I

THEORY, CONSTRUCTION, AND OPERATION

1

PRINCIPLES OF OPERATION OF SYNCHRONOUS MACHINES

The synchronous electrical generator (also called *alternator*) belongs to the family of electric rotating machines. Other members of the family are the direct-current (dc) motor or generator, the induction motor or generator, and a number of derivatives of all these three. What is common to all the members of this family is that the basic physical process involved in their operation is the conversion of electromagnetic energy to mechanical energy, and vice versa. Therefore, to comprehend the physical principles governing the operation of electric rotating machines, one has to understand some rudiments of electrical and mechanical engineering.

This chapter is written for those who are involved in operating, maintaining, and trouble-shooting electrical generators, and who want to acquire a better understanding of the principles governing machine design and operation, but who do not have an electrical engineering background. The chapter starts by introducing the rudiments of electricity and magnetism, quickly building up to a description of the basic laws of physics governing the operation of the synchronous electric machine, which is the type of machine to which all turbo-generators belong.

Handbook of Large Turbo-Generator Operation and Maintenance, Third Edition. Geoff Klempner and Isidor Kerszenbaum.

1.1 INTRODUCTION TO BASIC NOTIONS ON ELECTRIC POWER

1.1.1 Magnetism and Electromagnetism

Certain materials found in nature exhibit a tendency to attract or repel each other. These materials, called *magnets*, are also called *ferromagnetic* because they include the element iron as one of their constituent elements.

Magnets always have two poles: one called *north*, the other called *south*. Two north poles always repel each other, as do two south poles. However, north and south poles always attract each other. A *magnetic field* is defined as a physical field established between two poles. Its intensity and direction determine the forces of attraction or repulsion existing between the two magnets.

Figures 1.1 and 1.2 are typical representations of two interacting magnetic poles and the magnetic field established between them.

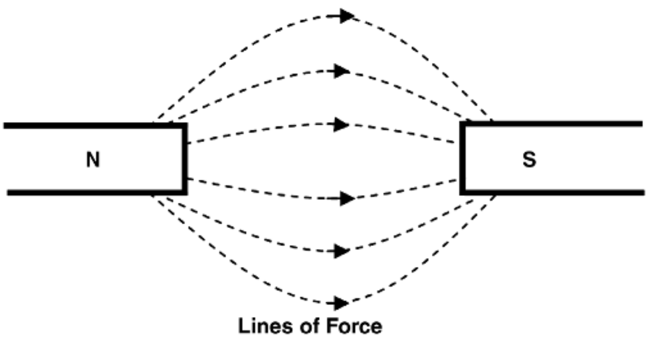


Fig. 1.1 Schematic representation of two magnetic poles of opposite polarity, with the magnetic field between them shown as "lines of force."

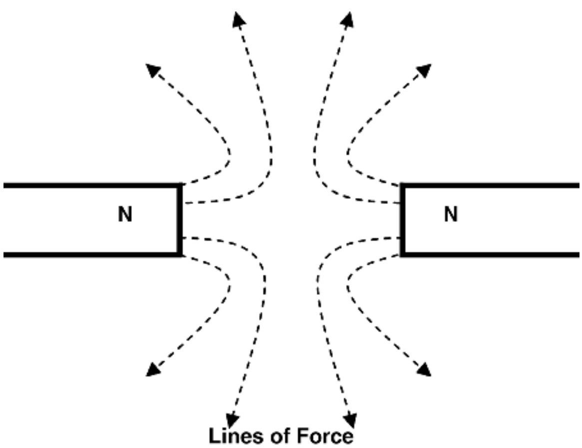


Fig. 1.2 Schematic representation of two north poles and the magnetic field between them. South poles will create similar field patterns, but the lines of force will point toward the poles.

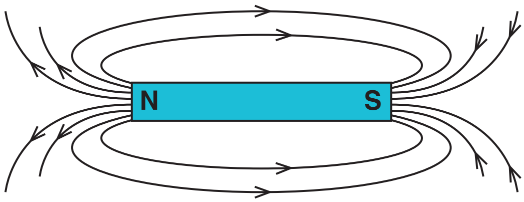


Fig. 1.3 Schematic representation of a "permanent magnet" showing the north and south poles and the magnetic field between them. Note that the magnetic field flows from north to south (outside the magnet).

Magnets are found in nature in all sorts of shapes and chemical constitution. Magnets used in industry are artificially made. Magnets that sustain their magnetism for long periods of time are denominated as "permanent magnets." The magnetic field produced by the north and the south pole of a permanent magnet is directional from north to south (see Fig. 1.3). These are widely used in several types of electric rotating machines, including synchronous machines. However, due to mechanical as well as operational reasons, permanent magnets in synchronous machines are restricted to those with ratings much lower than large turbine-driven generators, which are the subject of this book. Turbine-driven generators (for short: turbo-generators) take advantage of the fact that magnetic fields can be created by the flow of electric currents in conductors (see Fig. 1.4).

