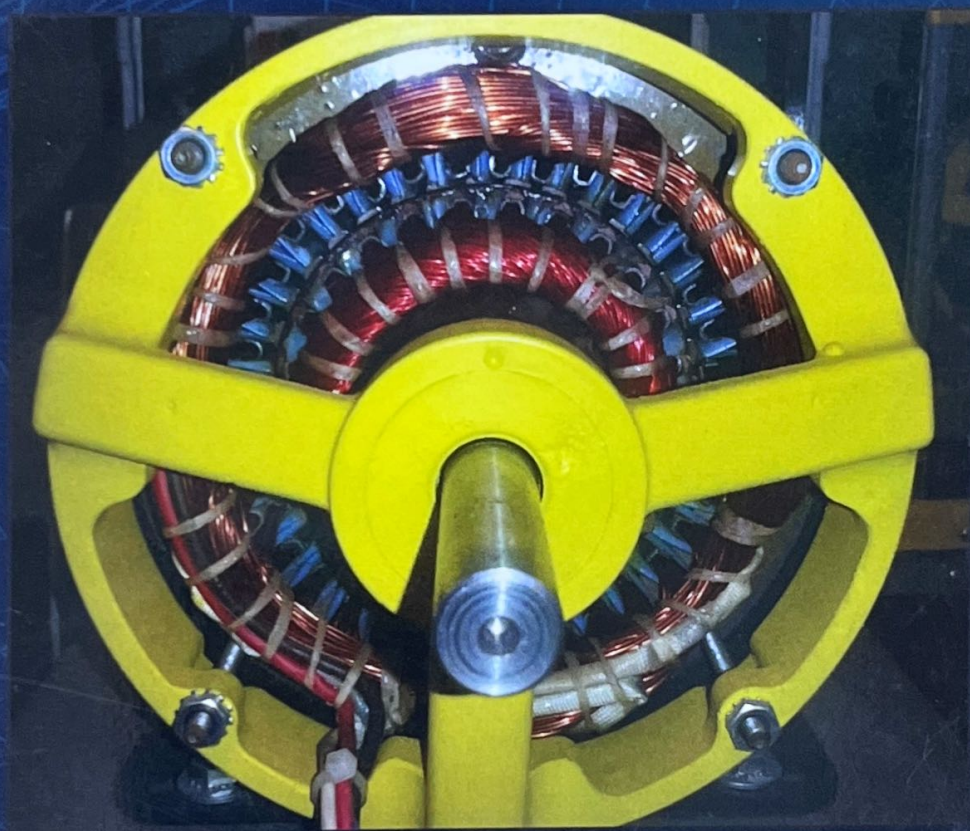


FUNDAMENTALS OF ELECTRIC MACHINES

A Primer with MATLAB®



WARSAME HASSAN ALI
SAMIR IBRAHIM ABOOD
MATTHEW N. O. SADIKU

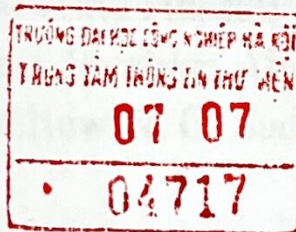


CRC Press
Taylor & Francis Group

4817.

Fundamentals of Electric Machines

with MATLAB®



CRC Press

2005

ISBN 0-8493-1410-9

0-8493-1410-9

9 780849 314109

Fundamentals of Electric Machines

A Primer with MATLAB®

Warsame Hassan Ali
Samir Ibrahim Abood
Matthew N. O. Sadiku



CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

Contents

Preface.....	xv
Acknowledgments	xvii
Authors.....	xix
1. Basic Concepts of Magnetism	1
1.1 History of Magnetism	1
1.2 The Cause of Magnetism	2
1.3 Types of Magnets	3
1.4 Applications of Magnet.....	4
1.5 Magnetic Materials	4
1.6 Lines of Magnetic Forces	6
1.7 Magnetic Force	8
1.8 The Direction of Magnetic Field Lines.....	8
1.9 Magnetic Field and Its Polarity	11
1.10 Magnetism of Magnetic Materials.....	12
1.11 Force Generated in the Field.....	13
1.12 Hysteresis Loop.....	16
Problems.....	17
2. Magnetic Circuit	19
2.1 Magnetic Quantities	19
2.1.1 Flux Density.....	19
2.1.2 Permeability.....	19
2.1.3 Magnetic Reluctance.....	20
2.2 Electromagnetic Induction	27
2.3 Induced Electric Motive Force (EMF).....	30
2.4 Types of Inductance.....	32
2.4.1 Self-Inductance.....	32
2.4.2 Mutual Inductance.....	33
2.5 Stored Energy	36
Problems.....	37
3. Alternating Current Power	39
3.1 Sinusoidal Wave Cycle and Frequency	39
3.2 Electric Power Generation	41
3.3 Terms and Concepts	42
3.4 AC Current Values	43
3.4.1 The Maximum Value of the Alternating Current	44
3.4.2 Average Value of Alternating Current (Mean Value).....	44
3.4.3 Actual AC Value.....	44
3.4.4 The Instantaneous Value of Alternating Current.....	44

