

Electric Circuit Theory



*Dr. M. Arumugam
N. Premakumaran*

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ELECTRIC CIRCUIT THEORY

Dr. M. Arumugam & Dr. N. Premakumaran
Deptt. of Electrical & Electronics Engg.
Regional Engineering College,
Trichy-T.N.



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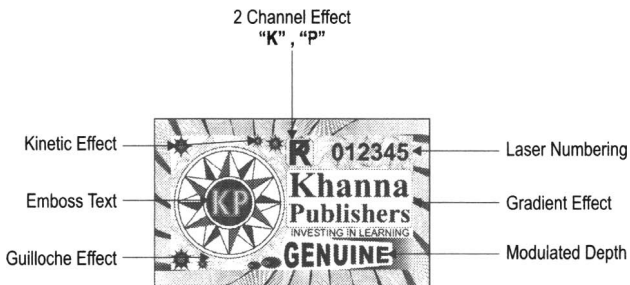
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CONTENTS

<i>Chap.</i>		<i>Page</i>
1.	INTRODUCTION ...	1—10
	Potential Difference—Electric Current—EMF—Resistance and Resistivity—Conductance and Conductivity—Temperature Effect on Resistance—Insulation Resistance—Exercises.	
2.	DIRECT CURRENT CIRCUITS-I ...	11—33
	Ohm's Law—Power—Energy—Resistors in Series and Parallel—Star-Delta Transformations—Exercises.	
3.	DIRECT CURRENT CIRCUITS-II ...	34—65
	Kirchhoff's Laws—Maxwell's Mesh Method—Matrix Solution—Maxwell's Equations by Inspection—Equivalence of Sources—Nodal Method—Exercises.	
4.	NETWORK THEOREMS ...	66—96
	Superposition Theorem—Thevenin's Theorem—Norton's Theorem—Maximum Power Transfer Theorem—Substitution Theorem—Reciprocity Theorem—Millman's Theorem—Tellegen's Theorem—Exercises.	
5.	ALTERNATING CURRENT FUNDAMENTALS ...	97—125
	Average and Effective Values—Form Factor—Peak Factor—Sinewave—Phase Difference—Phasor Representation—Vector Addition/Subtraction—Polar Notation—Complex Notation—Exercises.	
6.	A.C. CIRCUITS ...	126—160
	Resistance—Inductance—Energy Stored in an Induct-	

ance—Capacitance—Energy Stored in a Capacitance—
Series Circuits—RL, RC and RLC Circuits—Power Trian-
gle—Series and Parallel Circuits—Admittance—Exercises.

7. RESONANCE IN A.C. CIRCUITS ... **161—180**

Series Resonance—Frequency Variation—Inductance Vari-
ation—Capacitance Variation—Selectivity—Q-Factors—
Half Power Frequency—Bandwidth—Parallel Resonance—
Two Branch Parallel Circuits—Resistance Variation—
Resonance at all Frequencies—Magnitude and Phase
Plots—Tuned Circuits—Exercises.

**8. A.C. NETWORK ANALYSIS—LOCUS
DIAGRAMS** ... **181—200**

Mesh Current Method—Driving Point Impedance—Trans-
fer Impedance—Nodal Method—Driving Point Admit-
tance—Transfer Admittance—Locus Diagram—Series
Circuits—RL, RC and RLC Circuits—Parallel Circuits—
Exercises.

9. NETWORK THEOREMS ... **201—221**

Thevenin's and Nortons' Theorem—Reciprocity Theorem—
Substitution Theorem—Superposition Theorem—
Maximum Power Transfer Theorem—Star-Delta Transfor-
mation—Exercises.

10. COUPLED CIRCUITS ... **222—232**

Self Inductance—Mutual Inductance—Analysis of Coupled
Circuits—Natural Current—Dot Rule for Coupled
Circuits—Equivalent Circuit of Coupled Coils—Coupled
Circuits in Series and Parallel—Tuned Coupled Circuits—
Double Tuned Circuits—Exercises.

