Lic (4341105) - Problem Solver

Antigravity AI

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To my students,
who constantly inspire me to find new analogies,
break down complex theories, and make learning
an engineered science.

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Preface

About this Book

Welcome to **Computer Networks**! This textbook is meticulously designed to serve as a comprehensive problem solver and study companion. It provides a robust and intuitive foundation in the core principles of this subject, bridging the gap between theoretical models and practical applications. A unique feature of this book is its focus on decoding complex concepts using clear, step-by-step methodologies and real-world analogies.

Target Audience

This book is intended for students and professionals looking to master the concepts of Computer Networks. Whether you are revising for exams, seeking to solidify your fundamental understanding, or looking for practical examples to clarify abstract concepts, this book has been structured to support your learning journey. It serves as an accessible guide designed to remove the fear of complex topics, replacing it with an appreciation for the underlying mechanics.

Scope and Coverage

The coverage is divided logically to follow standard academic curriculums. Each chapter focuses on key topics, breaking them down into digestible sections:

- **Theoretical Insights** – Core concepts explained intuitively.
- **Method Blocks** – Standardized, step-by-step procedures for solving specific types of problems.
- **Worked Examples** – Fully solved problems that apply the methods in practice.

We hope this resource proves invaluable in your studies and helps you achieve excellence in **Computer Networks**. Happy learning!

Acknowledgments

Writing a comprehensive book that connects the fundamental forces of Chemistry with practical engineering applications requires more than just academic knowledge—it requires a community of support. I would like to express my sincere gratitude to everyone who contributed to the realization of this project.

Specially, I extend my heartfelt gratitude to the **Department of Technical Education (DTE), Government of Gujarat**, and **Government Polytechnic, Palanpur**, for providing an environment that fosters innovation, academic rigor, and continuous professional development.

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Finally, my deepest appreciation goes to my students. Your curiosity, challenging questions, and continuous feedback are the true driving force behind the unique analogies and streamlined structure of this book. This textbook was engineered for you.

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About the Author

Milav Jayeshkumar Dabgar is an engineering educator and R&D professional with over 9 years of experience in electronics hardware development, embedded systems, AI/ML, and full-stack software engineering. He currently serves as a **Lecturer (Class - II) & Innovation Leader** at Government Polytechnic, Palanpur, under the Education Department of the Government of Gujarat.

Milav holds a Master of Engineering (ME) in Communication Systems from L.D. College of Engineering and a Bachelor of Engineering (BE) in Electronics & Communication. He is also currently pursuing a **BS in Data Science and Applications from IIT Madras**, where he has completed both the **Diploma in Programming** and the **Diploma in Data Science** with distinction.

Most recently, he completed the **AICTE QIP PG Certificate Program in Deep Learning from SVNIT Surat** with a **perfect 10/10 CGPA**, topping his batch.

A dedicated mentor, Milav has guided numerous student teams in securing over **INR 45 lakhs** in innovation funding, including INR 25 lakhs from Shark Tank India and INR 20 lakhs through iHub Gujarat, resulting in two student patents. He is recognized as an **NPTEL Evangelist** and **NPTEL Discipline Star** in Computer Science, reflecting his commitment to continuous learning and academic excellence.

His technical expertise spans from embedded systems (8051, STM32, Arduino) to modern web technologies (Next.js, Python, PostgreSQL) and Data Science (TensorFlow, PyTorch). Through this textbook, he aims to simplify complex Engineering Chemistry concepts by integrating relatable, real-world analogies drawn from modern tech and engineering landscapes.

Milav is also an active content creator, running a popular **YouTube channel** (@milav.dabgar) where he shares technical tutorials and academic resources. He maintains a personal blog and resource hub at milav.in and can be reached for professional collaborations on LinkedIn.

CHAPTER 1

Amplifiers (Negative Feedback)

In this chapter, we focus on solving problems related to negative feedback amplifiers. The key concept across all problems is the **desensitivity factor** (or amount of feedback), given by $D = 1 + A\beta$, where A is the open-loop gain and β is the feedback factor. This factor determines how gain, impedances, bandwidth, and distortion change when negative feedback is applied.

Methodology:

Calculating Closed Loop Gain and Feedback Factor When a fraction of the output is fed back to the input out of phase (negative feedback), the overall gain of the amplifier is reduced.

1. **Identify Open-Loop Gain (A):** This is the gain of the basic amplifier without any feedback applied.
2. **Identify Feedback Fraction (β):** This is the ratio of the feedback signal to the output signal.
3. **Calculate Loop Gain:** Multiply A and β. The term $A\beta$ is the loop gain.
4. **Calculate Desensitivity Factor (D):** Compute $D = 1 + A\beta$.
5. **Calculate Closed-Loop Gain (A_f):** Apply the formula:

$$A_f = \frac{A}{1 + A\beta}$$

6. **Special Case ($A\beta \gg 1$):** If the loop gain is very large, the closed-loop gain can be approximated as $A_f \approx \frac{1}{\beta}$.

Worked Example:

Basic Calculation of Closed Loop Gain An amplifier has an open-loop gain of 1000. A negative feedback circuit is added with a feedback factor of 0.01. Calculate the closed-loop gain and the amount of feedback in decibels (dB).

Solution:

1. **Given:**
   - Open-loop gain $A = 1000$
   - Feedback factor $\beta = 0.01$
2. **Calculate the desensitivity factor:**

$$1 + A\beta = 1 + (1000 \times 0.01) = 1 + 10 = 11$$

3. **Calculate closed-loop gain (A_f):**

$$A_f = \frac{A}{1 + A\beta} = \frac{1000}{11} \approx 90.91$$

4. **Calculate amount of feedback in dB:** The amount of feedback in decibels is defined as:

$$N = 20\log_{10}\left(\frac{A}{A_f}\right) = 20\log_{10}(1 + A\beta)$$

$$N = 20\log_{10}(11) \approx 20.83 \text{ dB}$$

Final Answer: The closed-loop gain is 90.91 and the amount of feedback is 20.83 dB.

Worked Example:

Determining the Required Feedback Factor An amplifier has a voltage gain of -500 without feedback. What should be the value of the feedback fraction β to reduce the voltage gain to -100?

Solution:

1. **Given:**
   - Open-loop gain $A = -500$
   - Desired closed-loop gain $A_f = -100$

2. **Set up the feedback equation:**

$$A_f = \frac{A}{1 + A\beta}$$

3. **Substitute the known values:**

$$-100 = \frac{-500}{1 + (-500)\beta}$$

4. **Solve for β:**

$$\begin{aligned} -100(1 - 500\beta) &= -500 \\ 1 - 500\beta &= 5 \\ -500\beta &= 4 \\ \beta &= -\frac{4}{500} = -0.008 \end{aligned}$$

Final Answer: The required feedback fraction is $\beta = -0.008$. (Note: The negative signs in A and β indicate an inverting amplifier configuration).

Methodology:

Evaluating Gain Stability and Sensitivity Negative feedback improves the stability of the amplifier's gain against variations in the open-loop gain (caused by temperature or component replacement).

1. **Identify the Fractional Change in Open-Loop Gain:** Let the variation in open-loop gain be $\frac{\Delta A}{A}$. This is often given as a percentage.

2. **Calculate the Fractional Change in Closed-Loop Gain:** The percentage change in A_f is reduced by the desensitivity factor:

$$\frac{\Delta A_f}{A_f} = \frac{1}{1 + A\beta}\left(\frac{\Delta A}{A}\right)$$

3. **Determine the Sensitivity factor (S):** Sensitivity is defined as the ratio of the fractional change in A_f to the fractional change in A.

$$S = \frac{\frac{\Delta A_f}{A_f}}{\frac{\Delta A}{A}} = \frac{1}{1 + A\beta}$$

Worked Example:

Calculating Percentage Change in Gain The voltage gain of an amplifier without feedback is 3000. The gain decreases by 20% due to temperature variations. If a negative feedback of $\beta = 0.01$ is applied, calculate the percentage change in the closed-loop gain.

Solution:

1. **Given:**
   - Open-loop gain $A = 3000$
   - Fractional change in A: $\frac{\Delta A}{A} = 20\%$ or 0.20
   - Feedback fraction $\beta = 0.01$
2. **Calculate the desensitivity factor:**
$$1 + A\beta = 1 + (3000 \times 0.01) = 1 + 30 = 31$$
3. **Calculate the fractional change in A_f:**
$$\frac{\Delta A_f}{A_f} = \frac{1}{1 + A\beta}\left(\frac{\Delta A}{A}\right)$$
$$\frac{\Delta A_f}{A_f} = \frac{1}{31} \times 20\% \approx 0.645\%$$

Final Answer: The change in the closed-loop gain is drastically reduced to 0.645%.

Worked Example:

Determining Required Gain for a Desired Tolerance An amplifier requires a closed-loop gain of 100. The closed-loop gain must not vary by more than 1% when the open-loop gain varies by 20%. Calculate the required open-loop gain A and the feedback factor β.