3.5	AC Circuits.....	45
3.5.1	AC Circuit Containing Pure Resistance	45
3.5.2	AC Circuit with Inductive Reactance.....	46
3.5.3	AC Circuit with Capacitive Reactance.....	47
3.6	Series Impedance Connection to the AC Circuit.....	49
3.6.1	R-L Series Circuit.....	49
3.6.2	R-C Series Circuit.....	50
3.6.3	R-L-C Series Circuit	52
3.7	Parallel Connection.....	54
3.7.1	Parallel R-L Circuit.....	54
3.7.2	Parallel R-C Circuit	55
	Problems.....	62
4.	Transformers.....	65
4.1	Installation of the Transformer	65
4.2	Core Shape	67
4.3	Principle of Operation	69
4.4	Ideal Transformer.....	69
4.5	Transformer Rating.....	72
4.6	Transformer Operation	73
4.6.1	The Transformer Operation at No-Load.....	73
4.6.2	The Operation Transformer at Load	74
4.7	Non-ideal Transformer Equivalent Circuits.....	76
4.8	Determination of Equivalent Circuit Parameters.....	79
4.8.1	No-Load Test (Determine R_c and X_m).....	79
4.8.2	Short-Circuit Test (Determine $R_{eq,H}$ and $X_{eq,H}$).....	80
4.9	Transformer Voltage Regulation.....	81
4.10	Three-Phase Transformers.....	85
4.10.1	Three-Phase Transformer Configuration	85
4.10.2	Three-Phase Transformer Connections	85
4.10.2.1	Three-Phase Transformer Star and Delta Configurations	86
4.10.2.2	Transformer Star and Delta Configurations	87
4.10.2.3	Transformer Winding Identification	87
4.10.2.4	Transformer Delta and Delta Connections	88
4.10.2.5	Transformer Star and Star Connections	88
4.10.3	Three-Phase Voltage and Current	89
4.10.3.1	Star-Delta Turns Ratio	89
4.10.3.2	Delta-Star Turns Ratio	90
4.10.4	Three-Phase Transformer Construction.....	91
	Problems.....	92
5.	Transformer Design	93
5.1	The Output Equations	93
5.1.1	Single-Phase Core Type Transformer.....	94
5.1.2	Single-Phase Shell Type Transformer	95
5.1.3	Three-Phase Shell Type Transformer	96
5.2	Choice of Magnetic Loading (B_m)	97
5.3	Choice of Electric Loading (Δ)	97
5.4	Core Construction.....	98