11. POLY PHASE CIRCUITS ... **233—253**

Comparison between Single Phase and Polyphase
Systems—Generation of Three Phase Voltages—Phase
Sequence—Inter-connection of Three Phase Windings—Star

Connection—Delta Connection—Balanced Three Phase Loads—Power Measurement—Three Wattmeter Method—Two Wattmeter Method—Single Wattmeter Method—Unbalanced Loads Delta Connection—Star Connection—Unbalanced Three Phase, Four Wire Loads—Power Measurement in Unbalanced Loads—Two Phase System—Exercises.

12. SYMMETRICAL COMPONENTS ... **254—261**

Positive, Negative and Zero Sequence Components—Operators—Relationship between Symmetrical and Phase Quantities—Power in Terms of Symmetrical Components—Exercises.

13. CIRCUIT TRANSIENTS ... **262—305**

Laplace Transformations—Advantages—Laplace Transformation of some Functions—Table of Laplace Transforms—Theorems—Initial Value and Final Value Theorems—RL Transient—Decay of Current in RL Circuits—RC Transient : Decay of Current in RC Circuits—RLC Transient : Over-damped, Critically Damped and Underdamped—AC Transients—RL, RC and RLC Circuits—Natural Frequency and Damping Ratio—Logarithmic Decrement—Exercises.

14. DUALITY NETWORK FUNCTIONS, POLES AND ZEROS ... **306—315**

Duality—Table of Duals—Dot Method—Network Functions—Complex Frequency—Poles and Zeros—Exercises.

15. TWO-PORT NETWORKS ... **316—353**

One Port Networks—Two Port Networks—Y-Z-H—ABCD Parameters—Relationship between Different Parameters—Symmetry and Reciprocal Two Port Networks—Equivalent Networks—Open Circuit and Short Circuit Impedances—Image Parameters—Impedance Matching—Exercises.

16. ELECTRIC WAVE FILTERS ... **354—386**

Classification—Ideal Filter—Cut off Frequencies—Attenuation—Characteristic Impedance—Constant- k Filter— Design of Low Pass Filter—Prototype High Pass Filter—Characteristic Impedance—Design of High Pass Filter— m -derived Filter—Band-Pass Filter—Band Elimination Filter—Exercises.

17. FOURIER SERIES ... **387—409**

Fourier Series—Symmetry Conditions—Exponential Fourier Series—Fourier Integrals and Transforms—Responses by Fourier Methods—Exercises.

18. STATE-VARIABLE ANALYSIS ... **410—421**

State Variables—Step-by-Step Procedure—Exercises.

ONE

INTRODUCTION

In the study of electric circuits we are interested in the flow of electricity from one device to another. The simplest of electric devices will have a pair of terminals. 'Electricity' enters at one terminal and leaves from the other. The parameters of the device such as resistance etc., are assumed to be lumped or concentrated at one point. This is not quite true as is evident in the case of transmission lines. The resistance and other parameters of a transmission line are distributed throughout its length.

The energy associated with an electric system is measured by quantities like electric charge, potential and current. Historically electric charges were first observed by rubbing certain dry substances together. Atomic physicists now picture the electric charge as one of the building blocks of the universe. The negatively charged electron is one of the constituents of the atom. Its mass is 9.107×10^{-28} gm. As the electron is a very small unit, the practical unit of charge is the coulomb.

$$1 \text{ coulomb} = 6.24 \times 10^{18} \times Q_e$$

where Q_e is the electronic charge. The flow of electric charge (electrons) constitutes a current. The rate of flow of charge is defined as current (i) and its unit is the ampere. If one coulomb of charge is transferred in one second, the current is said to be one ampere.

$$i = \frac{dQ}{dt}$$

Current has direction depending on the flow of charge.