Solution:

1. **Given:**
   - Desired $A_f = 100$
   - Permissible variation in A_f: $\frac{\Delta A_f}{A_f} = 1\% = 0.01$
   - Expected variation in A: $\frac{\Delta A}{A} = 20\% = 0.20$
2. **Use the sensitivity formula to find $1 + A\beta$:**
$$\frac{\Delta A_f}{A_f} = \frac{1}{1 + A\beta}\left(\frac{\Delta A}{A}\right)$$
$$0.01 = \frac{1}{1 + A\beta}(0.20)$$
$$1 + A\beta = \frac{0.20}{0.01} = 20$$
3. **Use the closed-loop gain formula to find A:**
$$A_f = \frac{A}{1 + A\beta}$$
$$100 = \frac{A}{20}$$
$$A = 100 \times 20 = 2000$$

4. **Solve for β:**

$$1 + A\beta = 20$$
$$1 + 2000\beta = 20$$
$$2000\beta = 19$$
$$\beta = \frac{19}{2000} = 0.0095$$

Final Answer: The required open-loop gain is 2000 and the feedback factor is 0.0095.

Methodology:

Calculating Bandwidth and Distortion Improvements Negative feedback decreases distortion and noise and increases the amplifier's bandwidth.

1. **Calculate Bandwidth (BW_f):**

$$BW_f = BW_{open} \times (1 + A\beta)$$

where $BW = f_2 - f_1$.

2. **Calculate New Cutoff Frequencies:** The upper cutoff frequency increases and the lower cutoff frequency decreases:

$$f_{2f} = f_2(1 + A\beta)$$
$$f_{1f} = \frac{f_1}{1 + A\beta}$$

3. **Calculate Harmonic Distortion (D_f):**

$$D_f = \frac{D}{1 + A\beta}$$

where D is the initial distortion without feedback.

Worked Example:

Effect of Feedback on Bandwidth and Cutoff Frequencies An amplifier has an open-loop gain of 10^4, a lower cutoff frequency of 50 Hz, and an upper cutoff frequency of 20 kHz. A negative feedback of $\beta = 0.009$ is applied. Calculate the new bandwidth and the new cutoff frequencies.
Solution:

1. **Given:**
   - Open-loop gain $A = 10000$
   - Lower cutoff frequency $f_1 = 50$ Hz
   - Upper cutoff frequency $f_2 = 20$ kHz $= 20,000$ Hz
   - $\beta = 0.009$

2. **Calculate the desensitivity factor:**

$$1 + A\beta = 1 + (10000 \times 0.009) = 1 + 90 = 91$$

3. **Calculate the new lower cutoff frequency (f_{1f}):**

$$f_{1f} = \frac{f_1}{1 + A\beta} = \frac{50}{91} \approx 0.55 \text{ Hz}$$

4. **Calculate the new upper cutoff frequency (f_{2f}):**

$$f_{2f} = f_2(1 + A\beta) = 20,000 \times 91 = 1,820,000 \text{ Hz} = 1.82 \text{ MHz}$$

5. **Calculate the new bandwidth (BW_f):**

$$BW_f = f_{2f} - f_{1f} = 1,820,000 - 0.55 \approx 1.82 \text{ MHz}$$

Final Answer: The new lower cutoff frequency is 0.55 Hz, the new upper cutoff frequency is 1.82 MHz, and the new bandwidth is approximately 1.82 MHz.

Worked Example:

Reduction of Harmonic Distortion An amplifier delivers an output with 10% harmonic distortion without feedback. If a negative feedback circuit with $\beta = 0.05$ is added and the open-loop gain is 100. What is the new percentage of harmonic distortion?

Solution:

1. **Given:**
   - Initial distortion $D = 10\%$
   - $\beta = 0.05$
   - Open-loop gain $A = 100$

2. **Calculate the desensitivity factor:**

$$1 + A\beta = 1 + (100 \times 0.05) = 1 + 5 = 6$$

3. **Calculate the new distortion (D_f):**

$$D_f = \frac{D}{1 + A\beta} = \frac{10\%}{6} \approx 1.67\%$$

Final Answer: The harmonic distortion is reduced to 1.67%.

Methodology:

Calculating Impedances for Different Topologies Negative feedback modifies the input and output impedances depending on the sampling and mixing methods.

1. **Identify the Topology Properties:**
   - **Series Mixing:** Increases input impedance ($Z_{in} \uparrow$).
   - **Shunt Mixing:** Decreases input impedance ($Z_{in} \downarrow$).
   - **Voltage Sampling:** Decreases output impedance ($Z_{out} \downarrow$).
   - **Current Sampling:** Increases output impedance ($Z_{out} \uparrow$).

2. **Calculate Input Impedance (Z_{if}):**
   - Voltage-Series & Current-Series: $Z_{if} = Z_i(1 + A\beta)$
   - Voltage-Shunt & Current-Shunt: $Z_{if} = \frac{Z_i}{1+A\beta}$

3. **Calculate Output Impedance (Z_{of}):**
   - Voltage-Series & Voltage-Shunt: $Z_{of} = \frac{Z_o}{1+A\beta}$
   - Current-Series & Current-Shunt: $Z_{of} = Z_o(1 + A\beta)$

Worked Example:

Calculating Impedances in a Voltage Series Amplifier An amplifier has an open-loop voltage gain $A = 1000$, input impedance $Z_i = 10\ \text{k}\Omega$, and output impedance $Z_o = 100\ \Omega$. A voltage-series negative feedback with $\beta = 0.01$ is applied. Calculate the new input and output impedances.

Solution:

1. **Given:**
   - $A = 1000$
   - $Z_i = 10\ \text{k}\Omega = 10,000\ \Omega$
   - $Z_o = 100\ \Omega$
   - $\beta = 0.01$
   - Topology: Voltage-Series
2. **Calculate the desensitivity factor:**
$$1 + A\beta = 1 + (1000 \times 0.01) = 1 + 10 = 11$$
3. **Calculate Input Impedance (Z_{if}):** For series mixing:
$$Z_{if} = Z_i(1 + A\beta) = 10\ \text{k}\Omega \times 11 = 110\ \text{k}\Omega$$
4. **Calculate Output Impedance (Z_{of}):** For voltage sampling:
$$Z_{of} = \frac{Z_o}{1 + A\beta} = \frac{100\ \Omega}{11} \approx 9.09\ \Omega$$

Final Answer: The input impedance increases to 110 kΩ and the output impedance decreases to 9.09 Ω.

Worked Example:

Calculating Impedances in a Current Shunt Amplifier A current-shunt feedback amplifier has an open-loop gain $A = 500$, input impedance $Z_i = 2\ \text{k}\Omega$, and output impedance $Z_o = 50\ \text{k}\Omega$. The feedback fraction is $\beta = 0.02$. Calculate the closed-loop input and output impedances.

Solution:

1. **Given:**
   - $A = 500$
   - $Z_i = 2\ \text{k}\Omega = 2000\ \Omega$
   - $Z_o = 50\ \text{k}\Omega = 50,000\ \Omega$
   - $\beta = 0.02$
   - Topology: Current-Shunt
2. **Calculate the desensitivity factor:**
$$1 + A\beta = 1 + (500 \times 0.02) = 1 + 10 = 11$$
3. **Calculate Input Impedance (Z_{if}):** For shunt mixing:
$$Z_{if} = \frac{Z_i}{1 + A\beta} = \frac{2000}{11} \approx 181.82\ \Omega$$
4. **Calculate Output Impedance (Z_{of}):** For current sampling:
$$Z_{of} = Z_o(1 + A\beta) = 50\ \text{k}\Omega \times 11 = 550\ \text{k}\Omega$$

Final Answer: The input impedance drops to 181.82 Ω and the output impedance rises to 550 kΩ.

CHAPTER 2

Oscillators (Positive Feedback)

2.1 Barkhausen Criterion and Minimum Gain Requirement

Methodology:

Determining Oscillation Conditions using Barkhausen Criterion The Barkhausen criterion defines the mathematical conditions required for a circuit to produce sustained oscillations. To solve problems related to this criterion, follow these steps:

1. **Identify the Loop Parameters:** Determine the amplifier's forward voltage gain (A) and the feedback network's feedback fraction (β).
2. **Check the Loop Gain Condition (Magnitude):** For oscillations to start and be sustained, the magnitude of the loop gain must be equal to or slightly greater than unity:
$$|A\beta| \geq 1$$
3. **Calculate the Required Minimum Gain or Feedback:**
   - To find the minimum amplifier gain required for sustained oscillations:
   $$A \geq \frac{1}{\beta}$$
   - To find the required feedback fraction for a given gain:
   $$\beta \geq \frac{1}{A}$$
4. **Phase Shift Condition:** Ensure that the total phase shift around the closed loop is 0° or 360° (which implies positive feedback).

Worked Example:

Calculating Minimum Amplifier Gain An oscillator circuit has a feedback network with a feedback fraction of $\beta = 0.05$. Calculate the minimum forward voltage gain required for the amplifier to sustain oscillations.
Solution:

1. **Identify given parameters:** Feedback fraction, $\beta = 0.05$.
2. **Apply the Barkhausen loop gain condition:** For sustained oscillations, $|A\beta| \geq 1$.
3. **Calculate the minimum gain (A):**
$$A = \frac{1}{\beta} = \frac{1}{0.05} = 20$$

The minimum forward voltage gain required is 20.

2.2 Resonant Tank Circuits

Methodology:

Calculating the Resonant Frequency of a Tank Circuit A tank circuit consists of an inductor (L) and a capacitor (C) connected in parallel. It is responsible for setting the frequency of oscillation in LC oscillators.

1. **Identify the Component Values:** Determine the inductance (L) in Henrys (H) and the capacitance (C) in Farads (F).
2. **Apply the Resonant Frequency Formula:** The frequency at which the tank circuit oscillates is given by:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

3. **Unit Conversions:** Ensure to convert millihenrys (mH) or microhenrys (μH) to H, and microfarads (μF) or picofarads (pF) to F before calculating. The result f_r will be in Hertz (Hz).

