the output will be amplified by R_f/R_i and then inverted into a negative voltage, regardless of the input voltage [6].

3.2 Non-Inverting Operational Amplifier Circuit

The circuit configuration of the noninverting operational amplifier shown as the figure below.

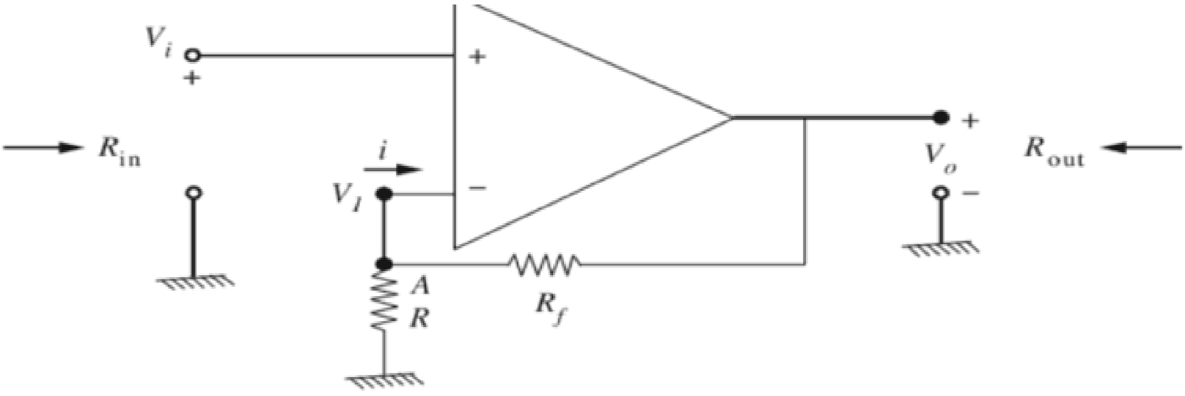


Figure 10. Non-inverting operational amplifier circuit [3]

The signal seems to go to the non-inverting input, but actually, the inverting input is placed at a voltage divider midpoint. The output will force the voltage on its inverting input to be exactly equal to that of the non-inverting one since it is connected through this voltage divider. This takes place because both resistors have similar currents flowing through them, resulting in voltage at inverting input being equal to that across non-inverting input. We can use Kirchhoff's Current Law (KCL) and some maths to explain how this circuit functions. Selecting the node of the inverting input gives us:

$$\frac{(V_{out}-V_{in})}{R_2} - \frac{V_{in}}{R_1} = 0 \tag{8}$$

or

$$\frac{V_{out}-V_{in}}{R_2} = \frac{V_{in}}{R_1} \tag{9}$$

By dividing both sides by V_{in} and multiplying both sides by R_2, this can be made simpler:

$$\frac{(V_{out}-V_{in})}{V_{in}} = \frac{R_2}{R_1} \tag{10}$$

This breaks down into:

$$\frac{V_{out}}{V_{in}} - 1 = \frac{R_2}{R_1} \tag{11}$$

Lastly, include one on each side:

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1} \tag{12}$$

Once more assigned "A," our gain, or amplification amount, provides us with:

$$A = 1 + \frac{R_2}{R_1} \tag{13}$$

Although they're less prevalent, non-inverting op-amp amplifier setups are incredibly helpful [4].

4. Operational Amplifier Key Parameters

A differential amplifier with noise immunity is called an op-amp. Through the use of a multistage amplifier circuit architecture, it also provides significant voltage gain. Furthermore, the input stage circuit in the internal schematic offers high input impedance. Low output impedance and the necessary current drive to supply output current to supply output power P_o (P_o=$V_o I_o$) of the load (Z_n) are provided by the output stage circuit. +Vcc and -Vcc are applied to internal transistor circuits to provide biasing. The 741 IC Pin Configuration is shown in figure11.

High input impedance and low output impedance characterize the op-amp. As a result, it will not use a lot of the external input voltage signal source's current. Consequently, the loading effect is bypassed. It produces the highest output because of its low output resistance. Numerous parameters are specified based on these characteristics, which are caused by the biasing voltages provided to the integrated circuit and the current the IC draws from the DC-supplying (bias) voltages. The part that follows provides an explanation of them [2].

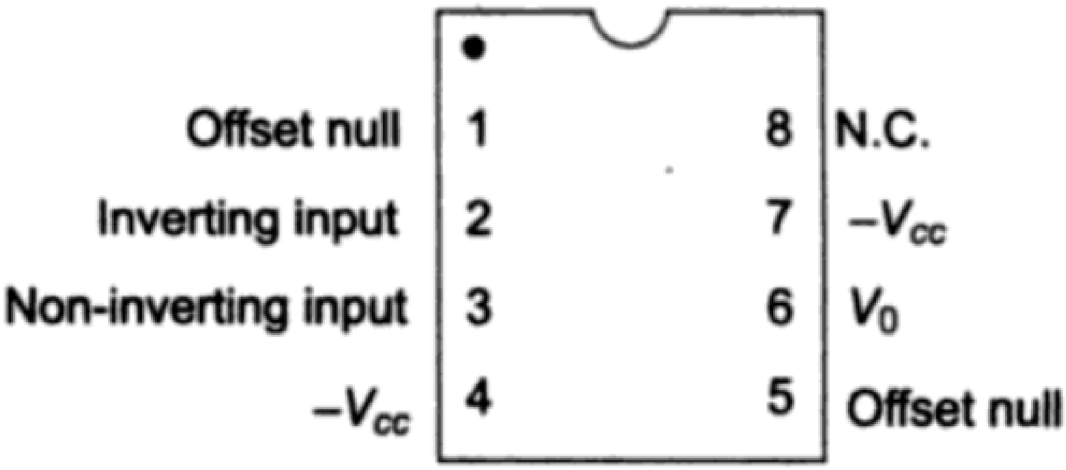


Figure 11. 741 Pinout Diagram [2].

4.1 Input Offset Voltage (V_{io})

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The output of the op-amp must be zero in the event that no external input signal is applied to any of the inverting or non-inverting input terminals. In other words, if V_i = 0, V_o = 0. However, the op-amp draws a limited bias current due to the supplied biasing supply voltages, +Vcc and -Vcc, and the output will not be zero due to asymmetry in the differential amplifier arrangement. We call this offset. Given that V_o must equal zero when V_i = 0, the input signal must be applied in a way that cancels the output offset and sets V_o to zero. We call this input offset voltage. It is the voltage required to neutralize an op-amp's output that must be applied between its two input terminals. This is shown in figure 12 V_{io} = 0 V is the optimal op-amp value. Typical practical value is 100 µV [2]

$$V_{OS}=V_{OS+}-V_{OS-} \quad (14)$$

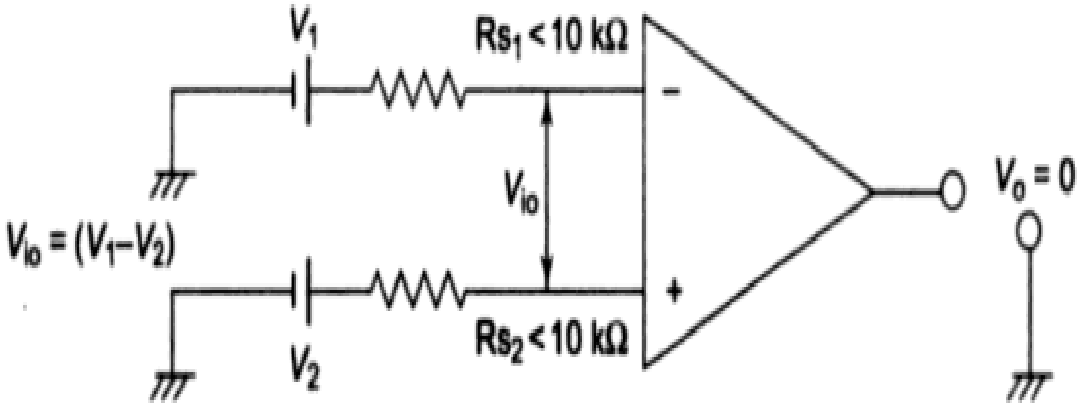

Figure 12. Input offset voltage [2].

4.2 Bias Current and Input Offset Current

While operating with operational amplifiers (op-amps), a small amount of DC current is required to flow into substitute so that it functions properly. Referred to as input bias current, it is the average of input current to the two input terminals. Figure 13 shows the input bias current.

$$I_B = \frac{I_{B1} + I_{B2}}{2} \tag{15}$$

Although the input impedance of an ideal op-amp is ∞, this is not often the case in practice. Therefore, regardless of how little the voltage source may be, the IC takes current from it.

Input offset current (I_{io}) is the algebraic difference between the currents into the inverting and non-inverting terminals.

The input offset current equation is:

$$I_{io} = |I_{B1} - I_{B2}| \tag{16}$$

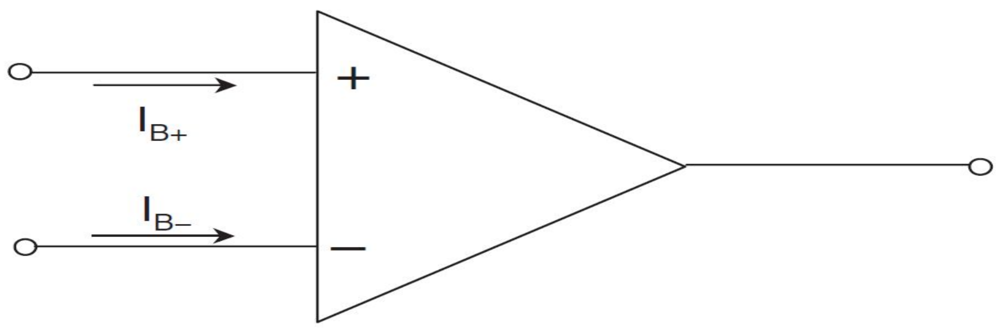

Figure 13. Input bias current.