Potential Difference (e). This is defined with respect to any two points and is measured in volts. Numerically, this is equal to the work done (in joules per coulomb) in moving a coulomb of charge between the two points.

1 volt = 1 joule/coulomb.

$$V = \frac{dW}{dQ}$$

Power can be obtained as a product of current and potential difference as

$$p = e \cdot i. \quad \dots(1)$$

The extent to which conduction of current (electrons) takes place is determined by the number of electrons which are free to move. In metals, a comparatively large current will be transmitted under a given applied electric pressure, as they have a larger number of free electrons. Silver, Copper and Aluminium are excellent conductors. In contrast rubber and porcelain are extremely poor conductors.

Electric Current

When one coulomb of electric charge continuously passes a given point every second, the electric current is said to be one ampere.

$$I = \frac{Q}{t} \quad \dots(2)$$

where I = current in amperes
 Q = charge in coulombs
 t = time in seconds.

Electromotive force (EMF)

This term represents the electric pressure or potential difference between two ends of a conductor that tends to create an electron flow. EMF may be developed in a battery or in a generator.

Electrical Resistance and Resistivity

Resistance in a circuit is the parameter which dissipates energy. Typical examples are the heating elements in stoves, filament bulbs etc. The amount of current passing through a conductor depends not only on the impressed voltage but on the properties of the conductor also. Electrical conductivity varies with different material. All substances may therefore be assumed to have a property which tends to oppose the flow of a current. This is called electrical resistance of a material and is very much like any other property of a material.

The unit of resistance is the ohm. The international ohm is defined to be the resistance at zero degrees centigrade of a column of mercury of uniform cross section, having a length of 106.3 cm and a mass of 14.4521 grams. The resistance of a conductor depends upon :

1. The material of the conductor.
2. Its length.
3. Cross-sectional area, and
4. The temperature.

The resistance of electrical materials are usually given per unit cross-sectional area and per unit length. This is called specific resistance or resistivity of the material represented by the letter ρ . Thus the resistivities of silver, copper and aluminium are 0.0147, 0.0173 and $0.0283 \mu \Omega\text{-m}$. If ρ of a material is specified, then the resistance of conductor of that material with length l and area of cross-section a is

$$R = \frac{\rho l}{a} \quad \dots(3)$$

In the MKS system of units, l is in metres a in square metres, and hence the unit of specific resistance is ohm-metre.

Example 1.1. Find the resistance of a copper wire 1 km long and 0.5 cm dia given the specific resistance of copper as $1.7 \times 10^{-8} \Omega\text{-m}$

Solution.

$$R = \frac{\rho l}{a}$$

$l = \text{length in metres} = 1000$

$$R = \frac{1.7 \times 10^{-8} \times 1000}{\frac{\pi}{4} \times \left(\frac{0.5}{100}\right)^2}$$

$$= \mathbf{0.866 \text{ ohm}}$$

Example 1.2. A copper wire whose diameter is 0.162 cm has a resistance of 0.4 ohm. If the wire is drawn through a series of dies until its diameter is reduced to 0.032 cm, what is the resistance of the lengthened conductor? Assume ρ remains constant.

Solution. Let l_1 and a_1 be the original length and area of cross section of the conductor and let l_2 and a_2 be the corresponding values after passing through the dies.

$$0.4 = \frac{\rho l_1}{a_1}$$

where

$$a_1 = \frac{\pi}{4} \left(\frac{0.162}{100}\right)^2$$

New Resistance

$$R = \frac{\rho l_2}{a_2}$$

where

$$a_2 = \frac{\pi}{4} \left(\frac{0.032}{100}\right)^2$$

As the volume of copper remains unchanged in the process,

$$a_1 l_1 = a_2 l_2$$

or
$$l_2 = \frac{a_1}{a_2} l_1$$

$$\therefore \frac{R}{0.4} = \frac{l_2 a_1}{l_1 a_2} = \left(\frac{a_1}{a_2}\right)^2 = \left(\frac{0.162}{0.032}\right)^4$$

i.e.
$$R = 0.4 \left(\frac{0.162}{0.032}\right)^4 = 262.7 \text{ ohms.}$$

Example 1.3. A bread toaster has a Nichrome unit ($\rho = 112 \times 10^{-8} \Omega\text{-m}$) of resistance 32 ohms. What is the resistance of a copper conductor of equal area of cross section but 10 times as long as the Nichrome wire ?

