Ie (4331103) - Problem Solver

Antigravity AI

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Ie

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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.

I am deeply thankful to my family for their unwavering patience and support during the countless hours spent researching, formatting, and refining these chapters.

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.

Antigravity AI

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

Introduction to Thyristors

1.1 Two Transistor Analogy of SCR

The two-transistor analogy models the Silicon Controlled Rectifier (SCR) as an interconnected PNP and NPN transistor. This mathematical model is crucial for understanding how the device switches from a blocking state to a conducting state and is used to compute the anode current based on the current gains of the constituent transistors.

Methodology:

Calculation of Anode Current using Two Transistor Model To calculate the anode current of an SCR using the two-transistor analogy, follow these steps:

1. Identify the common-base current gains of the internal PNP transistor (α_1) and the NPN transistor (α_2).
2. Identify the leakage currents of the two transistor sections (I_{CO1} and I_{CO2}).
3. Identify the applied gate current (I_G).
4. Use the total anode current formula to compute I_A:

$$I_A = \frac{\alpha_2 I_G + I_{CO1} + I_{CO2}}{1 - (\alpha_1 + \alpha_2)}$$

5. If the total combined leakage current is given as $I_{CO} = I_{CO1} + I_{CO2}$ rather than separate values, the formula simplifies to:

$$I_A = \frac{\alpha_2 I_G + I_{CO}}{1 - (\alpha_1 + \alpha_2)}$$

Worked Example:

Finding Anode Current in an SCR An SCR is modeled using two transistors with current gains $\alpha_1 = 0.45$ and $\alpha_2 = 0.48$. The total combined leakage current is given as $I_{CO} = 1.5$ mA. If a gate current of $I_G = 30$ mA is applied to trigger the device, calculate the resulting anode current.

Step 1: Identify given parameters.

- $\alpha_1 = 0.45$
- $\alpha_2 = 0.48$
- $I_{CO} = 1.5 \text{ mA} = 1.5 \times 10^{-3}$ A
- $I_G = 30 \text{ mA} = 30 \times 10^{-3}$ A

Step 2: Apply the simplified anode current formula.

$$I_A = \frac{\alpha_2 I_G + I_{CO}}{1 - (\alpha_1 + \alpha_2)}$$

Step 3: Substitute the values and compute.

$$I_A = \frac{0.48(30) + 1.5}{1 - (0.45 + 0.48)} \text{ mA}$$
$$I_A = \frac{14.4 + 1.5}{1 - 0.93} \text{ mA}$$
$$I_A = \frac{15.9}{0.07} \text{ mA}$$
$$I_A = 227.14 \text{ mA}$$

The calculated anode current is 227.14 mA.

1.2 UJT as a Relaxation Oscillator

The Unijunction Transistor (UJT) exhibits negative resistance characteristics which makes it an ideal component for relaxation oscillator circuits. These oscillators are predominantly used for generating sharp triggering pulses for SCRs and TRIACs.

Methodology:

Analysis of UJT Relaxation Oscillator To analyze and design a UJT relaxation oscillator circuit properly:

1. **Intrinsic Standoff Ratio (η):** If the internal base resistances R_{B1} and R_{B2} are known calculate η as:

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}}$$

2. **Peak Voltage (V_P):** Determine the minimum emitter voltage required to turn on the UJT:

$$V_P = \eta V_{BB} + V_D$$

where V_{BB} is the applied DC supply voltage and V_D is the diode forward voltage drop of the emitter junction (typically 0.7 V).

3. **Oscillation Frequency (f):** Compute the frequency based on the external timing resistor R and capacitor C:

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

4. **Limits on Timing Resistor (R):** To ensure the UJT successfully turns on and turns off the timing resistor must fall within absolute limits:

$$R_{min} = \frac{V_{BB} - V_V}{I_V}$$

$$R_{max} = \frac{V_{BB} - V_P}{I_P}$$

where V_V and I_V are the valley voltage and current while I_P is the peak point current.

Worked Example:

Calculating Frequency and Resistance Limits for UJT Oscillator A UJT relaxation oscillator operates from a $V_{BB} = 20$ V DC supply. The selected UJT possesses the following electrical parameters: $\eta = 0.6$, $I_P = 10\ \mu$A, $V_V = 2$ V, $I_V = 10$ mA. The emitter diode voltage drop is assumed to be $V_D = 0.7$ V. The external timing components used are $R = 50$ kΩ and $C = 0.1\ \mu$F.
Find the peak voltage V_P the oscillation frequency and verify whether the chosen timing resistance R allows reliable oscillation.

Step 1: Calculate the peak voltage V_P.

$$V_P = \eta V_{BB} + V_D = 0.6(20) + 0.7 = 12 + 0.7 = 12.7 \text{ V}$$

Step 2: Calculate the frequency of oscillation. The time period T is calculated first:

$$T = RC \ln\left(\frac{1}{1-\eta}\right) = (50 \times 10^3)(0.1 \times 10^{-6}) \ln\left(\frac{1}{1-0.6}\right)$$

$$T = 0.005 \times \ln(2.5) \approx 0.005 \times 0.9163 = 0.00458 \text{ s} = 4.58 \text{ ms}$$

The frequency f is:

$$f = \frac{1}{T} = \frac{1}{0.00458} \approx 218.3 \text{ Hz}$$

Step 3: Determine the functional limits for resistor R.

$$R_{max} = \frac{V_{BB} - V_P}{I_P} = \frac{20 - 12.7}{10 \times 10^{-6}} = \frac{7.3}{10 \times 10^{-6}} = 730 \text{ k}\Omega$$

$$R_{min} = \frac{V_{BB} - V_V}{I_V} = \frac{20 - 2}{10 \times 10^{-3}} = \frac{18}{10 \times 10^{-3}} = 1.8 \text{ k}\Omega$$

Step 4: Verify the chosen resistor. Since $R_{min}(1.8 \text{ k}\Omega) < R(50 \text{ k}\Omega) < R_{max}(730 \text{ k}\Omega)$ the chosen resistance value guarantees reliable periodic oscillation.

1.3 Resistance Triggering of SCR

R-triggering is the simplest and most basic form of generating firing pulses for an SCR directly from an AC supply. It allows adjusting the firing angle between 0° and slightly less than 90°.

Methodology:

Design of Resistance Triggering Circuit To mathematically deduce the firing angle or design the resistance required to trigger an SCR from an AC source:

1. Identify the input AC supply voltage equation $v_s(t) = V_m \sin(\omega t)$ where V_m is the peak voltage.
2. Identify the minimum gate trigger voltage (V_{GT}) and gate trigger current (I_{GT}) required to turn on the particular SCR.
3. The total resistance R in the gate circuit serves to limit the current. The SCR successfully triggers at an angle α precisely when the instantaneous source voltage is high enough to supply V_{GT} plus the voltage drop across the series gate resistance.
4. Use the governing triggering formula to evaluate the firing angle α:

$$V_m \sin(\alpha) = V_{GT} + I_{GT} R$$

5. To design a circuit for a specific desired firing angle isolate R:

$$R = \frac{V_m \sin(\alpha) - V_{GT}}{I_{GT}}$$

Worked Example:

Determining the Firing Angle and Resistance An SCR is deployed in a half-wave rectifier supplied by a 230 V (RMS) AC source. The datasheet for the SCR specifies a gate trigger voltage requirement of $V_{GT} = 1.5$ V and a gate trigger current requirement of $I_{GT} = 40$ mA. Calculate the exact resistance that must be inserted in the gate circuit to fire the SCR at an angle of 45°.

Step 1: Determine the peak supply voltage V_m. The given RMS voltage is $V_{rms} = 230$ V.

$$V_m = \sqrt{2} \times V_{rms} = \sqrt{2} \times 230 \approx 325.27 \text{ V}$$

Step 2: Use the mathematical triggering condition to find R. We desire the firing angle $\alpha = 45°$.

$$V_m \sin(\alpha) = V_{GT} + I_{GT} R$$

$$325.27 \sin(45°) = 1.5 + (40 \times 10^{-3}) R$$

Step 3: Solve algebraically for R.

$$325.27 \times 0.7071 = 1.5 + 0.04R$$

$$230 = 1.5 + 0.04R$$

$$228.5 = 0.04R$$

$$R = \frac{228.5}{0.04} = 5712.5\ \Omega \approx 5.71\ \text{k}\Omega$$

To successfully achieve a firing angle of 45° a total gate series resistance of 5.71 kΩ is necessary.

1.4 Thermal Resistance and Heat Sink Calculations

Thyristors handle significant current and as a result dissipate power in the form of heat primarily due to forward conduction losses. To safely transport this heat away and prevent device destruction due to overheating heat sinks are strictly required.