4.3 Slew Rate (SR)

This is the maximum output voltage change rate per unit of time. The op-amp circuit's input capacitance prohibits it from reacting instantly to high frequency impulses. The slope of the leading and trailing edges of a square wave or high-frequency pulse applied as input is measured at the output, and the bigger value is determined. Thus, SR is obtained.

The slew rate equation is provided by:

$$SR = \frac{\Delta V_o}{\Delta t} \tag{17}$$

4.4 Common-Mode Rejection Ratio (CMRR)

An op-amp's ability to reject a signal that is common to both inputs is measured by its CMRR. The ideal CMRR is infinite, meaning that any change in either input will have no effect on the output if they fluctuate by the same amount while staying constant in relation to one another. One attribute of differential amplifiers is the rejection of common modes. Since operational amplifiers (Op-amps) are differential input amplifiers, they are subject to common mode rejection.

When there is a "common voltage" or equal voltage across both of the amplifier's inputs, this is known as the common mode signal. In this scenario, the amplifier should either reject the signal and not amplify it, or its output should be zero.

The common mode voltage gain (A_{cm}) divided by the differential voltage gain (A_d) is known as the common mode ratio (CMRR).

$$CMRR = \frac{A_d}{A_{cm}} \tag{18}$$

The op-amp is configured as a differential voltage amplifier. A_d are typically big. A_{cm} is small. Because of this, CMRR has a high value. Decibels are used to express CMRR.

$$A_{cm} = \frac{V_{ocm}}{V_{icm}} \tag{19}$$

$$A_d = \frac{V_{out}}{V_{diff}} \tag{20}$$

The noise signals that are shared by the differential amplifier's two inputs will likewise be amplified in this setup. The noise will be changed rather than amplified if the amplifier's common mode gain is lower. As a result, the output Vo will have less noise and only the differential input will be amplified. This is the benefit of the differential amplifier that op-amps use. The CMRR value is high as a result.

4.5 Gain Bandwidth Product

The op-amp bandwidth in case the voltage gain is one unity.

Since,

$$X_c = \left[\frac{1}{2\pi f c}\right] \tag{21}$$

that means the gain will decrease as long as the frequency increases. Z_l decreases also, because $V_o = I_l \times Z_l$. As a result, the gain A_v drops. The gain BW product shows how much higher frequency input signals the op-amp can amplify.

A_v BW is sometimes referred to as unity gain bandwidth and closed-loop bandwidth.

Ideal value = ∞, Typical value = 1 MHz [2].

$$V_o = I_l \times Z_l \tag{22}$$

X_c: Capacitive reactance.

V_o: Output voltage.

I_l : Load current.

Z_l: Load impedance.

4.6 Rail-to-rail VS. Not

When an operational amplifier (op-amp) or other electronic device is said to be rail-to-rail (RTR), it means that it can operate with its output voltage range spanning from the lowest possible voltage (typically the ground or negative supply rail) to the highest possible voltage (typically the positive supply rail). This maximizes the device's useable dynamic range by enabling the output voltage to effectively reach both supply rails.

On the other hand, for non-rail-to-rail devices, the output voltage swing is limited. There may be a gap at both extremes of the output voltage range that the output voltage cannot reach since they may not be capable of covering the entire range between the two supplies rails. This restriction may be important in situations where the op-amp's entire dynamic range is needed, like in sensor interfaces, data gathering systems, and audio amplifiers [6].

5.Ideal and Non-Ideal Op-Amp

5.1 Ideal Op-Amps

Theoretically, an ideal op-amp can be used to streamline analysis in a variety of circuits. It possesses the following qualities; Infinite open-loop gain: An ideal op-amp is thought to have an endlessly high voltage gain, which allows it to amplify the input signal without bound. A perfect op-amp has an endlessly high input impedance, which indicates that no current enters the op-amp's input terminals. Zero output impedance: Since the output impedance of the perfect op-amp is believed to be zero, any load can be driven without affect the output voltage.

Unlimited bandwidth: An optimal operational amplifier possesses an unbounded bandwidth, which permits it to amplify signals of any frequency without experiencing distortion or attenuation. An optimal operational amplifier (op-amp) totally rejects any signal that is shared by both input terminals, resulting in an infinite common-mode rejection ratio (CMRR).

5.2 Non-ideal Op-Amps

Operational amplifiers that are not perfect: The constraints of electronic components and manufacturing methods result in defective op-amps in the real world. The following are features of non-ideal op-amps that differ from the ideal model;
Gain finite: The open-loop gain of real op-amps is typically quite large but not infinite. Manufacturers list this gain on the datasheet for the op-amp.
Finite input impedance: Non-ideal op-amps have a finite input impedance, which means that some current passes into the input terminals even though it is still high.
Non-zero output impedance: When driving large loads, a non-ideal op-amp's output

impedance, which is typically low but not zero, may have some effect on the output voltage. Restricted bandwidth: The performance of real op-amps may suffer at high frequencies due to their limited bandwidth. Finite CMRR: Non-ideal op-amps may not completely reject common-mode signals due to their finite common-mode rejection ratio. Circuit Modelling: Circuit symbols can be used to represent both ideal and non-ideal op-amps. The non-ideal op-amp may have extra parameters like input impedance, output impedance, and finite gain, whereas the ideal op-amp is commonly represented by a triangle symbol. By taking into account their properties during the circuit design and analysis, non-ideal op-amps can be accurately represented. For example, to account for the non-ideal behavior, we might add the output impedance, input impedance, and finite gain of the op-amp in the circuit equations. In order to get precise and dependable results in circuit design, it is imperative to utilize the particular properties of the chosen op-amp. By utilizing the appropriate model, engineers can forecast the circuit's behavior more accurately and make sure it adheres to the intended standards [5].

6. Comparison of 10 Different Operational Amplifier

To do this comparison we need to check the datasheet for each Op-Amp as shown in the table below we looked for the (Unity gain, Slew rate, RTR, CMRR, Prices and their offset voltage). Table 1 shows the comparison of the op-amps.

Table 1. Comparison of 10 Different Operational Amplifier

op-amps	unity gain	slew rate	bias	rail to rail	CMRR	price	offset voltage
LM741	1.5 MHz	0.5 V/µs	80 nA	Not	95 dB	0.80 €	1 mV
LM358	0.7 MHz	0.3 V/µs	-20 nA	Not	80 dB	0.34 €	3 mV

LM324	1.2 MHz	0.5 V/ μs	-20 nA	Not	80 dB	0.39 €	3mV
NE5532	10 MHz	9 v/μs	200 nA	Not	100 dB	1.17 €	0.5 mV
RC4558	3 MHz	1.7 V/μs	150 nA	Not	90 dB	1.21 €	0.5 mV
OP07	0.6 MHz	0.3 V/μs	±1.8 nA	Not	120 dB	1.78 €	0.06 mV
LT1498	10.5 MHz	4.5 V/μs	250 nA	RTR	90 dB	1.85 €	0.15 mV
TL072	3 MHz	20 V/μs	65 pA	Not	100 dB	1.39 €	3 mV
OPA2134	8 MHz	±20 V/μs	5 pA	Not	100 dB	5.61 €	±0.5 mV
LMH6629	330 MHz	1600 V/μs	-15 μA	RTR	87 dB	5.91 €	±0.15 mV

In table 2 we do the same thing but for the Op-amp by Analog Devices (a component manufacturer) that have parameters as close as possible to the previous one that were shown in table 1.

Table 2. Op-amp by Analog Devices (a component manufacturer).

Op-amps	unity gain	slew rate	bias	rail to rail	CMRR	price	offset voltage
LM741/ MAX9617	1.5 MHz	0.7 V/μs	31 pA	Not	135 dB	4,63 €	0.8 μV

LM358/ MAX4238	1 MHz	0.35V/µs	1 pA	RTR	140 dB	3,37 €	0.1 mV
LM324 / AD8544	0.98 MHz	0.75 V/µs	4 pA	Not	45 dB	2,13 €	1 mV
NE5532 / MAX4490	10 MHz	10 V/µs	± 2.5 nA	Not	75 dB	3.79 €	1.5 m V
RC4558 / AD820	1.9 MHz	3 V/µs	40 pA	Not	90 dB	4,34 €	0.3 mV
OP07/ MAX4237	7.5 MHz	1.3 V/µs	1 pA	Not	102dB	2,72 €	5 mV
TL1498/ MAX40018	9 KHz	6.4 V/µs	0.1 pA	RTR	95 dB	2,38 €	0.35 mV
TL072 / ADTL082	5 MHz	20 V/µs	2 pA	Not	86 dB	1,39 €	1.5 mV
OPA2134 / AD8510	8 MHz	20 V/µs	21 pA	Not	100 dB	3,70 €	1.0 mV
LMH6629 / MAX4305	340 MHz	1400 V/µs	32 µA	RTR	95 dB	4,79 €	1 mV

7. Design Process

Amplification value, feedback resistor and circuits are provided by the supervisor of this thesis.