Solution. $\rho_{Cu} = 1.7 \times 10^{-8} \text{ ohm-m}$

$$\rho_{Ni} = 112 \times 10^{-8} \text{ ohm-m}$$

$$R_{Ni} = 32 = 112 \times 10^{-8} \times \frac{l_{Ni}}{a_{Ni}}$$

$$R_{Cu} = \rho_{Cu} \frac{l_{Cu}}{a_{Cu}}$$

$$\frac{R_{Cu}}{32} = \frac{\rho_{Cu}}{\rho_{Ni}} \cdot \frac{l_{Cu}}{l_{Ni}} \cdot \frac{a_{Ni}}{a_{Cu}}$$

$$= \frac{1.7 \times 10^{-8}}{112 \times 10^{-8}} \times 10 = \frac{17}{112}$$

$$\therefore R_{Cu} = \frac{32 \times 17}{112} = 4.857 \text{ ohms.}$$

Example 1.4. An overhead busbar of copper is a tube with 3 cm internal diameter and 0.5 cm thickness. Find the resistance between the two ends of the busbar, if its length is 10 metres.

Solution.
$$R = \frac{\rho l}{a}$$

$$\rho = 1.7 \times 10^{-8} \text{ ohm-m for copper}$$

$$l = 10 \text{ m}$$

$$a = \frac{\pi}{4} \left(\frac{4^2 - 3^2}{100 \times 100} \right) \text{ sq. m}$$

$$\therefore R = \frac{1.7 \times 10^{-8} \times 10 \times 4 \times 10000}{\pi \times 7}$$

$$= 3.09 \times 10^{-4} \text{ ohm.}$$

Example 1.5. A 240 V generator supplies a motor through a pair of aluminium wires each 400 metres long. The terminal

voltage at the motor is 230 V and the current supplied is 20 A. Find the area of cross-section of the wires required (specific resistance of aluminium 2.83×10^{-8} ohm-m).

Solution. Voltage drop in the wires

$$= 240 - 230 = 10 \text{ V}$$

$$\text{Drop in each conductor} = 5 \text{ V}$$

$$\text{Current flowing} = 20 \text{ A}$$

$$\therefore \text{Resistance of each wire} = \frac{5}{20} = 0.25 \Omega$$

$$= \frac{\rho l}{a}$$

$$\therefore a = \frac{2.83 \times 10^{-8} \times 400}{0.25} \text{ sq. m}$$

$$= 0.4528 \text{ sq. cm.}$$

Conductance and Conductivity

The reciprocal of resistance is called conductance, it is represented by the letter G and its unit is the mho (Ω) siemens.

$$G = \frac{1}{R}$$

The reciprocal of resistivity is called conductivity and is represented by the symbol ν

$$\nu = \frac{1}{\rho} \text{ mho/metre.}$$

Temperature-Resistance Effect

It has been experimentally found that the resistance of most of the metals increases as the temperature is raised. This change is approximately proportional to the temperature change, except for very low and very high temperatures. Therefore within the usual operating range, the resistance may be said to vary linearly with temperature changes.

The change in resistance per ohm per degree temperature variation is called temperature co-efficient of resistance and is represented by the symbol α .

α itself varies with temperature. Thus α for copper is 0.00402 per $^{\circ}\text{C}$ at 20°C .

