PT. SOLUSI INTEK INDONESIA

OPERATIONAL AMPLIFIER

INTERMEDIATE ELECTRONICS TUTORIAL #02

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DEPARTMENT OF RESEARCH AND DEVELOPMENT

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CHAPTER 1

PHYSICS LAWS FOR ELECTRICITY

I. PHYSICS LAWS FOR ELECTRICITY

In electronics, several fundamental laws govern the behavior of electric circuits. These laws are essential for analyzing and designing circuits. Here, we'll discuss Ohm's Law, Kirchhoff's Laws, and a few other important principles.

I.1. Ohm's Law

Ohm's Law is one of the most fundamental principles in electronics. It relates the voltage (V), current (I), and resistance (R) in a circuit.

$$V = I \times R \tag{1. 1}$$

Where:

- V is the voltage across the resistor (in volts).
- I is the current flowing through the resistor (in amperes).
- R is the resistance (in ohms).

I.1.A. Applications Of Ohm's Law

- **Calculating Current**: If you know the voltage and resistance, you can find the current.

$$I = \frac{V}{R} \tag{1. 2}$$

- **Calculating Voltage**: If you know the current and resistance, you can find the voltage.

$$V = I \times R \tag{1. 3}$$

- **Calculating Resistance**: If you know the voltage and current, you can find the resistance.

$$R = \frac{V}{I} \tag{1. 4}$$

I.2. Kirchhoff's Laws

Kirchhoff's Laws are two principles that deal with the conservation of charge and energy in electrical circuits.

I.2.A. Kirchhoff's Current Law (Kcl)

KCL states that the total current entering a junction (or node) in a circuit equals the total current leaving the junction. This law is based on the principle of conservation of electric charge.

$$\sum I_{in} = \sum I_{out} \tag{1.5}$$

I.2.B. Kirchhoff's Voltage Law (Kvl)

KVL states that the sum of all electrical voltages around any closed loop in a circuit is equal to zero. This law is based on the principle of conservation of energy.

$$\sum V = 0 \tag{1.6}$$

I.2.C. Applications Of Kirchhoff's Laws

- **Analyzing Complex Circuits**: KCL and KVL are used to solve circuits with multiple loops and nodes.
- **Finding Unknown Values**: These laws help in finding unknown currents and voltages in a circuit.

I.3. Thevenin's And Norton's Theorems

These theorems simplify complex circuits to make analysis easier.

I.3.A. Thevenin's Theorem

Thevenin's Theorem states that any linear electrical network with voltage and current sources and resistances can be replaced by an equivalent circuit consisting of a single voltage source (Thevenin voltage, V_{th}) in series with a resistance (Thevenin resistance, R_{th}).

I.3.B. Norton's Theorem

Norton's Theorem states that any linear electrical network can be replaced by an equivalent circuit consisting of a single current source (Norton current, I_N) in parallel with a resistance (Norton resistance, R_N).

I.3.C. Conversion Between Thevenin And Norton

- **Resistance Conversion**

$$R_{th} = R_N \tag{1.7}$$

- **Voltage Conversion**

$$V_{th} = I_N \times R_N \tag{1.8}$$

- **Current Conversion**

$$I_N = \frac{V_{th}}{R_{th}} \tag{1.9}$$

I.3.D. Applications

- **Simplifying Analysis**: These theorems make it easier to analyze complex circuits by reducing them to simpler equivalent circuits.
- **Design and Testing**: Useful in designing and testing circuit components by focusing on essential characteristics.

I.4. Superposition Theorem

The Superposition Theorem states that in a linear circuit with multiple independent sources, the response (voltage or current) at any point in the circuit can be found by summing the responses caused by each independent source acting alone, with all other independent sources turned off (replaced by their internal impedances).

I.4.A. Applications

- **Analyzing Circuits with Multiple Sources**: This theorem is particularly useful for circuits with multiple voltage and current sources.
- **Simplifying Complex Calculations**: Allows for easier calculation of circuit behavior by considering one source at a time.

I.5. Maximum Power Transfer Theorem

The Maximum Power Transfer Theorem states that maximum power is delivered to a load when the load resistance (R_L) is equal to the Thevenin resistance (R_{th}) of the circuit supplying the power.

I.5.A. Application

- **Optimizing Power Delivery**: Used in designing power systems to ensure maximum efficiency.

I.6. Summary of Physics Laws for Electricity

Understanding these fundamental laws and theorems is crucial for anyone studying electronics. They provide the basis for analyzing, designing, and optimizing electrical circuits. Here is a quick recap:

1. **Ohm's Law**: Relates voltage, current, and resistance.
2. **Kirchhoff's Laws**: KCL (current conservation at nodes) and KVL (voltage conservation in loops).
3. **Thevenin's and Norton's Theorems**: Simplify complex circuits to single-source equivalents.
4. **Superposition Theorem**: Analyzes circuits with multiple sources by considering one source at a time.
5. **Maximum Power Transfer Theorem**: Ensures maximum power delivery to a load when load resistance equals source resistance.

CHAPTER 2

OP-AMP BASE PRINCIPLES

II. OP-AMP BASE PRINCIPLES

II.1. Overview

Operational amplifiers (op-amps) are fundamental building blocks in analog electronics. They are versatile components used in various applications, including signal amplification, filtering, and mathematical operations such as addition, subtraction, integration, and differentiation. This report provides an intermediate-level overview of op-amps, covering their basic operation, common configurations, differences between ideal and real op-amps, feedback and stability, and practical applications, with detailed examples for each.

