Industrial AC Machines

(Code : 22523)

Maharashtra State Board of Technical Education (MSBTE)

Semester V – Electrical Engineering Group (EE/EP/EU)

Strictly as per new revised 'I' Scheme w.e.f. academic year 2019-2020

J. S. Katre

M.E. (Electronics and Telecommunication)
Formerly, Assistant Professor
Department of Electronics Engineering
Vishwakarma Institute of Technology (V.I.T.), Pune.
Maharashtra, India

TechKnowledge™ Publications

MDO65C Price ₹ 225/-

(Book Code : MDO65C)

Industrial AC Machines (Code : 22523)

Third Year Diploma : Semester V (MSBTE), [Electrical Engineering Group (EE/EP/EU)]

J. S. Katre

Copyright © by Author. All rights reserved. No part of this publication may be reproduced, copied, or stored in a retrieval system, distributed or transmitted in any form or by any means, including photocopy, recording, or other electronic or mechanical methods, without the prior written permission of the publisher.

This book is sold subject to the condition that it shall not, by the way of trade or otherwise, be lent, resold, hired out, or otherwise circulated without the publisher's prior written consent in any form of binding or cover other than which it is published and without a similar condition including this condition being imposed on the subsequent purchaser and without limiting the rights under copyright reserved above.

First Printed in India	**:**	June 2008
First Edition as per I-Scheme	**:**	June 2019 **(TechKnowledge Publications)**
Second Revised Edition	**:**	August 2021
Third Revised Edition	**:**	June 2022

This edition is for sale in India, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka and designated countries in South-East Asia. Sale and purchase of this book outside of these countries is unauthorized by the publisher.

ISBN : 978-93-89233-61-2

Published by :

TechKnowledge Publications

Head Office : B/5, First floor, Maniratna Complex, Taware Colony, Aranyeshwar Corner,
Pune - 411 009. Maharashtra State, India

Ph : 91-20-24221234, 91-20-24225678.

Email : info@techknowledgebooks.com,

Website : www.techknowledgebooks.com

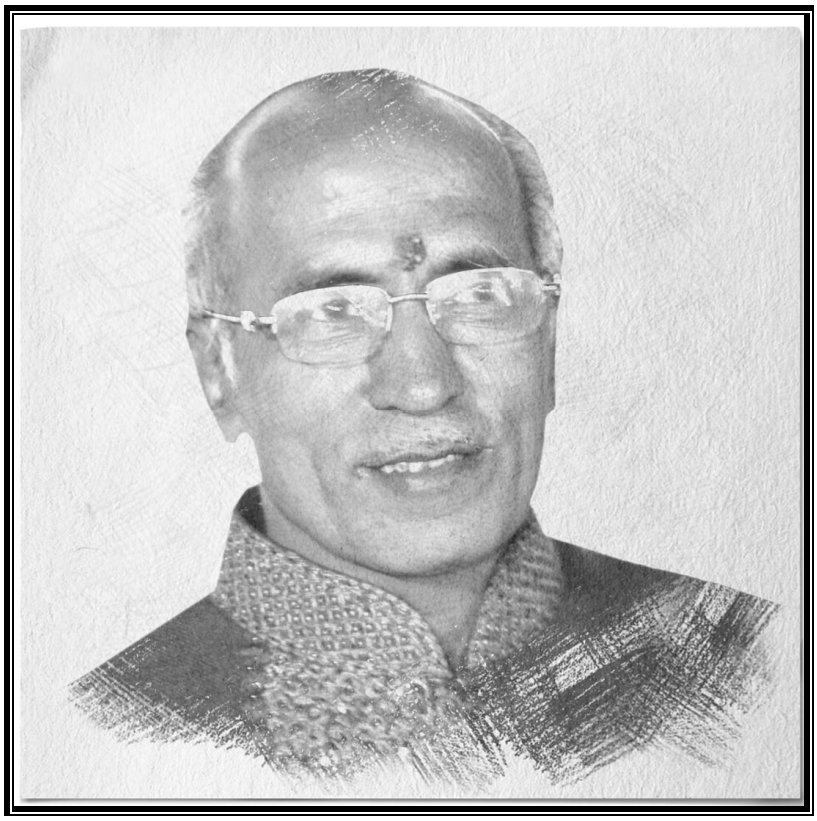
[22523] (FID : MDO65) (Book Code : MDO65C)

We dedicate this Publication soulfully and wholeheartedly,

in loving memory of our beloved founder director,

Late Shri. Pradeepji Lalchandji Lunawat,

who will always be an inspiration, a positive force and strong support behind us.