Table 3 below shows the op-amp circuit will be designed.

Op-Amps	Amplification	Circuit
TL1498	20 dB	Inverting
LM358	14 dB	Inverting
LM324	26 dB	Inverting
OP07	14dB	Noninverting
OPA2134	20 dB	Noninverting
LMH6629	26 dB	Noninverting

Feedback Resistor = 220 KΩ

7.1 Simulation

7.1.1 TL1498 circuit design

This circuit was simulated by LTspice simulation. It is an inverting circuit using a LT1498 operational amplifier with two resistors, the second resistor (R_f) is 220KΩ, and the amplification value is 20dB, in order to obtain R1 value we need to use equation (7) but firstly we need to convert the amplification value from decibel to voltage ratio by using equation (23).

The formula to convert decibels to voltage ratio is:

$$A_v = 10^{\frac{GdB}{20}} \qquad (23)$$

$A_v = 10^{\frac{20}{20}}$ = A_v = 10

For inverting op-amp circuit, the gain (A_v) is calculated using the formula:

$$A = -\frac{R_f}{R_i} \qquad (7)$$

Knowing that R_f=220 kΩ, and A_v =10

To solve R_1,

R1=-220/10 = -22

so R_1= 22 kΩ

In an ideal inverting configuration, the output voltage is inverted (opposite polarity) and amplified by a factor determined by the ratio of the feedback resistor (R_f) to the input resistor (R1). figure 14 shows the simulation and the AC analysis for the circuit, from the graph we could see that our voltage amplification in (dB) is right, and we could see also the cutoff frequency.

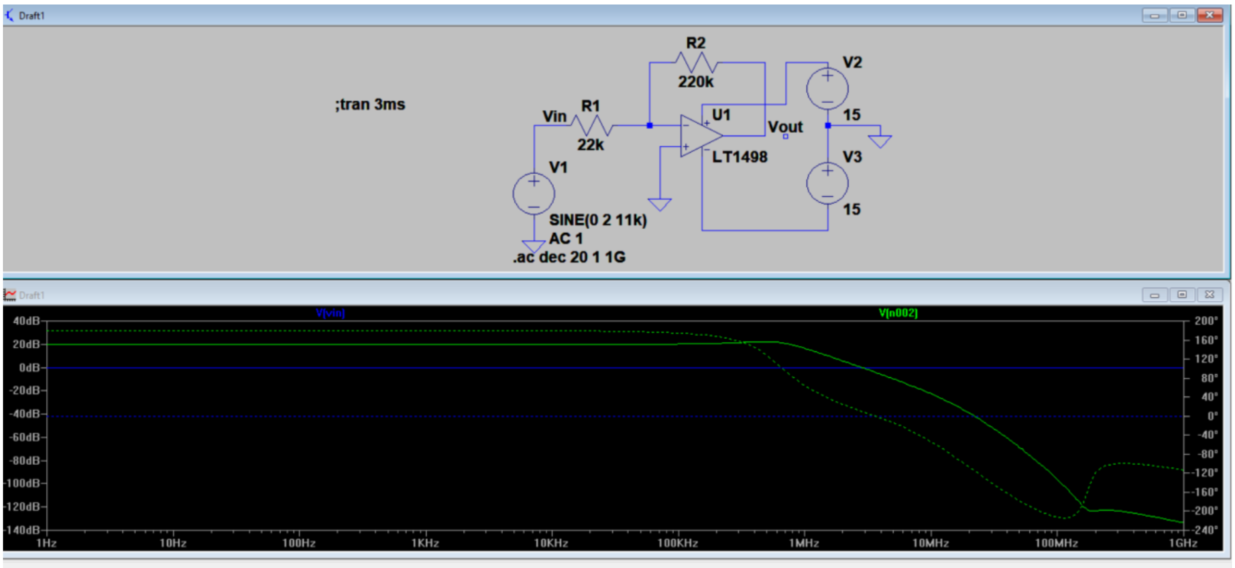

Figure 14. simulation and AC analysis of inverting op-amp (TL1498

Now we do small calculation to compare F_{3dB} to the theoretical value.

Mag = -3dB and F_{3dB} =3.42 MHz

-3dB = 10 MHz (from datasheet)

$$F_{3dB} = \frac{F_t}{1+\frac{R_2}{R_1}} \qquad [24]$$

Where F_t is (unity gain frequency of the amplifier), and we can find it from datasheet.

$$F_{3dB} = \frac{10}{1+\frac{220k}{22k}} = 0.9MHz$$

There is not that much difference, we can say its close to each other.

7.1.2 LM358 Circuit Design

The circuit was simulated by LTspice. It is an inverting circuit using a LM358 operational amplifier with two resistors, the second resistor (R_f) is 220KΩ it Determines the gain of the inverting amplifier, since the amplification value is 14 dB, so the first resistor is 44KΩ, R1 (44kΩ) sets the input impedance of the circuit. In an ideal inverting configuration, the output voltage is inverted (opposite polarity) and amplified by a factor determined by the ratio of the feedback resistor (R_f) to the input resistor (R1). The figure 15 shows the simulation and AC analysis.

The formula to convert decibels to voltage ratio is:

A_v= $10^{\frac{GdB}{20}}$ = A_v= $10^{\frac{14}{20}}$ = A_v = 5.01187

For inverting op-amp circuit, the gain (A_v) is calculated using the formula:

$$A = -\frac{R_f}{R_i} \quad (7)$$

Given that R_f=220 kΩ, and A_v = 5.01187

To solve R_1,

R1=-220/5.01187 = -43.91

so R_1= 44 kΩ

AC Analysis

The graph in figure 15 shows that our amplification value is right, and we can see the cutoff frequency also.

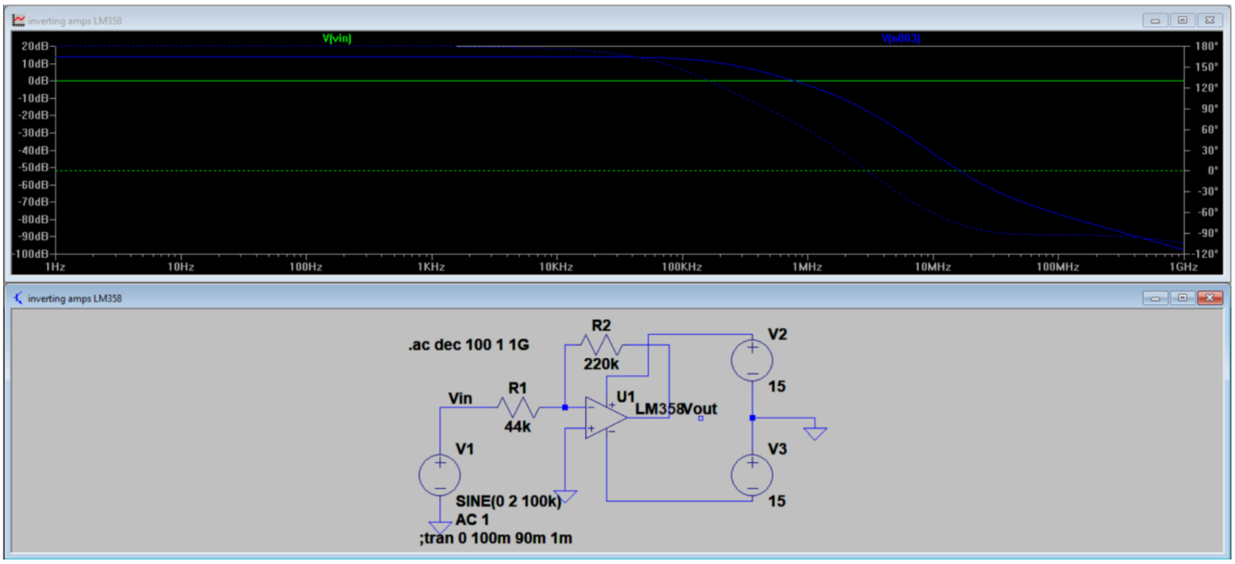

Figure 15. simulation and AC analysis of inverting op-amp (LM358)

From the figure above we can see the cutoff frequency at -3dB.

Mag = -3dB and F_{3dB} =1.05 MHz

Now we do small calculation to compare F_{3dB} to the theoretical value.

-3dB = 0.7 MHz (from datasheet)

$$F_{3dB} = \frac{F_t}{1+\frac{R_2}{R_1}} \quad (23)$$

F_t we obtain it for datasheet F_t(unity gain frequency of the amplifier)

$$F_{3dB} = \frac{0.7M}{1+\frac{220K}{44K}}$$

F_{3dB} = 0.16 MHz

They are very close to each other.

7.1.3 LM324 Circuit Design

The circuit was simulated by LTspice. It is an inverting circuit using a LM324 operational amplifier with two resistors, the second resistor (R_f) is 220KΩ, since the amplification value is 26 dB, therefore the first resistor is 11 KΩ. The figure 16 shows the simulation and AC analysis.