Worked Example:

Tank Circuit Frequency Calculation A tank circuit has an inductance of 2 mH and a capacitance of 50 pF. Calculate its resonant frequency.
Solution:

1. **Convert values to standard units:**

$$L = 2 \text{ mH} = 2 \times 10^{-3} \text{ H}$$

$$C = 50 \text{ pF} = 50 \times 10^{-12} \text{ F}$$

2. **Apply the resonant frequency formula:**

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

3. **Substitute the values and calculate:**

$$f_r = \frac{1}{2\pi\sqrt{(2 \times 10^{-3}) \times (50 \times 10^{-12})}}$$

$$f_r = \frac{1}{2\pi\sqrt{100 \times 10^{-15}}}$$

$$f_r = \frac{1}{2\pi\sqrt{1 \times 10^{-13}}} = \frac{1}{2\pi(3.162 \times 10^{-7})}$$

$$f_r \approx \frac{1}{1.987 \times 10^{-6}} \approx 503,292 \text{ Hz} \approx 503.3 \text{ kHz}$$

The resonant frequency of the tank circuit is approximately 503.3 kHz.

2.3 Hartley and Colpitts Oscillators

Methodology:

Solving Hartley Oscillator Problems A Hartley oscillator uses a split inductor (L_1 and L_2) and a single capacitor (C).

1. **Calculate Equivalent Inductance (L_{eq}):** If mutual inductance (M) is negligible:

$$L_{eq} = L_1 + L_2$$

If mutual inductance is given:

$$L_{eq} = L_1 + L_2 + 2M$$

2. **Calculate Oscillation Frequency (f):**

$$f = \frac{1}{2\pi\sqrt{L_{eq}C}}$$

3. **Calculate the Feedback Fraction (β):** The feedback is derived from the voltage across L_2.

$$\beta = \frac{L_2}{L_1}$$

4. **Determine Minimum Gain Requirement:** By Barkhausen criterion, the required gain $A \geq \frac{L_1}{L_2}$.

Worked Example:

Frequency and Gain of a Hartley Oscillator A Hartley oscillator is designed with $L_1 = 2$ mH, $L_2 = 20$ μH, and a variable capacitor set to 100 pF. Mutual inductance is negligible. Find the frequency of oscillation and the minimum required voltage gain of the amplifier.

Solution:

1. **Calculate the equivalent inductance:**

$$L_{eq} = L_1 + L_2 = 2 \times 10^{-3} \text{ H} + 20 \times 10^{-6} \text{ H} = 2.02 \times 10^{-3} \text{ H}$$

2. **Calculate the oscillation frequency:**

$$f = \frac{1}{2\pi\sqrt{L_{eq}C}}$$

$$f = \frac{1}{2\pi\sqrt{(2.02 \times 10^{-3}) \times (100 \times 10^{-12})}}$$

$$f = \frac{1}{2\pi\sqrt{2.02 \times 10^{-13}}} \approx \frac{1}{2\pi(4.494 \times 10^{-7})}$$

$$f \approx \frac{1}{2.824 \times 10^{-6}} \approx 354,115 \text{ Hz} \approx 354.1 \text{ kHz}$$

3. **Calculate the minimum required gain:**

$$\beta = \frac{L_2}{L_1} = \frac{20 \times 10^{-6}}{2 \times 10^{-3}} = 0.01$$

$$A_{min} = \frac{1}{\beta} = \frac{L_1}{L_2} = \frac{2 \times 10^{-3}}{20 \times 10^{-6}} = 100$$

The oscillator frequency is 354.1 kHz and the minimum amplifier gain must be 100.

Methodology:

Solving Colpitts Oscillator Problems A Colpitts oscillator uses a split capacitor (C_1 and C_2) and a single inductor (L).

1. **Calculate Equivalent Capacitance (C_{eq}):** The capacitors are in series from the perspective of the tank circuit:
$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$
2. **Calculate Oscillation Frequency (f):**
$$f = \frac{1}{2\pi\sqrt{LC_{eq}}}$$
3. **Calculate the Feedback Fraction (β):** The feedback is derived from the voltage across C_2.
$$\beta = \frac{C_1}{C_2}$$
4. **Determine Minimum Gain Requirement:** By Barkhausen criterion, the required gain $A \geq \frac{C_2}{C_1}$.

Worked Example:

Component Sizing for a Colpitts Oscillator A Colpitts oscillator needs to generate a 1 MHz signal. The inductor available is 10 μH. The amplifier provides a voltage gain of 10. Determine the required values for C_1 and C_2 to meet the oscillation conditions exactly.

Solution:

1. **Determine required equivalent capacitance (C_{eq}):**
$$f = 1 \times 10^6 \text{ Hz}, \quad L = 10 \times 10^{-6} \text{ H}$$
Rearranging the frequency formula:
$$f = \frac{1}{2\pi\sqrt{LC_{eq}}} \implies f^2 = \frac{1}{4\pi^2 LC_{eq}} \implies C_{eq} = \frac{1}{4\pi^2 Lf^2}$$
$$C_{eq} = \frac{1}{4\pi^2(10 \times 10^{-6})(1 \times 10^6)^2} = \frac{1}{39.478 \times 10} \approx 2.533 \times 10^{-9} \text{ F} = 2.533 \text{ nF}$$
2. **Use the gain to find the capacitor ratio:** For sustained oscillation, $A = \frac{C_2}{C_1}$. Given $A = 10$:
$$C_2 = 10C_1$$
3. **Solve for C_1 and C_2 using the series capacitance formula:**
$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2} = \frac{C_1(10C_1)}{C_1 + 10C_1} = \frac{10C_1^2}{11C_1} = \frac{10}{11}C_1$$
$$2.533 \text{ nF} = \frac{10}{11}C_1 \implies C_1 = \frac{11}{10} \times 2.533 \text{ nF} = 2.786 \text{ nF}$$
$$C_2 = 10C_1 = 27.86 \text{ nF}$$

The required capacitors are $C_1 \approx 2.786$ nF and $C_2 \approx 27.86$ nF.

2.4 Wien Bridge Oscillator

Methodology:

Determining Parameters of a Wien Bridge Oscillator The Wien Bridge oscillator relies on an RC network to produce oscillations, typically at lower (audio) frequencies.

1. **Identify Component Values:** Determine the resistor (R) and capacitor (C) values in the lead-lag feedback network. Typically, $R_1 = R_2 = R$ and $C_1 = C_2 = C$.

2. **Calculate Oscillation Frequency:**

$$f = \frac{1}{2\pi RC}$$

3. **Check Amplifier Gain Requirement:** For a balanced Wien Bridge network ($R_1 = R_2$, $C_1 = C_2$), the feedback fraction is $\beta = \frac{1}{3}$. Therefore, the amplifier must have a non-inverting voltage gain of exactly:

$$A \geq 3$$

If the amplifier is built using an Op-Amp, the gain is set by feedback resistors R_f and R_i:

$$A = 1 + \frac{R_f}{R_i} \geq 3 \implies R_f \geq 2R_i$$

Worked Example:

Design of a Wien Bridge Oscillator Design the frequency determining network of a Wien Bridge oscillator to operate at 5 kHz, using capacitors of 0.01 μF. Also, determine the required ratio of the amplifier's feedback to input resistors (R_f/R_i).

Solution:

1. **Identify known parameters:**

$$f = 5000 \text{ Hz}, \quad C = 0.01 \times 10^{-6} \text{ F}$$

2. **Calculate required resistor (R):**

$$f = \frac{1}{2\pi RC} \implies R = \frac{1}{2\pi fC}$$

$$R = \frac{1}{2\pi(5000)(0.01 \times 10^{-6})} = \frac{1}{3.1416 \times 10^{-4}} \approx 3183\ \Omega \approx 3.18\ \text{k}\Omega$$

3. **Determine resistor ratio for the amplifier:** For a Wien Bridge, the minimum required closed-loop gain is 3.

$$A = 1 + \frac{R_f}{R_i} = 3 \implies \frac{R_f}{R_i} = 2$$

The required resistance is 3.18 kΩ and the required resistor ratio R_f/R_i is 2.

2.5 UJT Relaxation Oscillator

Methodology:

Analyzing a UJT Relaxation Oscillator A Unijunction Transistor (UJT) produces a non-sinusoidal sawtooth or pulse waveform. The frequency depends on an RC timing circuit and the intrinsic standoff ratio (η) of the UJT.

1. **Identify Component Parameters:** Get the charging resistor (R), charging capacitor (C), and the intrinsic standoff ratio (η).
2. **Calculate the Time Period (T):** The time it takes for the capacitor to charge to the UJT trigger voltage is:
$$T = RC\ln\left(\frac{1}{1-\eta}\right)$$
3. **Calculate the Oscillation Frequency (f):**
$$f = \frac{1}{T}$$
4. **Approximation (Optional):** If $\eta \approx 0.63$, the natural log term becomes roughly 1, simplifying the equation to $T \approx RC$. Only use this if η is exactly $1 - e^{-1} \approx 0.632$.