"My work is my prayer to God"

- Lt. Shri. Pradeepji L. Lunawat

Soulful Tribute and Gratitude for all Your Sacrifices, Hardwork and 40 years of Strong Vision…

(Book Code : MDO65C)

Syllabus…

Industrial AC Machines : Sem. V (Electrical Engineering Group (MSBTE))

Unit-I

1. Three Phase Induction Motor :

Working principle : Production of rotating magnetic field, Synchronous speed, Rotor speed and slip, Constructional details of 3 phase induction motors : Squirrel cage induction motor and slip ring induction motor. Rotor quantities : Frequency, Induced emf, Power factor at starting and running condition, Characteristics of torque versus slip (Speed), Torques : Starting, Full load and maximum with relations among them. Induction motor as a generalized transformer with phasor diagram, Four quandrant operation, Power flow diagram, Starters : Need and types : Stator resistance, Auto transformer, Start delta, Rotor resistance and soft starters, Speed control methods : Stator voltage, Pole changing, Rotor resistance and VVVF. Motor selection for different applications as per the load torque speed requirements, Maintenance of three phase induction motors. **(Refer Chapter 1)**

Unit-II

2. Single Phase Induction Motors :

Double field revolving theory, Principle of making these motors self start, Construction and working : Resistance start induction run, Capacitor start induction run, Capacitor start capacitor run, Shaded pole, Repulsion type, Series motor, Universal motor, Hysteresis motor. Torque-speed characteristics for all of the above motors, Motor selection for different applications as per the load torque speed requirements, Maintenance of single phase induction motors.

(Refer Chapter 2)

Unit-III

3. Three Phase Alternators :

Principle of working, Moving and stationary armatures, Constructional details : Parts and their functions, Rotor Constructions, Windings : Single and double layer, E.M.F. equation of Alternator with numerical by considering short pitch factor and distribution factor. Alternator loading : Factors affecting the terminal voltage of alternator ; Armature resistance and leakage reactance drops, Armature reaction at various power factors and synchronous impedance, voltage regulation ; direct loading and synchronous impedance methods, maintenance of alternators.

(Refer Chapter 3)

Unit-IV

4. Synchronous Motors :

Principle of working / Operation, Significance of load angle, Torques : Starting torque, Running torque, Pull in torque, Pull out torque, Synchronous motor on load with constant excitation (numerical), Effect of excitation at constant load (numerical). V-Curves and Inverted V-Curves, Hunting and phase swinging. Methods of starting of synchronous motor, Losses in synchronous motors and efficiency (no numericals), Applications areas.

(Refer Chapter 4)

(Book Code : MDO65C)

Unit-V

5. Fractional Horse Power Motors (FHP) :

Construction and working : Synchronous Reluctance motor, Switched reluctance motor, BLDC, Permanent magnet synchronous motors, Stepper motors, AC and DC servomotors, Torque speed characteristics of above motors, Applications of above motors. **(Refer Chapter 5)**

❑❑❑

Unit–I

Chapter 1 : Three Phase Induction Motor 1-1 to 1-74

Syllabus : Working principle : Production of rotating magnetic field, Synchronous speed, Rotor speed and slip. Constructional details of three phase induction motor : Squirrel-cage and slip-ring induction motor, Rotor quantities : Frequency, Induced emf, Power factor at starting and running condition, Characteristics of torque versus slip (speed),Torques : Starting, Full load and maximum with relations among them. Induction motor as a generalized transformer with phasor diagram, Four quadrant operation, Power flow diagram, Starters : Need and types, Stator resistance, Auto transformer, Star-Delta, Rotor resistance and soft starters, Speed control methods : Stator voltage, Pole changing, Rotor resistance and VVVF. Motor selection for different applications as per the load torque speed requirements, Maintenance of three phase induction motors.

