

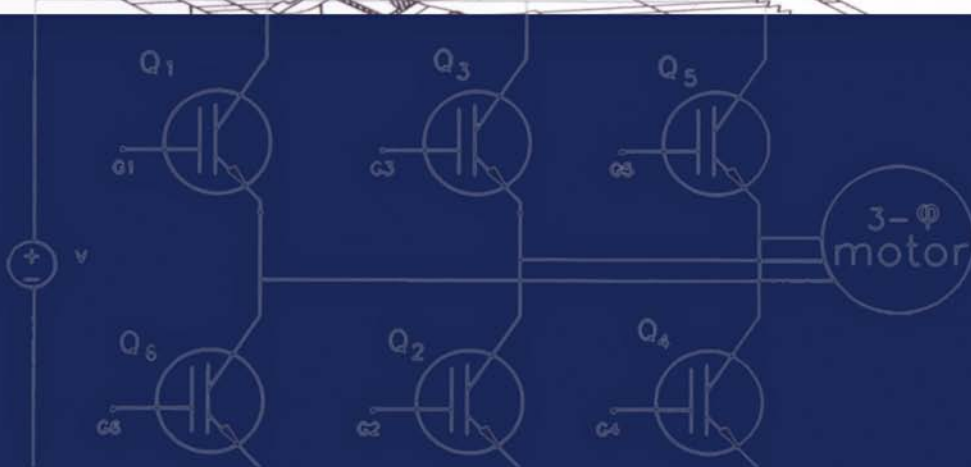
SECOND EDITION

# Electric Machines

Principles, Applications,  
and Control Schematics



**Dino Zorbas**



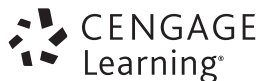
# Electric Machines

Principles, Applications,  
and Control Schematics

Second Edition

**Dino Zorbas**

*McGill University*



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Australia • Brazil • Japan • Korea • Mexico • Singapore • Spain • United Kingdom • United States

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**Dino Zorbas**

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*To all those who believe that the preparation of tomorrow's professionals must include organized practical training.*

*Fortune favors the prepared mind.*

***Louis Pasteur***

*Don't talk to me of your Archimedes lever . . . .*

*Give me the right word and the right  
accent and I will move the world.*

***Joseph Conrad***



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The purpose of this revision to *Electric Machines: Principles, Applications, and Control Schematics* is threefold:

1. To update the technical data and applications of the electrical equipment discussed (transformers, motors, controls, and energy reduction per unit output) since the first printing.
2. To both expand upon and further simplify the basic concepts of electrical engineering. For example, the basic law of nature (action is equal and opposite to reaction) is used in conjunction with Ohm's law in magnetic circuits to explain the principle of induction and the operation of transformers and electric machines. This revision expands on important concepts such as harmonics, induction currents, energy conservation, electrical safety, and others. These are summarized in a tabular form for easy understanding, review, and industrial usage. Where possible, all concepts are illustrated graphically.
3. To provide detailed additional information in the web section on programming logic controllers (PLC), electrical safety, and energy conservation.

In summary, this book aims to describe and simplify the basic concepts of the design and operation of electric machines, to ease the transition from classroom work to that of the practicing engineer, and to give an efficient start to those who will find themselves in engineering departments of industrial or commercial enterprises.

The following list is a brief summary of the chapter contents, together with a description of corresponding web chapters.

## Chapter I Basic Electromagnetic Concepts

The basic elements (resistors, inductors, and capacitors) are each illustrated with more than 10 highlights with emphasis placed on their practical aspects. The various forms of power (complex, apparent, real, and reactive) are introduced including the concepts of actual and apparent power factor. Examples are given with actual utility penalties for low-power factor operation. The generation and effects of harmonics are also discussed. For easy understanding, KVL is illustrated by using exercises from electronic circuits. The section on magnetism discusses the concepts and applications of induction currents, magnetic equivalent circuits, and the force produced by electromagnets.

To ease the student's introduction to electric machines, summary tables are included on electric and magnetic circuit parameters, power, and energy. These points are included in order to facilitate understanding of their analogous magnetic circuit concepts. One complements the other.

Finally, we use a simple circuit (Problem 1-28) as a real-world example. If it could be realized, it would produce all humanity's energy requirements.

Chapter 1W on the web includes additional solved and unsolved problems on the theory of circuits and forces that are produced by rotating transducers.