5.5	Electric Motive Force (EMF) per Turn.....	99
5.6	Estimation of Core X-Sectional Area A_1	100
5.7	Graphical Method to Calculate Dimensions of the Core	101
5.8	Estimation of Main Dimensions	102
5.9	Estimation of Core Loss and Core Loss Component of No-Load Current I_c	103
5.10	Estimation of Magnetizing Current of No-Load Current I_m	104
5.11	Estimation of No-Load Current and Phasor Diagram	105
5.12	Estimation of Number of Turns on LV and HV Windings	105
5.13	Estimation of Sectional Area of Primary and Secondary Windings.....	105
5.14	Determination of R_1 , R_2 , and Copper Losses.....	106
5.15	Determination of Efficiency.....	107
5.16	Estimation of Leakage Reactance	107
5.17	Calculation of Voltage Regulation of Transformer.....	109
5.18	Transformer Tank Design	110
5.19	Calculation of Temperature Rise	111
5.20	Calculation Cooling Tubes Numbers.....	111
5.21	The Weight of Transformer.....	112
5.22	MATLAB Programs	113
	5.22.1 Single-Phase Transformer Design Using MATLAB Program	113
	5.22.2 Three-Phase Transformer Design Using MATLAB Program.....	116
	5.22.3 Three-Phase Transformer Design Using MATLAB Program.....	119
	Problems.....	122
6.	Direct Current Machines	125
6.1	DC Machines.....	125
6.2	DC Machine Parts	125
	6.2.1 Stator	125
	6.2.2 Rotor.....	128
	6.2.3 Commutator	128
	6.2.4 Armature Coils.....	129
	6.2.4.1 Lap Winding	129
	6.2.4.2 Wave Winding	129
6.3	DC Generator.....	130
	6.3.1 Calculate the Motive Force Generated by the Generator (E.M.F)	130
	6.3.2 Method of Excitation of DC Machines.....	131
	6.3.2.1 Separately Excited Generator.....	131
	6.3.2.2 Self-Excited Generator	131
	6.3.3 Losses in DC Generator.....	144
	6.3.4 Efficiency Calculation.....	146
6.4	DC Motors.....	148
	6.4.1 Types of DC Motors	150
	6.4.1.1 Series Motor.....	150
	6.4.1.2 Shunt Motor.....	154
	6.4.1.3 Compound DC Motor.....	158
	6.4.2 DC Motor Speed Control.....	161
	6.4.2.1 Speed Control of the Shunt Motor	161
	6.4.2.2 Speed Control of the Series Motor	162
	6.4.3 Starting Methods.....	163
	Problems.....	163

7. AC Motors	165
7.1 Single-Phase Motor	165
7.1.1 Induction Motors	165
7.1.1.1 Motor Construction.....	166
7.1.1.2 The Speed	169
7.1.1.3 The Theory of Work	170
7.1.1.4 Starting Methods of the Motor.....	170
7.1.2 Synchronous Motors	174
7.1.2.1 Synchronous Motor Construction	175
7.1.2.2 Synchronous Motor Operation Theory.....	175
7.1.2.3 Synchronous Motor Features	175
7.1.3 Universal Motor	175
7.1.3.1 Universal Motor Construction	176
7.1.4 Centrifuge Switches.....	176
7.2 Three-Phase Induction Motor	178
7.2.1 Construction of Induction Machines	178
7.2.1.1 Squirrel Cage Motor.....	179
7.2.1.2 Slip Ring Motors.....	179
7.2.2 Operation	181
7.2.3 Speed-Torque Characteristics of Induction Motor	182
7.2.4 Speed-Torque Characteristics of Induction Motors Using MATLAB Program.....	183
7.2.5 Basic Equations and Equivalent Circuit Diagram.....	183
7.2.6 No-Load Test and Blocked Rotor Test.....	187
7.2.6.1 No-Load Test.....	187
7.2.6.2 Blocked Rotor Test.....	189
Problems.....	191
8. Power Electronics	193
8.1 Rectifiers (AC-DC Converters).....	193
8.1.1 Rectifier Types	193
8.1.2 Performance Parameters.....	194
8.1.3 Uncontrolled Rectifiers	196
8.1.3.1 Half-Wave Uncontrolled Rectifiers	196
8.1.3.2 Full-Wave Rectifiers	203
8.1.4 Rectifiers with Filter Circuits	212
8.1.5 Controlled Rectifiers.....	213
8.1.5.1 Thyristor Firing Circuits	213
8.1.5.2 The Use of a Thyristor in the Controlled Rectifier Circuits...	214
8.1.5.3 Single-Phase Half-Wave Controlled Rectifier with Resistive Load	215
8.1.5.4 Single-Phase Half-Wave Control Rectifier with R-L Load	216
8.1.5.5 Single-Phase Full-Wave Control Rectifier with R-L Load	220
8.1.5.6 Single-Phase Full-Wave Half Control Rectifier with R-L Load.....	223
8.2 Power Electronics Circuits with MATLAB Program	226
8.2.1 MATLAB Simulation of Single-Phase Half-Wave Uncontrolled Rectifier	226