The formula to convert decibels to voltage ratio is:

$A_v = 10^{\frac{GdB}{20}}$ = $A_v = 10^{\frac{26}{20}}$ = A_v = 19.95

For inverting op-amp circuit, the gain (A_v) is calculated using the formula:

$$A = -\frac{R_f}{R_i} \qquad (7)$$

Given that R_f=220 kΩ, and A_v = 19.95

To solve R_1,

R1=-220/19.95 = -11

so R_1= 11 kΩ

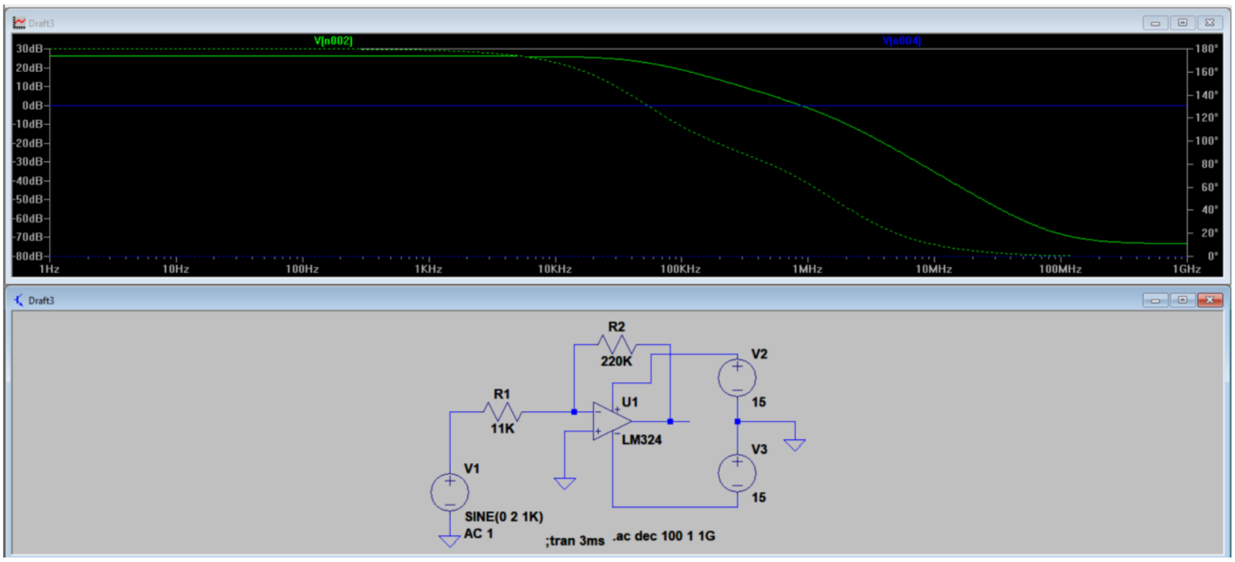

Figure 16. Simulation and AC analysis of inverting op-amp (LM324)

From figure 16 we could do the calculation to compare the value we have with the theoretical value that we will get from the datasheet.

Mag = -3dB and F_{3dB} =1.16 MHz

Now we do small calculation to compare F_{3dB} to the theoretical value.

-3dB = 1.2 (from datasheet)

$$F_{3dB} = \frac{F_t}{1+\frac{R_2}{R_1}} \tag{24}$$

F_t we obtain it for datasheet F_t(unity gain frequency of the amplifier)

$$F_{3dB} = \frac{1.2M}{1+\frac{220k}{11k}}$$

$$F_{3dB} = 0.5\ MHz$$

They are very close to each other.

7.1.4 OP07 Circuit Design

The circuit was simulation by LTspice. It is noninverting circuit using a OP07 operational amplifier with two resistors, the second resistor (R_f) is 220KΩ, since the amplification value is 14 dB, so the first resistor is 11 KΩ. Figure 17 shows the simulation and AC analysis.

The formula to convert decibels to voltage ratio is:

$$A_v = 10^{\frac{GdB}{20}} \quad = \quad A_v = 10^{\frac{14}{20}} \quad = \quad A_v = 5.012$$

For a noninverting op-amp circuit, the gain (A_v) is calculated using the formula:

$$A_v = 1 + \frac{R_2}{R_1}$$

Since A_v = 5.012 and Rf = 220KΩ so,

$$5.012 = 1 + \frac{220K\Omega}{R_1}$$

R_1 = 47.6 KΩ

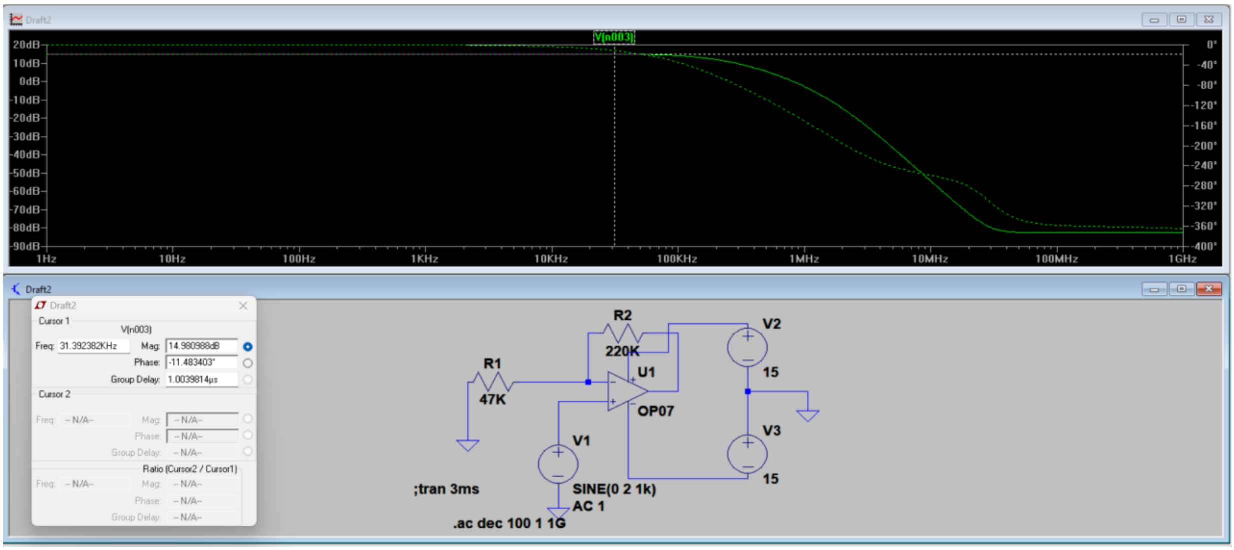

Figure 17. Schematic and AC analysis of non-inverting op-amp (OP07)

From the figure above we could see that our magnitude of the amplification is right, and we can see the cutoff frequency.

From figure 17 we could do the calculation to compare the value we have with the theoretical value that we will get from the datasheet.

Mag = -3dB and F_{3dB} =1.03 MHz

Now we do small calculation to compare F_{3dB} to the theoretical value.

-3dB = 0.6 (from datasheet)

we use the same formula for the inverting and non-inverting op-amp.

$$F_{3dB} = \frac{F_t}{1+\frac{R_2}{R_1}} \tag{24}$$

F_t we obtain it for datasheet F_t(unity gain frequency of the amplifier)

$$F_{3dB} = \frac{0.6M}{1+\frac{220K}{47.6K}} = 0.1MHz$$

They are close to each other.

7.1.5 OPA2134 Circuit Design

The circuit was simulated by LTspice. It is noninverting circuit using a OPA2134 operational amplifier with two resistors, the second resistor (R_f) is 220KΩ, since the amplification value is 20 dB, so the first resistor is 11 KΩ. Figure 18 shows the simulation and AC analysis.

The formula to convert decibels to voltage ratio is:

$$A_v = 10^{\frac{GdB}{20}} \quad = \quad A_v = 10^{\frac{20}{20}} \quad = \quad A_v = 10$$

For a noninverting op-amp circuit, the gain (A_v) is calculated using the formula:

$$A_v = 1 + \frac{R_2}{R_1}$$

Since A_v = 10 and Rf = 220KΩ so,

$$10 = 1 + \frac{220K\Omega}{R_1}$$

R_1 = 24.44kΩ

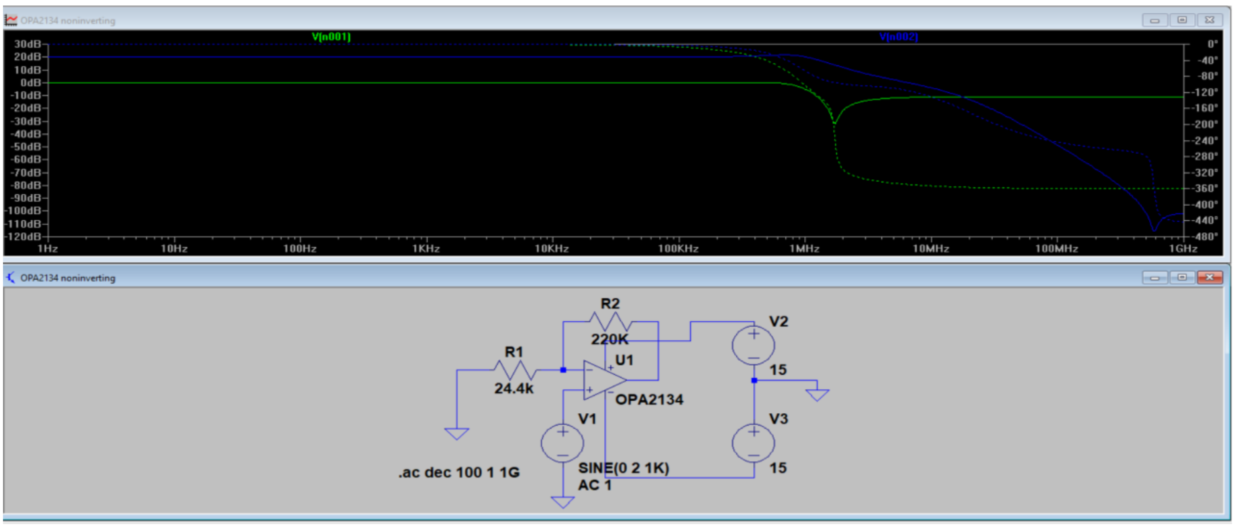

Figure 18. Simulation and AC analysis of non-inverting op-amp (OPA2134)

From the figure above we could see that our magnitude of the amplification is right and we can see the cutoff frequency.