## Chapter 2 Transformers

Transformers change the voltage from one level to another, constituting a bottleneck effect on a power distribution system. One has to be aware of the continuous improvement of their characteristics. Transformers depend on the selection of the downstream protective devices. Their applications require knowledge of the per-unit system that is further detailed in the Appendixes.

A detailed description is included on standard 1- $\phi$ , 3-phase transformers, parallel operation, and special winding connections.

Chapter 2W on the web includes wiring diagrams and analog meters found in substation apparatus.

## Chapter 3 Three-Phase Induction Motors

Three-phase induction motors are the working horse of industry and have evolved not so much in their design but on the electronic control of their speed. As such, they replace the older design with variable speed controls resulting in higher efficiency and a better match of their torque-speed characteristics to that of the load. More specifically, the following are included:

- derivation of the equivalent circuit,
- methods of starting,
- torque-speed characteristics,
- matching of the load characteristics to that of the motor, and
- detailed analysis of the asynchronous generator that transform wind power to electrical power.

Chapter 3W on the web includes the transient response and special applications of three-phase induction motors.

## Chapter 4 Single-Phase Motors

This chapter discusses the development of two-rotating magnetic fields from 1- $\phi$  voltage supply and how eliminating one of them reduces the noise associated with their interaction. The various types of 1- $\phi$  machines, phasor diagrams, and the corresponding torque-speed characteristics are also examined. The 1- $\phi$  phase type of motors are mainly used for control and ventilation applications.

Chapter 4W on the web explains the development of magnetic fields produced by a two-phase voltage supply and the speed control of two-phase motors.

## Chapter 5 Synchronous Machines

Three-phase synchronous machines are suitable for loads that require constant speed. All power generation is through three-phase synchronous generators; their constant operating speed ensures constant voltage frequency. A detailed analysis

is included on cylindrical and salient rotor machines, on the derivation of their equivalent circuits, on the VEE curves, and on their phasor diagrams. The latter are simplified using a clearly identified unique sequential approach.

Chapter 5W on the web describes the transient waveforms of stator and rotor currents and the resulting current when a three-phase fault occurs. The latter constitutes the basics of selecting circuit breakers in a power distribution system.

## Chapter 6 DC Machines

DC machines have widespread applications because their torque-speed characteristics can be adjusted easily to match those of the driven load. Their operating efficiency and flexibility improved with the advent of variable speed controls.

Chapter 6W on the web covers the transient response of dc machines providing an additional insight on their operation.

## Chapter 7 Control Schematics

The classical relay-contact diagrams are described along with their usage in the control of 1- $\phi$ , MV induction motors, and synchronous motors. Understanding of an industrial process requires the design and selection of controls. This chapter is a prerequisite to understanding the drawings that depict the operation of simple and/or complicated industrial controls.

Chapter 7W on the web discusses the basic controls of 3- $\phi$  induction motors and those of dc machines. Logic circuits and programmable logic controllers (PLC) are introduced.

## Chapter 8 Electrical Safety and Reduction in Energy Consumption

The electrical safety section covers the safety of personnel in various situations: at home, within industries, in swimming pools, in plumbing systems, at farms, and so on. As per recent statistics, there are 10,000 electrical injuries per year in the United State alone.

The energy conservation section outlines many areas of energy conservation in commercial buildings and industrial plants.

Chapter 8W presents a detailed analysis with many solved and end-of-chapter problems on the issues of electrical safety and energy conservation.

## Appendices

The appendices include prerequisite concepts that are required for a better understanding of the subject matter under consideration (three-phase systems, per unit system of values, economic aspects, and protective device designation).

Chapter AP-W on the web is an extension of the book's appendices. It includes additional examples on 3- $\phi$  systems, per unit values, photo-voltaics, and a detailed description of the basic blocks of electronic speed control (i.e., diodes, bipolar transistors, insulated gate bipolar transistors and thyristors).

## MindTap Online Course and Reader

In addition to the print version, this textbook is also available online through MindTap, a personalized learning program. Students who purchase the MindTap version will have access to the book's MindTap Reader and will be able to complete homework and assessment material online, through their desktop, laptop, or iPad. If your class is using a Learning Management System (such as Blackboard, Moodle, or Angel) for tracking course content, assignments, and grading, you can seamlessly access the MindTap suite of content and assessments for this course.