If R_1 is the resistance of a conductor at t_1 $^{\circ}\text{C}$ and

R_2 is its resistance at t_2 $^{\circ}\text{C}$, then

$$R_2 = R_1 [1 + \alpha_1(t_2 - t_1)] \quad \dots(4)$$

The value of α_1 is the temperature co-efficient of resistance at the temperature t_1 °C.

Example 1.6. *The resistance of a coil of wire increases from 50 ohms at 25°C to 62 ohms at 75°C. Calculate the temperature coefficient of the material of the wire at 0°C.*

Solution. The resistance at 25°C, $R_{25} = 50 = R_0 [1 + \alpha_0 (25 - 0)]$
and at 75°C, $R_{75} = 62 = R_0 [1 + \alpha_0 (75 - 0)]$

Dividing one by the other,

$$\frac{62}{50} = \frac{1 + 75 \alpha_0}{1 + 25 \alpha_0}$$

$$1.24 (1 + 25 \alpha_0) = 1 + 75 \alpha_0$$

$$0.24 = \alpha_0 (75 - 31) = 44 \alpha_0$$

or $\alpha_0 = 0.24/44 = 0.00545.$

Example 1.7. *An incandescent lamp takes 2.5 Amps at 240 V at the instant of switching it on. At the normal operating temperature the current drops to 0.2 Amp. Find the temperature of the heated filament. Take room temperature as 20°C and the corresponding temperature co-efficient of the filament as 0.005 per °C.*

Solution. Let t be the normal operating temperature.

$$R_{20} = \frac{240}{2.5} = 96 \text{ ohms.}$$

$$R_t = \frac{250}{0.2} = 1200 \text{ ohms}$$

$$R_t = R_{20} [1 + \alpha_{20} (t - 20)]$$

$$1200 = 96 [1 + 0.005 (t - 20)]$$

or $t = \frac{1113.6}{0.48} = 2320^\circ\text{C}.$

Example 1.8. *Two conductors, one of copper and the other of iron, are connected in parallel. At 20°C, they carry equal currents. If the temperature is now raised to 150°C, what proportion of the total current will each conductor carry ?*

$$\alpha_{Cu} = 0.0043; \quad \alpha_{Fe} = 0.0063 \text{ per}^\circ\text{C at } 20^\circ\text{C}.$$

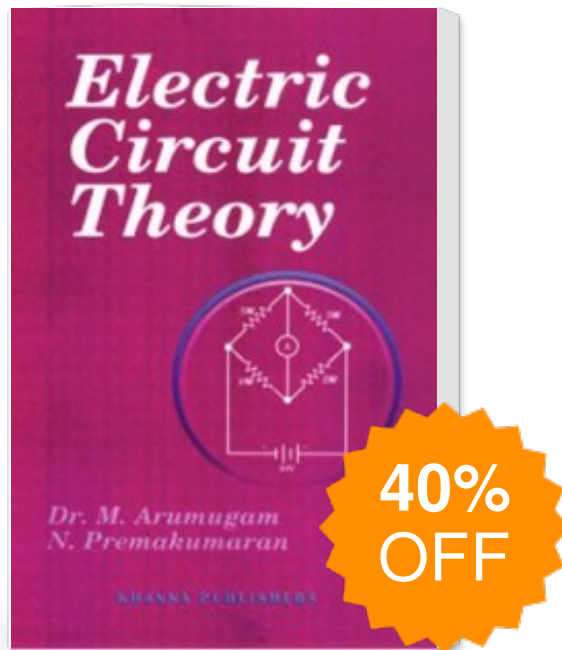
Solution. At 20°C, the currents carried by the 2 conductors are equal. Hence their resistances are equal at 20°C say R .

Let R_{Cu} be the resistance of the copper conductor at 150°C, and R_{Fe} the corresponding resistance of the iron conductor at 150°C.

$$R_{Cu} = R [1 + 0.0043 (150 - 20)] = 1.559 R$$

$$R_{Fe} = R [1 + 0.0063 (150 - 20)] = 1.819 R$$

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