From figure 18 we could do the calculation to compare the value we have with the theoretical value that we will get from the datasheet.

Mag = -3dB and F_{3dB} =9.17 MHz

Now we do small calculation to compare F_{3dB} to the theoretical value.

-3dB = 8 MHz (from datasheet)

we use the same formula for the inverting and non-inverting op-amp.

$$F_{3dB} = \frac{F_t}{1+\frac{R_2}{R_1}} \qquad (24)$$

F_t we obtain it for datasheet F_t(unity gain frequency of the amplifier)

$$F_{3dB} = \frac{8M}{1+\frac{220k}{24.4k}} = 0.7MHz$$

7.1.6 LMH6629 Circuit Design

The circuit was simulated by LTspice. It is noninverting circuit using a LMH6629 operational amplifier with two resistors, the second resistor (R_f) is 220KΩ, since the amplification value is 26 dB, so the first resistor is 11 KΩ. Figure 19 shows the simulation and AC analysis.

To formula to convert decibels to voltage ratio is:

$$A_v = 10^{\frac{GdB}{20}} \quad = \quad A_v = 10^{\frac{26}{20}} \quad = \quad A_v = 19.9$$

For a noninverting op-amp circuit, the gain (A_v) is calculated using the formula:

$$A_v = 1 + \frac{R_2}{R_1}$$

Since A_v = 19.9 and Rf = 220KΩ so,

$$19.9 = 1 + \frac{220K\Omega}{R_1}$$

R_1 = 11.6kΩ

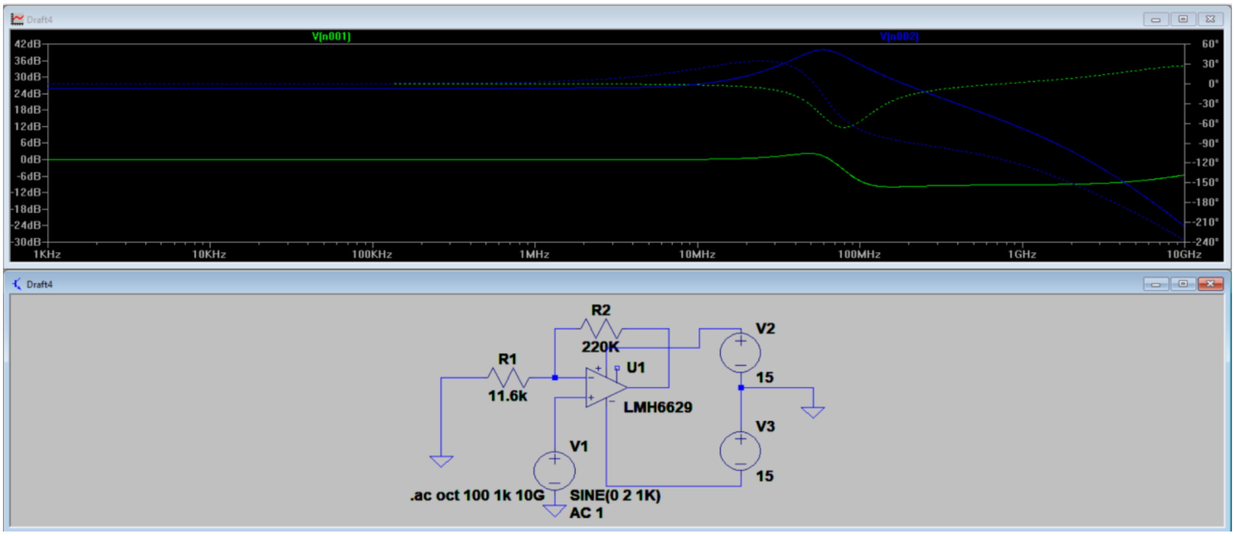

Figure 19 Simulation and AC analysis of non-inverting op-amp (LMH6629)

from the figure above we could see that our magnitude of the amplification is right and we can see the cutoff frequency.

From the above graph we could do the calculation to compare the value we have with the theoretical value that we will get from the datasheet.

Mag = -3dB and F_{3dB} =3.09 MHz

Now we do small calculation to compare F_{3dB} to the theoretical value.

F_t = 190 MHz (from datasheet)

we use the same formula for the inverting and non-inverting op-amp.

$$F_{3dB} = \frac{F_t}{1+\frac{R_2}{R_1}} \qquad (24)$$

F_t we obtain it for datasheet F_t (unity gain frequency of the amplifier)

$$F_{3dB} = \frac{190\ M}{1+\frac{220K}{11.6K}}$$

$$F_{3dB} = 9.5\ MHz$$

7.2 Schematic and PCB Design

7.2.1 LT1498/MAX40018 Schematic and PCB Design

The figure below shows the schematic of LT1498 designed by Altium design, the component that we used had two resistors, LT1498 op-amp, test points and two connectors for the voltage sources and the ground. op-amp pinout was obtained from op-amp datasheet. Figure 20 and 21 shows the schematic and PCB design.

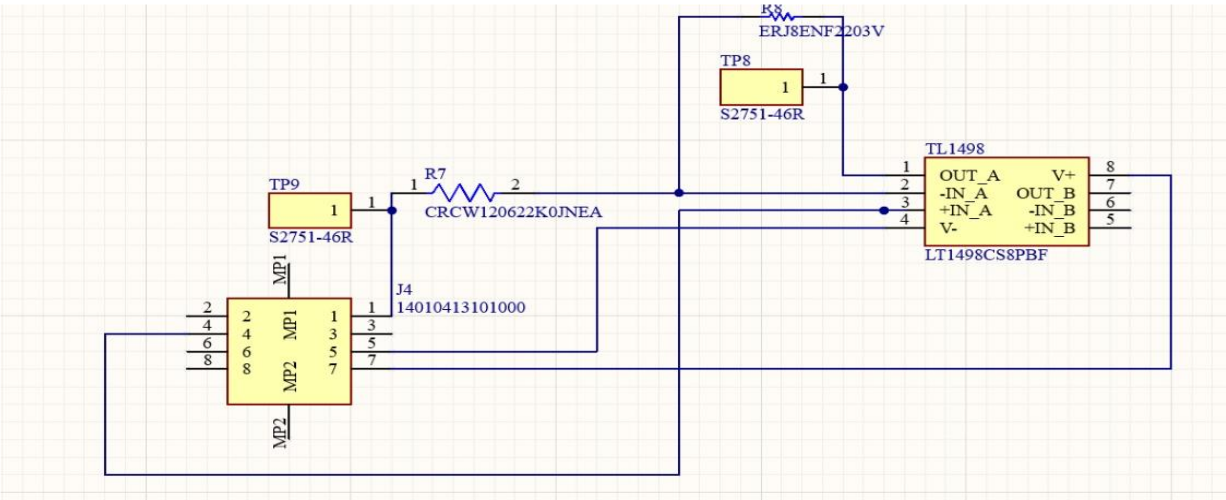

Figure 20. Schematic design

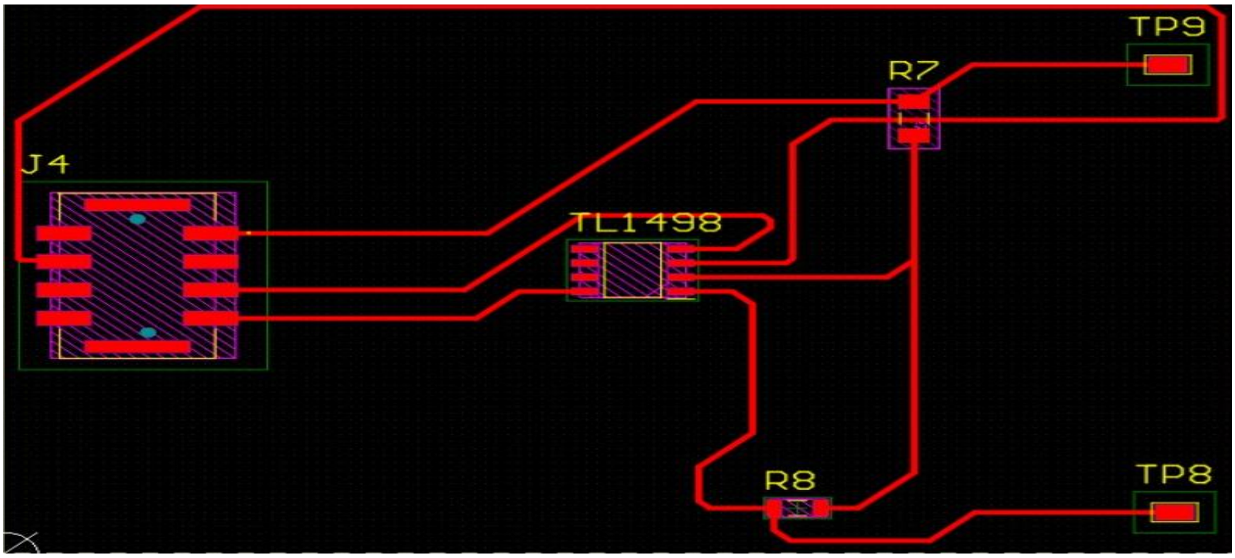

Figure 21. PCB design

7.2.2 LM358/MAX4238 schematic and PCB design

The figure below shows the schematic of LM358 designed by Altium design, the component that we used had two resistors, LM358 op-amp, test points and two connectors for the voltage sources and the ground. op-amp pinout was obtained from op-amp datasheet. Figure 22 and 23 shows the schematic and PCB design.