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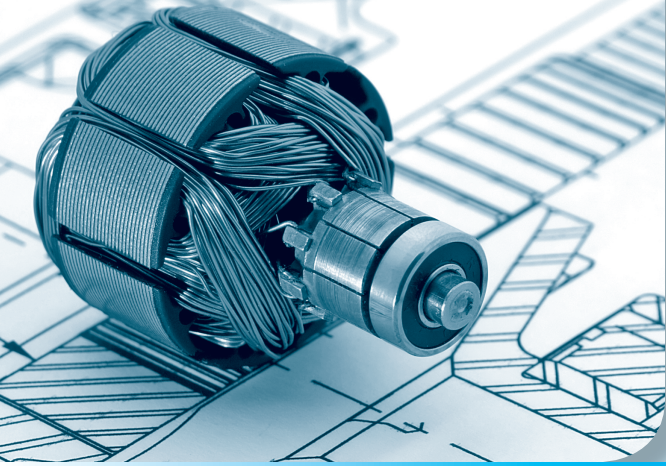
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# Basic Electromagnetic Concepts

- 1.0 Introduction
- 1.1 Electric Circuit Concepts
- 1.2 Magnetic Circuit Concepts
- 1.3 Force, Energy, and Torque
- 1.4 Summary
- 1.5 Review Questions
- 1.6 Problems

## What You Will Learn in This Chapter

### A. Theoretical Aspects

- 1 The concept of voltage and the parameters of electric fields.
- 2 The concepts of resistance, inductance, and capacitance.
- 3 The resonance condition, the time constant, and the principles of electric circuits.
- 4 The various forms of power, power factor, and power-factor correction.
- 5 The harmonics in a power distribution system.
- 6 The magnetic flux lines, magnetic field density, and magnetic field intensity.
- 7 The permeability and the principles of magnetic circuits.
- 8 The equivalent circuit of coils, their self and mutual inductances.
- 9 The magnetic energy stored in a coil, the force of an electromagnet, and the torque produced by a rotating coil.
- 10 The general concepts of power and energy.

### B. Practical Highlights—Interface

- 1 The failures of the Spaceship Apollo 13 (1970) and the Russian *Salyut I* (1971).
- 2 The frequently ineffective current drawn from the utility, the corresponding utility penalty, and how to remove it (for the same reasons that it is not very effective when trying to lose weight while walking in the park and why in the 1940s the German antitank rockets could not destroy the Russian T-34 tanks).
- 3 The advantages and disadvantages of using capacitors to improve the power factor.
- 4 The alternate definition of the time constant supplements the accurate but incomplete truths of the equivalent concepts that are found in publications of chemistry, physics, and even electrical engineering.
- 5 The concept of the induction principle and its associate advantages/disadvantages are simplified and illuminated by just using the concept of “Action is equal and opposite to reaction.”
- 6 The principle of motors, generators, and relays operation is analogous to that of “boy attracts girl and vice versa.”
- 7 The analog meters of the utilities cannot measure all the power consumed by nonlinear loads such as computers, variable speed drives, lighting fixtures, and other digital equipment.
- 8 The resistance and inductance of electric circuits is analogous to the friction and mass/polar moment of inertia of mechanical moving/rotating bodies.
- 9 The degaussing of the British fleet, the potentially catastrophic effects of the induction current, and the broader overview of power and energy.
- 10 Magnetic levitation and high-speed trains.

### C. Additional Students' Aid on the Web

Examples and Problems on Electric Circuits

Example of Force Developed by a Rotating Electromagnet

# 1.0 Introduction

## General Overview

This chapter discusses the basic parameters and principles of electric and magnetic circuits and the development of force and torque. Electric circuit parameters are normally covered in other basic courses, but they are briefly reviewed here in order to facilitate the understanding of magnetic circuit parameters.

Each electric circuit concept is analogous to a corresponding magnetic circuit concept. As a result, mastering the theory of electric circuits will help you grasp the more abstract concepts of magnetism. In order to understand electric machines, you first need a very thorough knowledge of both magnetism and electric circuits.

## 1.1 Electric Circuit Concepts

This section covers the concepts of electric potential, electric field intensity, resistance, capacitance, inductance, impedance, principles of electric circuits, the characteristics of the power drawn from a single-phase voltage source, the apparent and actual power factors, theorems, and harmonics.