Methodology:

Thermal Calculation for SCR Heat Sinks To calculate thermal constraints and evaluate heat sink requirements apply thermal physics principles:

1. Identify the absolute maximum allowable junction temperature (T_j), the worst-case ambient operating temperature (T_a), and the average power dissipated by the thyristor (P_{avg}).
2. Identify the specific thermal resistances acting in series within the system:
   - θ_{jc}: Junction-to-case thermal resistance (°C/W)
   - θ_{cs}: Case-to-sink thermal resistance (°C/W)
   - θ_{sa}: Sink-to-ambient thermal resistance (°C/W)
3. Model the thermal circuit using the equilibrium equation:

$$T_j - T_a = P_{avg}(\theta_{jc} + \theta_{cs} + \theta_{sa})$$

4. Solve for the specific unknown parameter. For instance when selecting an appropriate heat sink isolate θ_{sa}:

$$\theta_{sa} = \frac{T_j - T_a}{P_{avg}} - (\theta_{jc} + \theta_{cs})$$

Worked Example:

Calculating Required Thermal Resistance of a Heat Sink An SCR component is meant to operate continuously in an environment featuring an ambient temperature of 40°C and will dissipate an average power of 25 W. The manufacturer specifies a maximum allowable junction temperature of 125°C. The junction-to-case thermal resistance is rated at 1.2°C/W and the thermal paste creates a case-to-sink thermal resistance of

0.3°C/W. Calculate the maximum permissible thermal resistance of the external heat sink (θ_{sa}) required to cool this SCR.

Step 1: List the known thermal parameters.

- $T_a = 40°\text{C}$
- $T_j = 125°\text{C}$
- $P_{avg} = 25 \text{ W}$
- $\theta_{jc} = 1.2°\text{C/W}$
- $\theta_{cs} = 0.3°\text{C/W}$

Step 2: Apply the governing thermal equilibrium equation.

$$T_j - T_a = P_{avg}(\theta_{jc} + \theta_{cs} + \theta_{sa})$$

Step 3: Substitute the known quantities into the equation.

$$125 - 40 = 25(1.2 + 0.3 + \theta_{sa})$$

$$85 = 25(1.5 + \theta_{sa})$$

Step 4: Solve algebraically for the required sink thermal resistance θ_{sa}.

$$\frac{85}{25} = 1.5 + \theta_{sa}$$

$$3.4 = 1.5 + \theta_{sa}$$

$$\theta_{sa} = 3.4 - 1.5 = 1.9°\text{C/W}$$

To guarantee the junction temperature safely remains at or below 125°C the selected heat sink must possess a thermal resistance of exactly 1.9°C/W or less.

CHAPTER 2

Turn on and Turn off methods of Thyristor

In power electronics, the successful turn-on (triggering) and turn-off (commutation) of thyristors are fundamental to circuit operation. Because thyristors are semi-controlled devices, they require external circuits to initiate conduction and to force them back into the blocking state when operating on DC supplies. Furthermore, protection circuits must be carefully calculated to prevent device destruction during rapid voltage or current transitions.

2.1 Triggering Methods of SCR

A thyristor can be turned on by several methods: forward voltage triggering, thermal triggering, dv/dt triggering, light triggering, and gate triggering. Gate triggering is the most efficient and reliable method. Among gate triggering techniques, the UJT (Unijunction Transistor) relaxation oscillator is widely used due to its ability to generate sharp, synchronized pulses.

Methodology:

UJT Relaxation Oscillator Design A UJT relaxation oscillator generates a train of pulses used to trigger the SCR. The design involves selecting appropriate values for the timing resistor R and capacitor C based on the UJT parameters.

1. Given Parameters:

- V_{BB}: DC supply voltage.
- η: Intrinsic stand-off ratio.
- V_D: Forward voltage drop of the emitter diode (typically 0.5 V to 0.8 V).
- I_p, I_v: Peak point and valley point currents.
- V_v: Valley point voltage.

2. Key Formulas:

- **Peak Voltage (V_p):** The voltage at which the UJT fires.

$$V_p = \eta V_{BB} + V_D$$

- **Time Period (T):** The time taken for capacitor C to charge up to V_p.

$$T = R \cdot C \ln\left(\frac{1}{1-\eta}\right)$$

- **Frequency of Oscillation (f):**

$$f = \frac{1}{T}$$

- **Resistor Limits:** To ensure the UJT reliably turns on and turns off, the charging resistor R must fall within a specific range:

$$R_{min} \leq R \leq R_{max}$$

Where:

$$R_{max} = \frac{V_{BB} - V_p}{I_p} \quad \text{and} \quad R_{min} = \frac{V_{BB} - V_v}{I_v}$$

Worked Example:

Design of UJT Oscillator **Problem:** Design a UJT relaxation oscillator to generate a triggering pulse train of 1 kHz. The DC supply voltage V_{BB} is 20 V. The UJT has the following parameters: $\eta = 0.66$, $I_p = 10\,\mu$A, $I_v = 10$ mA, $V_v = 2$ V, and diode drop $V_D = 0.8$ V. Assume the timing capacitor $C = 0.1\,\mu$F. Verify if the calculated resistor R permits reliable operation.

Step 1: Calculate the required Time Period.

$$T = \frac{1}{f} = \frac{1}{1000} = 1 \text{ ms} = 1 \times 10^{-3} \text{ s}$$

Step 2: Calculate the timing resistor R. Using the time period formula:

$$T = R \cdot C \ln\left(\frac{1}{1-\eta}\right)$$

$$1 \times 10^{-3} = R \times (0.1 \times 10^{-6}) \times \ln\left(\frac{1}{1-0.66}\right)$$

$$1 \times 10^{-3} = R \times 10^{-7} \times \ln(2.941)$$

$$1 \times 10^{-3} = R \times 10^{-7} \times 1.078$$

$$R = \frac{10^{-3}}{1.078 \times 10^{-7}} \approx 9276\ \Omega = 9.276\ \text{k}\Omega$$

Step 3: Calculate the Peak Voltage V_p.

$$V_p = \eta V_{BB} + V_D = (0.66 \times 20) + 0.8 = 13.2 + 0.8 = 14 \text{ V}$$

Step 4: Check if R is within operational limits. Calculate maximum allowed resistance (R_{max}):

$$R_{max} = \frac{V_{BB} - V_p}{I_p} = \frac{20 - 14}{10 \times 10^{-6}} = \frac{6}{10 \times 10^{-6}} = 600\ \text{k}\Omega$$

Calculate minimum allowed resistance (R_{min}):

$$R_{min} = \frac{V_{BB} - V_v}{I_v} = \frac{20 - 2}{10 \times 10^{-3}} = \frac{18}{10 \times 10^{-3}} = 1.8\ \text{k}\Omega$$

Since $1.8\ \text{k}\Omega \leq 9.276\ \text{k}\Omega \leq 600\ \text{k}\Omega$, the calculated value of R is valid and will ensure proper turning on and turning off of the UJT.

2.2 Thyristor Protection

Thyristors are sensitive to excessive rates of current rise (di/dt), excessive rates of voltage rise (dv/dt), over-voltages, and gate irregularities.

- **Over-current and di/dt protection:** Handled by fast-acting fuses and series inductors. A series inductor limits the initial rate of rise of anode current.
- **Over-voltage and dv/dt protection:** Handled by nonlinear resistors (varistors) for surges, and snubber circuits (RC networks) in parallel with the SCR for dv/dt limits.

- **Gate protection:** Zener diodes are connected across the gate-cathode terminals to limit over-voltage, and a series resistor limits gate over-current.

Methodology:

Snubber Circuit and Series Inductor Design To protect the SCR during transitions, a series inductor (L) and a parallel snubber circuit (resistor R_s and capacitor C_s) are used.
1. Design of Series Inductor for di/dt Protection: When the SCR is turned on, the initial rate of change of current is limited solely by the series inductance.

$$L = \frac{V_{max}}{(di/dt)_{max}}$$

Where V_{max} is the maximum supply voltage and $(di/dt)_{max}$ is the maximum allowable rate of rise of current for the SCR.
2. Design of Snubber Circuit for dv/dt Protection: When a step voltage is suddenly applied to the circuit (with the SCR off), the LC_s combination forms an underdamped resonant circuit. The maximum rate of rise of voltage across the SCR is approximated by:

$$\left(\frac{dv}{dt}\right)_{max} = \frac{V_{max}}{\sqrt{LC_s}}$$

Rearranging this gives the value of the snubber capacitor:

$$C_s = \frac{V_{max}^2}{L \cdot \left(\frac{dv}{dt}\right)_{max}^2}$$

To limit the peak discharge current of C_s when the SCR is subsequently turned on, and to damp the oscillations, a snubber resistor R_s is inserted. If a specific damping factor ζ (typically between 0.5 and 0.7) is required:

$$R_s = 2\zeta\sqrt{\frac{L}{C_s}}$$

Worked Example:

Design of Snubber and di by dt Inductor **Problem:** A thyristor operates on a DC supply of 300 V. The specified ratings for the thyristor are $(di/dt)_{max} = 60$ A/μs and $(dv/dt)_{max} = 150$ V/μs. Determine the values of the series inductor L and the snubber circuit parameters R_s and C_s. Assume the required damping factor ζ is 0.6.
Step 1: Calculate the Series Inductor L.

$$L = \frac{V_{max}}{(di/dt)_{max}} = \frac{300}{60 \times 10^6 \text{ A/s}} = 5 \times 10^{-6} \text{ H} = 5\,\mu\text{H}$$

Step 2: Calculate the Snubber Capacitor C_s.

$$C_s = \frac{V_{max}^2}{L \cdot \left(\frac{dv}{dt}\right)_{max}^2}$$

Substitute the known values:

$$C_s = \frac{300^2}{5 \times 10^{-6} \times (150 \times 10^6)^2}$$

$$C_s = \frac{90000}{5 \times 10^{-6} \times 22500 \times 10^{12}} = \frac{90000}{112500 \times 10^6}$$

$$C_s = 0.8 \times 10^{-6} \text{ F} = 0.8\,\mu\text{F}$$

Step 3: Calculate the Snubber Resistor R_s.

$$R_s = 2\zeta\sqrt{\frac{L}{C_s}}$$

$$R_s = 2 \times 0.6 \times \sqrt{\frac{5 \times 10^{-6}}{0.8 \times 10^{-6}}}$$

$$R_s = 1.2 \times \sqrt{6.25} = 1.2 \times 2.5 = 3\ \Omega$$

Therefore, the designed values are $L = 5\,\mu\text{H}$, $C_s = 0.8\,\mu\text{F}$, and $R_s = 3\ \Omega$.

