Electrical Machinery Fundamentals Stephen J. Chapman



Contents

- 1. Introduction to Machinery Principles
- 2. Transformers
- 3. Introduction to Power Electronics
- 4. AC Machinery Fundamentals
- 5. Synchronous Generators
- 6. Synchronous Motors
- 7. Induction Motors
- 8. DC Machinery Fundamentals
- 9. DC Motors and Generators
- 10. Single-Phase and Special-Purpose Motors
- Appendix A Three-Phase Circuits
- Appendix B Coil Pitch and Distributed Windings
- Appendix C Salient-Pole Theory of Synchronous Machines
- Appendix D Tables of Constants and Conversion Factors
- Index

1. Introduction to Machinery Principles

- 1.1 Electrical Machines, Transformers, and Daily Life
- 1.2 A Note on Units and Notation

Notation

1.3 Rotational Motion, Newton's Law, and Power Relationships

Angular Position θ / Angular Velocity ω / Angular Acceleration α / Torque τ / Newton's Law of Rotation / Work W Power P

1.4 The Magnetic Field

Production of a Magnetic Field / Magnetic Circuits / Magnetic Behavior of Ferromagnetic Materials / Energy Losses in a Ferromagnetic Core

- 1.5 Faraday's Law-Induced Voltage from a Time-Changing Magnetic Field
- 1.6 Production of Induced Force on a Wire
- 1.7 Induced Voltage on a Conductor Moving in a Magnetic Field

1.8 The Linear DC Machine – A Simple Example

Starting the Linear DC Machine / The Linear DC Machine as a Motor / The Linear DC machine as a Generator/Starting Problems with the Linear Machine

1.9 Real, Reactive, and Apparent Power in AC Circuits

Alternative Forms of the Power Equations / Complex Power / The Relationships between impedance Angles, Current Angle, and Power / The Power Triangle

1.10 Summary (Questions, Problems, References)

2. Transformers

- 2.1 Why Transformers Are Important to Modern Life
- 2.2 Type and Construction of Transformers
- 2.3 The Ideal Transformer

Power in an Ideal Transformer / Impedance Transformation through a Transformer / Analysis of Circuits Containing Ideal Transformers

2.4 Theory of Operation of Real Single-Phase Transformers

The Voltage Ratio across a Transformer / The Magnetization Current in a Real Transformer / The Current Ratio on a Transformer and the Dot Convention

2.5 The Equivalent Circuit of a Transformer

The Exact Equivalent Circuit of a Real Transformer / Approximate Equivalent Circuits of a Transformer / Determining the Values of Components in the Transformer Model

- 2.6 The Pure-Unit System of Measurements
- 2.7 Transformer Voltage Regulation and Efficiency

The Transformer Phasor Diagram / Transformer Efficiency

2.8 Transformer Taps Voltage Regulation

2.9 The Autotransformer

Voltage and Current Relationships in an Autotransformer / The Apparent Power Rating Advantage of Autotransformers / The Internal Impedance of an Autotransformer

2.10 Three-Phase Transformers

Three-Phase Transformer Connections / The Per-Unit System for Three-Phase Transformers

2.11 Three-Phase Transformation Using Two Transformers

The Open- Δ (or V-V) Connection / The Open-Wye-Open-Delta Connection / The Scott-T Connection / The Three-Phase T Connection

2.12 Transformer Ratings and Related Problems

The Voltage and Frequency Ratings of a Transformer / The apparent Power Ratings of a Transformer / The Problem of Current Inrush / The Transformer Nameplate

2.13 Instrument Transformers

2.14 Summary (Questions, Problems, References)

3. Introduction to Power Electronics

3.1 Power Electronic Components

The Diode / The Two-Wire Thyristor or PNPN Diode / The Three-Wire Thyristor of SCR / The Gate Turnoff Thyristor / The DIAC / The TRIAC / The Power Transistor / The Insulated-Gate Bipolar Transistor / Power and Speed Comparison of Power Electronic Components