Worked Example:

Frequency of a UJT Relaxation Oscillator A UJT relaxation oscillator has a timing resistor of 50 kΩ and a capacitor of 0.1 μF. The UJT has an intrinsic standoff ratio $\eta = 0.6$. Calculate the frequency of oscillation.
Solution:

1. **Calculate the RC time constant:**
$$RC = (50 \times 10^3) \times (0.1 \times 10^{-6}) = 5 \times 10^{-3} \text{ seconds} = 5 \text{ ms}$$
2. **Calculate the precise time period (T):**
$$T = RC\ln\left(\frac{1}{1-\eta}\right)$$
$$T = 0.005 \times \ln\left(\frac{1}{1-0.6}\right) = 0.005 \times \ln\left(\frac{1}{0.4}\right) = 0.005 \times \ln(2.5)$$
$$T \approx 0.005 \times 0.9163 = 0.00458 \text{ seconds} = 4.58 \text{ ms}$$
3. **Calculate the frequency (f):**
$$f = \frac{1}{T} = \frac{1}{0.00458} \approx 218.3 \text{ Hz}$$

The oscillator frequency is approximately 218.3 Hz.

2.6 Crystal Oscillator Resonant Frequencies

Methodology:

Calculating Series and Parallel Resonant Frequencies of a Crystal A quartz crystal has an equivalent electrical circuit consisting of a series R-L-C branch (motional parameters R_s, L_s, C_s) in parallel with a mounting capacitance (C_p). It possesses two resonant frequencies.

1. **Calculate Series Resonant Frequency (f_s):** This frequency occurs when the series inductance (L_s) and series capacitance (C_s) resonate:
$$f_s = \frac{1}{2\pi\sqrt{L_s C_s}}$$
2. **Calculate Parallel Resonant Frequency (f_p):** This frequency occurs when the series branch resonates with the parallel mounting capacitance (C_p). First, find the equivalent series capacitance of

C_s and C_p:

$$C_{eq} = \frac{C_s C_p}{C_s + C_p}$$

Then, calculate the frequency:

$$f_p = \frac{1}{2\pi\sqrt{L_s C_{eq}}}$$

Note: f_p is always slightly greater than f_s.

Worked Example:

Crystal Oscillator Frequencies A quartz crystal has the following equivalent circuit parameters: $L_s = 0.4$ H, $C_s = 0.085$ pF, and $C_p = 1$ pF. Calculate both its series and parallel resonant frequencies.

Solution:

1. **Calculate the series resonant frequency (f_s):**

$$f_s = \frac{1}{2\pi\sqrt{L_s C_s}}$$

$$f_s = \frac{1}{2\pi\sqrt{0.4 \times (0.085 \times 10^{-12})}} = \frac{1}{2\pi\sqrt{3.4 \times 10^{-14}}}$$

$$f_s = \frac{1}{2\pi(1.844 \times 10^{-7})} \approx \frac{1}{1.1585 \times 10^{-6}} \approx 863,193 \text{ Hz} \approx 863.2 \text{ kHz}$$

2. **Calculate the equivalent capacitance for parallel resonance (C_{eq}):**

$$C_{eq} = \frac{C_s C_p}{C_s + C_p} = \frac{0.085 \times 1}{0.085 + 1} \text{ pF} = \frac{0.085}{1.085} \text{ pF} \approx 0.07834 \text{ pF}$$

3. **Calculate the parallel resonant frequency (f_p):**

$$f_p = \frac{1}{2\pi\sqrt{L_s C_{eq}}}$$

$$f_p = \frac{1}{2\pi\sqrt{0.4 \times (0.07834 \times 10^{-12})}} = \frac{1}{2\pi\sqrt{3.1336 \times 10^{-14}}}$$

$$f_p = \frac{1}{2\pi(1.77 \times 10^{-7})} \approx \frac{1}{1.112 \times 10^{-6}} \approx 899,280 \text{ Hz} \approx 899.3 \text{ kHz}$$

The series resonant frequency is approximately 863.2 kHz and the parallel resonant frequency is approximately 899.3 kHz.

CHAPTER 3

Power Amplifiers

This chapter emphasizes computational problem-solving for power amplifiers. We focus purely on methodologies, formulas, and step-by-step worked examples to calculate efficiency, power dissipation, and load matching for various classes of power amplifiers.

3.1 Series-Fed Class A Power Amplifiers

Methodology:

Calculating Power and Efficiency in Series-Fed Class A Amplifiers To calculate the parameters of a series-fed Class A power amplifier, follow these steps:

1. **Determine DC Input Power (P_{DC}):** The DC power supplied by the source is the product of the supply voltage and the quiescent collector current.

$$P_{DC} = V_{CC} \times I_{CQ}$$

2. **Determine AC Output Power (P_{AC}):** The AC power delivered to the load can be calculated using peak values (V_p, I_p), peak-to-peak values (V_{p-p}, I_{p-p}), or RMS values.

   - Using peak values:

$$P_{AC} = \frac{V_p \times I_p}{2} = \frac{V_p^2}{2R_L} = \frac{I_p^2 R_L}{2}$$

   - Using peak-to-peak values:

$$P_{AC} = \frac{V_{p-p} \times I_{p-p}}{8} = \frac{V_{p-p}^2}{8R_L} = \frac{I_{p-p}^2 R_L}{8}$$

3. **Calculate the Efficiency (η):** The power efficiency is the ratio of AC output power to DC input power.

$$\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$$

   Note: The maximum theoretical efficiency for this amplifier type is 25%.

4. **Calculate Power Dissipation (P_D):** The power dissipated by the transistor as heat is the difference between input and output power.

$$P_D = P_{DC} - P_{AC}$$

Worked Example:

Series-Fed Class A Parameter Calculation A series-fed Class A amplifier operates with a supply voltage of $V_{CC} = 20$ V and a quiescent collector current of $I_{CQ} = 1$ A. If the peak AC output voltage is 10 V across a $10\,\Omega$ load, determine the DC input power, AC output power, efficiency, and power dissipated by the transistor.

Solution:

1. **DC Input Power:**
$$P_{DC} = V_{CC} \times I_{CQ} = 20 \times 1 = 20 \text{ W}$$
2. **AC Output Power:** Given $V_p = 10$ V and $R_L = 10\,\Omega$, we use the voltage formula:
$$P_{AC} = \frac{V_p^2}{2R_L} = \frac{(10)^2}{2 \times 10} = \frac{100}{20} = 5 \text{ W}$$
3. **Efficiency:**
$$\eta = \frac{P_{AC}}{P_{DC}} \times 100\% = \frac{5}{20} \times 100\% = 25\%$$
4. **Power Dissipation:**
$$P_D = P_{DC} - P_{AC} = 20 - 5 = 15 \text{ W}$$

3.2 Transformer-Coupled Class A Power Amplifiers

Methodology:

Calculating Impedance Matching and Efficiency A transformer is often used to match the load impedance to the amplifier's required output impedance for maximum power transfer.

1. **Calculate Reflected (Effective) Load Impedance (R'_L):** The load R_L on the secondary is reflected to the primary as R'_L.
$$R'_L = a^2 R_L = \left(\frac{N_1}{N_2}\right)^2 R_L$$
where $a = N_1/N_2$ is the turns ratio (primary to secondary).
2. **Determine DC Input Power (P_{DC}):**
$$P_{DC} = V_{CC} \times I_{CQ}$$
3. **Determine AC Output Power (P_{AC}):** Using the reflected load R'_L and peak-to-peak primary voltage V_{p-p}:
$$P_{AC} = \frac{V_{p-p}^2}{8R'_L}$$
Alternatively, if maximum and minimum swings are given:
$$P_{AC} = \frac{(V_{CE(\max)} - V_{CE(\min)})(I_{C(\max)} - I_{C(\min)})}{8}$$
4. **Calculate Efficiency (η):**
$$\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$$
Note: The maximum theoretical efficiency for a transformer-coupled Class A amplifier is 50%.

Worked Example:

Impedance Matching and Efficiency A transformer-coupled Class A amplifier drives an $8\,\Omega$ speaker through a transformer with a turns ratio of $N_1 : N_2 = 3 : 1$. The supply voltage is 12 V and the quiescent current is $I_{CQ} = 200$ mA. If the AC output voltage on the primary swings 10 V peak-to-peak, calculate the reflected load, AC power, and efficiency.
Solution:

1. **Reflected Load Impedance (R'_L):**

$$R'_L = \left(\frac{N_1}{N_2}\right)^2 \times R_L = (3)^2 \times 8 = 9 \times 8 = 72\,\Omega$$

2. **AC Output Power:** Given $V_{p-p} = 10$ V across the primary:

$$P_{AC} = \frac{V_{p-p}^2}{8R'_L} = \frac{10^2}{8 \times 72} = \frac{100}{576} \approx 0.174 \text{ W}$$

3. **DC Input Power:**

$$P_{DC} = V_{CC} \times I_{CQ} = 12 \times 0.2 = 2.4 \text{ W}$$

4. **Efficiency:**

$$\eta = \frac{P_{AC}}{P_{DC}} \times 100\% = \frac{0.174}{2.4} \times 100\% \approx 7.25\%$$

3.3 Class B Push-Pull Power Amplifiers

Methodology:

Calculating Output, Dissipation, and Efficiency in Class B In a Class B push-pull amplifier, two transistors each conduct for half a cycle.

1. **Determine Peak Current (I_p):** Find the peak current across the load using the peak output voltage (V_p).

$$I_p = \frac{V_p}{R_L}$$

2. **Calculate DC Input Power (P_{DC}):** The DC source must supply the average current over a full cycle. For a half-wave rectified waveform (since each transistor conducts half the time), the total average DC current is $I_{DC} = \frac{2I_p}{\pi}$.

$$P_{DC} = V_{CC} \times I_{DC} = V_{CC} \times \left(\frac{2I_p}{\pi}\right)$$

3. **Calculate AC Output Power (P_{AC}):**

$$P_{AC} = \frac{V_p \times I_p}{2} = \frac{V_p^2}{2R_L}$$

4. **Calculate Efficiency (η):**

$$\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$$

Note: Maximum efficiency is $\frac{\pi}{4} \approx 78.5\%$.