### 1.1.1 Electric Potential

Electric potential, electromotive force (emf), electrical pressure and voltage are synonymous terms. In the SI system of units, they are expressed or measured in volts. When the voltage at a power outlet is 120 volts, the electric potential, electric voltage, and the electric pressure at the outlet is of the same magnitude:

$$1 \text{ volt} = \frac{1 \text{ Joule}}{\text{Coulomb}}$$

$$10^3 \text{ V} = 1 \text{ kV}$$

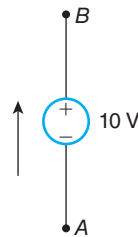
$$10^{-3} \text{ V} = 1 \text{ mV}$$

Voltage is the intensity of an electrical energy source just as temperature is the intensity of a heat source. Voltage and temperature are destructive only when they are associated with high-energy sources. For example, the temperature of a lighted match is about 95°C. When you place your finger on the match, it hurts, but it does not kill you. In contrast, somebody immersed in a home's hot water tank (60°C) would be seriously injured. Similarly, the threshold of static sensation, which is about 4000 V, does not injure because it is not accompanied by sufficient electrical charges. In contrast, the 120 V across a home's receptacle may be fatal to anyone who comes in contact with it. Voltage has a meaning when and only when it is measured with respect to the reference point. The reference terminal is often

the neutral or the ground wire. These two wires as per electrical code requirements are connected together in the premises' electrical entrance. Stating that the voltage at a particular point is 120 V implies what this voltage is with respect to ground.

### Designation

Refer to Fig. 1-1. The voltage at terminal B is at 10 V with respect to that of terminal A. Mathematically,



**FIG. 1-1** Voltage designation.

$$V_{BA} = 10 \text{ V}$$

The voltage, however, at A is at  $-10 \text{ V}$  with respect to point B.

$$V_{AB} = -10 \text{ V}$$

Instead of the polarities + and -, you may use an arrow to indicate relative polarities, as shown in Fig. 1-1.

All main and secondary power distribution networks are characterized by a voltage source. The voltage source may be of constant amplitude (a dc voltage source) or of alternating waveform (an ac voltage source). The various waveforms—whether they represent voltage, current, or power—can be described in terms of their instantaneous, effective, or average values.

### Instantaneous Value

The instantaneous value of a waveform is given by a general equation that describes the waveform as a function of time. For example, the instantaneous value of the voltage waveform that is available in a residential single-phase power outlet is

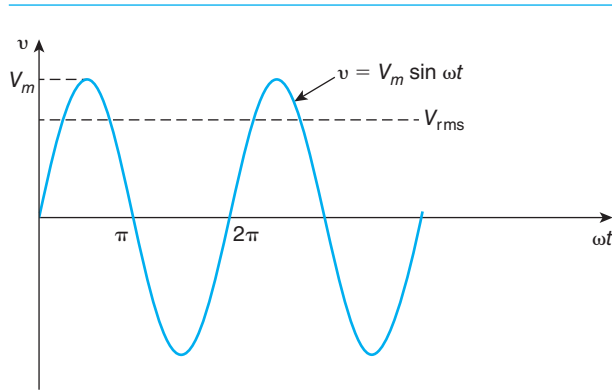
$$v = V_m \sin \omega t \quad (1.1)$$

where  $v$  is the instantaneous value of the voltage,  $V_m$  is its maximum value, and  $\omega$  is its angular frequency of oscillation.

The angular frequency of oscillation is given by

$$\omega = 2\pi f = \frac{2\pi}{T} \text{ rad/s} \quad (1.2)$$

where  $f$  and  $T$  are, respectively, the frequency and the period of oscillation of the voltage waveform. A sinusoidal voltage waveform is shown in Fig. 1-2.



**FIG. 1-2** A sinusoidal voltage waveform.

The standard frequency of oscillation of the current and voltage waveforms of single-phase and three-phase power sources in North America is usually 60 Hz. In some other parts of the world it is 50 Hz.

The instantaneous values of the various functions are in general represented by the lower-case letters with or without the time-function notation. Thus,  $v$  (or  $v(t)$ ) and  $i$  (or  $i(t)$ ) represent the instantaneous values of voltage and current.