3.2 Basic Rectifier Circuits

The Half-Wave Rectifier / The Full-Wave Rectifier / The Three-Phase Half-Wave Rectifier / The Three-Phase Full-Wave Rectifier / Filtering Rectifier Output

3.3 Pulse Circuits

A Relaxation Oscillator using a PNPN Diode / Pulse Synchronization

3.4 Voltage Variation by AC Phase Control

AC Phase Control for a DC Load Driven from an AC Source / AC Phase Angle Control for a AC Load / The Effect of Inductive Loads on Phase Angle Control

3.5 DC-to-DC Power Control – Choppers

Forced Commutation in Chopper Circuits / Series-Capacitor Commutation Circuits / Parallel-Capacitor Commutation Circuits

3.6 Inverters

The Rectifier / External Commutation Inverters / Self-Commutation Inverters / A Single-Phase Current Source Inverter / A Three-Phase Current Source Inverter / A Three-Phase Voltage Source Inverter / Pulse-Width Modulation Inverters

3.7 Cycloconverters

Basic Concepts / Noncirculating Current Cycloconverters / Circulating Current Cycloconverters

3.8 Harmonic Problems

3.9 Summary (Questions, Problems, References)

4. AC Machinery Fundamentals

- 4.1 A Simple Loop in a Uniform Magnetic Field The Voltage Induced in a Simple Rotating Loop The Torque Induced in a Current-Carrying Loop
- 4.2 The Rotating Magnetic Field
 - Proof of the Rotating Magnetic Field Concept / The Relationship between Electrical Frequency and the Speed of Magnetic Field Rotation / Reversing the Direction of Magnetic Field Rotation
- 4.3 Magnetomotive Force and Flux Distribution on AC Machines
- 4.4 Induced Voltage in AC Machines

The Induced Voltage in a Coil on a Two-Pole Stator / The Induced Voltage in a Three-Phase Set of Coils / The RMS Voltage in a Three-Phase Stator

- 4.5 Induced Torque in an AC Machine
- 4.6 Winding Insulation in an AC Machine
- 4.7 AC Machine Power Flows and Losses

The Losses in AC Machines / The Power-Flow Diagram

- 4.8 Voltage Regulation and Speed Regulation
- 4.9 Summary (Questions, Problems, References)

5. Synchronous Generators

- 5.1 Synchronous Generator Construction
- 5.2 The Speed of Rotation of a Synchronous Generator
- 5.3 The Internal Generated Voltage of a Synchronous Generator
- 5.4 The Equivalent Circuit of a Synchronous Generator
- 5.5 The Phasor Diagram of a Synchronous Generator
- 5.6 Power and Torque in Synchronous Generators
- 5.7 Measuring Synchronous Generator Model Parameters The Short-Circuit Ratio
- 5.8 The Synchronous Generator Operating Alone The Effect of Load Changes on Synchronous Generator Operating Alone / Example Problems
- 5.9 Parallel Operation of AC Generators

The Conditions Required for Paralleling / The General Procedure for Paralleling Generators / Frequency-Power and Voltage-Reactive Power Characteristics of a Synchronous Generator / Operation of Generators in Parallel with Large Power Systems / Operation of Generators in Parallel with Other Generators of the Same Size

5.10 Synchronous Generator Transients

Transient Stability of Synchronous Generators / Short-circuit Transients in Synchronous Generators

5.11 Synchronous Generator Ratings

The Voltage, Speed, and Frequency Ratings / Apparent Power and Power-Factor Ratings / Synchronous Generator Capability Curves / Short-Time Operation and Service Factor

5.12 Summary (Questions, Problems, References)

6. Synchronous Motors

6.1 Basic Principles of Motor Operation

The Equivalent Circuits of a Synchronous Motor / The Synchronous Motor from a Magnetic Field Perspective

6.2 Steady-State Synchronous Motor Operation

The Synchronous Motor Torque-Speed Characteristic Curve / The effect of Load Changes on a Synchronous Motor / The Effect of Field Changes on a Synchronous Motor / The Synchronous Motor and Power-Factor Correction / The Synchronous Capacitor or Synchronous Condenser