2.3 Commutation Techniques of SCR

Commutation is the process of turning off an conducting SCR. While natural commutation occurs automatically in AC circuits when the current crosses zero, forced commutation is required in DC circuits. The external circuits force the SCR current to zero and reverse bias it for a duration greater than its turn-off time t_q. The primary forced commutation techniques are categorized from Class A to Class F. For computational analysis, Class C (Complementary) and Class D (Impulse) commutation are most prominent.

Methodology:

Class C Commutation Circuit Parameters Class C commutation, also known as complementary commutation, employs two SCRs (T_1 and T_2). Triggering one SCR automatically reverse-biases and turns off the other.
1. Load Current: The steady-state load currents through the parallel branches are:

$$I_{L1} = \frac{V_s}{R_1} \quad \text{and} \quad I_{L2} = \frac{V_s}{R_2}$$

2. Circuit Turn-off Time (t_c): When T_2 is triggered to turn off T_1, the commutating capacitor C (initially charged to V_s) discharges through R_1. The time t_{c1} for which T_1 is reverse-biased is:

$$t_{c1} = R_1 C \ln(2) \approx 0.693 R_1 C$$

Similarly, to turn off T_2:

$$t_{c2} = R_2 C \ln(2) \approx 0.693 R_2 C$$

For successful commutation, the circuit turn-off time t_c must be greater than the device turn-off time t_q.
3. Peak SCR Current: When an SCR is triggered, it carries its own load current plus the charging current of the capacitor. The peak current through T_1 is:

$$I_{T1(peak)} = \frac{V_s}{R_1} + \frac{2V_s}{R_2}$$

The peak current through T_2 is:

$$I_{T2(peak)} = \frac{V_s}{R_2} + \frac{2V_s}{R_1}$$

Worked Example:

Capacitor Calculation for Class C Commutation **Problem:** A Class C commutation circuit is connected to a DC supply of $V_s = 200$ V. The load resistances in the two branches are $R_1 = 15\ \Omega$ and $R_2 = 40\ \Omega$. The device turn-off time is $t_q = 30\,\mu$s. Determine the minimum commutating capacitor C required to ensure both SCRs turn off successfully, and find the peak current flowing through each SCR.
Step 1: Calculate Minimum Capacitance for T_1. To turn off T_1 successfully:

$$t_{c1} \geq t_q \implies 0.693 R_1 C_1 \geq t_q$$

$$C_1 \geq \frac{30 \times 10^{-6}}{0.693 \times 15} = \frac{30 \times 10^{-6}}{10.395} \approx 2.886\,\mu\text{F}$$

Step 2: Calculate Minimum Capacitance for T_2. To turn off T_2 successfully:

$$t_{c2} \geq t_q \implies 0.693 R_2 C_2 \geq t_q$$

$$C_2 \geq \frac{30 \times 10^{-6}}{0.693 \times 40} = \frac{30 \times 10^{-6}}{27.72} \approx 1.082\,\mu\text{F}$$

Step 3: Select the Final Capacitor Value. To ensure both devices commutate reliably, the capacitor must be large enough to satisfy both conditions. We must select the larger of the two values.

$$C = 2.886\,\mu\text{F (Standard value of } 3\,\mu\text{F could be chosen)}$$

Step 4: Calculate Peak Currents for T_1 and T_2. For T_1:

$$I_{T1(peak)} = \frac{V_s}{R_1} + \frac{2V_s}{R_2} = \frac{200}{15} + \frac{2 \times 200}{40} = 13.33 + \frac{400}{40} = 13.33 + 10 = 23.33 \text{ A}$$

For T_2:

$$I_{T2(peak)} = \frac{V_s}{R_2} + \frac{2V_s}{R_1} = \frac{200}{40} + \frac{2 \times 200}{15} = 5 + \frac{400}{15} = 5 + 26.67 = 31.67 \text{ A}$$

Methodology:

Class D Commutation Circuit Parameters Class D commutation, or impulse commutation, utilizes an auxiliary SCR (T_A) alongside a resonant LC circuit to turn off the main SCR (T_M).

1. Peak Ringing Current (I_p): When T_M turns on, the initially charged capacitor rings through the inductor L and T_M. The peak of this resonant current is:

$$I_p = V_s\sqrt{\frac{C}{L}}$$

For reliable operation, I_p must be strictly greater than the load current I_o. Commonly, $I_p \geq 1.5I_o$.

2. Circuit Turn-off Time (t_c): When the auxiliary SCR T_A fires, the main SCR is reverse-biased by the capacitor voltage. Assuming the load current I_o remains constant during commutation, it discharges the capacitor linearly. The time taken for the capacitor voltage to fall from $-V_s$ to 0 is the turn-off time t_c:

$$t_c = \frac{C \cdot V_s}{I_o}$$

This value t_c must be greater than the device turn-off time t_q.

3. Component Design Relations: From the above, commutating capacitor C is found directly:

$$C = \frac{I_o \cdot t_c}{V_s}$$

Once C is determined and I_p is assumed based on the safety factor, the commutating inductor L is evaluated as:

$$L = C\left(\frac{V_s}{I_p}\right)^2$$

Worked Example:

Design of Class D Commutation Circuit **Problem:** Design the commutating components (L and C) for a Class D commutation circuit. The main SCR carries a constant load current $I_o = 50$ A from a DC source $V_s = 250$ V. The turn-off time of the main SCR is $t_q = 40\,\mu$s. The design requires the circuit turn-off time t_c to be 1.5 times t_q, and the peak ringing current I_p to be double the load current.

Step 1: Determine Circuit Turn-off Time (t_c) and Peak Ringing Current (I_p).

$$t_c = 1.5 \times t_q = 1.5 \times 40\,\mu\text{s} = 60\,\mu\text{s} = 60 \times 10^{-6} \text{ s}$$

$$I_p = 2 \times I_o = 2 \times 50 = 100 \text{ A}$$

Step 2: Calculate Commutating Capacitor C. Using the turn-off time equation:

$$C = \frac{I_o \cdot t_c}{V_s} = \frac{50 \times 60 \times 10^{-6}}{250} = \frac{3000 \times 10^{-6}}{250} = 12\,\mu\text{F}$$

Step 3: Calculate Commutating Inductor L. Using the peak current equation:

$$L = C\left(\frac{V_s}{I_p}\right)^2$$

Substitute the known values:

$$L = 12 \times 10^{-6} \times \left(\frac{250}{100}\right)^2$$

$$L = 12 \times 10^{-6} \times (2.5)^2$$

$$L = 12 \times 10^{-6} \times 6.25 = 75\,\mu\text{H}$$

The required commutating components are $C = 12\,\mu\text{F}$ and $L = 75\,\mu\text{H}$.

CHAPTER 3

Power Converters

Power converters form the foundation of industrial electronics by allowing the transformation of electrical energy from one form to another. This chapter focuses on the computational aspects of phase-controlled rectifiers (AC to DC), DC-DC choppers, and inverters (DC to AC).

3.1 Phase-Controlled Rectifiers

Phase-controlled rectifiers convert AC voltage to variable DC voltage using thyristors (SCRs). The output voltage is controlled by varying the firing angle (α) of the thyristors.

Methodology:

Single Phase Half Wave Controlled Rectifier For a single-phase half-wave controlled rectifier with a resistive load R and a firing angle α:

1. **Maximum Input Voltage:** $V_m = \sqrt{2} \times V_s$ where V_s is the RMS input voltage.
2. **Average DC Output Voltage:**
$$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$
3. **Average DC Load Current:** $I_{dc} = \frac{V_{dc}}{R}$
4. **RMS Output Voltage:**
$$V_{rms} = \frac{V_m}{2}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}}$$
Note: α must be in radians when used outside trigonometric functions (i.e., in the $\frac{\alpha}{\pi}$ term).
5. **DC Output Power:** $P_{dc} = V_{dc} \times I_{dc} = \frac{V_{dc}^2}{R}$

Worked Example:

Analysis of Half Wave Controlled Rectifier A single-phase half-wave controlled rectifier is connected to a 230 V, 50 Hz AC supply. The load is purely resistive with $R = 100\Omega$ and the firing angle is $\alpha = 60°$. Calculate the average output voltage and average load current.