5. **Calculate Maximum Power Dissipation ($P_{D(\max)}$):** The maximum total power dissipated by both transistors occurs when the output voltage is $V_p = \frac{2}{\pi}V_{CC}$.

$$\text{Total } P_{D(\max)} = \frac{2V_{CC}^2}{\pi^2 R_L}$$

The maximum power dissipated per transistor is half of this value.

Worked Example:

Class B Push-Pull Performance A Class B push-pull amplifier operates with $V_{CC} = 20$ V and drives a $10\,\Omega$ load. If the peak output voltage is 15 V, calculate the DC input power, AC output power, efficiency, power dissipated per transistor, and the absolute maximum possible dissipation per transistor.

Solution:

1. **Peak Current (I_p):**
$$I_p = \frac{V_p}{R_L} = \frac{15}{10} = 1.5 \text{ A}$$

2. **DC Input Power:**
$$I_{DC} = \frac{2 \times 1.5}{\pi} = \frac{3}{\pi} \approx 0.955 \text{ A}$$
$$P_{DC} = V_{CC} \times I_{DC} = 20 \times 0.955 = 19.1 \text{ W}$$

3. **AC Output Power:**
$$P_{AC} = \frac{V_p^2}{2R_L} = \frac{(15)^2}{2 \times 10} = \frac{225}{20} = 11.25 \text{ W}$$

4. **Efficiency:**
$$\eta = \frac{11.25}{19.1} \times 100\% \approx 58.9\%$$

5. **Power Dissipated per Transistor:** Total dissipation $P_D = P_{DC} - P_{AC} = 19.1 - 11.25 = 7.85$ W.
$$\text{Dissipation per transistor} = \frac{7.85}{2} = 3.925 \text{ W}$$

6. **Maximum Possible Dissipation per Transistor:**
$$\text{Total } P_{D(\max)} = \frac{2V_{CC}^2}{\pi^2 R_L} = \frac{2 \times (20)^2}{\pi^2 \times 10} = \frac{800}{98.7} \approx 8.1 \text{ W}$$
$$\text{Max Dissipation per transistor} = \frac{8.1}{2} = 4.05 \text{ W}$$

3.4 Harmonic Distortion in Power Amplifiers

Methodology:

Calculating Total Harmonic Distortion (THD) Power amplifiers often introduce non-linearities, causing harmonics at multiples of the fundamental frequency.

1. **Calculate Individual Harmonic Distortion (D_n):** The distortion factor for the n-th harmonic is the ratio of the amplitude of the n-th harmonic (A_n) to the fundamental amplitude (A_1).

$$D_n = \frac{|A_n|}{|A_1|} \times 100\%$$

2. **Calculate Total Harmonic Distortion (THD):** THD is the square root of the sum of the squares of individual distortions.

$$\text{THD} = \sqrt{D_2^2 + D_3^2 + D_4^2 + \dots}$$

3. **Calculate Total Power with Distortion (P_{total}):** If the fundamental power is P_1, the total power delivered to the load including harmonics is:

$$P_{total} = P_1(1 + \text{THD}^2)$$

where THD is used as a decimal (e.g., 0.10 for 10%).

Worked Example:

Calculating THD and Total Power A power amplifier produces a fundamental voltage output of 10 V peak. It also produces a second harmonic of 1.5 V, a third harmonic of 0.5 V, and a fourth harmonic of 0.2 V. Calculate the individual harmonic distortions, the Total Harmonic Distortion (THD), and the total power delivered to a $4\,\Omega$ load.

Solution:

1. **Individual Harmonic Distortions:**

$$D_2 = \frac{1.5}{10} = 0.15 \quad (15\%)$$

$$D_3 = \frac{0.5}{10} = 0.05 \quad (5\%)$$

$$D_4 = \frac{0.2}{10} = 0.02 \quad (2\%)$$

2. **Total Harmonic Distortion (THD):**

$$\text{THD} = \sqrt{D_2^2 + D_3^2 + D_4^2} = \sqrt{(0.15)^2 + (0.05)^2 + (0.02)^2}$$

$$\text{THD} = \sqrt{0.0225 + 0.0025 + 0.0004} = \sqrt{0.0254} \approx 0.1593 \quad (15.93\%)$$

3. **Total Power Delivered:** First, find the fundamental power P_1:

$$P_1 = \frac{V_{1(peak)}^2}{2R_L} = \frac{10^2}{2 \times 4} = \frac{100}{8} = 12.5 \text{ W}$$

Now calculate the total power:

$$P_{total} = P_1(1 + \text{THD}^2) = 12.5(1 + 0.0254) = 12.5 \times 1.0254 = 12.8175 \text{ W}$$

CHAPTER 4

Operational Amplifiers (Op Amps)

4.1 IC-741 Introduction and Basic Block Diagram

The Operational Amplifier (Op-Amp) is a high-gain direct-coupled amplifier. The IC-741 is the most widely used general-purpose op-amp.

Basic Block Diagram Stages:

1. **Input Stage:** Dual-input balanced-output differential amplifier. Provides high input impedance.
2. **Intermediate Stage:** Dual-input unbalanced-output differential amplifier. Provides additional voltage gain.
3. **Level Shifter Stage:** Shifts the DC level to zero volts at the output.
4. **Output Stage:** Push-pull amplifier. Provides low output impedance and high current driving capability.

IC-741 Pin Configuration (8-pin DIP):

Pin No.	Function	Pin No.	Function
1	Offset Null	5	Offset Null
2	Inverting Input $(-)$	6	Output
3	Non-Inverting Input $(+)$	7	Positive Power Supply $(+V_{CC})$
4	Negative Power Supply $(-V_{EE})$	8	No Connection (NC)

4.2 Open Loop and Closed Loop Configurations

An op-amp can be operated in two main modes:

- **Open Loop:** No feedback is applied from output to input. The voltage gain is the open-loop gain (A_{OL}), which is ideally infinite (typically 10^5 for IC-741). Output quickly saturates to $\pm V_{sat}$.
- **Closed Loop:** A portion of the output is fed back to the input. Negative feedback reduces the overall gain to a stable and predictable value (A_{CL}) determined by external resistors.

4.3 Operational Amplifier Parameters

Methodology:

Calculating Op Amp Parameters

1. **Input Bias Current (I_B):** The average of the currents entering the two input terminals.

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

2. **Input Offset Current (I_{io}):** The difference between the two input bias currents.

$$I_{io} = |I_{B1} - I_{B2}|$$

3. **Input Offset Voltage (V_{io}):** The voltage that must be applied between the input terminals to force the output voltage to zero.

4. **Common Mode Rejection Ratio (CMRR):** The ratio of differential voltage gain (A_d) to common-mode voltage gain (A_c).

$$\text{CMRR} = \frac{A_d}{A_c}$$

$$\text{CMRR in dB} = 20\log_{10}\left(\frac{A_d}{A_c}\right)$$

5. **Slew Rate (SR):** The maximum rate of change of output voltage with respect to time.

$$\text{SR} = \frac{\Delta V_{out}}{\Delta t} \quad \text{(typically in } V/\mu s\text{)}$$

For a sinusoidal output $V_{out} = V_m \sin(2\pi f t)$, the maximum frequency without distortion is:

$$f_{max} = \frac{\text{SR}}{2\pi V_m}$$

Worked Example:

Calculating Bias and Offset Currents In a given op-amp circuit the base currents entering the inverting and non-inverting terminals are $22\,\mu$A and $18\,\mu$A respectively. Calculate the input bias current and input offset current.

Solution:

1. Identify the given values:

$$I_{B1} = 22\,\mu\text{A}, \quad I_{B2} = 18\,\mu\text{A}$$

2. Calculate the Input Bias Current (I_B):

$$I_B = \frac{I_{B1} + I_{B2}}{2} = \frac{22 + 18}{2} = \frac{40}{2} = 20\,\mu\text{A}$$

3. Calculate the Input Offset Current (I_{io}):

$$I_{io} = |I_{B1} - I_{B2}| = |22 - 18| = 4\,\mu\text{A}$$

Worked Example:

Calculating CMRR An op-amp has a differential gain of 10^5 and a common-mode gain of 0.25. Calculate the CMRR and express it in decibels (dB).

Solution:

1. Identify the given values:

$$A_d = 10^5, \quad A_c = 0.25$$

2. Calculate the ordinary CMRR:

$$\text{CMRR} = \frac{A_d}{A_c} = \frac{100,000}{0.25} = 400,000$$

3. Convert CMRR to decibels:

$$\text{CMRR (dB)} = 20\log_{10}(400,000) = 20 \times 5.602 = 112.04 \text{ dB}$$

Worked Example:

Maximum Operating Frequency from Slew Rate An op-amp has a slew rate of $0.5\,\mathrm{V}/\mu\mathrm{s}$. What is the maximum frequency of a sinusoidal output with a peak amplitude of 5 V that can be produced without distortion?