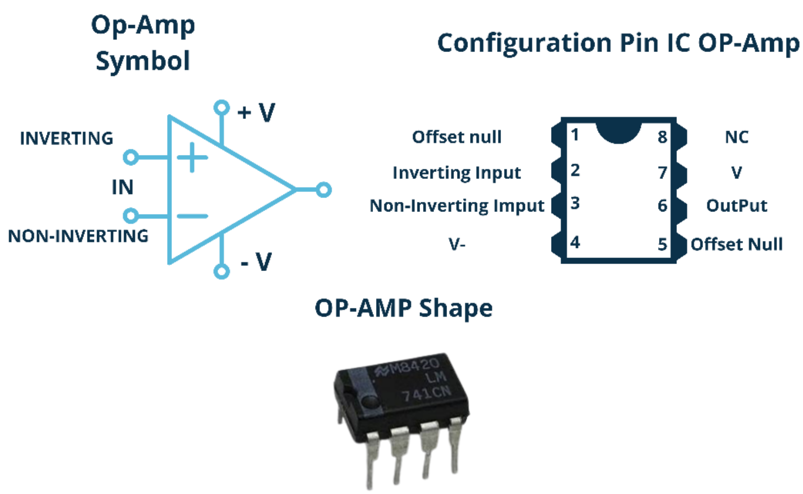

Figure 2. 1. OP-Amp

II.2. Basic Op-Amp Operation

An operational amplifier is a high-gain voltage amplifier with differential inputs and, usually, a single-ended output. The key characteristics of an ideal op-amp include:

- Infinite open-loop gain: The gain without feedback is infinite.
- Infinite input impedance: No current flows into the input terminals.
- Zero output impedance: The output can drive any load without impedance.
- Voltage Difference between Inputs is Zero: The inverting input follows non-inverting input voltage.
- Infinite bandwidth: The op-amp can amplify any frequency signal.
- Zero offset voltage: The output is zero when the input is zero.

A typical op-amp has five main pins:

- Non-inverting input (+): The input voltage applied here is amplified without phase inversion.
- Inverting input (−): The input voltage applied here is amplified with a 180-degree phase inversion.
- Output: The amplified signal is output here.
- Positive power supply (Vcc): The positive voltage supply.
- Negative power supply (Vee or ground): The negative voltage supply or ground.

II.3. Ideal vs. Real Op-Amps

Ideal op-amps have the following characteristics:

- Infinite gain
- Infinite input impedance
- Zero output impedance
- Infinite bandwidth
- Zero offset voltage

Real op-amps have limitations:

- Finite gain: The gain is very high but not infinite.
- Finite input impedance: High, but not infinite, leading to a small input current.
- Non-zero output impedance: Low, but not zero.
- Limited bandwidth: Gain decreases with frequency.
- Offset voltage: Small voltage difference between inputs even when inputs are zero.

II.4. Feedback and Stability

Feedback is used to control the gain and behavior of an op-amp circuit. Negative feedback stabilizes the gain, improves bandwidth, and reduces distortion. Positive feedback can lead to oscillation.

Stability is crucial in op-amp circuits to prevent oscillations and ensure reliable operation. Proper feedback network design and compensation techniques are used to maintain stability.

Example: A simple RC network can be used for frequency compensation to ensure stability in a high-gain op-amp circuit.

CHAPTER 3

OP-AMP APPLICATIONS

III. OP-AMP CONFIGURATION AND APPLICATIONS

III.1. Open-loop Amplifier as Comparator

An open-loop amplifier can be used as a comparator. In this configuration, the operational amplifier (op-amp) operates without any feedback, meaning it functions in open-loop mode. The op-amp compares two input voltages and outputs a high or low signal depending on which input is greater. This is useful in digital circuits for converting analog signals to digital ones.

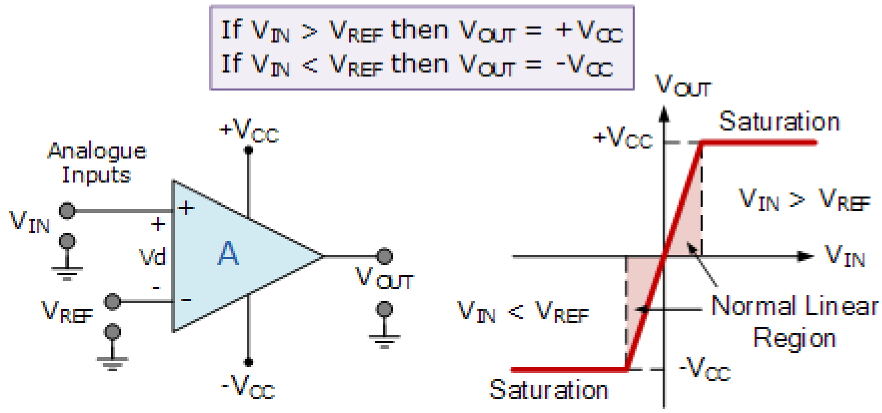

Figure 3. 1. Op-Amp Comparator Circuit

III.1.A. Working Principle

In an open-loop configuration, the op-amp has a very high gain, typically in the range of 10^5 to 10^6. Because of this high gain, even a tiny difference between the input voltages can drive the output to the maximum positive or negative voltage, which corresponds to the supply voltage.

III.1.A.i. Example: Non-inverting Comparator

Non-inverting Comparator: The input signal is applied to the non-inverting input $+$, and a reference voltage V_{ref} is applied to the inverting input $-$. When the input signal V_{in} exceeds V_{ref}, the output of the op-amp swings to the positive supply voltage. When V_{in} is less than V_{ref}, the output swings to the negative supply voltage.

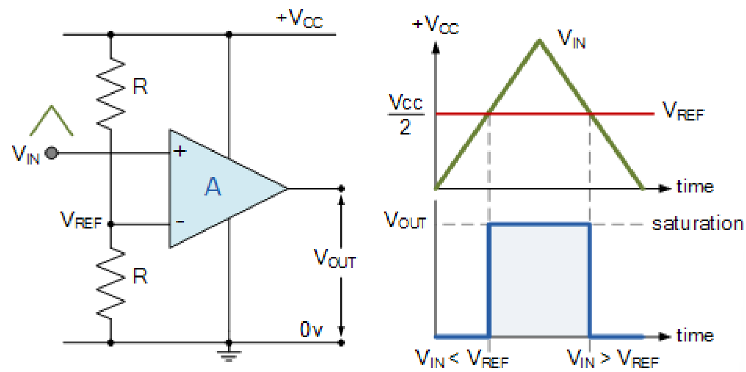

Figure 3. 2. Non-Inverting Comparator Circuit

Consider a non-inverting comparator where $V_{ref} = 2.5V$ and the supply voltages are $\pm 15V$.