Solution:

1. **Identify given parameters:** $V_s = 230$ V, $R = 100\Omega$, $\alpha = 60°$.
2. **Calculate maximum input voltage V_m:**
$$V_m = \sqrt{2} \times V_s = \sqrt{2} \times 230 = 325.27 \text{ V}$$
3. **Calculate average DC output voltage V_{dc}:**
$$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

$$V_{dc} = \frac{325.27}{2\pi}(1 + \cos(60°))$$

$$V_{dc} = 51.77 \times (1 + 0.5) = 51.77 \times 1.5 = 77.65 \text{ V}$$

4. **Calculate average load current I_{dc}:**

$$I_{dc} = \frac{V_{dc}}{R} = \frac{77.65}{100} = 0.7765 \text{ A}$$

Methodology:

Single Phase Full Wave Controlled Rectifier For a single-phase full-wave controlled rectifier (mid-point or bridge type) with a resistive load R and firing angle α:

1. **Maximum Input Voltage:** $V_m = \sqrt{2} \times V_s$
2. **Average DC Output Voltage:**

$$V_{dc} = \frac{V_m}{\pi}(1 + \cos\alpha)$$

3. **Average DC Load Current:** $I_{dc} = \frac{V_{dc}}{R}$
4. **RMS Output Voltage:**

$$V_{rms} = \frac{V_m}{\sqrt{2}}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}}$$

Worked Example:

Analysis of Full Wave Controlled Rectifier A single-phase full-wave bridge rectifier is supplied from a 120 V, 60 Hz source. The load resistance is 20Ω and the firing angle is set to $\alpha = 90°$. Determine the average output voltage, the RMS output voltage, and the average load current.

Solution:

1. **Identify given parameters:** $V_s = 120$ V, $R = 20\Omega$, $\alpha = 90°$ (which is $\frac{\pi}{2}$ radians).
2. **Calculate maximum input voltage V_m:**

$$V_m = \sqrt{2} \times 120 = 169.71 \text{ V}$$

3. **Calculate average output voltage V_{dc}:**

$$V_{dc} = \frac{V_m}{\pi}(1 + \cos(90°))$$

$$V_{dc} = \frac{169.71}{\pi}(1 + 0) = 54.02 \text{ V}$$

4. **Calculate average load current I_{dc}:**

$$I_{dc} = \frac{V_{dc}}{R} = \frac{54.02}{20} = 2.701 \text{ A}$$

5. **Calculate RMS output voltage V_{rms}:** Here $\alpha = \frac{\pi}{2}$ radians.

$$V_{rms} = \frac{V_m}{\sqrt{2}}\sqrt{1 - \frac{\pi/2}{\pi} + \frac{\sin(180°)}{2\pi}}$$

$$V_{rms} = \frac{169.71}{1.414}\sqrt{1 - 0.5 + 0}$$

$$V_{rms} = 120 \times \sqrt{0.5} = 120 \times 0.707 = 84.85 \text{ V}$$

3.2 DC-DC Converters (Choppers)

Choppers convert fixed DC input voltage to a variable DC output voltage. They are widely used in DC motor control and battery-operated vehicles.

Methodology:

Step Down Chopper Analysis A step-down chopper (buck converter) produces an average output voltage lower than the input voltage.

1. **Chopping Period:** $T = T_{on} + T_{off}$
2. **Chopping Frequency:** $f = \frac{1}{T}$
3. **Duty Cycle:** $D = \frac{T_{on}}{T} = \frac{T_{on}}{T_{on}+T_{off}}$
4. **Average Output Voltage:** $V_o = D \times V_s = V_s \frac{T_{on}}{T}$
5. **Average Output Current:** $I_o = \frac{V_o}{R}$

Worked Example:

Calculating Step Down Chopper Output A DC chopper operates from a 200 V DC supply. The load is purely resistive with $R = 10\Omega$. The ON time of the chopper is 2 ms and the OFF time is 3 ms. Calculate the chopping frequency, duty cycle, and average output voltage.

Solution:

1. **Identify given parameters:** $V_s = 200$ V, $R = 10\Omega$, $T_{on} = 2$ ms $= 2 \times 10^{-3}$ s, $T_{off} = 3$ ms $= 3 \times 10^{-3}$ s.
2. **Calculate chopping period T and frequency f:**

$$T = T_{on} + T_{off} = 2 \text{ ms} + 3 \text{ ms} = 5 \text{ ms} = 5 \times 10^{-3} \text{ s}$$

$$f = \frac{1}{T} = \frac{1}{5 \times 10^{-3}} = 200 \text{ Hz}$$

3. **Calculate duty cycle D:**

$$D = \frac{T_{on}}{T} = \frac{2}{5} = 0.4$$

4. **Calculate average output voltage V_o:**

$$V_o = D \times V_s = 0.4 \times 200 = 80 \text{ V}$$

Methodology:

Step Up Chopper Analysis A step-up chopper (boost converter) produces an average output voltage higher than the input voltage.

1. **Duty Cycle:** $D = \frac{T_{on}}{T}$
2. **Average Output Voltage:**

$$V_o = \frac{V_s}{1 - D} = V_s \frac{T}{T_{off}}$$

Worked Example:

Calculating Step Up Chopper Output A step-up chopper has an input voltage of 50 V. It feeds a load requiring a voltage of 150 V. If the OFF time of the chopper is 40μs, compute the required ON time and the chopping frequency.

Solution:

1. **Identify given parameters:** $V_s = 50$ V, $V_o = 150$ V, $T_{off} = 40\mu$s.
2. **Use the voltage relation to find duty cycle D:**

$$V_o = \frac{V_s}{1-D} \implies 150 = \frac{50}{1-D}$$

$$1 - D = \frac{50}{150} = \frac{1}{3}$$

$$D = 1 - \frac{1}{3} = \frac{2}{3} \approx 0.667$$

3. **Calculate chopping period T:** Since $D = \frac{T_{on}}{T}$ and $T - T_{on} = T_{off}$, we have $1 - D = \frac{T_{off}}{T}$.

$$\frac{1}{3} = \frac{40\mu\text{s}}{T} \implies T = 3 \times 40\mu\text{s} = 120\mu\text{s}$$

4. **Calculate ON time T_{on}:**

$$T_{on} = T - T_{off} = 120\mu\text{s} - 40\mu\text{s} = 80\mu\text{s}$$

5. **Calculate chopping frequency f:**

$$f = \frac{1}{T} = \frac{1}{120 \times 10^{-6}} = 8333.33 \text{ Hz} = 8.33 \text{ kHz}$$

3.3 Inverters

Inverters convert fixed DC voltage into AC voltage of variable magnitude and frequency.

Methodology:

Single Phase Bridge Inverters For a single-phase square-wave bridge inverter operating from a DC supply V_s with a resistive load R:

1. **RMS Output Voltage (V_{or}):**
   - For Half-Bridge Inverter: $V_{or} = \frac{V_s}{2}$
   - For Full-Bridge Inverter: $V_{or} = V_s$
2. **Fundamental RMS Output Voltage (V_1):** The output is a square wave which contains fundamental and harmonic components.
   - For Half-Bridge: $V_1 = \frac{2V_s}{\pi\sqrt{2}} \approx 0.45V_s$
   - For Full-Bridge: $V_1 = \frac{4V_s}{\pi\sqrt{2}} \approx 0.90V_s$
3. **Output Power (P_o):** $P_o = \frac{V_{or}^2}{R}$

Worked Example:

Performance of Single Phase Full Bridge Inverter A single-phase full-bridge inverter operates from a 100 V DC source and supplies a resistive load of 10Ω. Calculate the RMS output voltage, the fundamental component of the RMS output voltage, and the output power.

Solution:

1. **Identify given parameters:** $V_s = 100$ V, $R = 10\Omega$.
2. **Calculate RMS output voltage V_{or}:** For a full-bridge inverter, the output square wave swings between $+V_s$ and $-V_s$.
$$V_{or} = V_s = 100 \text{ V}$$
3. **Calculate fundamental RMS output voltage V_1:**
$$V_1 = \frac{4V_s}{\pi\sqrt{2}} = \frac{4 \times 100}{\pi \times 1.414}$$
$$V_1 = \frac{400}{4.442} \approx 90.05 \text{ V}$$
4. **Calculate output power P_o:**
$$P_o = \frac{V_{or}^2}{R} = \frac{(100)^2}{10} = \frac{10000}{10} = 1000 \text{ W} = 1 \text{ kW}$$

CHAPTER 4

Industrial Electronics Applications

4.1 Electric Heating Systems

Electric heating is widely used in industry for processes such as melting, forging, curing, and drying. The primary computational focus is on determining the power required, heating time, and the electrical parameters of the heating elements for resistance, induction, and dielectric heating.