8.2.2	MATLAB Simulation of Single-Phase Half-Wave Controlled Rectifier	228
8.2.3	MATLAB Simulation of Single-Phase Half-Wave Controlled Rectifier with an Inductive Load	230
8.3	DC-DC Converter Basics	237
8.3.1	Step-Down (Buck) Converter	237
8.3.1.1	Transition between Continuous and Discontinuous	238
8.3.1.2	Voltage Ratio of Buck Converter (Discontinuous Mode).....	239
8.3.2	Step-Up (Boost) Converter.....	240
8.3.3	Buck-Boost Converter	242
8.3.4	Converter Comparison.....	243
	Problems.....	246
9.	Concept of DC Drive.....	251
9.1	DC Motors Drive.....	251
9.1.1	Advantages	251
9.1.1.1	Easy to Understand the Design.....	251
9.1.1.2	Easy to Control the Speed	252
9.1.1.3	Easy to Control Torque	252
9.1.1.4	Simple, Cheap Drive Design.....	252
9.1.2	Disadvantages	252
9.2	Torque-Speed Characteristics.....	257
9.3	DC Motors Parametric Methods.....	260
9.3.1	Separate Excited and Shunt Motor	260
9.3.1.1	Adding Resistance to the Armature.....	262
9.3.1.2	Changing the Armature Supply Voltage	265
9.3.1.3	Changing the Field Flux.....	265
9.3.2	Series Motor	269
9.4	DC Drive Circuits.....	272
9.4.1	DC Drive Rectifier Circuits	272
9.4.1.1	Single-Phase Half-Wave Converter Drives a Separately Excited DC Motor.....	272
9.4.1.2	Single-Phase Full-Wave Converter Drives a Separately Excited DC Motor.....	276
9.5	DC Chopper Drive	280
9.6	Electrical Braking of Separate Excited DC Motor	284
9.6.1	Generator Braking.....	284
9.6.2	Supply Reversing Braking	286
9.6.3	Dynamic Braking.....	289
	Problems.....	296
10.	AC Drives	299
10.1	Advantages of AC Drives.....	299
10.2	Disadvantages of AC Drives.....	299
10.3	Speed Control of Three-Phase Induction Motor	300
10.4	Methods of Control Techniques.....	303
10.4.1	Speed Control of Three-Phase Induction Motors	303
10.4.1.1	Stator Voltage Control.....	305
10.4.1.2	Stator Frequency Control	307

10.4.1.3	Stator Voltage and Frequency Control	310
10.4.1.4	V/f Control Theory	311
10.4.1.5	Static Rotor-Resistance Control	312
10.4.1.6	Slip-Energy Recovery Control	317
Problems	.....	318
11. Special Machines	.....	321
11.1 Stepper Motors	.....	321
11.1.1 Step Angle	.....	322
11.1.2 How Stepper Motors Work	.....	323
11.1.3 DC Motors versus Stepper Motors	.....	326
11.1.4 Advantages of Stepper Motors	.....	327
11.1.5 Disadvantages of Stepper Motors	.....	327
11.1.6 Specification of Stepping Motor Characteristics	.....	327
11.1.6.1 Static Characteristics	.....	327
11.1.6.2 Dynamic Characteristics	.....	329
11.1.7 Steady State Phasor Analysis	.....	330
11.1.7.1 Phasor Expression of Variable Reluctance Stepping Motor	....	330
11.1.7.2 Phasor Expression of PM and Hybrid Stepping Motors	.....	331
11.1.7.3 Equivalent Circuit in Frequency Domain	.....	331
11.1.7.4 Pull-Out Torque Expression	.....	332
11.1.8 Applications	.....	333
11.2 Permanent-Magnet DC Motor	.....	333
11.2.1 Construction	.....	333
11.2.2 Working	.....	334
11.2.3 Performance	.....	335
11.2.4 Speed Control	.....	335
11.2.5 Advantages	.....	335
11.2.6 Disadvantages	.....	335
11.2.7 Applications	.....	335
11.3 Low-Inertia DC Motors	.....	336
11.3.1 Shell-Type Low-Inertia DC Motor	.....	337
11.3.2 Printed-Circuit (Disc) DC Motor	.....	337
11.4 Servo Motors	.....	338
11.4.1 Mathematical Model of Servo Motor	.....	340
11.4.2 The Difference between Stepper Motors and Servos Motor	.....	342
11.5 Brushed DC Motors	.....	343
11.5.1 Stator	.....	343
11.5.2 Rotor	.....	344
11.5.3 Brushless Motor Basics	.....	344
11.5.4 Advantage and Disadvantage of the Brushless DC Motor	.....	344
Problems	.....	345

Appendix A: Mathematical Formula347

Appendix B: Complex Numbers357

Appendix C: Introduction to MATLAB®365

Appendix D: Answer to Odd-Numbered Problems379

Selected Bibliography383

Index385

and power electronics. This book presents the relation of power quantities for the machine as the current, voltage power flow, power losses, and efficiency. The control condition presents the methods of speed control and electrical drive. Power electronics is important to machine control and drive.