- **Reference Voltage V_{ref}** : $2.5V$
- **Input Voltage V_{in}**: Variable

Operation:

- When $V_{in} > 2.5\ V$, the output V_{out} will be $+15\ V$.
- When $V_{in} < 2.5\ V$, the output V_{out} will be $-15\ V$.

III.1.A.ii. Example: Inverting Comparator

Inverting Comparator: The input signal is applied to the inverting input $-$, and the reference voltage V_ref is applied to the non-inverting input $+$. The output behavior is opposite to that of the non-inverting comparator. When V_{in} exceeds V_{ref}, the output swings to the negative supply voltage. When V_{in} is less than V_{ref}, the output swings to the positive supply voltage.

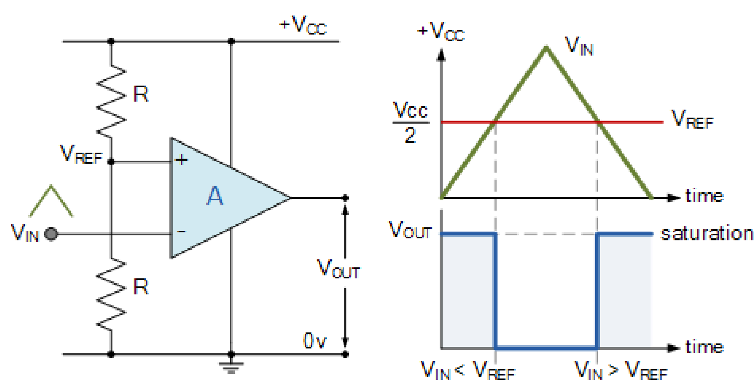

Figure 3. 3. Inverting Comparator Circuit

Consider an inverting comparator where V_{ref} and the supply voltages are $\pm 15\ V$.

- **Reference Voltage $\boldsymbol{V_{ref}}$** : $2.5V$
- **Input Voltage $\boldsymbol{V_{in}}$** : Variable

Operation:

- When $V_{in} > 2.5\ V$, the output V_{out} will be $-15\ V$.
- When $V_{in} < 2.5\ V$, the output V_{out} will be $+15\ V$.

III.1.A.iii. Practical Considerations

- **Hysteresis**: To prevent noise from causing rapid switching near the threshold, hysteresis can be added to a comparator. This involves adding a small amount of positive feedback.
- **Speed**: The speed of the comparator can be limited by the slew rate and bandwidth of the op-amp.
- **Power Supply**: Ensure that the power supply voltages are appropriate for the desired output levels.

III.1.B. Application of Comparator

III.1.B.i. Logical Detector

A comparator can be used as a logical detector to convert analog signals into digital logic levels. This involves using the comparator to compare an input signal with a reference voltage and output a high or low voltage level based on the comparison. The output can then be used in digital circuits for further processing.

A logical detector uses a comparator to determine if an input signal exceeds or falls below a certain threshold (reference voltage). The comparator's high gain ensures that the output switches sharply between high and low states, making it suitable for generating digital logic signals.

III.1.B.ii. Zero-crossing Detector

A zero-crossing detector is a specific application of a comparator that detects when an input signal crosses the zero-voltage level. This is useful in various applications, such as phase-locked loops, frequency counters, and waveform generation. The zero-crossing detector outputs a digital signal indicating when the input signal transitions from positive to negative or vice versa.

The zero-crossing detector uses a comparator with its reference voltage V_{ref} set to $0V$. The input signal V_{in} is applied to one of the comparator's inputs, and the comparator switches its output state whenever the input signal crosses zero volts.

III.1.B.ii.1. Zero-Crossing Detector Operation

- **Non-inverting Zero-Crossing Detector**: The input signal is applied to the non-inverting input $+$, and the inverting input $-$ is connected to $0V$ (ground). When V_{in} is greater than $0V$, the output of the comparator goes high. When V_{in} is less than $0V$, the output goes low.
- **Inverting Zero-Crossing Detector**: The input signal is applied to the inverting input $-$, and the non-inverting input $+$ is connected to $0V$ (ground). The output behavior is opposite to that of the non-inverting zero-crossing detector. When V_{in} is greater than 0V, the output goes low. When V_{in} is less than $0V$, the output goes high.

III.1.B.ii.2. Implementation

- **Phase-Locked Loops (PLLs)**: Zero-crossing detectors are used in PLLs to synchronize the phase of an oscillator with an input signal.
- **Frequency Counters**: Detecting zero crossings allows accurate measurement of the frequency of AC signals.
- **Waveform Generation**: Zero-crossing detectors can be used to generate square waves from sinusoidal inputs.
- **Overcurrent Protection**: In power electronics, zero-crossing detectors can be used to identify current spikes and trigger protective measures.

III.2. Amplifier

III.2.A. Inverting Amplifier

In this configuration, the input signal is applied to the inverting input, and the non-inverting input is grounded. The output voltage is inverted and proportional to the input voltage, scaled by the ratio of the feedback resistor to the input resistor.