1.1 Introduction 1-2

1.1.1 Advantages of Induction Motors over DC Motors 1-2

1.1.2 Disadvantages of Induction Motors 1-2

1.1.3 Applications of Induction Motor 1-2

1.2 Rotating Magnetic Field (RMF) 1-2

1.2.1 Production of RMF 1-3

1.2.2 Direction of RMF 1-5

1.3 Construction of 3-Phase Induction Motor 1-5

1.3.1 Induction Motor Parts and their Functions 1-7

1.4 Types of Induction Motor 1-7

1.4.1 Wound Rotor or Slip Ring Type Rotor 1-8

1.4.2 Squirrel Cage Rotor 1-8

1.4.3 Comparison of Two Types of Rotor 1-9

1.5 Principle of Operation 1-10

1.5.1 Direction of Rotation 1-11

1.5.2 Why an I.M. can Never Run at N_S ? 1-11

1.6 Effect of Loading on Induction Motor 1-11

1.7 Electrical Characteristics of Induction Motors 1-12

1.7.1 Synchronous Speed (N_S) 1-12

1.7.2 Slip s 1-12

1.7.3 Frequency of Rotor Induced emf (f_r) (Slip Frequency) 1-12

1.7.4 Induced Voltage in the Rotor 1-13

1.7.5 Rotor Resistance (R_2) 1-13

1.7.6 Rotor Reactance(X_2) 1-13

1.7.7 Rotor Impedance 1-13

1.7.8 Rotor Power Factor 1-14

1.7.9 Rotor Current 1-14

1.7.10 Power Transferred 1-14

1.8 Torque Equation of Induction Motor 1-18

1.8.1 Full Load Torque 1-19

1.8.2 Starting Torque 1-19

1.8.3 Condition for Maximum Torque 1-19

1.8.4 Expression For Maximum Torque [T_m] 1-20

1.9 Torque Slip Characteristics of Induction Motor 1-20

1.9.1 Analysis of the Torque-Slip Characteristics 1-21

1.9.2 Pull Out Torque or Breakdown Torque 1-22

1.9.3 Other Regions of Operation 1-22

1.10 Various Torque Ratios for an Induction Motor 1-23

1.10.1 Starting Torque to Maximum Torque Ratio 1-23
1.10.2 Ratio of Full Load Torque and Maximum Torque 1-23
1.11 Effect of Change in Rotor Resistance on Torque 1-34
1.12 Effect of Change in Supply Voltage on Torque Slip Characteristics 1-34
1.12.1 Effect of Change in Supply Frequency 1-35
1.13 Two / Four Quadrant Operation 1-35
1.13.1 Two Quadrant Operation of Induction Motor 1-35
1.13.2 Four Quadrant Operation of Induction Motor 1-36
1.14 Losses in Induction Motor 1-37
1.14.1 Variable Losses 1-37
1.14.2 Constant Losses 1-37
1.15 Power Flow Diagram (Power Stages) for Induction Motor 1-37
1.16 Efficiency of an Induction Motor 1-39
1.17 Induction Motor as a Transformer 1-51
1.18 Equivalent Circuit of Induction Motor 1-52
1.18.1 Equivalent Circuit Referred to Stator 1-52
1.18.2 Approximate Equivalent Circuit 1-53
1.19 Vector Diagram of Induction Motor 1-53
1.20 Need of Starter for Induction Motor 1-54
1.20.1 Types of Starters 1-55
1.20.2 Stator Resistance Starter 1-55
1.20.3 Autotransformer Starter 1-56
1.20.4 Star-Delta Starter 1-57
1.20.5 Rotor Resistance Starter 1-58
1.20.6 Soft Starting 1-59
1.20.7 Direct On Line (DOL) Starter 1-60
1.20.8 Comparison of Different Starters 1-61
1.21 Speed Control of Three Phase Induction Motors 1-61
1.21.1 Stator Voltage Control 1-62
1.21.2 Stator Frequency Control or V/f or VVVF Control 1-63
1.21.3 Pole Changing 1-65
1.21.4 Speed Control using External Rotor Resistance 1-65
1.22 Reversal of Direction of Rotation 1-66
1.23 Applications of Induction Motors 1-66
1.23.1 Applications of Squirrel Cage Motors 1-66
1.23.2 Applications of Slipring Induction Motors 1-67
1.23.3 Comparison of I.M. and DC Motors 1-67
1.24 Maintenance of a 3 Phase Induction Motor 1-67
1.24.1 Preventive Maintenance 1-68
1.25 Motor Selection for Different Applications as per the Load Torque Requirements 1-69
1.26 MSBTE Questions and Answers 1-72
1.27 I-Scheme Questions and Answers 1-74
• **Review Questions 1-71**

Unit–II

Chapter 2 : Single Phase Induction Motors 2-1 to 2-24

Syllabus : Double field revolving theory, Principle of making these motors self start, Construction and working : Resistance start induction run, Capacitor start induction run, Capacitor start capacitor run, Shaded pole, Repulsion type, Series motor, Universal motor, Hysteresis motor, Torque – Speed characteristics for all of the above motors, Motor selection for different applications as per the load torque

requirements, Maintenance of single phase induction motors.