4.1.1 Resistance Heating

In resistance heating, heat is produced by passing an electric current through a resistive element ($H = I^2Rt$).

Methodology:

Resistance Heating Element Design

1. **Determine Electrical Power:** Calculate the power P rating of the oven or heater based on the supply voltage V and required heat output.
2. **Calculate Circuit Parameters:**
   - Load Current: $I = \frac{P}{V}$ (for single-phase DC or AC).
   - Element Resistance: $R = \frac{V^2}{P}$ or $R = \frac{V}{I}$.
3. **Determine Element Dimensions:** Given the maximum allowable current density J and resistivity ρ:
   - Cross-sectional Area: $A = \frac{I}{J}$.
   - Length of Wire: $L = \frac{R \cdot A}{\rho}$.

Worked Example:

Design of a Resistance Heating Element A resistance oven is rated at 15 kW and operates on a 230 V, single-phase supply. The heating element is made of Nichrome wire with a resistivity of $1.03 \times 10^{-6}\ \Omega \cdot \text{m}$. If the maximum allowable current density is $5\ \text{A/mm}^2$, calculate the required length and cross-sectional area of the wire.

Solution:

1. **Calculate the load current:**
$$I = \frac{P}{V} = \frac{15000}{230} = 65.22\ \text{A}$$
2. **Calculate the cross-sectional area (A):** Using the allowable current density $J = 5\ \text{A/mm}^2$:
$$A = \frac{I}{J} = \frac{65.22}{5} = 13.04\ \text{mm}^2 = 13.04 \times 10^{-6}\ \text{m}^2$$

3. **Calculate the required resistance (R):**

$$R = \frac{V}{I} = \frac{230}{65.22} = 3.527\ \Omega$$

4. **Calculate the length of the wire (L):** Using the resistance formula $R = \frac{\rho L}{A}$:

$$L = \frac{R \cdot A}{\rho} = \frac{3.527 \times (13.04 \times 10^{-6})}{1.03 \times 10^{-6}} = 44.65\ \text{m}$$

4.1.2 Induction Heating

Induction heating relies on inducing eddy currents within a conductive workpiece using an alternating magnetic field. The thermal requirement is derived from the specific heat and latent heat of the material.

Methodology:

Induction Heating Thermal Power Calculation

1. **Calculate Heat Energy Required (Q):**
   - Sensible Heat: $Q_s = m \cdot s \cdot (T_2 - T_1)$
   - Latent Heat (if melting occurs): $Q_l = m \cdot L$
   - Total Heat: $Q_{\text{total}} = Q_s + Q_l$

   where m is mass, s is specific heat, ΔT is temperature rise, and L is latent heat of fusion.

2. **Convert Heat Units:** Convert Q_{total} from Joules to equivalent electrical energy units if needed ($1\ \text{kWh} = 3.6 \times 10^6\ \text{J}$).

3. **Calculate Input Power:**

$$P_{\text{input}} = \frac{Q_{\text{total}}}{t \cdot \eta}$$

   where t is the heating time in seconds and η is the overall efficiency.

Worked Example:

Induction Furnace Melting Time Calculation Calculate the time taken to melt 2 kg of steel by an induction furnace taking 5 kW at an overall efficiency of 50%. Given: Initial temperature = 20°C, Melting point of steel = 1370°C, Specific heat of steel = 450 J/kg°C, Latent heat of steel = 270 kJ/kg.
Solution:

1. **Calculate total heat required (Q_{total}):** Sensible heat to raise temperature from 20°C to 1370°C:

$$Q_s = m \cdot s \cdot (T_2 - T_1) = 2 \times 450 \times (1370 - 20) = 1,215,000\ \text{J} = 1215\ \text{kJ}$$

   Latent heat to melt the steel:

$$Q_l = m \cdot L = 2 \times 270,000 = 540,000\ \text{J} = 540\ \text{kJ}$$

   Total heat energy:

$$Q_{\text{total}} = 1215\ \text{kJ} + 540\ \text{kJ} = 1755\ \text{kJ} = 1,755,000\ \text{J}$$

2. **Calculate useful power output to the material:**

$$P_{\text{useful}} = P_{\text{input}} \times \eta = 5000 \times 0.5 = 2500\ \text{W} = 2.5\ \text{kJ/s}$$

3. **Calculate time taken (t):**

$$t = \frac{Q_{\text{total}}}{P_{\text{useful}}} = \frac{1755 \text{ kJ}}{2.5 \text{ kJ/s}} = 702 \text{ seconds}$$

In minutes: $702/60 = 11.7$ minutes.

4.1.3 Dielectric Heating

Dielectric heating is used to heat non-conducting materials (insulators) by subjecting them to a high-frequency alternating electric field. The material acts as the dielectric of a capacitor.

Methodology:

Dielectric Heating Power and Voltage

1. **Calculate the Capacitance:**

$$C = \frac{\epsilon_0 \epsilon_r A}{d}$$

where $\epsilon_0 = 8.854 \times 10^{-12}$ F/m, ϵ_r is relative permittivity, A is the area of the electrodes (m^2), and d is the thickness of the dielectric (m).

2. **Calculate the Power Dissipated:**

$$P = V^2 \omega C \tan\delta = V^2 (2\pi f) C \tan\delta$$

where V is the RMS voltage across the material, f is the frequency, and $\tan\delta$ is the power factor (or dissipation factor) of the dielectric material.

3. **Determine Required Voltage or Frequency:** Rearrange the formula to solve for the unknown parameter.

Worked Example:

Dielectric Heating of a Wood Slab A slab of wood of 100 cm^2 area and 2 cm thick is to be heated by dielectric heating. The frequency of the supply is 30 MHz and the applied RMS voltage is 2 kV. The relative permittivity of the wood is 5 and its power factor ($\tan\delta$) is 0.05. Calculate the power absorbed by the wood.
Solution:

1. **Convert dimensions to standard units:** Area $A = 100 \text{ cm}^2 = 100 \times 10^{-4} \text{ m}^2 = 0.01 \text{ m}^2$ Thickness $d = 2 \text{ cm} = 0.02 \text{ m}$

2. **Calculate the capacitance (C):**

$$C = \frac{8.854 \times 10^{-12} \times 5 \times 0.01}{0.02} = 22.135 \times 10^{-12} \text{ F} = 22.135 \text{ pF}$$

3. **Calculate the angular frequency (ω):**

$$\omega = 2\pi f = 2\pi \times 30 \times 10^6 = 1.885 \times 10^8 \text{ rad/s}$$

4. **Calculate the power absorbed (P):**

$$P = V^2 \omega C \tan\delta = (2000)^2 \times (1.885 \times 10^8) \times (22.135 \times 10^{-12}) \times 0.05$$

$$P = 4 \times 10^6 \times 1.885 \times 10^8 \times 22.135 \times 10^{-12} \times 0.05 = 834.4 \text{ W}$$

4.2 Resistance Welding

Resistance welding utilizes the heat generated by electrical resistance at the joint interface.

Methodology:

Resistance Welding Heat Calculation

1. **Calculate Total Required Energy:** Determine the thermal energy H required to form the weld nugget (often derived from mass and thermal capacity, or provided directly).
2. **Account for Efficiency:** Actual electrical energy to be generated $E = \frac{H}{\eta}$, where η is the heat transfer efficiency.
3. **Calculate Welding Current:** Using Joule's law of heating $E = I^2Rt$, solve for current:

$$I = \sqrt{\frac{E}{R \cdot t}}$$

where R is the effective resistance of the joint and t is the welding time.

Worked Example:

Spot Welding Current Calculation Two 1.5 mm thick steel plates are to be spot welded. The welding time is set to 0.1 seconds, and the effective resistance of the joint interface is 120 $\mu\Omega$. If the required heat energy to successfully form the weld nugget is 800 J and the heat transfer efficiency is 60%, calculate the necessary RMS welding current.

Solution:

1. **Calculate actual electrical energy required:**

$$E = \frac{H}{\eta} = \frac{800}{0.6} = 1333.33 \text{ J}$$

2. **Calculate the required welding current (I):** Using $E = I^2Rt$:

$$1333.33 = I^2 \times (120 \times 10^{-6}) \times 0.1$$

$$I^2 = \frac{1333.33}{12 \times 10^{-6}} = 111,110,833.3$$

$$I = \sqrt{111,110,833.3} \approx 10541 \text{ A} = 10.54 \text{ kA}$$

4.3 Industrial Timer Circuits

The 555 timer IC is ubiquitously used in industrial controls for generating accurate time delays (monostable mode) and oscillator frequencies (astable mode).

4.3.1 Astable Multivibrator Design

Methodology:

555 Timer Astable Configuration Design

1. **Identify Requirements:** Determine the target frequency f and duty cycle D (where $D > 50\%$ in a standard configuration).
2. **Select Capacitor:** Choose a standard capacitor value C (e.g., 0.01μF, 0.1μF, 1μF) that suits the frequency range.