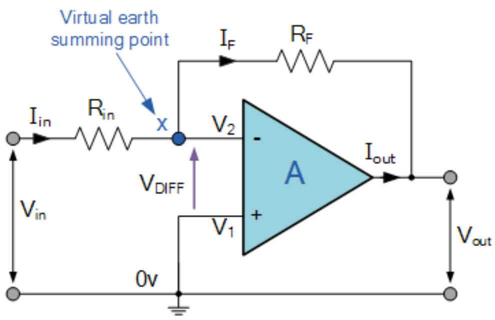

Figure 3. 4. Inverting Amplifier Circuit

Example:

- Input Voltage (V_{in}): $1V$
- Feedback Resistor (R_f): $10k\Omega$
- Input Resistor (R_{in}): $1k\Omega$

The gain (A) of an inverting amplifier is given by:

$$Gain\ (A) = -\frac{R_f}{R_{in}} \quad \text{Equation 3. 1}$$

$$A = -\frac{10k\Omega}{1k\Omega} = -10$$

The output voltage (V_{out}) is:

$$V_{out} \; = \; A \cdot V_{in} \quad \text{Equation 3. 2}$$

$$V_{out} = -10 \cdot 1V = -10V$$

III.2.B. Non-Inverting Amplifier

Here, the input signal is applied to the non-inverting input. The output voltage is in phase with the input and is proportional to the input voltage, scaled by the feedback network.

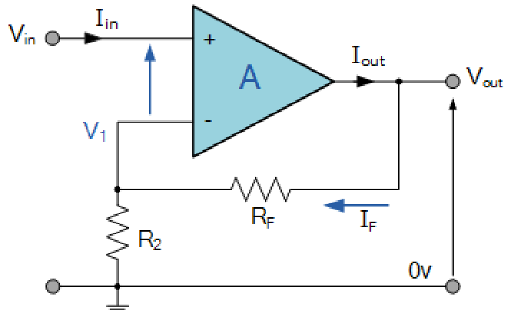

Figure 3. 5. Non – Inverting Amplifier Circuit

Example:

- Input Voltage (V_{in}): $1V$
- Feedback Resistor (R_f): $10k\Omega$
- Ground Resistor (R_1): $1k\Omega$

The gain (A) of a non-inverting amplifier is given by:

$$Gain\ (A) = 1 + \frac{R_f}{R_1}$$ *Equation 3. 3*

$$A = 1 + \frac{10k\Omega}{1k\Omega} = 11A$$

The output voltage (V_{out}) is:

$$V_{out} = A \cdot Vin$$ *Equation 3. 4*

$$V_{out} = 11 \cdot 1V = 11V$$

III.2.C. Differential Amplifier

This configuration amplifies the difference between two input signals. It is useful in applications where the signal of interest is the difference between two voltages.

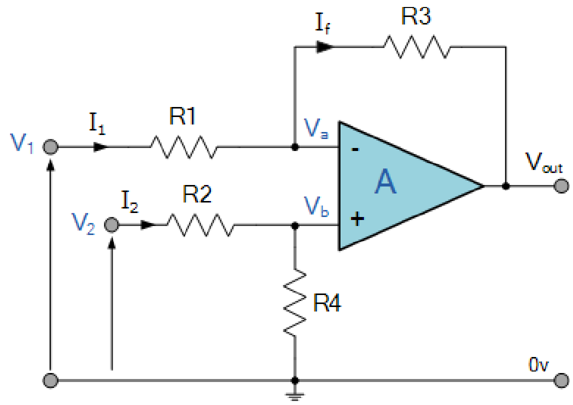

Figure 3. 6. Differential Amplifier Circuit

Example:

- Input Voltages (V_1, V_2): $1V$ and $0.5V$
- Resistors (R_f, R_1): All $10k\Omega$

The output voltage (V_{out}) is given by:

$$Vout = \frac{R_f}{R_1} \cdot (V2 - V1)$$ *Equation 3. 5*

$$Vout = \frac{10k\Omega}{10k\Omega} \cdot (1V - 0.5V) = 0.5V$$

III.2.D. Summing Amplifier

Overview

A summing amplifier is an operational amplifier (op-amp) configuration used to combine several input signals into a single output signal. This configuration is often used in audio mixers, digital-to-analog converters, and other applications requiring the addition of multiple signals.

Basic Concept

A summing amplifier takes multiple input voltages and sums them, providing a single output voltage that is a weighted sum of the input voltages. This is achieved using the inverting input of the op-amp, where the input resistors determine the weight of each input voltage.

Circuit Diagram

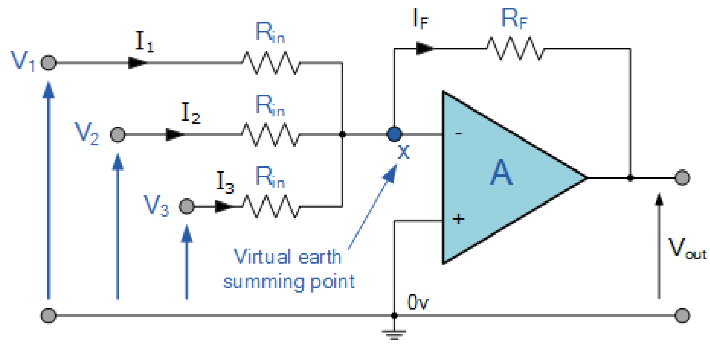

Figure 3. 7. Summing Amplifier Circuit

Components:

- Op-amp (e.g., 741 or LM324)
- Resistors $R1, R2, \dots, Rn$ (input resistors)
- Feedback resistor R_f
- Input voltages $V_1, V_2, \dots, V_n$

Practical Applications

- **Audio Mixing:** In audio applications, a summing amplifier can combine signals from different audio sources into a single output, allowing for mixing of multiple audio tracks.
- **Digital-to-Analog Conversion:** In DACs, summing amplifiers combine the weighted voltages corresponding to binary inputs to produce an analog output.