2.1 Introduction 2-2

2.2 Single Phase Induction Motors 2-2

2.2.1 Construction of Single Phase Induction Motors 2-2

2.2.2 Double Revolving Field Theory 2-2

2.2.3 Torque Speed Characteristics of Single Phase Induction Motor 2-3

2.2.4 Split Phasing Principle of Starting 2-4

2.2.5 Types of Single Phase Induction Motors 2-4

2.3 Split Phase I.M. (Resistance Start Induction Run) 2-4

2.3.1 Principle of Operation 2-5

2.3.2 Phasor Diagram 2-5

2.3.3 Torque Speed Characteristics 2-5

2.3.4 Applications of Split Phase Induction Motor 2-6

2.3.5 Possible Reasons for Slow Speed 2-6

2.4 Capacitor Start Induction Run Motors 2-7

2.4.1 Phasor Diagram 2-7

2.4.2 Torque Speed Characteristics 2-8

2.5 Capacitor Start Capacitor Run Motor 2-8

2.5.1 Phasor Diagram 2-9

2.5.2 Role of Capacitor 2-9

2.5.3 Advantages and Disadvantages 2-9

2.5.4 Torque Speed Characteristics 2-9

2.5.5 Applications 2-9

2.6 Shaded Pole Induction Motors 2-10

2.6.1 Advantages 2-11

2.6.2 Disadvantages 2-11

2.6.3 Applications 2-11

2.6.4 Comparison of Polyphase I.M. and Single Phase I.M. 2-11

2.6.5 Comparison of Resistance Split Phase Motor and Capacitor Split Phase Motor 2-11

2.7 Repulsion Motors 2-12

2.7.1 Repulsion Motor 2-12

2.8 Single Phase A.C. Series Motors 2-13

2.8.1 Modifications 2-14

2.8.2 Construction of AC Series Motor 2-15

2.8.3 Torque-Speed Characteristics 2-15

2.8.4 Applications 2-16

2.9 Universal Motor 2-16

2.9.1 Uncompensated Universal Motor 2-16

2.9.2 Compensated Universal Motor 2-17

2.9.3 Advantages of Universal Motors 2-18

2.9.4 Disadvantages of Universal Motors 2-18

2.9.5 Speed Range and Direction Reversal 2-18

2.9.6 Applications of Universal Motors 2-18

2.10 Hysteresis Motor 2-18

2.11 Motor Selection for Different Applications as per the Load Torque Requirements 2-20

2.11.1 Speed-Torque Characteristics of DC Shunt Motor 2-20

2.11.2 Speed-Torque Characteristics of DC Series Motor 2-20

2.11.3 Torque Speed Characteristics of DC Compound Motors 2-21
2.11.4 Torque-Slip Characteristics of Induction Motor 2-21
2.11.5 Torque Speed Characteristics of Synchronous Motor 2-21
2.12 Different Applications and Motors 2-21
2.12.1 Rolling Mills 2-21
2.12.2 Shear Press and Mechanical Press 2-21
2.12.3 Cranes, Winches, Hoists 2-21
2.12.4 Traction 2-22
2.12.5 Textile Industry 2-22
2.12.6 Coal and Mining Industry 2-22
2.13 Motors and their Applications with Reasons 2-22
2.14 Maintenance of a Single Phase Induction Motor 2-22
2.14.1 Preventive Maintenance 2-23
2.15 MSBTE Questions and Answers 2-24
2.16 I-Scheme Questions and Answers 2-24
• **Review Questions 2-23**

Unit–III

Chapter 3 : Three Phase Alternators 3-1 to 3-51

Syllabus : Principle of working : Moving and stationary armatures, Constructional details : Parts and their functions. Rotor constructions : Windings; Single and double layer. E.M.F. equation of alternator with numerical by considering short pitch factor and distribution factor, Alternator loading : Factors affecting the terminal voltage of alternator, Armature resistance and leakage reactance drops, Armature reaction at various power factors and synchronous impedance, Voltage regulation : Direct loading and synchronous impedance methods, Maintenance of alternator.