3. **Calculate Timing Intervals:**
   - Total Time Period: $T = \frac{1}{f}$
   - High Time: $T_{\text{HIGH}} = D \times T$
   - Low Time: $T_{\text{LOW}} = T - T_{\text{HIGH}}$
4. **Calculate Resistor Values:** Using the standard 555 timer equations:
   - $T_{\text{LOW}} = 0.693 R_B C \implies R_B = \frac{T_{\text{LOW}}}{0.693C}$
   - $T_{\text{HIGH}} = 0.693(R_A + R_B)C \implies R_A = \frac{T_{\text{HIGH}}}{0.693C} - R_B$

Worked Example:

Astable Multivibrator Component Calculation Design an astable multivibrator using a 555 timer to generate a square wave of 1 kHz with a duty cycle of 60%. Assume the timing capacitor $C = 0.1\mu\text{F}$.
Solution:

1. **Calculate time period and intervals:**

$$T = \frac{1}{f} = \frac{1}{1000} = 1 \text{ ms} = 10^{-3} \text{ s}$$

$$T_{\text{HIGH}} = 0.60 \times 1 \text{ ms} = 0.6 \text{ ms}$$

$$T_{\text{LOW}} = 1 \text{ ms} - 0.6 \text{ ms} = 0.4 \text{ ms}$$

2. **Calculate Resistor R_B:**

$$T_{\text{LOW}} = 0.693 R_B C \implies 0.4 \times 10^{-3} = 0.693 \times R_B \times 0.1 \times 10^{-6}$$

$$R_B = \frac{0.4 \times 10^{-3}}{0.693 \times 10^{-7}} = 5772\ \Omega \approx 5.8\ \text{k}\Omega$$

3. **Calculate Resistor R_A:**

$$T_{\text{HIGH}} = 0.693(R_A + R_B)C \implies 0.6 \times 10^{-3} = 0.693 \times (R_A + 5772) \times 0.1 \times 10^{-6}$$

$$R_A + 5772 = \frac{0.6 \times 10^{-3}}{0.693 \times 10^{-7}} = 8658\ \Omega$$

$$R_A = 8658 - 5772 = 2886\ \Omega \approx 2.9\ \text{k}\Omega$$

4.3.2 Monostable Multivibrator Design

Methodology:

555 Timer Monostable Configuration Design

1. **Identify Required Pulse Width:** Determine the target output delay or pulse duration T.
2. **Select Capacitor:** Choose a standard capacitor value C.
3. **Calculate Timing Resistor:** Use the monostable formula $T = 1.1RC$ to find R:

$$R = \frac{T}{1.1C}$$

Worked Example:

Monostable Timer Delay Calculation Design a monostable multivibrator using a 555 timer to produce a time delay of 5 ms. Select a suitable capacitor and calculate the required resistor.

Solution:

1. **Select a capacitor value:** Assume $C = 1\mu\text{F} = 10^{-6}$ F.
2. **Calculate the timing resistor (R):** Using $T = 1.1RC$:

$$5 \times 10^{-3} = 1.1 \times R \times 10^{-6}$$

$$R = \frac{5 \times 10^{-3}}{1.1 \times 10^{-6}} = 4545.45\ \Omega \approx 4.54\ \text{k}\Omega$$

4.4 Uninterruptible Power Supplies and Battery Backup

Industrial electronics systems frequently require battery backup to prevent data loss or process disruption during power failures.

Methodology:

UPS Battery Capacity Calculation

1. **Determine Active Load Power (P_{load}):** If the load is given in VA and power factor (pf) is known, calculate $P_{\text{load}} = \text{VA} \times pf$ in Watts.
2. **Calculate Power Drawn from Battery (P_{batt}):** Account for inverter inefficiency:

$$P_{\text{batt}} = \frac{P_{\text{load}}}{\eta_{\text{inv}}}$$

where η_{inv} is the efficiency of the UPS inverter.

3. **Calculate Battery Current (I_{batt}):**

$$I_{\text{batt}} = \frac{P_{\text{batt}}}{V_{\text{batt}}}$$

where V_{batt} is the total DC bus voltage of the battery bank.

4. **Calculate Required Capacity (Ah):**

$$\text{Capacity} = I_{\text{batt}} \times t_{\text{backup}}$$

where t_{backup} is the required backup time in hours.

Worked Example:

Sizing a UPS Battery Bank A 1 kVA UPS with a power factor of 0.8 is used to supply a critical industrial load. The inverter efficiency is 85% and the system uses a 24V DC bus (two 12V batteries in series). Calculate the required battery capacity in Ah to provide a backup time of 2 hours.

Solution:

1. **Calculate the active load power:**

$$P_{\text{load}} = 1000\ \text{VA} \times 0.8 = 800\ \text{W}$$

2. **Calculate the total power drawn from the batteries:**

$$P_{\text{batt}} = \frac{800}{0.85} = 941.17\ \text{W}$$

3. **Calculate the current drawn from the battery bank:**

$$I_{\text{batt}} = \frac{P_{\text{batt}}}{V_{\text{batt}}} = \frac{941.17}{24} = 39.21 \text{ A}$$

4. **Calculate the required Ampere-hour (Ah) capacity:**

$$\text{Capacity} = 39.21 \text{ A} \times 2 \text{ hours} = 78.43 \text{ Ah}$$

Therefore, two 12V, 80 Ah batteries connected in series would be suitable to meet this requirement.

CHAPTER 5

Solid State Controls

5.1 Single-Phase Controlled Rectifiers

Methodology:

Calculation of Voltage for Controlled Rectifiers **1. Single-Phase Half-Wave Controlled Rectifier (Resistive Load)**

1. **Average Output Voltage (V_{dc}):**

$$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

   where V_m is the peak input voltage ($V_m = V_{rms} \times \sqrt{2}$) and α is the firing angle.

2. **RMS Output Voltage ($V_{rms,out}$):**

$$V_{rms,out} = V_m\sqrt{\frac{1}{4} - \frac{\alpha}{4\pi} + \frac{\sin(2\alpha)}{8\pi}}$$

2. Single-Phase Full-Wave Controlled Rectifier (Resistive Load)

1. **Average Output Voltage (V_{dc}):**

$$V_{dc} = \frac{V_m}{\pi}(1 + \cos\alpha)$$

2. **RMS Output Voltage ($V_{rms,out}$):**

$$V_{rms,out} = V_m\sqrt{\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{\sin(2\alpha)}{4\pi}}$$

Worked Example:

Half-Wave Controlled Rectifier Output Calculation A single-phase half-wave controlled rectifier is connected to a 230 V 50 Hz AC supply and a resistive load of 10 Ω. If the firing angle is $\alpha = 60^\circ$ ($\frac{\pi}{3}$ rad) calculate the average output voltage and average load current.

Step 1: Determine the peak supply voltage.

$$V_m = V_{rms} \times \sqrt{2} = 230 \times \sqrt{2} = 325.27 \text{ V}$$

Step 2: Calculate the average output voltage.

$$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

$$V_{dc} = \frac{325.27}{2\pi}(1 + \cos 60^\circ) = \frac{325.27}{2\pi}(1 + 0.5) = 77.65 \text{ V}$$

Step 3: Calculate the average load current.

$$I_{dc} = \frac{V_{dc}}{R} = \frac{77.65}{10} = 7.765 \text{ A}$$

Worked Example:

Full-Wave Controlled Rectifier Firing Angle A single-phase full-wave fully controlled bridge rectifier is supplied from a 120 V AC source. The load is purely resistive with $R = 20\ \Omega$. Determine the firing angle required to deliver an average output voltage of 90 V.

Step 1: Determine the peak supply voltage.

$$V_m = 120 \times \sqrt{2} = 169.71 \text{ V}$$

Step 2: Use the full-wave rectifier voltage formula.

$$V_{dc} = \frac{V_m}{\pi}(1 + \cos\alpha)$$

$$90 = \frac{169.71}{\pi}(1 + \cos\alpha)$$

Step 3: Solve for α.

$$1 + \cos\alpha = \frac{90 \times \pi}{169.71} = 1.666$$

$$\cos\alpha = 1.666 - 1 = 0.666$$

$$\alpha = \cos^{-1}(0.666) \approx 48.24^\circ$$

5.2 AC Voltage Controllers

Methodology:

Single-Phase AC Voltage Controller An AC voltage controller converts a fixed AC input voltage into a variable AC output voltage without changing the frequency. It typically uses two SCRs in anti-parallel or a TRIAC.

1. **RMS Output Voltage ($V_{rms,out}$) for Resistive Load:**

$$V_{rms,out} = V_s\sqrt{\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin(2\alpha)}{2}\right)}$$

   where V_s is the RMS supply voltage and α is the firing angle in radians.

2. **Output Power (P_{out}):**

$$P_{out} = \frac{V_{rms,out}^2}{R}$$

3. **Input Power Factor (PF):**

$$PF = \frac{V_{rms,out}}{V_s} = \sqrt{\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin(2\alpha)}{2}\right)}$$

Worked Example:

AC Voltage Controller with Resistive Load A single-phase AC voltage controller has a 230 V 50 Hz supply and a resistive load of 50 Ω. If the delay angle of the thyristors is $\alpha = 90^\circ$ ($\frac{\pi}{2}$ rad) calculate the RMS output voltage the output power and the input power factor.