Summing Amplifier Equation

$$-V_{out} = (\frac{R_f}{R_{in1}} V_1 + \frac{R_f}{R_{in2}} V_2 + \frac{R_f}{R_{in3}} V_3 \dots \dots etc) \quad \text{Equation 3. 6}$$

Gain (A)

$$Gain\ (A) = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}} \quad \text{Equation 3. 7}$$

Example

- Input Voltages ($V_{in1} = 1\,V, V_{in2} = 2\,V, V_{in3} = 3V$)
- Resitors ($R_1 = R_2 = R_3 = 10\ k\Omega$; $\mathrm{R_f} = 20\ k\Omega$

The output voltage (V_{out}) given by :

$$V_{out} = -\left(\frac{20k\Omega}{10k\Omega} \cdot 1\,V + \frac{20k\Omega}{10k\Omega} \cdot 2\,V + \frac{20k\Omega}{10k\Omega} \cdot 3\,V\right) = -12\,V$$

III.2.E. Instrumentation Amplifier

Overview

An instrumentation amplifier is a type of differential amplifier with high input impedance and high common-mode rejection ratio (CMRR). It is commonly used in applications that require precise and accurate measurement of small differential signals in the presence of large common-mode voltages, such as in medical instrumentation, strain gauge transducers, and data acquisition systems.

Basic Concept

An instrumentation amplifier amplifies the difference between two input signals while rejecting any signals that are common to both inputs. This is achieved using a combination of op-amps and resistors configured to provide high input impedance and accurate gain control.

Circuit Diagram

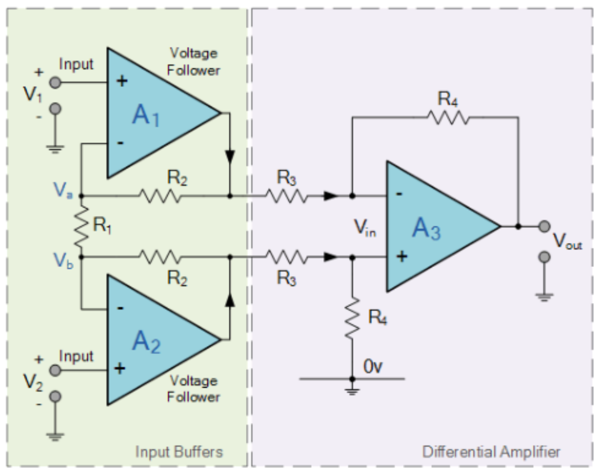

Figure 3. 8. Instrumentation Amplifier Circuit

Gain formula

$$Gain\ (A) = \frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2} \quad \text{Equation 3. 8}$$

Instrumentation Amplifier Equation

$$V_{out} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2}(V_2 - V_1) \quad \text{Equation 3. 9}$$

Example

Given:

- $R1 = 10k\Omega$
- $Rgain = 5k\Omega$
- $R2 = 10k\Omega$
- $R3 = 10k\Omega$
- $V1 = 1V$
- $V2 = 3V$

Steps:

Calculate the Gain Factor:

$$G_1 = 1 + \frac{2R_1}{R_{gain}} = 1 + 2 \times \frac{10k\Omega}{5k\Omega} = 1 + 4 = 5$$

Calculate the Output Voltage:

$$V_{out} = G_1 \times \frac{R_3}{R_2} \times (V_2 - V_1)$$

$$V_{out} = 5 \times \frac{10k\Omega}{10k\Omega} \times (3\,V - 1\,V)$$

$$V_{out} = 5 \times 1 \times (2\,V) = 10\,V$$

III.3. Mathematical Operations

III.3.A. Adder

An adder (summing amplifier) sums multiple input voltages into a single output voltage. The output voltage is a weighted sum of the input voltages.

Example :

For an adder with

$$V_1 = 1V\,, V_2 = 2V, R_1 = R_2 = 10k\Omega, and\ R_f = 10k\Omega:$$

$$V_{out} = -\frac{10k\Omega}{10k\Omega} \cdot 1\,V + \frac{10k\Omega}{10k\Omega} \cdot 2\,V$$

$$V_{out} = -(1\,V + 2\,V) = -3\,V$$

III.3.B. Substractor

A subtractor (differential amplifier) subtracts one input voltage from another, providing the difference as the output voltage.

Example :

For a subtractor with equal resitors

$$V_1 = 2\,V \; and \; V_2 = 5\,V$$

$$R_1 = R_2 = 10k\Omega \; and \; R_3 = R_4 = 10k\Omega$$

$$V_{out} = \frac{R_3}{R_1}(V_2 - V_1)$$

$$V_{out} = \frac{10k\Omega}{10k\Omega}(5\,V - 2\,V) = 3\,V$$

III.3.C. Integrator

An integrator circuit produces an output that is proportional to the integral of the input signal over time. It is used in signal processing applications.

Example:

- Input Voltage (V_{in}): Square wave
- Feedback Capacitor (C_f): $1\mu F$
- Input Resistor (R_{in}): $10k\Omega$

The output voltage (V_{out}) is:

$$V_{out}(t) = -\frac{1}{R_{in} \cdot C_f} \int V_{in}(t)\,dt$$

$$V_{out}(t) = -\frac{1}{10k\Omega \cdot 1\mu F} \int V_{in}(t)\,dt$$

For a square wave input, the output will be a triangular wave.

III.3.D. Differentiator

A differentiator circuit produces an output that is proportional to the rate of change (derivative) of the input signal. It is useful for detecting changes in signals.

Example:

- Input Voltage (V_{in}): Triangular wave
- Input Capacitor (C_{in}): 1µF
- Feedback Resistor (R_f): $10k\Omega$

The output voltage (V_{out}) is:

$$V_{out}(t) = -R_f \cdot C_{in} \cdot \frac{d}{dt} V_{in}(t)$$

For a triangular wave input, the output will be a square wave.

III.4. Active Filters

Op-amps are used in active filter circuits to process signals and remove unwanted frequencies (low-pass, high-pass, band-pass, and band-stop filters).

Example: An op-amp-based low-pass filter can remove high-frequency noise from a sensor signal.

III.4.A. Low Pass Filter

A low-pass filter allows signals with a frequency lower than a certain cutoff frequency to pass through and attenuates signals with frequencies higher than the cutoff frequency.