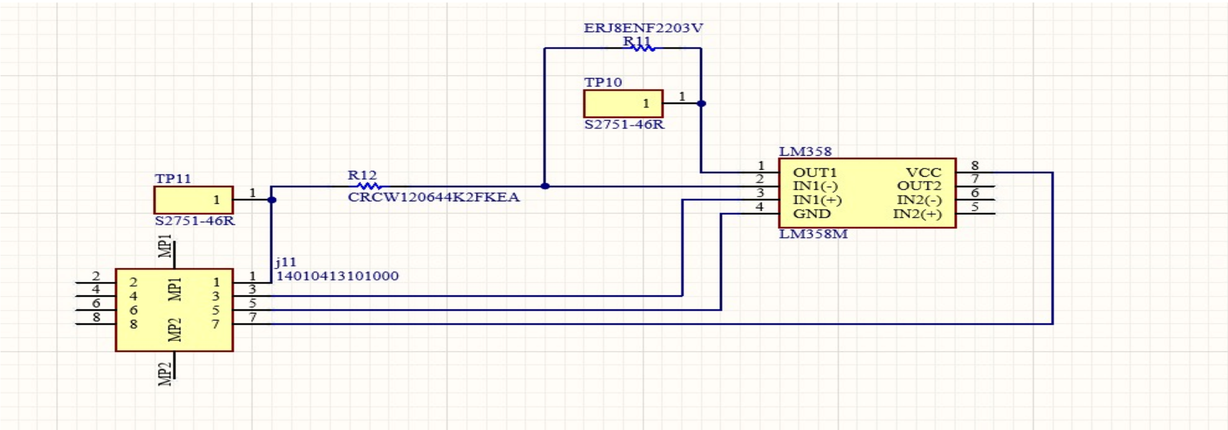

Figure 22. Schematic design

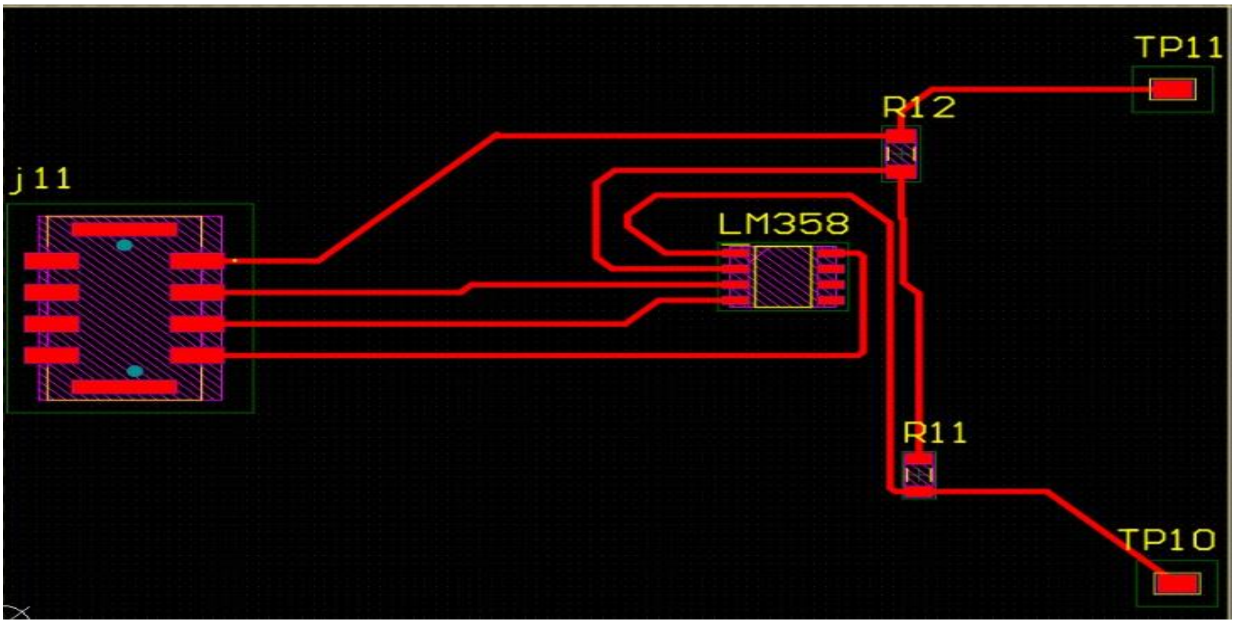

Figure 23. PCB design

7.2.3 LM324/AD8544 schematic and PCB design

The figure below shows the schematic of LM324 designed by Altium design, the component that we used had two resistors, LM324 op-amp, test points and two connectors for the voltage sources and the ground. op-amp pinout was obtained from op-amp datasheet. Figure 24 and 25 shows the schematic and PCB design.

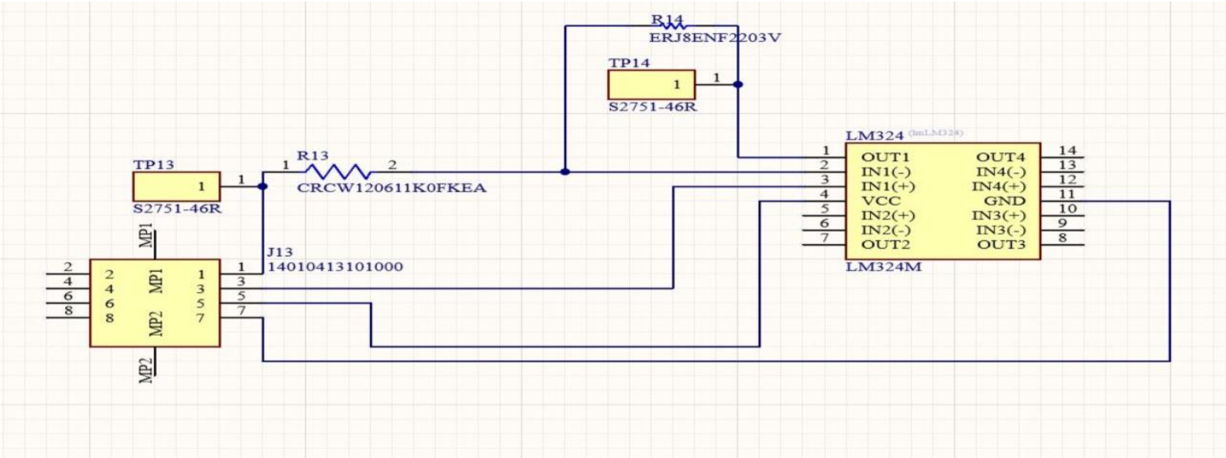

Figure 24. Schematic design

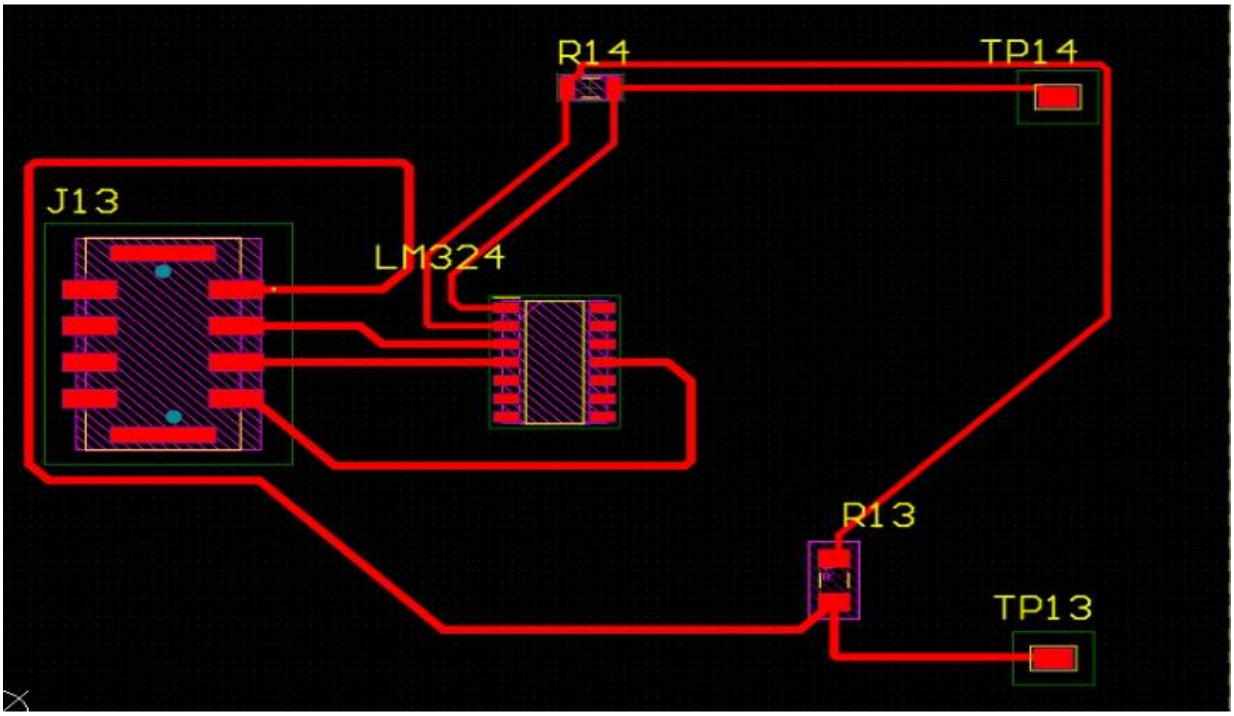

Figure 25. PCB design

7.2.4 OP07/MAX4236 schematic and PCB design

The figure below shows the schematic of OP07 designed by Altium design, the component that we used had two resistors, OP07 op-amp, test points and two connectors for the voltage sources and the ground. op-amp pinout was obtained from op-amp datasheet. Figure 26 and 27 shows the schematic and PCB design.