### Effective Value

The effective or root mean square (rms) of a voltage waveform is given by

$$V_{\text{rms}}^2 = \frac{1}{T} \int_0^T v^2 dt \quad (1.3)$$

where  $v$  is the instantaneous value of the voltage waveform.

Root-mean-square values have been introduced because the heating effect of an ideal sinusoidal voltage waveform in a resistor is equal to that produced by a dc source that has the same voltage as the rms value of the given ac waveform. In addition, the usage of rms values simplifies the final form of voltage, current, and power formulas. In designating rms values, the capital letter of the parameter is usually used without any subscript. Thus,  $V$  and  $I$  correspond, respectively, to the rms values of the voltage and current. The voltage rating of all ac apparatuses is given by the equivalent rms values. Thus, when a voltage is indicated as being 208 V or 480 V, it is understood that the magnitude is an rms value. The single-phase voltages delivered to a typical North American residence are 120 V (line-to-neutral) and 240 V (line-to-line).

The graphical interpretation of Eq. (1.3) is

$$V_{\text{rms}}^2 = \frac{\text{accumulation of areas under the voltage squared-time diagram over a complete cycle}}{\text{duration of one cycle}} \quad (1.4)$$

The graphical interpretation of Eq. (1.3), or of any other equation, helps you develop a better understanding. Understanding a concept is often as important as solving the equation itself, especially when there is no time to review the equations or when dealing with plant personnel who do not know much about integration.

### Average Value

The average value ( $V_{\text{av}}$ ) of a voltage waveform is defined as follows:

$$V_{\text{av}} = \frac{1}{T} \int_0^T v \, dt \quad (1.5a)$$

The graphical interpretation of Eq. (1.5a) is

$$V_{\text{av}} = \frac{\text{accumulation of areas under the } v\text{-}t \text{ diagram over a complete cycle}}{\text{duration of one cycle}} \quad (1.5b)$$

The average value of a symmetrical sinusoidal waveform is, as seen by inspection, equal to zero. The average value is also referred to as a dc value.

### EXAMPLE | - |

Determine the rms value of the sinusoidal voltage waveform shown in Fig. 1-2.

#### SOLUTION

The instantaneous value of the voltage is

$$v = V_m \sin \omega t$$

Substituting into Eq. (1.3), we get

$$\begin{aligned} V_{\text{rms}}^2 &= \frac{1}{2\pi} \int_0^{2\pi} (V_m \sin \omega t)^2 \, d\omega t \\ &= \frac{V_m^2}{2\pi} \int_0^{2\pi} \left( \frac{1 - \cos 2\omega t}{2} \right) \, d\omega t \\ &= \frac{V_m^2}{4\pi} \left[ \omega t \Big|_0^{2\pi} - \frac{1}{2} \sin 2\omega t \Big|_0^{2\pi} \right] \\ &= \frac{V_m^2}{2} \end{aligned}$$

from which

$$V_{\text{rms}} = \frac{V_m}{\sqrt{2}}$$

The rms value of the voltage waveform is shown in Fig. 1-2.

Find the rms and average values of the waveform shown in Fig. 1-3. Verify the answer graphically.

## Exercise 1-1

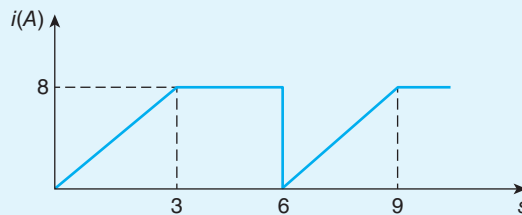


FIG. 1-3

**Answer** 6.53 A rms, 6A

### 1.1.2 Complex Numbers

The designation and significance of the letter  $J$  go back several centuries. At that time, mathematicians, when finding the roots of equations with negative square roots, thought that their physical interpretation was impossible or imaginary. Further studies by many mathematicians, and in particular Demoivre and Euler, demonstrated that a phasor can be represented by its polar form or rectangular form incorporating the factor  $j$ . For example, a phasor can be written as follows

$$\underbrace{re^{j\theta}}_{\text{Polar form}} = \underbrace{r(\cos \theta + j \sin \theta)}_{\text{Rectangular form}} \quad (1.6)$$

The factor  $r$  is the magnitude of the phasor. This equation can be derived by using the Maclaurin series or the exponential representation of the trigonometric functions.

Figure 1-4 illustrates the polar and rectangular form of phasors.