Circuit Diagram

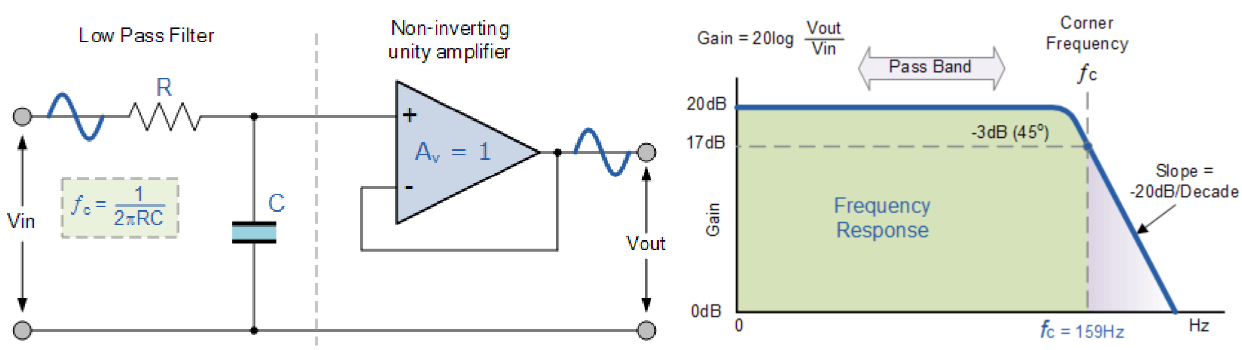

Figure 3. 9. Active Low Pass Filter Circuit and Frequency Response Curve

Components:

- Op-amp
- Resistor RRR
- Capacitor CCC

Formula

The cutoff frequency (f_c) for a low-pass filter is given by:

$$f_c = \frac{1}{2\pi \cdot RC} \quad \text{Equation 3. 10}$$

Example

For a low-pass filter with

$$R = 10k\Omega \; and \; C = 0.01\mu F$$

$$f_c = \frac{1}{2\pi \cdot 10k\Omega \cdot 0.01\mu F}$$

$$f_c = \frac{1}{2\pi \cdot 10 \cdot 10^3 \cdot 0.01 \cdot 10^{-6}}$$

$$f_c \approx 1.59kHz$$

III.4.B. High Pass Filter

A high-pass filter allows signals with a frequency higher than a certain cutoff frequency to pass through and attenuates signals with frequencies lower than the cutoff frequency.

Circuit Diagram

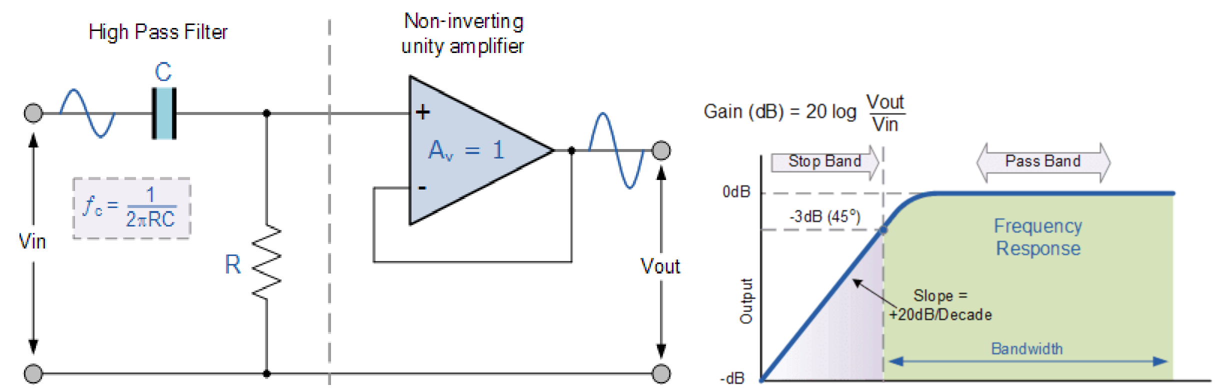

Figure 3. 10. Active High Pass Filter Circuit and Frequency Response Curve

Components:

- Op-amp
- Resistor RRR
- Capacitor CCC

Formula

The cutoff frequency (f_c) for a high-pass filter is given by:

$$f_c = \frac{1}{2\pi \cdot RC}$$ *Equation 3. 11*

Example Calculation

For a high-pass filter with

$$R = 10k\Omega \ and \ C = 0.01\mu F$$

$$f_c = \frac{1}{2\pi \cdot 10k\Omega \cdot 0.01\mu F}$$

$$f_c = \frac{1}{2\pi \cdot 10 \cdot 10^3 \cdot 0.01 \cdot 10^{-6}}$$

$$f_c \approx 1.59kHz$$

III.4.C. Band Pass Filter

A band-pass filter allows signals within a certain frequency range (band) to pass through and attenuates signals outside this range.

Circuit Diagram

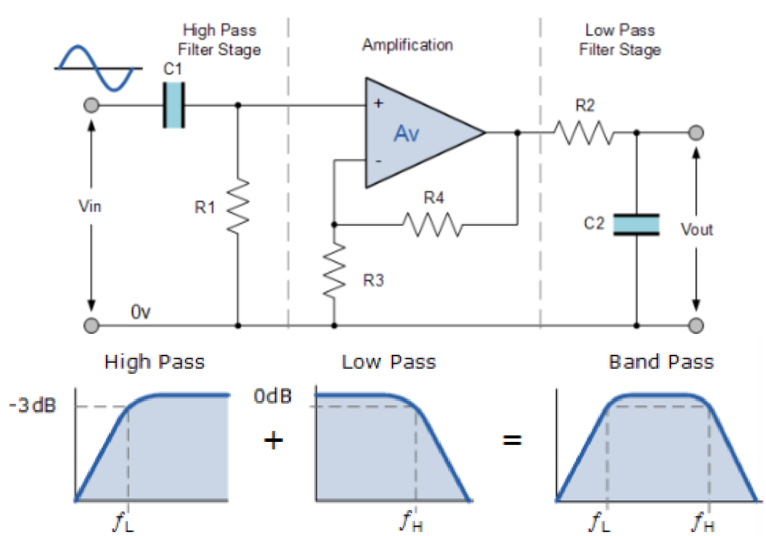

Figure 3. 11. Active Band Pass Filter and the differences between High pass filter, Low pass filter and Band pass filter