3.1 Introduction to Alternators 3-2
3.2 Classification of Alternators 3-2
3.3 Construction of an Alternator 3-3
3.3.1 Stator Construction 3-3
3.3.2 Construction of a Rotor : (Types of Alternators According to Types of Rotors) 3-4
3.3.3 Comparison of Salient Pole and Smooth Cylindrical Rotor 3-5
3.3.4 Excitation System 3-6
3.3.5 Ventilation System 3-6
3.3.6 Slip Ring and Brush Assembly 3-6
3.4 Advantages of Rotating Field Construction over the Rotating Armature Construction 3-7
3.5 Principle of Operation 3-8
3.5.1 Moving Armature Type 3-8
3.5.2 Stationary Armature Type 3-8
3.6 Induced (Generated) EMF 3-9
3.6.1 Frequency of Induced EMF 3-9
3.6.2 Synchronous Speed (Relation between N_S and f) 3-9
3.7 Derivation of the Relation between N_S and f 3-10
3.8 Armature Windings 3-10
3.9 Armature Winding and Related Definitions 3-10
3.10 Types of Armature Windings 3-11
3.10.1 Single Layer and Double Layer Winding 3-11
3.10.2 Concentric or Distributed Windings 3-11
3.10.3 Full Pitch and Short Pitch Winding 3-13

3.10.4 Pitch Factor or Coil Span Factor (K_c or K_p) 3-14

3.10.5 Distribution Factor or Breadth Factor or Winding Factor or Spread Factor (K_d) 3-15

3.11 E.M.F. Equation of an Alternator 3-16

3.12 Parameters of Armature Winding 3-23

3.12.1 Armature Resistance R_a 3-23

3.12.2 Armature Leakage Reactance X_L 3-24

3.13 Armature Reaction at Various Power Factors 3-24

3.13.1 Effect of Lagging Power Factor Load 3-24

3.13.2 Effect of Unity Power Factor Load 3-25

3.13.3 Effect of Zero Leading Power Factor 3-25

3.14 Synchronous Reactance (X_S) and Synchronous Impedance (Z_S) 3-26

3.15 Equivalent Circuit of an Alternator 3-27

3.16 Voltage Equation and Factors Affecting the Terminal Voltage 3-28

3.17 Voltage Regulation of an Alternator 3-29

3.17.1 Regulation by Direct Loading Method 3-29

3.17.2 Indirect Methods to Find Regulation 3-30

3.18 Regulation of an Alternator by Synchronous Impedance Method 3-31

3.18.1 Open Circuit Test 3-31

3.18.2 Short Circuit Test 3-32

3.18.3 To Obtain Synchronous Impedance Z_S 3-33

3.18.4 Regulation Calculations 3-33

3.18.5 Phasor Diagrams and Regulation Calculation 3-34

3.18.6 Precautions in OC and SC Tests 3-35

3.19 Rating of an Alternator 3-47

3.20 Losses and Efficiency 3-47

3.21 Maintenance of an Alternator 3-48

3.22 MSBTE Questions and Answers 3-49

3.23 I-Scheme Questions and Answers 3-51

• Review Questions 3-49

Unit–IV

Chapter 4 : Synchronous Motors 4-1 to 4-21

Syllabus : Principle of working / operation, Significance of load angle. Torques : Starting torque, Running torque, Pull in torque, Pull out torque, Synchronous motor on load with constant excitation (numerical), Effect of excitation at constant load (numerical), V-curves and inverted V-curves, Hunting and phase swinging, Methods of starting of synchronous motor, Losses in synchronous motors and efficiency (no numericals), Applications areas.