6.3 Starting Synchronous Motors

Motor Starting by Reduced Electrical frequency / Motor Starting with an External Prime Mover / Motor Starting by Using Amortisseur Windings / The Effect of Amortisseur Windings on Motor Stability

- 6.4 Synchronous Generators and Synchronous Motors
- 6.5 Synchronous Motors Ratings
- 6.6 Summary (Questions, Problems, References)

7. Induction Motors

- 7.1 Induction Motor Construction
- 7.2 Basic Induction Motor Concepts

The Development of Induced Torque in an Induction Motor / The Concept of Rotor Slip / The Electrical Frequency on the Rotor

7.3 The Equivalent Circuit of an Induction Motor

The transformer Model of an Induction Motor / The Rotor Circuit Model / The Final Equivalent Circuit

7.4 Power and Torque in Induction Motors

Losses and the Power-Flow Diagram / Power and Torque in an Induction Motor / Separating the Rotor Copper Losses and the Power Converted in an Induction Motor's Equivalent Circuit

7.5 Induction Motor Torque-Speed Characteristics

Induced Torque from a Physical Standpoint / the Derivation of the Induction Motor Induced Torque Equation / Comments on the Induction Motor Torque-Speed Curve / Maximum (Pullout) Torque in an Induction Motor

7.6 Variations in Induction Motor Torque-Speed Characteristics

Control of Motor Characteristics by Cage Rotor Design / Deep-Bar and Double-Cage Rotor Designs / Induction Motor Design Classes

7.7 Trends in Induction Motor Design

7.8 Starting Induction Motors Induction Motor Starting Circuits

7.9 Speed Control of Induction Motors

Induction Motor Speed Control by Pole Changing / Speed Control by Charging the Line Frequency / Speed Control by Charging the Line Voltage / Speed Control by Charging the Rotor Resistance

7.10 Solid-State Induction Motor Drives

Frequency (Speed) Adjustment / A Choice of Voltage and Frequency Patterns / Independently Adjustable Acceleration and Deceleration Ramps / Motor Protection

7.11 Determining Circuit Model Parameters

The No-Load Test / The DC Test for Stator Resistance / The Locked-Rotor Test

7.12 The Induction Generator

The Induction Generator Operating Alone / Induction Generator Applications

- 7.13 Induction Motor Ratings
- 7.14 Summary (Questions, Problems, References)

8. DC Machinery Fundamentals

- 8.1 A Simple Rotating Loop between Curved Pole Faces The Voltage Induced in a Rotating Loop / Getting DC Voltage out of the Rotating Loop / The Induced Torque in The Rotating Loop
- 8.2 Commutation in a Simple Four-Loop DC Machine
- 8.3 Commutation and Armature Construction in Real DC Machines

The Rotor Coils / Connections to the Commutator Segments / The lap Winding / The Wave Winding / The Frog-Leg Winding

8.4 Problems with Commutation in Real Machines

Armature Reaction / L di/dt Voltages / Solutions to the Problems with Commutation

- 8.5 The Internal Generated Voltage and Induced Torque Equations of Real DC Machines
- 8.6 The Construction of DC Machines

Pole and Frame Construction / rotor or Armature Construction / Commutator and Brushes / Winding Insulation

8.7 Power Flow and Losses DC Machine

The Losses in DC Machines / The Power-Flow Diagram

8.8 Summary (Questions, Problems, References)

9. DC Motors and Generators

- 9.1 Introduction to DC Motors
- 9.2 The Equivalent Circuit of a DC Motor
- 9.3 The Magnetization Curve of a DC Motor
- 9.4 Separately Excited and Shunt DC Motors

The Terminal Characteristic of a Shunt DC Motor / Nonlinear Analysis of a Shunt DC Motor / Speed Control of Shunt DC Motors / The Effect of an Open Field Circuit

9.5 The Permanent-Magnet DC Motor

9.6 The Series DC Motor

Induced Torque in a Series DC Motor / The Terminal Characteristic of a Series DC Motor / Speed Control of Series DC Motors