Step 1: Calculate the RMS output voltage.

$$V_{rms,out} = V_s\sqrt{\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin(2\alpha)}{2}\right)}$$

Substitute $V_s = 230$ V and $\alpha = \frac{\pi}{2}$:

$$V_{rms,out} = 230\sqrt{\frac{1}{\pi}\left(\pi - \frac{\pi}{2} + \frac{\sin(180^\circ)}{2}\right)}$$

$$V_{rms,out} = 230\sqrt{\frac{1}{\pi}\left(\frac{\pi}{2} + 0\right)} = 230\sqrt{0.5} = \frac{230}{\sqrt{2}} \approx 162.63 \text{ V}$$

Step 2: Calculate the output power.

$$P_{out} = \frac{V_{rms,out}^2}{R} = \frac{(162.63)^2}{50} = \frac{26450}{50} = 529 \text{ W}$$

Step 3: Calculate the input power factor.

$$PF = \frac{V_{rms,out}}{V_s} = \frac{162.63}{230} = 0.707$$

5.3 DC Choppers

Methodology:

Analysis of DC Chopper Circuits A chopper is a static device that converts fixed DC input voltage to a variable DC output voltage directly.

1. **Duty Cycle (D or α):**

$$D = \frac{T_{on}}{T} = \frac{T_{on}}{T_{on} + T_{off}} = f \times T_{on}$$

   where T_{on} is the on-time T_{off} is the off-time T is the total chopping period and f is the chopping frequency.

2. **Step-Down Chopper (Buck Converter):**

$$V_{dc} = D \times V_s$$

3. **Step-Up Chopper (Boost Converter):**

$$V_{dc} = \frac{V_s}{1 - D}$$

Worked Example:

Step-Down Chopper Output Calculation A step-down DC chopper operates from a 200 V DC source. The load is resistive with $R = 10\ \Omega$. If the chopper frequency is 1 kHz and the ON time is 400 μs determine the average output voltage and the average output current.

Step 1: Determine the total period.

$$T = \frac{1}{f} = \frac{1}{1000} = 1 \text{ ms} = 1000\ \mu\text{s}$$

Step 2: Calculate the duty cycle.

$$D = \frac{T_{on}}{T} = \frac{400\ \mu\text{s}}{1000\ \mu\text{s}} = 0.4$$

Step 3: Calculate the average output voltage.

$$V_{dc} = D \times V_s = 0.4 \times 200 = 80 \text{ V}$$

Step 4: Calculate the average output current.

$$I_{dc} = \frac{V_{dc}}{R} = \frac{80}{10} = 8 \text{ A}$$

Worked Example:

Step-Up Chopper Duty Cycle A step-up chopper has an input voltage of 50 V and feeds a load that requires 150 V. If the non-conducting time of the thyristor (T_{off}) is 100 μs calculate the necessary ON time and the chopping frequency.

Step 1: Relate input and output voltage for a step-up chopper.

$$V_{dc} = \frac{V_s}{1-D}$$

$$150 = \frac{50}{1-D}$$

Step 2: Solve for the duty cycle.

$$1 - D = \frac{50}{150} = \frac{1}{3}$$

$$D = 1 - \frac{1}{3} = \frac{2}{3}$$

Step 3: Express duty cycle in terms of time.

$$D = \frac{T_{on}}{T_{on} + T_{off}}$$

$$\frac{2}{3} = \frac{T_{on}}{T_{on} + 100\ \mu\text{s}}$$

$$2(T_{on} + 100\ \mu\text{s}) = 3T_{on}$$

$$2T_{on} + 200\ \mu\text{s} = 3T_{on} \implies T_{on} = 200\ \mu\text{s}$$

Step 4: Calculate the chopping frequency.

$$T = T_{on} + T_{off} = 200\ \mu\text{s} + 100\ \mu\text{s} = 300\ \mu\text{s}$$

$$f = \frac{1}{T} = \frac{1}{300 \times 10^{-6}} = 3.33 \text{ kHz}$$

5.4 UJT Relaxation Oscillator

Methodology:

Design of UJT Relaxation Oscillator The UJT (Unijunction Transistor) relaxation oscillator generates a sawtooth wave and is commonly used as a firing circuit for SCRs.

1. **Peak Voltage (V_P):**

$$V_P = \eta V_{BB} + V_D$$

where η is the intrinsic standoff ratio V_{BB} is the supply voltage and V_D is the diode forward voltage drop (approx. 0.7 V).

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

$$f = \frac{1}{T} = \frac{1}{R_T C_T \ln(\frac{1}{1-\eta})}$$

An approximate empirical formula often used is $f \approx \frac{1}{R_T C_T}$.

3. **Condition for Oscillation:** To ensure proper turn-on and turn-off of the UJT the timing resistor R_T must satisfy:

$$\frac{V_{BB} - V_P}{I_P} > R_T > \frac{V_{BB} - V_V}{I_V}$$

where I_P is peak-point current and I_V is valley-point current V_V is valley voltage.

Worked Example:

Calculating Frequency of UJT Oscillator A UJT relaxation oscillator uses a 24 V DC supply. The UJT has an intrinsic standoff ratio $\eta = 0.6$ and $V_D = 0.7$ V. The timing components are $R_T = 50$ kΩ and $C_T = 0.1$ μF. Determine the peak voltage and the frequency of oscillation.

Step 1: Calculate the peak voltage V_P.

$$V_P = \eta V_{BB} + V_D = (0.6 \times 24) + 0.7 = 14.4 + 0.7 = 15.1 \text{ V}$$

Step 2: Calculate the frequency using the exact formula.

$$f = \frac{1}{R_T C_T \ln\left(\frac{1}{1-\eta}\right)}$$

$$R_T C_T = 50 \times 10^3 \times 0.1 \times 10^{-6} = 5 \times 10^{-3} \text{ s}$$

$$\ln\left(\frac{1}{1-0.6}\right) = \ln\left(\frac{1}{0.4}\right) = \ln(2.5) \approx 0.916$$

$$f = \frac{1}{5 \times 10^{-3} \times 0.916} = \frac{1}{4.58 \times 10^{-3}} \approx 218.3 \text{ Hz}$$

Worked Example:

Validating Timing Resistor Range For a UJT oscillator $V_{BB} = 20$ V $\eta = 0.65$ $V_V = 2$ V $I_V = 10$ mA $I_P = 10$ μA. Assume $V_D = 0.7$ V. Find the minimum and maximum permissible values for the timing resistor R_T.

Step 1: Calculate Peak Voltage.

$$V_P = (0.65 \times 20) + 0.7 = 13 + 0.7 = 13.7 \text{ V}$$

Step 2: Calculate the Maximum Permissible R_T.

$$R_{T(max)} = \frac{V_{BB} - V_P}{I_P}$$

$$R_{T(max)} = \frac{20 - 13.7}{10 \times 10^{-6}} = \frac{6.3}{10 \times 10^{-6}} = 630 \text{ k}\Omega$$

Step 3: Calculate the Minimum Permissible R_T.

$$R_{T(min)} = \frac{V_{BB} - V_V}{I_V}$$

$$R_{T(min)} = \frac{20 - 2}{10 \times 10^{-3}} = \frac{18}{0.01} = 1.8 \text{ k}\Omega$$

Conclusion: The timing resistor must be selected in the range $1.8 \text{ k}\Omega < R_T < 630 \text{ k}\Omega$.

5.5 Single-Phase Inverters

Methodology:

Voltage Output of Single-Phase Inverters Inverters convert DC to AC power. The output waveform is typically a square wave unless PWM techniques are used.

1. **Single-Phase Half-Bridge Inverter:**
   - **RMS Output Voltage:** $V_{rms} = \frac{V_s}{2}$
   - **Fundamental Component (RMS):** $V_{1(rms)} = \frac{2V_s}{\pi\sqrt{2}} = \frac{\sqrt{2}V_s}{\pi} \approx 0.45V_s$
2. **Single-Phase Full-Bridge Inverter:**
   - **RMS Output Voltage:** $V_{rms} = V_s$
   - **Fundamental Component (RMS):** $V_{1(rms)} = \frac{4V_s}{\pi\sqrt{2}} = \frac{2\sqrt{2}V_s}{\pi} \approx 0.90V_s$
3. **Output Frequency (f):**

$$f = \frac{1}{T}$$

   where T is the total period of one AC cycle.

Worked Example:

Inverter Voltage Calculation A single-phase full-bridge inverter is supplied from a 48 V DC source and operates at a frequency of 50 Hz. It supplies a purely resistive load of 12 Ω. Determine the RMS output voltage the RMS output fundamental voltage and the fundamental output power.