The purpose of this book is to provide a good understanding of the machine behavior and its drive. The book begins with the study of salient features of electrical DC and AC machines. Then it presents their applications in the different types of configurations in field drive. This book is intended for college students, both in community colleges and universities.

This book organized into 11 chapters. With a short review of the basic concept of magnetism in Chapter 1, it starts with a discussion of magnetism and electricity, history of magnetism, types of magnets, and magnetic materials. It also discusses the lines of magnetic forces and force generated in the field. Chapter 2 presents magnetic circuits and quantities. The description of electrical circuit elements, its connection in series and parallel, and its phasor diagram are discussed in Chapter 3 under the title of Alternating Current Power.

Chapter 4 deals with an electric transformer, installation of the transformer, core shape, principle of operation, and the operation of the transformer under no-load and full load conditions. Chapter 5 deals with the transformer design techniques. It includes the conventional design of core and shell type for single- and three-phase transformers. It illustrates all the calculation that is required to design a transformer. The description details of all types of DC machine and related voltage, current, power, and efficiency are covered in Chapter 6. All types of AC machines are also covered in Chapter 7. The chapter also elaborates the related voltage, current, power, and efficiency.

In Chapter 8, the principles of conversion from AC to DC involving single-phase as well as three-phase are presented. DC choppers and the study of several applications of power electronics are also mentioned. Chapter 9 discusses electric drives in general and concept of DC drive in particular. Chapter 10 describes the basic principles of speed control techniques employed in three-phase induction motors using power electronics converters.

Chapter 11 introduces some machines that have special applications. The examples explained in this chapter include stepper motors, brushless DC motor, switched reluctance motor, servomotors, synchro motors, and resolvers.

Several problems are provided at the end of each chapter. The answers to odd-number problems appear in Appendix D.

Preface

An electric machine is a device that converts mechanical energy into electrical energy or vice versa. It can take the form of an electric generator, electric motor, or transformer. Electric generators produce virtually all electric power we use all over the world.

Electric machine blends the three major areas of electrical engineering: power, control, and power electronics. This book presents the relation of power quantities for the machine as the current, voltage power flow, power losses, and efficiency. The control condition presents the methods of speed control and electrical drive. Power electronics is important to machine control and drive.

The purpose of this book is to provide a good understanding of the machine behavior and its drive. The book begins with the study of salient features of electrical DC and AC machines. Then it presents their applications in the different types of configurations in lucid detail. This book is intended for college students, both in community colleges and universities.

This book organized into 11 chapters. With a short review of the basic concept of magnetism in Chapter 1, it starts with a discussion of magnetism and electricity, history of magnetism, types of magnets, and magnetic materials. It also discusses the lines of magnetic forces and force generated in the field. Chapter 2 presents magnetic circuits and quantities. The description of electrical circuit elements, its connection in series and parallel, and its phasor diagram are discussed in Chapter 3 under the title of Alternating Current Power.

Chapter 4 deals with an electric transformer, installation of the transformer, core shape, principle of operation, and the operation of the transformer under no load and full load conditions. Chapter 5 deals with the transformer design techniques. It includes the conventional design of core and shell type for single- and three-phase transformers. It illustrates all the calculation that is required to design a transformer. The description details of all types of DC machine and related voltage, current, power, and efficiency are covered in Chapter 6. All types of AC machines are also covered in Chapter 7. The chapter also elaborates the related voltage, current, power, and efficiency.

In Chapter 8, the principles of conversion from AC to DC involving single-phase as well as three-phase are presented. DC choppers and the study of several applications of power electronics are also mentioned. Chapter 9 discusses electric drives in general and concept of DC drive in particular. Chapter 10 describes the basic principles of speed control techniques employed in three-phase induction motors using power electronics converters.

Chapter 11 introduces some machines that have special applications. The examples explained in this chapter include stepper motors, brushless DC motor, switched reluctance motor, servomotors, synchro motors, and resolvers.

Several problems are provided at the end of each chapter. The answers to odd-number problems appear in Appendix D.

It is not necessary that the reader has previous knowledge of MATLAB®. The material of this text can be learned without MATLAB. However, the authors highly recommend that the reader studies this material in conjunction with the MATLAB Student Version. Appendix C of this text provides a practical introduction to MATLAB.

MATLAB® and Simulink® are registered trademarks of The MathWorks, Inc. For product information, please contact:

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098 USA
Tel: 508 647 7000
Fax: 508-647-7001
E-mail: info@mathworks.com
Web: www.mathworks.com