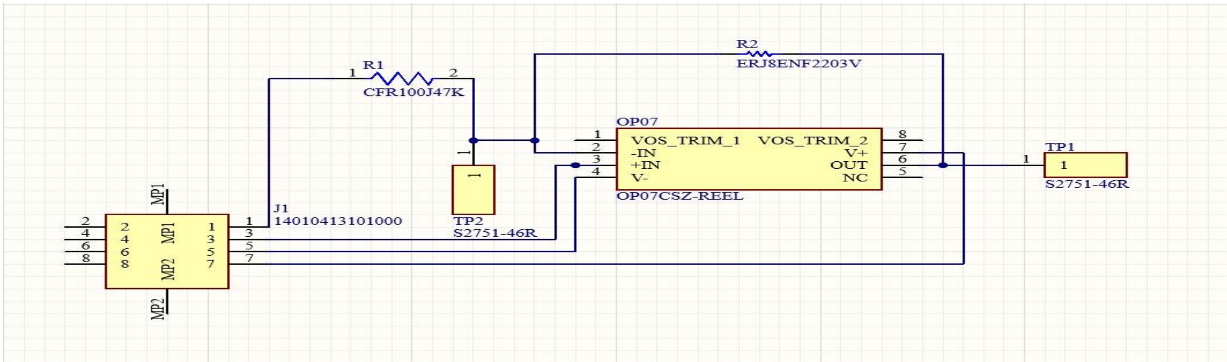

Figure 26. Schematic design

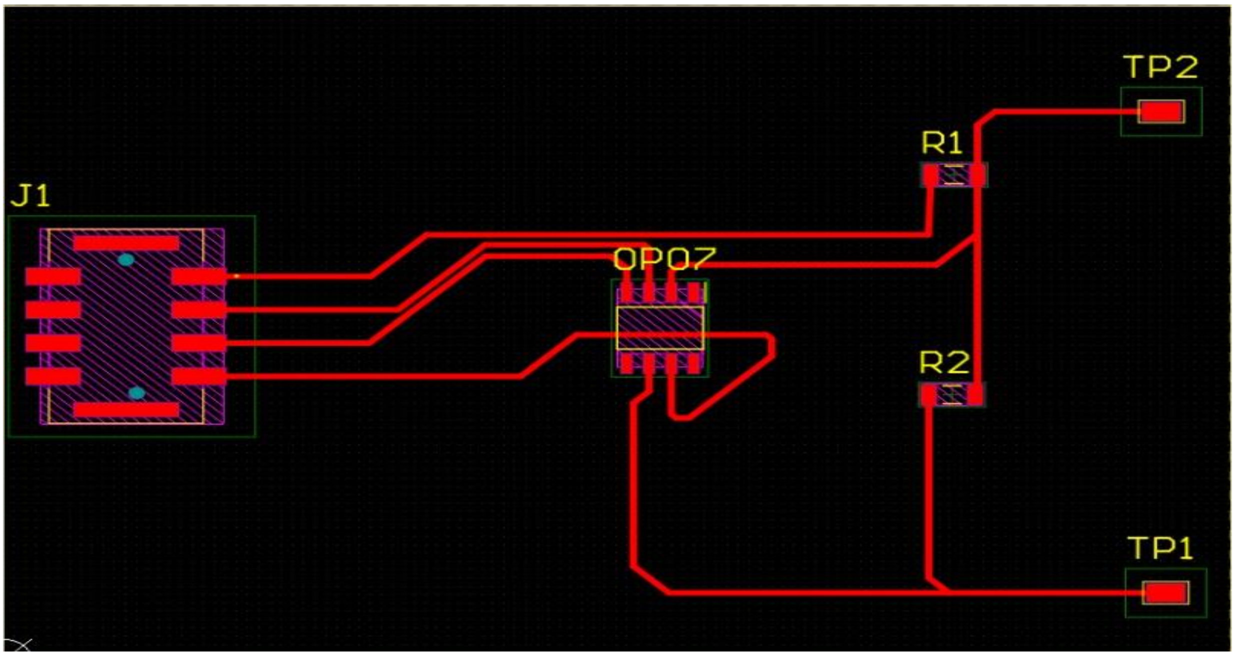

Figure 27. PCB design

7.2.5 OPA2134/AD8510 schematic and PCB design

The figure below shows the schematic of OPA2134 designed by Altium design, the component that we used had two resistors, OPA2134 op-amp, test points and two connectors for the voltage sources and the ground. op-amp pinout was obtained from op-amp datasheet. Figure 28 and 29 shows the schematic and PCB design.

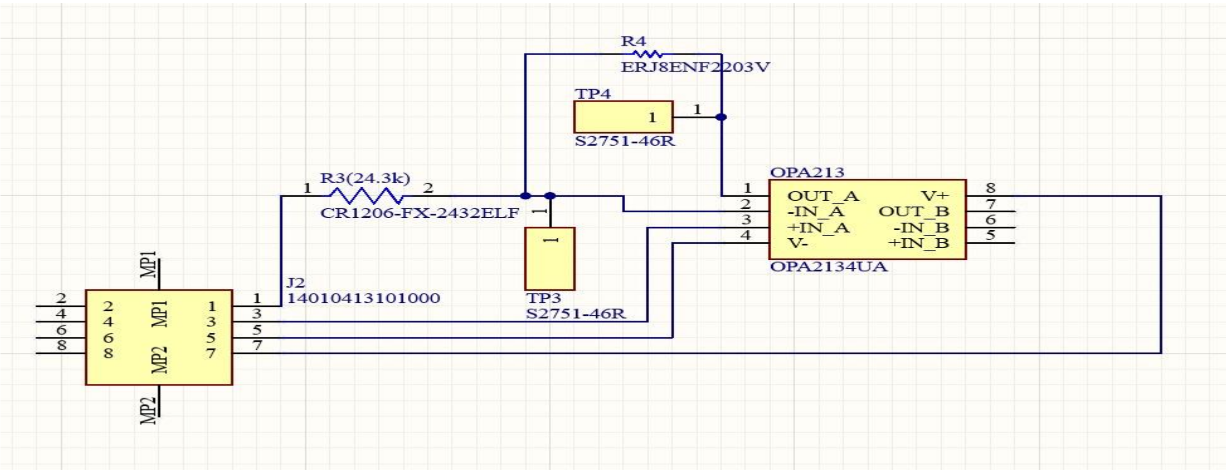

Figure 28. Schematic design

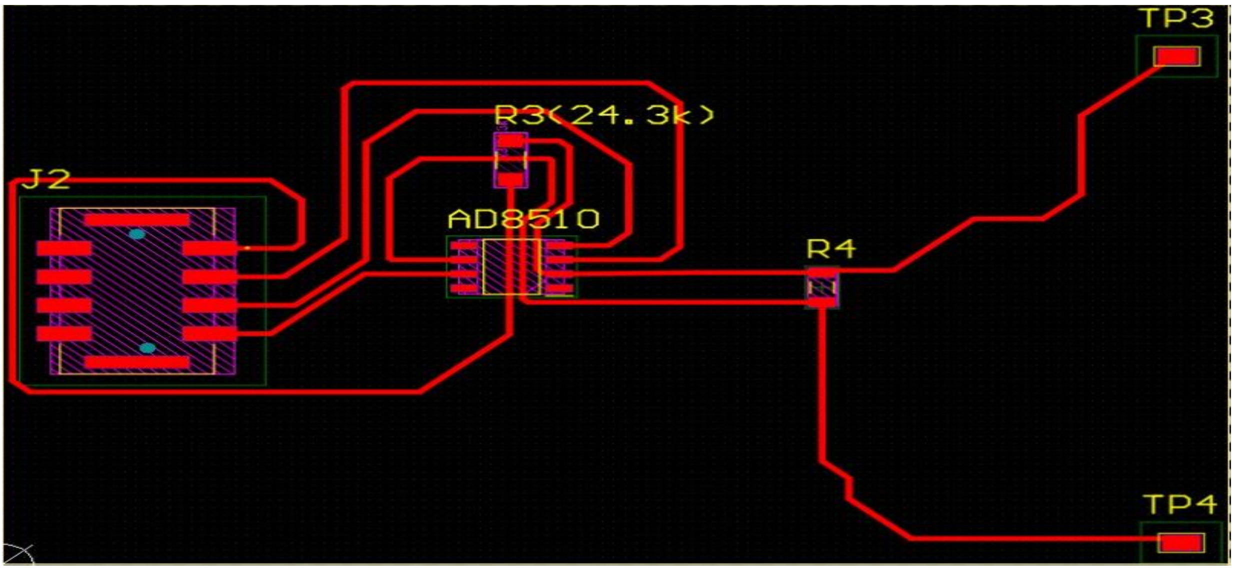

Figure 29. PCB design

7.2.6 LMH6629/MAX4305 schematic and PCB design

The figure below shows the schematic of LMH6629 designed by Altium design, the component that we used had two resistors, LMH6629 op-amp, test points and two connectors for the voltage sources and the ground. op-amp pinout was obtained from op-amp datasheet. Figure 30 and 31 shows the schematic and PCB design.