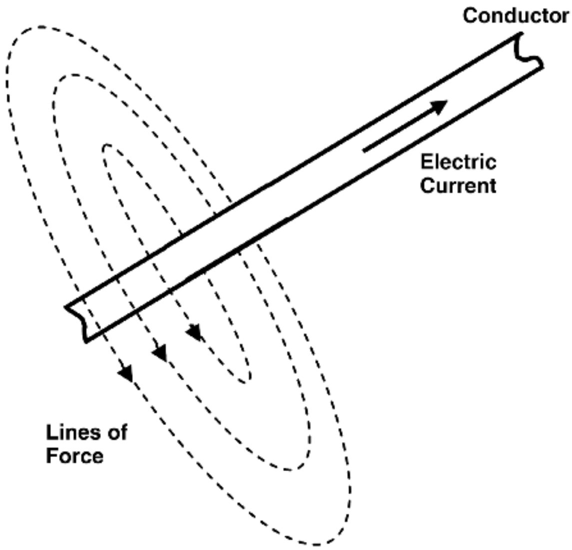


Fig. 1.4 Schematic representation of a magnetic field created by the flow of current in a conductor. The direction of the *lines of force* is given by the "law of the screwdriver": mentally follow the movement of a screw as it is screwed in the same direction as that of the current; the lines of force will then follow the circular direction of the head of the screw. The magnetic lines of force are perpendicular to the direction of current.

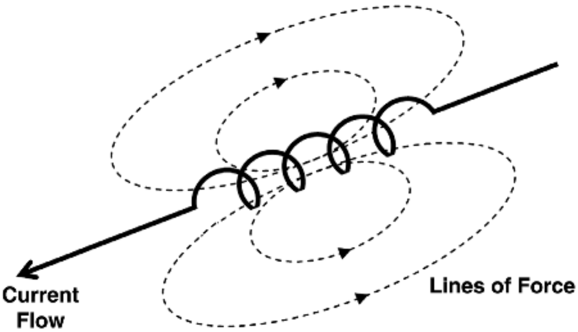


Fig. 1.5 Schematic representation of a magnetic field produced by the flow of electric current in a coil-shaped conductor.

A very useful phenomenon is that forming the conductor into the shape of a coil can augment the intensity of the magnetic field created by the flow of current through the conductor. In this manner, as more turns are added to the coil, the same current produces larger and larger magnetic fields. For practical reasons, all magnetic fields created by current in a machine are generated in coils (see Fig. 1.5).

The use of coils to amplify the magnetic field intensity requires a significant amount of control so that the resulting flux is produced in an effective way. When the coil is suspended in air, the magnetic field direction, shape, and intensity depend on the number of turns in the coil, the size of the coil, and the direction of electric current flow in the coil winding. The flux produced is basically divided into two types: one is the *effective flux* that links the entire coil and does the useful work, and the other is the *leakage flux* that is a more localized effect and does no useful work. In fact, the leakage flux creates additional losses that make the coil less efficient, electromagnetically speaking (see Fig. 1.6). The principles illustrated here become very important later on as we discuss the magnetic field in the generator and stray losses.

To use as much of the flux produced in a coil as effectively as possible, highly *magnetically permeable* materials—basically, *ferromagnetic* materials—are used to capture and direct the flux so that the amount of leakage flux is minimized. This allows the coil to do more useful work and keeps losses to a minimum. Iron in various derivatives is by far the most widely used material because it has all the magnetic characteristics required, is structurally suitable, and cost-effective due to its abundance on planet Earth. When an "iron" core is used within the coil and current is flowing, the magnetic field produced is shaped effectively and the iron core essentially becomes a north–south magnet in the process (see Fig. 1.7). This is why rotor forgings and stator cores of generators are made of iron. The iron allows the principles discussed above to become a reality and is one of the reasons generators can be built to at least 98.5% efficiency.