Solution:

1. Identify the given values:

$$\mathrm{SR} = 0.5\,\mathrm{V}/\mu\mathrm{s} = 0.5 \times 10^6 \text{ V/s}, \quad V_m = 5 \text{ V}$$

2. Use the slew rate frequency formula:

$$f_{max} = \frac{\mathrm{SR}}{2\pi V_m}$$

3. Substitute the values and calculate f_{max}:

$$f_{max} = \frac{0.5 \times 10^6}{2\pi \times 5} = \frac{500,000}{31.416} \approx 15,915.5 \text{ Hz} = 15.9 \text{ kHz}$$

4.4 Inverting and Non-inverting Amplifiers

Methodology:

Voltage Gain and Output Voltage Calculation

1. **Inverting Amplifier:** The input signal is applied to the inverting terminal $(-)$ through resistor R_1, and the non-inverting terminal $(+)$ is grounded. Feedback resistor R_f connects output to the inverting terminal.

$$\text{Voltage Gain } (A_v) = -\frac{R_f}{R_1}$$

$$V_{out} = A_v \times V_{in} = -\frac{R_f}{R_1} V_{in}$$

2. **Non-Inverting Amplifier:** The input signal is applied to the non-inverting terminal $(+)$. Resistor R_1 connects the inverting terminal to ground, and R_f provides feedback.

$$\text{Voltage Gain } (A_v) = 1 + \frac{R_f}{R_1}$$

$$V_{out} = A_v \times V_{in} = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

3. **Voltage Follower (Buffer):** A special case of the non-inverting amplifier where $R_f = 0$ and $R_1 = \infty$.

$$A_v = 1, \quad V_{out} = V_{in}$$

Worked Example:

Inverting Amplifier Calculation An inverting amplifier has an input resistor $R_1 = 10 \text{ k}\Omega$ and a feedback resistor $R_f = 100 \text{ k}\Omega$. If an input voltage of 0.5 V is applied calculate the voltage gain and output voltage.

Solution:

1. Identify the given values:

$$R_1 = 10 \text{ k}\Omega, \quad R_f = 100 \text{ k}\Omega, \quad V_{in} = 0.5 \text{ V}$$

2. Calculate the voltage gain (A_v):

$$A_v = -\frac{R_f}{R_1} = -\frac{100\ \text{k}\Omega}{10\ \text{k}\Omega} = -10$$

3. Calculate the output voltage (V_{out}):

$$V_{out} = A_v \times V_{in} = -10 \times 0.5\ \text{V} = -5\ \text{V}$$

The negative sign indicates a phase shift of 180°.

Worked Example:

Non-Inverting Amplifier Calculation A non-inverting amplifier is designed with $R_1 = 2\ \text{k}\Omega$ and $R_f = 18\ \text{k}\Omega$. Calculate the output voltage if the input voltage is 1.2 V.

Solution:

1. Identify the given values:

$$R_1 = 2\ \text{k}\Omega, \quad R_f = 18\ \text{k}\Omega, \quad V_{in} = 1.2\ \text{V}$$

2. Calculate the voltage gain (A_v):

$$A_v = 1 + \frac{R_f}{R_1} = 1 + \frac{18\ \text{k}\Omega}{2\ \text{k}\Omega} = 1 + 9 = 10$$

3. Calculate the output voltage (V_{out}):

$$V_{out} = A_v \times V_{in} = 10 \times 1.2\ \text{V} = 12\ \text{V}$$

4.5 Summing and Differential Amplifiers

Methodology:

Summing and Differential Amplifiers Calculation

1. **Inverting Summing Amplifier:** Adds multiple input voltages applied to the inverting terminal, each with its own input resistor.

$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \cdots + \frac{R_f}{R_n}V_n\right)$$

If all input resistors are equal ($R_1 = R_2 = R_n = R$), then:

$$V_{out} = -\frac{R_f}{R}(V_1 + V_2 + \cdots + V_n)$$

2. **Differential Amplifier (Subtractor):** Amplifies the difference between two input signals. Let V_1 be applied to the inverting input through R_1 and V_2 to the non-inverting input through R_2. Feedback resistor is R_f, and the non-inverting input is grounded through R_g.

$$V_{out} = \left(\frac{R_1 + R_f}{R_1}\right)\left(\frac{R_g}{R_2 + R_g}\right)V_2 - \left(\frac{R_f}{R_1}\right)V_1$$

If the circuit is balanced ($R_1 = R_2$ and $R_f = R_g$), the equation simplifies to:

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

Worked Example:

Summing Amplifier Output Calculation An inverting summing amplifier has three inputs: $V_1 = 1$ V, $V_2 = 2$ V, and $V_3 = 3$ V. The corresponding input resistors are $R_1 = 10$ kΩ, $R_2 = 20$ kΩ, and $R_3 = 30$ kΩ. The feedback resistor is $R_f = 60$ kΩ. Find the output voltage.

Solution:

1. Identify the given parameters:

$$R_f = 60 \text{ k}\Omega$$
$$V_1 = 1 \text{ V}, R_1 = 10 \text{ k}\Omega$$
$$V_2 = 2 \text{ V}, R_2 = 20 \text{ k}\Omega$$
$$V_3 = 3 \text{ V}, R_3 = 30 \text{ k}\Omega$$

2. Apply the summing amplifier formula:

$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

3. Substitute the values and evaluate each term:

$$\frac{R_f}{R_1}V_1 = \frac{60}{10} \times 1 = 6 \times 1 = 6 \text{ V}$$
$$\frac{R_f}{R_2}V_2 = \frac{60}{20} \times 2 = 3 \times 2 = 6 \text{ V}$$
$$\frac{R_f}{R_3}V_3 = \frac{60}{30} \times 3 = 2 \times 3 = 6 \text{ V}$$

4. Calculate the final output voltage:

$$V_{out} = -(6 + 6 + 6) = -18 \text{ V}$$

Worked Example:

Differential Amplifier Output Calculation A balanced differential amplifier has an input resistor $R_1 = 5$ kΩ and a feedback resistor $R_f = 25$ kΩ. Input voltages $V_1 = 4$ V (to the inverting terminal) and $V_2 = 7$ V (to the non-inverting terminal) are applied. Calculate the output voltage.

Solution:

1. Check if the circuit is balanced: The problem states it is a balanced differential amplifier, meaning $R_1 = R_2$ and $R_f = R_g$.

2. Identify the given values:

$$R_1 = 5 \text{ k}\Omega, \quad R_f = 25 \text{ k}\Omega, \quad V_1 = 4 \text{ V}, \quad V_2 = 7 \text{ V}$$

3. Apply the simplified formula for a balanced subtractor:

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

4. Substitute the values and calculate:

$$V_{out} = \frac{25 \text{ k}\Omega}{5 \text{ k}\Omega}(7 \text{ V} - 4 \text{ V}) = 5 \times 3 \text{ V} = 15 \text{ V}$$

4.6 Integrator

Methodology:

Integrator Output Voltage Calculation

1. **Basic Integrator:** An op-amp circuit that performs the mathematical operation of integration. The feedback element is a capacitor C and the input element is a resistor R.

2. **Output Voltage Formula:**
$$V_{out} = -\frac{1}{RC}\int_0^t V_{in}\,dt + V_C(0)$$
where $V_C(0)$ is the initial voltage across the capacitor at $t = 0$. Assuming zero initial conditions:
$$V_{out} = -\frac{1}{RC}\int_0^t V_{in}\,dt$$

3. **Response to Constant Input:** If a constant DC voltage $V_{in} = V$ is applied, the output becomes a linear ramp:
$$V_{out} = -\frac{1}{RC}\int_0^t V\,dt = -\frac{V}{RC}t$$

Worked Example:

Integrator Response to a DC Input An integrator circuit consists of a resistor $R = 100\ \text{k}\Omega$ and a capacitor $C = 1\,\mu\text{F}$. A step input of $V_{in} = 2$ V is applied at $t = 0$. Calculate the output voltage after 0.5 seconds. Assume the initial voltage across the capacitor is zero.

Solution:

1. Identify the given values:
$$R = 100\ \text{k}\Omega = 100 \times 10^3\,\Omega$$
$$C = 1\,\mu\text{F} = 1 \times 10^{-6}\ \text{F}$$
$$V_{in} = 2\ \text{V (constant)}, \quad t = 0.5\ \text{s}$$

2. Calculate the time constant RC:
$$RC = (100 \times 10^3) \times (1 \times 10^{-6}) = 0.1\ \text{s}$$

3. Apply the integrator formula for a constant input:
$$V_{out}(t) = -\frac{V_{in}}{RC}t$$

4. Substitute the values for $t = 0.5$ s:
$$V_{out}(0.5) = -\frac{2}{0.1} \times 0.5 = -20 \times 0.5 = -10\ \text{V}$$
After 0.5 seconds, the output voltage is -10 V.

CHAPTER 5

Timer Circuits

5.1 Astable Multivibrator using IC 555

Methodology:

Analysis and Design of Astable Multivibrator An astable multivibrator continuously alternates between HIGH and LOW states. The output parameters depend on two timing resistors (R_A and R_B) and a timing capacitor (C).