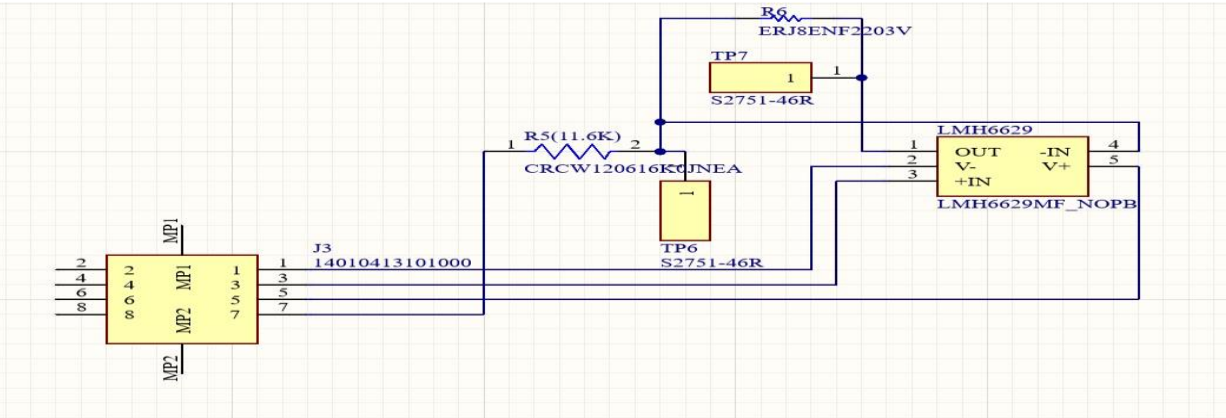

Figure 30. Schematic design

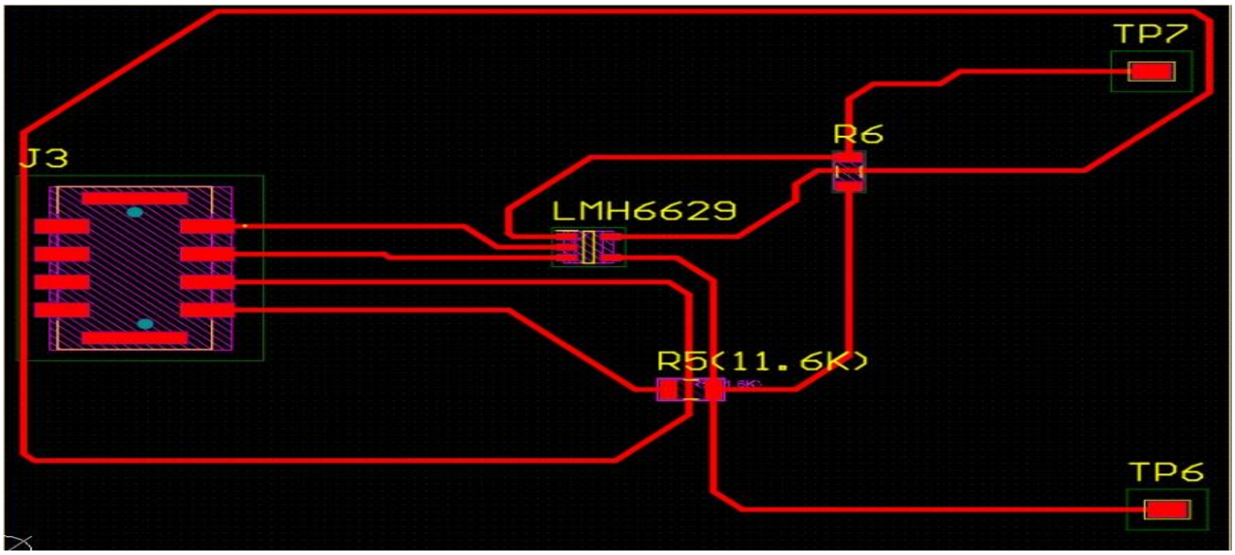

Figure 31. PCB design

7.3 Measurement

The PCB of the AD8510 amplifier was connected to power supply that provide ±15 V, function generator that providing sine wave with 2 Vpp and 0 offset voltage and oscilloscope to obtain the changes in both amplitude and phase in order to compare the results with the simulated AC analysis. Figure 32 shows the setup of the tested op-amp circuit.

Figure 32. The setup of the tested op-amp circuit

The power supply powers the circuit with ±15 V, the blue wire is -15v is connected to pin 4 of the op-amp, the red one +15v is connected to pin 8 of the op-amp and the ground was connected to pin 2 of op-amp through a resistor with 24.4 Kohm. From the function generator we provide the amplitude which was connected to pin 3 and has the value of 2 Vpp. From the oscilloscope we connect two channels for the input and output to the test points in the PCB.

The below figure illustrate the amplitude and the phase changes over the frequency range and from the result that we have obtained we can see it is similar to the simulation process of the OPA 2134 op-amp which has the closest key parameters.

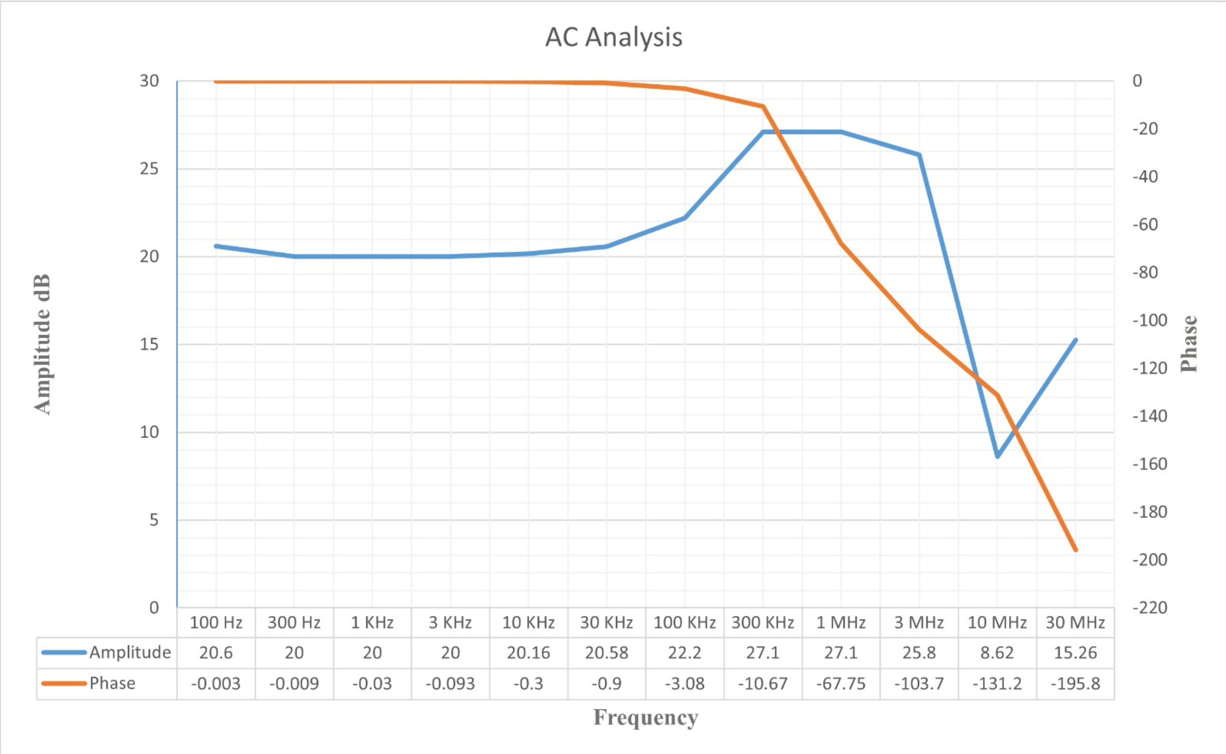

Figure 33. The practical AC analysis of AD 8501 op-amp

8 Conclusion

The thesis offers an analysis of operational amplifiers or op-amps. This is intended to give a good explanation of the basic theory used to design them and how they operate in real world applications. These are all areas that have been addressed by this study using theoretical approaches a LTspice simulations and Altium design.

The role of input offset voltage, bias current, slew rate, common mode rejection ratio (CMRR) and gain bandwidth product (GBP) as key parameters for explaining circuit performance has also been explored.

Examples of practical circuits presented in this study which use operational amplifier ICs like LT1498 and LM358 demonstrate how component values can be calculated in order to obtain desired gain settings on an inverting amplifier configuration. Validation through simulation gives an insight about their behavior as well as voltage gains and frequency responses.

The thesis is a useful source of information for electronics engineers who want to know more about operational amplifiers and their place in electronic circuitry. This study contributes to analog electronics development through linking theoretical concepts with practical realizations and creates basis for future research and experiments in op-amp-related circuitry.

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