4.1 Synchronous Motors 4-2

4.1.1 Important Characteristics of Synchronous Motors 4-2

4.2 Construction of Three Phase Synchronous Motor 4-2

4.3 Rotating Magnetic Field (RMF) 4-2

4.4 Types of Synchronous Motors 4-2

4.5 Principle of Operation 4-3

4.5.1 Why Synchronous Motor is not Self Starting ? 4-4

4.6 Effect of Variation of Load 4-4

4.6.1 Back Emf 4-4

4.6.2 Synchronous Impedance Z_S 4-5

4.6.3 Power Developed by a Synchronous Motor 4-5

4.7 Ideal Synchronous Motor on No Load 4-6

4.7.1 Synchronous Motor on No Load (With Losses) 4-6

4.7.2 Synchronous Motor on Load 4-7

4.7.3 Torque Angle Characteristics 4-7

4.8 Different Torques of a Synchronous Motor 4-8

4.9 Starting Methods for a Synchronous Motor 4-8

4.9.1 Using a Small DC Machine 4-8

4.9.2 Using a Small Induction Motor 4-8

4.9.3 Using the Damper Winding 4-9

4.10 Different Operating Conditions for a Synchronous Motor 4-9

4.11 Complete Phasor Diagram Under Normal Working Condition 4-9

4.12 Effect of Change in Excitation at Constant Load 4-10

4.12.1 Phasor Diagram for Normal Excitation 4-10

4.12.2 Phasor Diagram for Under Excitation 4-10

4.12.3 Phasor Diagram for the Over Excitation 4-11

4.12.4 Phasor Diagram for Critical Excitation 4-11

4.13 V - Curves and Inverted V - Curves 4-11

4.13.1 V Curves 4-12

4.13.2 Inverted V Curve 4-12

4.13.3 Set up to Plot the V-curves and Inverted V-curves 4-12

4.14 Power Flow within a Synchronous Motor 4-13

4.15 Synchronous Condenser 4-13

4.15.1 Power Factor Correction using Synchronous Condenser 4-14

4.16 Hunting in Synchronous Motor 4-14

4.16.1 Effects of Hunting 4-15

4.16.2 Phasor Diagram of Synchronous Motor While Hunting 4-15

4.17 Applications, Advantages and Disadvantages of Synchronous Motor 4-15

4.17.1 Applications 4-15

4.17.2 Advantages 4-16

4.17.3 Disadvantages 4-16

4.18 Comparison between 3 Phase Induction Motor and 3 Phase Synchronous Motor 4-16

4.18.1 Examples on Synchronous Motor 4-16

4.19 I-Scheme Questions and Answers 4-21

• **Review Questions 4-19**

Unit–V

Chapter 5 : Fractional Horse Power Motors (FHP) 5-1 to 5-22

Syllabus : Construction and working: Synchronous reluctance motor, Switched reluctance motor, BLDC, Permanent magnet synchronous motors, Stepper motors, DC and AC servomotors, Torque speed characteristics of above motors, Applications of above motors.

5.1 Introduction 5-2

5.2 Single Phase Synchronous Motors 5-2

5.2.1 Synchronous Reluctance Motor 5-2

5.3 Switched Reluctance Motor (SRM) 5-3

5.3.1 Advantages 5-5

5.3.2 Disadvantages 5-5

5.3.3 Applications 5-5

5.4 Brushless DC Motor (BLDC Motor) 5-5

5.4.1 Advantages of BLDC Motor Over DC Motor 5-6

5.4.2 Types of BLDC Motor 5-6

5.4.3 Unipolar (Half Wave) BLDC Motor 5-6

5.4.4 Principle of Operation 5-7

5.4.5 A Bipolar (Full Wave) BLDC Motor 5-8

5.4.6 Torque-Speed Characteristics of BLDC Motor 5-9

5.4.7 Advantage, Disadvantages and Applications 5-9

5.5 Permanent Magnet Synchronous Motor 5-10

5.6 Servomotors 5-11

5.6.1 A.C. Servomotor 5-11

5.6.2 Torque Speed Characteristics 5-12

5.6.3 Advantages of AC Servomotors 5-12

5.6.4 Applications of AC Servomotors 5-13

5.7 DC Servomotors 5-13

5.7.1 Field Controlled DC Servomotor 5-13

5.7.2 Armature Controlled DC Servomotor 5-13

5.7.3 Applications of DC Servomotor 5-14

5.7.4 Comparison of AC and DC Servomotors 5-14

5.7.5 Comparison of Armature Controlled and Field Controlled DC Servomotors 5-14

5.8 Stepper Motor 5-15

5.8.1 Advantages of Stepper Motors 5-15

5.9 Classification of Stepper Motors 5-15

5.9.1 Types of Stepper Motors 5-15

5.10 Variable Reluctance (V.R.) Stepper Motor 5-16

5.11 Permanent Magnet Stepper Motors 5-17

5.11.1 Comparison of V.R. Motor and P.M. Motor 5-18

5.12 Hybrid Step Motors 5-19

5.13 Important Definitions Related to Stepper Motors 5-20

5.14 Stepper Motor Characteristics 5-21

5.14.1 Static Characteristics 5-21

5.14.2 Dynamic Characteristics 5-21

5.14.3 Limitations of Stepper Motor 5-21

5.14.4 Applications of Stepper Motor 5-21

5.15 I-Scheme Questions and Answers 5-22

- **Review Questions 5-22**

❑❑❑