Components:

- Op-amp
- Resistors R_1, R_2
- Capacitors C_1, C_2

Formula

The center frequency (f_0) and bandwidth (BW) for a band-pass filter are given by:

$$f_0 = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$ *Equation 3. 12*

$$BW = \frac{1}{2\pi\ R_1\ C_1} + \frac{1}{2\pi\ R_2\ C_2}$$ *Equation 3. 13*

Example Calculation

For a band-pass filter with

$$R_1 = R_2 = 10k\Omega, C1 = C2 = 0.01\mu F$$

$$f_0 = \frac{1}{2\pi\sqrt{10k\Omega \cdot\ 10k\Omega \cdot\ 0.01\mu\ F \cdot\ 0.01\mu\ F}}$$

$$f_0 = \frac{1}{2\pi\sqrt{10 \times\ 10^3 \cdot\ 10 \times\ 10^3 \cdot\ 0.01 \times\ 10^{-6} \cdot\ 0.01 \times\ 10^{-6}}}$$

$$f_0 \approx 1.59kHz$$

III.4.D. Band Rejected

A band-stop filter attenuates signals within a certain frequency range (notch) and allows signals outside this range to pass through.

Circuit Diagram

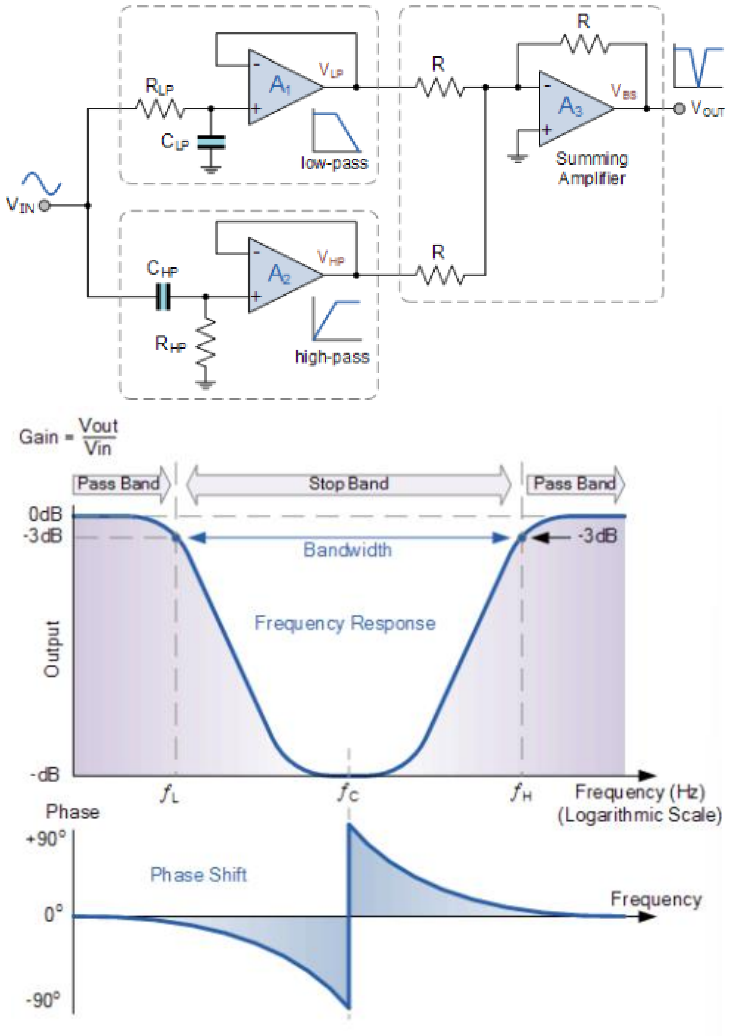

Figure 3. 12. Active Band Rejected Filtrer Circuit and Frequency Reponse Curve

Components:

- Op-amp
- Resistors R_1, R_2
- Capacitors C_1, C_2

Formula

The center frequency (f_0) and bandwidth (BW) for a band-stop filter are given by:

$$f_0 = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} \quad \textit{Equation 3. 14}$$

$$BW = \frac{1}{2\pi R_1 C_1} + \frac{1}{2\pi R_2 C_2} \quad \textit{Equation 3. 15}$$

Example Calculation

For a band-stop filter with

$$R1 = R2 = 10k\Omega, C1 = C2 = 0.01\mu F:$$

$$f_0 = \frac{1}{2\pi\sqrt{10k\Omega \cdot 10k\Omega \cdot 0.01\mu F \cdot 0.01\mu F}}$$

$$f_0 = \frac{1}{2\pi\sqrt{10 \times 10^3 \cdot 10 \times 10^3 \cdot 0.01 \times 10^{-6} \cdot 0.01 \times 10^{-6}}}$$

$$f_0 \approx 1.59kHz$$

III.5. Oscillators

Operational amplifiers (op-amps) are widely used in the design of oscillators, which are circuits that generate periodic waveforms without an external input signal. Oscillators are essential in many applications, including signal generation, clock generation, and waveform synthesis.

III.5.A. Principles of Oscillation

An oscillator circuit typically consists of an amplifier and a feedback network. The basic principles required for sustained oscillations are:

- **Barkhausen Criterion**: For sustained oscillations, the loop gain of the circuit (product of amplifier gain and feedback network gain) must be equal to one, and the phase shift around the loop must be zero or a multiple of 360 degrees.