Step 1: Calculate the RMS output voltage. For a full-bridge square wave inverter:

$$V_{rms} = V_s = 48 \text{ V}$$

Step 2: Calculate the RMS fundamental component.

$$V_{1(rms)} = \frac{2\sqrt{2}V_s}{\pi} = \frac{2\sqrt{2}(48)}{\pi} \approx 43.22 \text{ V}$$

Step 3: Calculate the fundamental output power.

$$P_1 = \frac{V_{1(rms)}^2}{R} = \frac{(43.22)^2}{12} = \frac{1867.97}{12} \approx 155.66 \text{ W}$$

Worked Example:

Half-Bridge vs Full-Bridge Output Compare the peak fundamental output voltage of a half-bridge and a full-bridge inverter when both are powered by a 100 V DC source.

Step 1: Peak fundamental voltage of Half-Bridge Inverter. The amplitude (peak) of the fundamental component is given by the Fourier series coefficient a_1:

$$V_{1(peak)} = \frac{2V_s}{\pi} = \frac{2 \times 100}{\pi} \approx 63.66 \text{ V}$$

Step 2: Peak fundamental voltage of Full-Bridge Inverter.

$$V_{1(peak)} = \frac{4V_s}{\pi} = \frac{4 \times 100}{\pi} \approx 127.32 \text{ V}$$

Conclusion: The full-bridge inverter produces twice the peak fundamental voltage compared to the half-bridge configuration for the same DC input source.

Formulae

Appendix: Key Formulae

This appendix provides a quick reference to the key formulae and mathematical relationships discussed in this book.

Unit 1: Power Semiconductor Devices

1. Peak Voltage (V_m)

$$V_m = \sqrt{2} \times V_{rms}$$

2. Frequency and Time Period

$$f = \frac{1}{T}$$

3. Two-Transistor Model of SCR The anode current (I_A) is given by:

$$I_A = \frac{\alpha_2 I_G + I_{CO1} + I_{CO2}}{1 - (\alpha_1 + \alpha_2)}$$

Where α_1, α_2 are the current gains of the two transistors, I_G is the gate current, and I_{CO1}, I_{CO2} are the leakage currents.

4. Gate Triggering Circuit The required gate series resistance (R) can be found using:

$$V_m \sin(\alpha) = V_{GT} + I_{GT} R \implies R = \frac{V_m \sin(\alpha) - V_{GT}}{I_{GT}}$$

Where V_{GT} and I_{GT} are the gate trigger voltage and current, and α is the firing angle.

5. UJT (Unijunction Transistor) Characteristics The intrinsic standoff ratio (η) is defined as:

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}}$$

The peak voltage (V_P) required to turn on the UJT:

$$V_P = \eta V_{BB} + V_D$$

Where V_{BB} is the interbase voltage and V_D is the diode forward voltage drop.

6. UJT Relaxation Oscillator The time period of oscillation (T) is given by:

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

The limiting values for the charging resistor (R) are:

$$R_{min} = \frac{V_{BB} - V_V}{I_V}, \quad R_{max} = \frac{V_{BB} - V_P}{I_P}$$

Where V_V, I_V are the valley point voltage and current, and I_P is the peak point current.

7. Thermal Characteristics and Heatsink Design The junction temperature (T_j) relationship is:

$$T_j - T_a = P_{avg}(\theta_{jc} + \theta_{cs} + \theta_{sa})$$

The required thermal resistance of the heatsink (θ_{sa}) is:

$$\theta_{sa} = \frac{T_j - T_a}{P_{avg}} - (\theta_{jc} + \theta_{cs})$$

Where T_a is ambient temperature, P_{avg} is average power dissipation, and $\theta_{jc}, \theta_{cs}, \theta_{sa}$ are the thermal resistances between junction-case, case-sink, and sink-ambient respectively.

Unit 2: Protection and Commutation Circuits

1. Gate Power Dissipation

$$P_g = V_g I_g$$

For pulsed gate drive, the duty cycle (δ) and average power are:

$$\delta = f \cdot t_p$$

$$P_{g(avg)} = \delta \cdot P_{gm} = f \cdot t_p \cdot P_{gm}$$

Where t_p is pulse width, f is frequency, and P_{gm} is peak gate power.

2. di/dt Protection The snubber inductor (L_s) required to limit the rate of rise of current:

$$L_s = \frac{V_m}{(di/dt)_{max}}$$

3. dv/dt Protection (RC Snubber) The snubber resistance (R_s) limits the discharge current (I_{TD}):

$$R_s = \frac{V_m}{I_{TD}}$$

The damping ratio (ζ) determines the relationship between R_s, L_s, and C_s:

$$R_s = 2\zeta\sqrt{\frac{L_s}{C_s}}$$

For critical damping ($\zeta = 1$), the required snubber capacitance (C_s) is:

$$C_s = \frac{4L_s}{R_s^2}$$

4. Commutation Circuits For Class A (Resonant) Commutation, the commutation time (t_c) is:

$$t_c = \frac{\pi}{2}\sqrt{LC}$$

Peak reverse commutation current:

$$I_p = V_s\sqrt{\frac{C}{L}}$$

For Class C/D Commutation, the circuit turn-off time (t_c) must be greater than device turn-off time (t_q):

$$t_c = R_L C \ln(2) \approx 0.693 R_L C$$

Minimum commutation capacitance (C_{min}):

$$C_{min} = \frac{t_q}{R_L \ln(2)}$$

Unit 3: Phase-Controlled Rectifiers and Choppers

1. DC Load Current and Output Power

$$I_{dc} = \frac{V_{dc}}{R}, \quad P_o = \frac{V_{rms}^2}{R}$$

2. Single-Phase Half-Wave Controlled Rectifier Average DC output voltage (for resistive load):

$$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

RMS output voltage:

$$V_{rms} = \frac{V_m}{2}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}}$$

3. Single-Phase Full-Wave Semi-Converter (or with Freewheeling Diode) Average DC output voltage:

$$V_{dc} = \frac{V_m}{\pi}(1 + \cos\alpha)$$

RMS output voltage:

$$V_{rms} = \frac{V_m}{\sqrt{2}}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}}$$

4. DC Choppers Duty cycle (D) and chopping frequency (f):

$$D = \frac{T_{on}}{T}, \quad f = \frac{1}{T}, \quad T = T_{on} + T_{off}$$

Step-down (Buck) chopper output voltage:

$$V_o = D \times V_s$$

Step-up (Boost) chopper output voltage:

$$V_o = \frac{V_s}{1 - D} = V_s \frac{T}{T_{off}}$$

Unit 4: Heating Systems, Timers, and Battery Sizing

1. Heating Systems Energy Requirements Sensible heat (energy to raise temperature):

$$Q_s = m \cdot s \cdot (T_2 - T_1)$$

Latent heat (energy for phase change):

$$Q_l = m \cdot L$$

Total heat energy ($Q_{\text{total}} = Q_s + Q_l$). Electrical power input required:

$$P_{\text{input}} = \frac{Q_{\text{total}}}{t \cdot \eta_{thermal}}$$

Electrical energy (E) and current (I) relation:

$$E = \frac{H}{\eta}, \quad I = \sqrt{\frac{E}{R \cdot t}}$$

2. Dielectric Heating Capacitance of a parallel plate capacitor:

$$C = \frac{\epsilon_0 \epsilon_r A}{d}$$

Power dissipation in a dielectric material:

$$P = V^2 \omega C \tan\delta = V^2 (2\pi f) C \tan\delta$$

3. Conductor Resistance and Current Density Current density (J):

$$J = \frac{I}{A} \implies A = \frac{I}{J}$$

Length of conductor (L) from resistance (R), resistivity (ρ), and area (A):

$$L = \frac{R \cdot A}{\rho}$$

4. 555 Timer Astable Multivibrator HIGH and LOW state durations:

$$T_{\text{HIGH}} = 0.693(R_A + R_B)C$$

$$T_{\text{LOW}} = 0.693 R_B C$$

Total period for simple timer circuit:

$$T \approx 1.1RC \implies R = \frac{T}{1.1C}$$

5. **Inverter Battery Sizing** Power drawn from the battery:

$$P_{\text{batt}} = \frac{P_{\text{load}}}{\eta_{\text{inv}}}$$

Battery current (I_{batt}) and required capacity (Ah):

$$I_{\text{batt}} = \frac{P_{\text{batt}}}{V_{\text{batt}}}, \quad \text{Capacity (Ah)} = I_{\text{batt}} \times t_{\text{backup}}$$

Unit 5: Inverters

1. **Single-Phase Half-Bridge Inverter** RMS output voltage:

$$V_{rms} = \frac{V_s}{2}$$

Fundamental RMS output voltage:

$$V_{1(rms)} = \frac{2V_s}{\pi\sqrt{2}} = \frac{\sqrt{2}V_s}{\pi} \approx 0.45V_s$$

2. **Single-Phase Full-Bridge Inverter** RMS output voltage:

$$V_{rms} = V_s$$

Fundamental RMS output voltage:

$$V_{1(rms)} = \frac{4V_s}{\pi\sqrt{2}} = \frac{2\sqrt{2}V_s}{\pi} \approx 0.90V_s$$