Analysis Steps:

1. Identify the given component values: R_A, R_B and C.
2. Calculate the High state time duration (T_{ON}):
$$T_H = 0.693(R_A + R_B)C$$
3. Calculate the Low state time duration (T_{OFF}):
$$T_L = 0.693 R_B C$$
4. Calculate the total time period (T):
$$T = T_H + T_L = 0.693(R_A + 2R_B)C$$
5. Calculate the frequency of oscillation (f):
$$f = \frac{1}{T} = \frac{1.44}{(R_A + 2R_B)C}$$
6. Calculate the percentage duty cycle (D):
$$\%D = \frac{T_H}{T} \times 100 = \left(\frac{R_A + R_B}{R_A + 2R_B}\right) \times 100$$

Design Steps:

1. Identify the desired frequency (f) and Duty Cycle (D). If duty cycle is not given, assume $D > 50\%$ (e.g. 60%) because standard 555 astable circuits cannot produce exactly 50% duty cycle without modification.
2. Select a standard value for the timing capacitor C (e.g. 0.1μF or 0.01μF).
3. Use the duty cycle formula to find the relationship between R_A and R_B:
$$D = \frac{R_A + R_B}{R_A + 2R_B}$$
4. Substitute the chosen C and the resistor relationship into the frequency equation to solve for R_B.
5. Calculate R_A using the relationship established in step 3.

Worked Example:

Determining Frequency and Duty Cycle An astable multivibrator using IC 555 has $R_A = 2.2$ kΩ, $R_B = 3.9$ kΩ and $C = 0.1\mu$F. Calculate the high time, low time, free-running frequency and duty cycle.

Solution:

1. **Identify Given Values:** $R_A = 2.2 \times 10^3\ \Omega$, $R_B = 3.9 \times 10^3\ \Omega$, $C = 0.1 \times 10^{-6}$ F.
2. **Calculate High Time (T_H):**
$$\begin{aligned} T_H &= 0.693(R_A + R_B)C \\ &= 0.693 \times (2.2\ \text{k}\Omega + 3.9\ \text{k}\Omega) \times 0.1\mu\text{F} \\ &= 0.693 \times (6.1 \times 10^3) \times (0.1 \times 10^{-6}) \\ &= 0.4227\ \text{ms} \end{aligned}$$

3. **Calculate Low Time (T_L):**

$$\begin{aligned} T_L &= 0.693 R_B C \\ &= 0.693 \times (3.9 \times 10^3) \times (0.1 \times 10^{-6}) \\ &= 0.2703 \text{ ms} \end{aligned}$$

4. **Calculate Total Time Period (T):**

$$T = T_H + T_L = 0.4227 \text{ ms} + 0.2703 \text{ ms} = 0.693 \text{ ms}$$

5. **Calculate Frequency (f):**

$$f = \frac{1}{T} = \frac{1}{0.693 \times 10^{-3}} = 1.443 \text{ kHz}$$

6. **Calculate Duty Cycle (D):**

$$\%D = \frac{T_H}{T} \times 100 = \frac{0.4227}{0.693} \times 100 = 61.0\%$$

Worked Example:

Designing an Astable Multivibrator Design an astable multivibrator using IC 555 to generate a square wave of 1 kHz frequency with a duty cycle of 60%.

Solution:

1. **Identify Requirements:** $f = 1$ kHz, $D = 0.60$.

2. **Relate Resistors using Duty Cycle:**

$$D = \frac{R_A + R_B}{R_A + 2R_B}$$

$$0.60 = \frac{R_A + R_B}{R_A + 2R_B}$$

$$0.60(R_A + 2R_B) = R_A + R_B$$

$$0.60R_A + 1.2R_B = R_A + R_B$$

$$0.2R_B = 0.4R_A \implies R_A = 0.5R_B$$

3. **Select Capacitor:** Let $C = 0.01\mu\text{F} = 10 \times 10^{-9}$ F.

4. **Calculate Resistors using Frequency Formula:**

$$f = \frac{1.44}{(R_A + 2R_B)C}$$

Substitute $R_A = 0.5R_B$:

$$1000 = \frac{1.44}{(0.5R_B + 2R_B) \times 0.01 \times 10^{-6}}$$

$$1000 = \frac{1.44}{2.5R_B \times 10^{-8}}$$

$$2.5R_B \times 10^{-5} = 1.44$$

$$R_B = \frac{1.44}{2.5 \times 10^{-5}} = 57.6 \text{ k}\Omega$$

5. **Calculate R_A:**

$$R_A = 0.5R_B = 0.5 \times 57.6 \text{ k}\Omega = 28.8 \text{ k}\Omega$$

6. **Final Component Values:** $R_A = 28.8$ kΩ, $R_B = 57.6$ kΩ and $C = 0.01\mu$F.

5.2 Exact 50 Percent Duty Cycle Astable Multivibrator

Methodology:

Designing for 50 Percent Duty Cycle To achieve exactly a 50% duty cycle, a bypass diode is connected in parallel with resistor R_B. This modifies the charging and discharging paths.

Steps for 50 Percent Duty Cycle Design:

1. Recognize that the capacitor charges through R_A and the diode (bypassing R_B) and discharges through R_B.
2. Calculate the High state time duration:
$$T_H = 0.693 R_A C$$
3. Calculate the Low state time duration:
$$T_L = 0.693 R_B C$$
4. Set $T_H = T_L$ for 50% duty cycle. This requires $R_A = R_B = R$.
5. Calculate the total time period (T):
$$T = 0.693(2R)C = 1.386RC$$
6. Calculate the frequency (f):
$$f = \frac{1}{1.386RC}$$
7. **Design Process:** Select a standard capacitor C, substitute the desired frequency f and solve for the common resistor value R.

Worked Example:

Design of a 50 Percent Duty Cycle Oscillator Design an astable multivibrator using IC 555 that produces a 50% duty cycle square wave at a frequency of 2 kHz.

Solution:

1. **Recognize Required Circuit:** A 50% duty cycle requires the addition of a bypass diode across R_B and making $R_A = R_B = R$.
2. **Identify Requirements:** $f = 2$ kHz, $D = 50\%$.
3. **Select Capacitor:** Choose a standard capacitor value, e.g. $C = 0.047\mu$F.
4. **Calculate the Resistor Value (R):** Use the modified frequency formula:
$$f = \frac{1}{1.386RC}$$
$$2000 = \frac{1}{1.386 \times R \times 0.047 \times 10^{-6}}$$
$$R = \frac{1}{2000 \times 1.386 \times 0.047 \times 10^{-6}}$$
$$R = \frac{1}{1.30284 \times 10^{-4}} \approx 7675\ \Omega = 7.67\ \text{k}\Omega$$
5. **Final Component Values:** $R_A = 7.67$ kΩ, $R_B = 7.67$ kΩ, $C = 0.047\mu$F and a diode across R_B pointing towards the capacitor.

5.3 Monostable Multivibrator using IC 555

Methodology:

Analysis and Design of Monostable Multivibrator A monostable multivibrator generates a single output pulse of a specific duration when triggered by an external input. The pulse width depends on a single resistor (R) and capacitor (C).

Analysis Steps:

1. Identify the timing resistor R and timing capacitor C.
2. Calculate the output pulse width (T):
$$T = 1.1RC$$

Design Steps:

1. Identify the desired output pulse duration (T).
2. Select a suitable standard value for the timing capacitor C (e.g. 1μF or 10μF).
3. Use the pulse width formula to calculate the required value for resistor R:
$$R = \frac{T}{1.1C}$$
4. Ensure the calculated resistance is practical (between 1 kΩ and 10 MΩ). If not, choose a different capacitor value and recalculate.

Worked Example:

Calculating Pulse Width of Monostable Multivibrator In an IC 555 monostable multivibrator, the timing components are $R = 100$ kΩ and $C = 10\mu$F. Find the duration of the output pulse.

Solution:

1. **Identify Given Values:** $R = 100 \times 10^3\ \Omega$, $C = 10 \times 10^{-6}$ F.
2. **Calculate Output Pulse Width (T):**
$$\begin{aligned} T &= 1.1RC \\ &= 1.1 \times (100 \times 10^3) \times (10 \times 10^{-6}) \\ &= 1.1 \times 1 \\ &= 1.1 \text{ seconds} \end{aligned}$$
3. **Conclusion:** The duration of the output pulse is 1.1 seconds.

Worked Example:

Designing a Monostable Timer Design a monostable timer using IC 555 to provide an output pulse width of 5 ms.

Solution:

1. **Identify Requirements:** Desired pulse width, $T = 5$ ms $= 5 \times 10^{-3}$ s.
2. **Select Capacitor:** Choose a practical capacitor value, e.g. $C = 0.1\mu\text{F} = 0.1 \times 10^{-6}$ F.
3. **Calculate Resistor Value (R):**
$$T = 1.1RC$$
$$5 \times 10^{-3} = 1.1 \times R \times 0.1 \times 10^{-6}$$

$$R = \frac{5 \times 10^{-3}}{1.1 \times 0.1 \times 10^{-6}}$$
$$R = \frac{5 \times 10^{-3}}{0.11 \times 10^{-6}}$$
$$R \approx 45454\ \Omega = 45.45\ \text{k}\Omega$$

4. **Final Component Values:** $R = 45.45$ kΩ (use a standard 47 kΩ resistor or a variable resistor for precision) and $C = 0.1\mu$F.

5.4 Sequential Timer using IC 555

Methodology:

Design of Sequential Timer A sequential timer coordinates multiple events to occur one after another. It is constructed by cascading multiple IC 555 monostable multivibrators. The trailing edge (falling edge) of the output pulse from one stage is used to trigger the next stage.
Steps for Design:

1. Identify the number of sequential stages required and the time delay for each stage (T_1, T_2, T_3, etc.).
2. For Stage 1, use the monostable formula $T_1 = 1.1R_1C_1$.
3. Select a capacitor C_1 and calculate the timing resistor $R_1 = \frac{T_1}{1.1C_1}$.
4. For Stage 2, apply the formula $T_2 = 1.1R_2C_2$.
5. Select a capacitor C_2 and calculate $R_2 = \frac{T_2}{1.1C_2}$.
6. Repeat this process for all subsequent stages.
7. Note the interconnection: The output (Pin 3) of Stage n is connected to the trigger input (Pin 2) of Stage $n + 1$ via a small differentiator circuit to convert the falling edge into a sharp negative trigger pulse.