#### About $j$

In engineering, the coefficient  $j$  represents the component of a phasor in the  $y$ -axis, which is referred to as the imaginary axis. It is not imaginary, however. It is

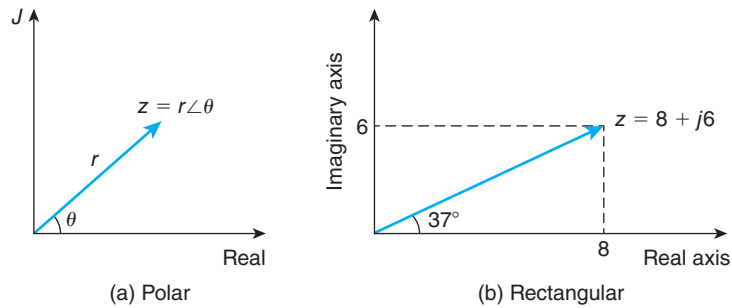


FIG. 1-4 Phasors.

so designated because the  $x$ -axis is named the real axis. Some of the highlights of  $j$  are the following:

$$\text{I)} \quad j = \sqrt{-1} \quad (1.7)$$

$$\text{II)} \quad j = 1 \angle 90 \quad (1.8)$$

$$\text{III)} \quad \text{If} \quad A + jB = C + jD \quad (1.9)$$

Then

$$A = C, \quad B = D$$

IV) It changes differential equations of linear systems to algebraic form. It is part of the Laplace operator(s)

$$s = j\omega + \alpha \quad (1.10)$$

where  $\alpha$  approaches zero and  $\omega$  is the angular speed of the phasor in radians/second (voltage, current, etc.).

When a linear differential equation (DE) is written in terms of  $s$  (see Appendices), then you can use algebra to solve it. In general, a time-domain function has its equivalent Laplace domain representation and vice versa. These representations or transformations are available in Laplace transform tables.

Besides that, representation of a function by its equivalent Laplace equivalent reveals (as will be demonstrated in the follow-up sections) the value of the function at time equal to zero and at time equal to infinite.

### Properties of Complex Numbers

When two phasors  $Z_1$  and  $Z_2$  are as follows

$$Z_1 = R_1 + jX_1 = r_1 \angle \Theta_1 \quad (1.11)$$



$$Z_2 = R_2 + j X_2 = r_2 \angle \Theta_2 \Omega \quad (1.12)$$

Then from the properties of complex numbers,

$$Z_1 + Z_2 = R_1 + R_2 + j(X_1 + X_2) \Omega \quad (1.13)$$

$$Z_1 Z_2 = r_1 r_2 \angle \Theta_1 + \Theta_2 \Omega \quad (1.14)$$

$$\frac{Z_1}{Z_2} = \frac{r_1}{r_2} \angle \Theta_1 - \Theta_2 \Omega \quad (1.15)$$

The addition, multiplication, and division of complex numbers are used in many aspects of Electrical Engineering and, as such, will be used throughout this book.

When  $Z_1 = 3 + j4 \Omega$  and  $Z_2 = 10 \angle -37^\circ \Omega$ , determine  $Z_1 + Z_2$ ,  $Z_1 Z_2$  and  $\frac{Z_1}{Z_2}$

### EXAMPLE 1-2

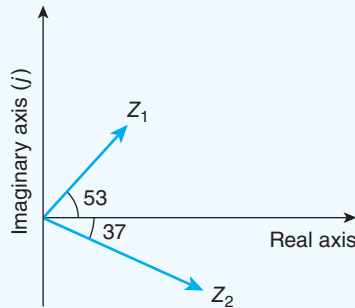


FIG. 1-5 Complex phasors.

### SOLUTION

Refer to Fig. 1-5.

$$Z_1 = 3 + j4 = 5 \angle 53^\circ \Omega, \quad Z_2 = 8 - j6 \Omega$$

and

$$Z_1 + Z_2 = 3 + 8 + j(4-6) = 11 - j2 = 11.18 \angle -10.3^\circ \Omega$$

$$Z_1 Z_2 = 5 \angle 53^\circ (10 \angle -37^\circ) = 50 \angle 16^\circ \Omega$$

$$\frac{Z_1}{Z_2} = \frac{5 \angle 53^\circ}{10 \angle -37^\circ} = 0.5 \angle 90^\circ = j0.5 \Omega$$