  For sustained oscillations, the circuit must satisfy the Barkhausen criterion:

  1. The loop gain (product of amplifier gain A and feedback factor β) must be equal to one: $A\beta = 1A$
  2. The phase shift around the loop must be zero or an integer multiple of 2π.

III.5.B. Types of Oscillators

III.5.B.i. RC Phase-Shift Oscillator

The RC phase-shift oscillator uses a combination of resistors and capacitors to produce a phase shift. The op-amp amplifies the signal, and the feedback network shifts the phase, creating a positive feedback loop.

Circuit Diagram

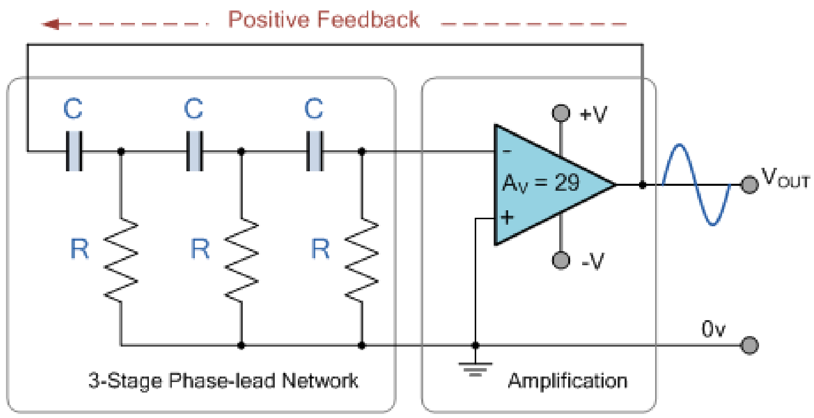

Figure 3. 13. Op – Amp Phase-lead RC Oscillator Circuit

Operation

- The feedback network consists of three RC stages, each providing a 60-degree phase shift, resulting in a total of 180 degrees.
- The inverting amplifier stage provides an additional 180-degree phase shift, achieving the required 360-degree total phase shift.

Example Calculation

For a given RC combination, the oscillation frequency f is:

$$f = \frac{1}{2\pi\sqrt{6}RC}$$ *Equation 3. 16*

Component Values

- $R = 10k\Omega$
- $C = 0.01\mu F$

$$f = \frac{1}{2\pi\sqrt{6 \times 10\ k\Omega \times 0.01\ \mu\ F}} \approx 1.3\ kHz$$

III.5.B.ii. Wien Bridge Oscillator

The Wien bridge oscillator uses a Wien bridge network in the feedback loop. It is known for producing low-distortion sine waves and is widely used in audio frequency generation.

Circuit Diagram

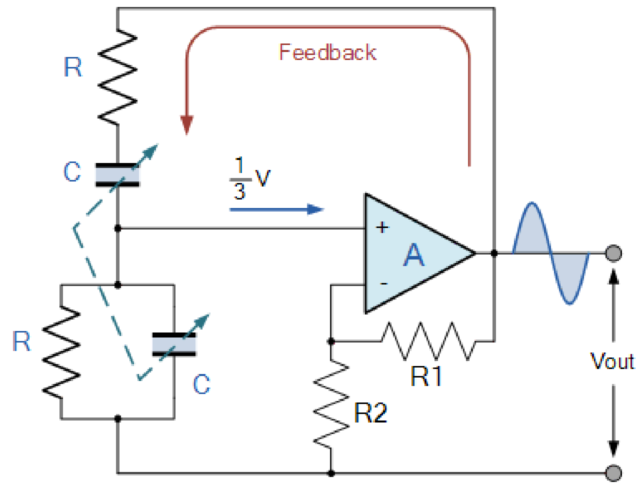

Figure 3. 14. Wein Bridge Oscillator

Operation

- The Wien bridge network consists of two resistors and two capacitors, forming a lead-lag frequency-selective network.
- The frequency of oscillation is determined by the values of these resistors and capacitors.

Example Calculation The oscillation frequency f is given by:

$$f = \frac{1}{2\pi RC}$$ *Equation 3. 17*

Component Values

- $R = 10k\Omega$
- $C = 0.01\mu F$

$$f = \frac{1}{2\pi \times 10k\Omega \times 0.01\mu F} \approx 1.6kHz$$

Stabilizing the Amplitude To maintain a stable amplitude, a non-linear component such as a thermistor or diode can be added to adjust the gain dynamically.

III.5.B.iii. Square Wave Oscillator (Astable Multivibrator)

The astable multivibrator generates a square wave. It has no stable states, continuously switching between high and low output levels.

Circuit Diagram

Operation

- The circuit uses an op-amp with a feedback network consisting of resistors and a capacitor.
- The output toggles between high and low states as the capacitor charges and discharges.

Example Calculation The frequency f of the square wave is given by:

$$f = \frac{1}{2RC \ln 1 + \frac{2R_2}{R_1}}$$

Equation 3. 18

Component Values

- $R_1 = 10k\Omega$
- $R_2 = 10k\Omega$
- $C = 0.01\mu F$

$$f = \frac{1}{2 \times 10\, k\Omega \times 0.01\, \mu\, F \times \ln 3} \approx 3.3kHz$$

III.5.C. Conclusion of Oscillator

Operational amplifiers are versatile components for designing various types of oscillators. By understanding the principles of oscillation and the specific characteristics of different oscillator configurations, you can design circuits that generate a wide range of waveforms for different applications. Whether generating sine waves with low distortion using a Wien bridge oscillator or creating precise square waves with an astable multivibrator, op-amp oscillators are fundamental tools in analog electronics.

CHAPTER 4

OP-AMP SUMMARY

IV. SUMMARY

Operational amplifiers are versatile and essential components in analog electronics. Understanding their basic operation, common configurations, and practical applications is crucial for designing and analyzing electronic circuits. While ideal op-amps provide a theoretical foundation, real-world op-amps come with limitations that must be considered in practical designs. Mastery of op-amps enables the creation of complex and reliable electronic systems.