9.7 The Compounded DC Motor

The Torque-Speed Characteristic of a Cumulatively Compounded DC Motor / The Torque-Speed Characteristic of a Differentially Compounded DC Motor / The Nonlinear Analysis of Compounded DC Motors / Speed Control in the Cumulatively Compounded DC Motor

9.8 DC Motor Starters

DC Motor Problems on Starting / DC Motor Starting Circuits

9.9 The Ward-Leonard System and Solid-State Speed Controllers

Protection Circuit Section / Start/Stop Circuit Section / High-Power Electronics Section / Low-Power Electronics Section

- 9.10 DC Motor Efficiency Calculations
- 9.11 Introduction to DC Generators
- 9.12 The Separately Excited Generator

The Terminal Characteristic of a Separately Excited DC Generator / Control of Terminal Voltage / Nonlinear Analysis of a Separately Excited DC Generator

9.13 The Shunt DC Generator

Voltage Buildup in a Shunt Generator / The Terminal Characteristic of a Shunt DC Generator / Voltage Control for a Shunt DC Generator / The Analysis of Shunt DC Generators

9.14 The Series DC Generator

The Terminal Characteristic of a Series DC Generator

9.15 The Cumulatively Compounded DC Generator

The Terminal Characteristic of a Cumulatively Compounded DC Generator / Voltage Control of Cumulatively Compounded DC Generators / Analysis of Cumulatively Compounded DC Generators

9.16 The Differentially Compounded DC Generator

The Terminal Characteristic of a Differentially Compounded DC Generator / Voltage Control of Differentially Compounded DC Generators / Graphical Analysis of a Differentially Compounded DC Generator

9.17 Summary (Questions, Problems, References)

10. Single-Phase and Special-Purpose Motors

10.1 The Universal Motor

Applications of Universal Motors / Speed Control of Universal Motors

10.2 Introduction to Single-Phase Induction Motors

The Double-Revolving-Field Theory of Single-Phase Induction Motors / The Cross-Field Theory of Single-Phase Induction Motors

10.3 Starting Single-Phase Induction Motors

Split-Phase Windings / Capacitor-Start Motors / Permanent Split-Capacitor and Capacitor-Start, Capacitor-Run Motors / Shaded-Pole Motors / Comparison of Single-Phase Induction Motors

10.4 Speed Control of Single-Phase Induction Motors

10.5 The Circuit Model of a Single-Phase Induction Motor

Circuit Analysis with the Single-Phase Induction Motor Equivalent Circuit

10.6 Other Types of Motors

Reluctance Motors / Hysteresis Motors / Stepper Motors / Brushless DC Motors

10.7 Summary (Questions, Problems, References)

Appendix A Three-Phase Circuits

- A.1 Generation of Three-Phase Voltages and Currents
- A.2 Voltages and Currents in a Three-Phase Circuit

Voltages and Currents in the Wye (Y) Connection / Voltages and Currents in the Delta (Δ) Connection

A.3 Power Relationships in Three-Phase Circuits

Three-Phase Power Equations Involving Phase Quantities / Three-Phase Power Equations Involving Line Quantities

A.4 Analysis of Balanced Three-Phase Systems

A.5 One-Line Diagrams

A.6 Using the Power Triangle (Questions, Problems, References)

Appendix B Coil Pitch and Distributed Windings

B.1 The Effect of Coil Pitch on AC Machines

The Pitch of a Coil / The Induced Voltage of a Fractional-Pitch Coil / Harmonic Problems and Fractional-Pitch Windings

B.2 Distributed Windings in AC Machines

The Breadth or Distribution Factor / The Generated Voltage Including Distribution Effects / Tooth or Slot Harmonics

B.3 Summary (Questions, Problems, References)

Appendix C Salient-Pole Theory of Synchronous Machines

C.1 Development of the Equivalent Circuit of a Salient-Pole Synchronous Generator

C.2 Torque and Power Equations of Salient-Pole Machine (Problems)

Appendix D Tables of Constants and Conversion Factors