Worked Example:

Design of a Two-Stage Sequential Timer Design a two-stage sequential timer using IC 555. Stage 1 should have a delay of 2 seconds and upon its completion, Stage 2 should immediately turn ON for 4 seconds.
Solution:

1. **Identify Requirements:** Stage 1 delay (T_1) = 2 s.
   Stage 2 delay (T_2) = 4 s.
2. **Design Stage 1 (Monostable 1):**
   - Pulse width $T_1 = 2$ s.
   - Select capacitor $C_1 = 10\mu$F.
   - Calculate R_1:
   $$R_1 = \frac{T_1}{1.1C_1} = \frac{2}{1.1 \times 10 \times 10^{-6}}$$
   $$R_1 = \frac{2}{11 \times 10^{-6}} \approx 181818\ \Omega = 181.8\ \text{k}\Omega$$
3. **Design Stage 2 (Monostable 2):**
   - Pulse width $T_2 = 4$ s.

- Select capacitor $C_2 = 10\mu\text{F}$.
- Calculate R_2:

$$R_2 = \frac{T_2}{1.1C_2} = \frac{4}{1.1 \times 10 \times 10^{-6}}$$

$$R_2 = \frac{4}{11 \times 10^{-6}} \approx 363636\ \Omega = 363.6\ \text{k}\Omega$$

4. **Interconnection:** Connect the output of Stage 1 to a differentiator circuit (e.g. $0.01\mu\text{F}$ in series and 10 kΩ to V_{CC}), whose output feeds the trigger input (Pin 2) of Stage 2.

5. **Final Component Values:** Stage 1: $R_1 = 181.8$ kΩ, $C_1 = 10\mu\text{F}$.
Stage 2: $R_2 = 363.6$ kΩ, $C_2 = 10\mu\text{F}$.

Formulae

Appendix: Formulae

Amplifiers (Negative Feedback)

- **Closed-Loop Voltage Gain (A_f):**

$$A_f = \frac{A}{1 + A\beta}$$

where A is the open-loop gain and β is the feedback factor.

- **Feedback in Decibels (N):**

$$N = 20\log_{10}\left(\frac{A}{A_f}\right) = 20\log_{10}(1 + A\beta)$$

- **Fractional Change in Gain (Sensitivity):**

$$\frac{\Delta A_f}{A_f} = \frac{1}{1 + A\beta}\left(\frac{\Delta A}{A}\right)$$

- **Desensitivity (D):**

$$D = 1 + A\beta$$

- **Bandwidth with Feedback (BW_f):**

$$BW_f = BW_{open} \times (1 + A\beta)$$

- **Cutoff Frequencies with Feedback (f_{1f}, f_{2f}):**

$$f_{1f} = \frac{f_1}{1 + A\beta}, \quad f_{2f} = f_2(1 + A\beta)$$

- **Distortion with Feedback (D_f):**

$$D_f = \frac{D}{1 + A\beta}$$

- **Input Impedance with Feedback (Z_{if}):**

$$Z_{if} = Z_i(1 + A\beta) \quad \text{(Series Mixing)}$$

$$Z_{if} = \frac{Z_i}{1 + A\beta} \quad \text{(Shunt Mixing)}$$

- **Output Impedance with Feedback (Z_{of}):**

$$Z_{of} = \frac{Z_o}{1 + A\beta} \quad \text{(Voltage Sampling)}$$

$$Z_{of} = Z_o(1 + A\beta) \quad \text{(Current Sampling)}$$

Oscillators (Positive Feedback)

- **Barkhausen Criterion for Sustained Oscillations:**

$$|A\beta| \geq 1, \quad \angle A\beta = 0^\circ \text{ or } 360^\circ$$

- **LC Resonant Frequency:**

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

- **Hartley Oscillator:**

$$L_{eq} = L_1 + L_2 + 2M \quad \text{(with mutual inductance)}$$

$$f = \frac{1}{2\pi\sqrt{L_{eq}C}}, \quad \beta = \frac{L_2}{L_1}$$

$$A_{min} = \frac{1}{\beta} = \frac{L_1}{L_2}$$

- **Colpitts Oscillator:**

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

$$f = \frac{1}{2\pi\sqrt{LC_{eq}}}, \quad \beta = \frac{C_1}{C_2}$$

- **Wien Bridge Oscillator:**

$$f = \frac{1}{2\pi RC}$$

$$A = 1 + \frac{R_f}{R_i} \geq 3 \implies R_f \geq 2R_i$$

- **UJT Relaxation Oscillator Time Period:**

$$T = RC \ln\left(\frac{1}{1-\eta}\right)$$

- **Crystal Oscillator Frequencies:**

$$f_s = \frac{1}{2\pi\sqrt{L_s C_s}} \quad \text{(Series Resonance)}$$

$$C_{eq} = \frac{C_s C_p}{C_s + C_p}, \quad f_p = \frac{1}{2\pi\sqrt{L_s C_{eq}}} \quad \text{(Parallel Resonance)}$$

Power Amplifiers

- **DC Input Power:**

$$P_{DC} = V_{CC} \times I_{CQ}$$

- **AC Output Power:**

$$P_{AC} = \frac{V_p \times I_p}{2} = \frac{V_p^2}{2R_L} = \frac{I_p^2 R_L}{2}$$

$$P_{AC} = \frac{V_{p-p} \times I_{p-p}}{8} = \frac{V_{p-p}^2}{8R_L} = \frac{I_{p-p}^2 R_L}{8}$$

- **Efficiency (η):**

$$\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$$

- **Power Dissipation (P_D):**

$$P_D = P_{DC} - P_{AC}$$

- **Transformer-Coupled Amplifier Reflected Load:**

$$R'_L = a^2 R_L = \left(\frac{N_1}{N_2}\right)^2 R_L$$

- **Class B Push-Pull Amplifier:**

$$I_{DC} = \frac{2I_p}{\pi}$$

$$P_{DC} = V_{CC} \times I_{DC} = \frac{2V_{CC}I_p}{\pi}$$

$$\text{Total } P_{D(\max)} = \frac{2V_{CC}^2}{\pi^2 R_L}$$

- **Harmonic Distortion:**

$$D_n = \frac{|A_n|}{|A_1|} \times 100\%$$

$$\text{THD} = \sqrt{D_2^2 + D_3^2 + D_4^2 + \dots}$$

$$P_{total} = P_1(1 + \text{THD}^2)$$

Operational Amplifiers (Op-Amps)

- **Input Bias and Offset Current:**

$$I_B = \frac{I_{B1} + I_{B2}}{2}, \quad I_{io} = |I_{B1} - I_{B2}|$$

- **Common-Mode Rejection Ratio (CMRR):**

$$\text{CMRR} = \frac{A_d}{A_c}$$

$$\text{CMRR (dB)} = 20\log_{10}\left(\frac{A_d}{A_c}\right)$$

- **General Output Voltage Equation:**

$$V_o = A_d V_d + A_c V_c$$

- **Slew Rate (SR) and Maximum Operating Frequency:**

$$\text{SR} = \frac{\Delta V_o}{\Delta t}$$

$$f_{max} = \frac{\text{SR}}{2\pi V_m}$$

- **Inverting Amplifier:**

$$A_v = -\frac{R_f}{R_{in}}, \quad V_{out} = -\left(\frac{R_f}{R_{in}}\right) V_{in}$$

- **Non-Inverting Amplifier:**

$$A_v = 1 + \frac{R_f}{R_1}, \quad V_{out} = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

- **Summing Amplifier (Inverting):**

$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \cdots + \frac{R_f}{R_n}V_n\right)$$

- **Difference Amplifier:**

$$V_{out} = \left(\frac{R_1 + R_f}{R_1}\right)\left(\frac{R_g}{R_2 + R_g}\right)V_2 - \left(\frac{R_f}{R_1}\right)V_1$$

$$V_{out} = \frac{R_f}{R_1}(V_2 - V_1) \quad (\text{if } R_1 = R_2 \text{ and } R_f = R_g)$$

- **Integrator:**

$$V_{out}(t) = -\frac{1}{RC}\int_0^t V_{in}(t)\,dt + V_{out}(0)$$

Timer Circuits

- **555 Timer Monostable Multivibrator:**

$$T = 1.1RC$$

- **555 Timer Astable Multivibrator:**

$$T_H = 0.693(R_A + R_B)C \quad (\text{Time High})$$

$$T_L = 0.693R_BC \quad (\text{Time Low})$$

$$T = T_H + T_L = 0.693(R_A + 2R_B)C \quad (\text{Total Time Period})$$

$$f = \frac{1}{T} = \frac{1.44}{(R_A + 2R_B)C} \quad (\text{Frequency})$$

$$\%D = \frac{T_H}{T} \times 100\% = \left(\frac{R_A + R_B}{R_A + 2R_B}\right) \times 100\% \quad (\text{Duty Cycle})$$

- **555 Timer Modified Astable (50% Duty Cycle using a Diode):**

$$T_H = 0.693R_AC, \quad T_L = 0.693R_BC$$

$$\text{If } R_A = R_B = R: \quad T = 1.386RC, \quad f = \frac{1}{1.386RC}$$