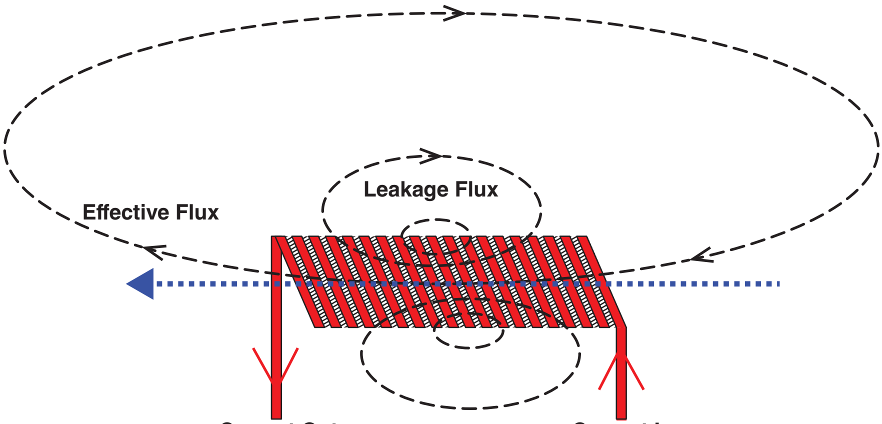


Fig. 1.6 Schematic representation of a magnetic field produced by the flow of electric current in a coil-shaped conductor operating in air, showing the effective and leakage flux components of the magnetic field produced.

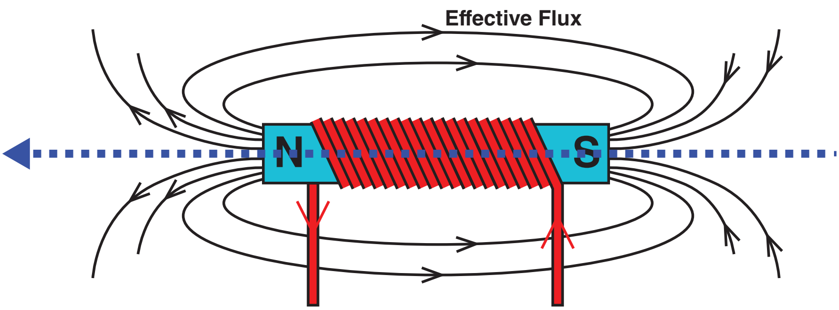


Fig. 1.7 Schematic representation of a magnetic field produced by the flow of electric current in a coil-shaped conductor with an “iron” core. The majority of the field produced is effective flux and the leakage field is reduced to a minimum.

1.1.2 Electricity

Electricity is the flow of positive or negative charges. Electricity can flow in electrically conducting elements (called *conductors*), or it can flow as clouds of ions in space or within gases. As will be shown in later chapters, both types of electrical conduction are found in turbo-generators (see Fig. 1.8).

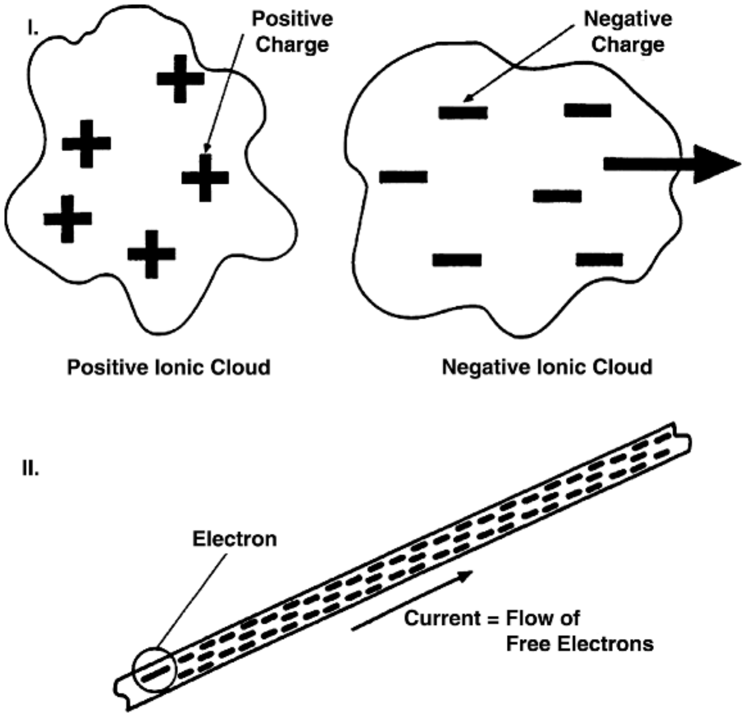


Fig. 1.8 Electricity. (I) Ionic clouds of positive and negative currents. The positive clouds are normally atoms that have lost one or more electrons; the negative clouds are normally free electrons. This effect can be found inside the generator as *partial discharge* in the stator winding. (II) The flow of electrons inside a conductor material, for example, the copper windings of the rotor and stator.

1.2 ELECTRICAL–MECHANICAL EQUIVALENCE

There is an interesting equivalence between the various parameters describing electrical and mechanical forms of energy. People with either electrical or mechanical background find this equivalence useful to the understanding of the physical process in either form of energy. Figure 1.9 describes the various forms of electrical–mechanical equivalence.

1.3 ALTERNATING CURRENT (ac)

As will be shown later, alternators operate with both ac and dc electric power. The direct current can be considered a particular case of the general alternating current, with frequency equal to zero.

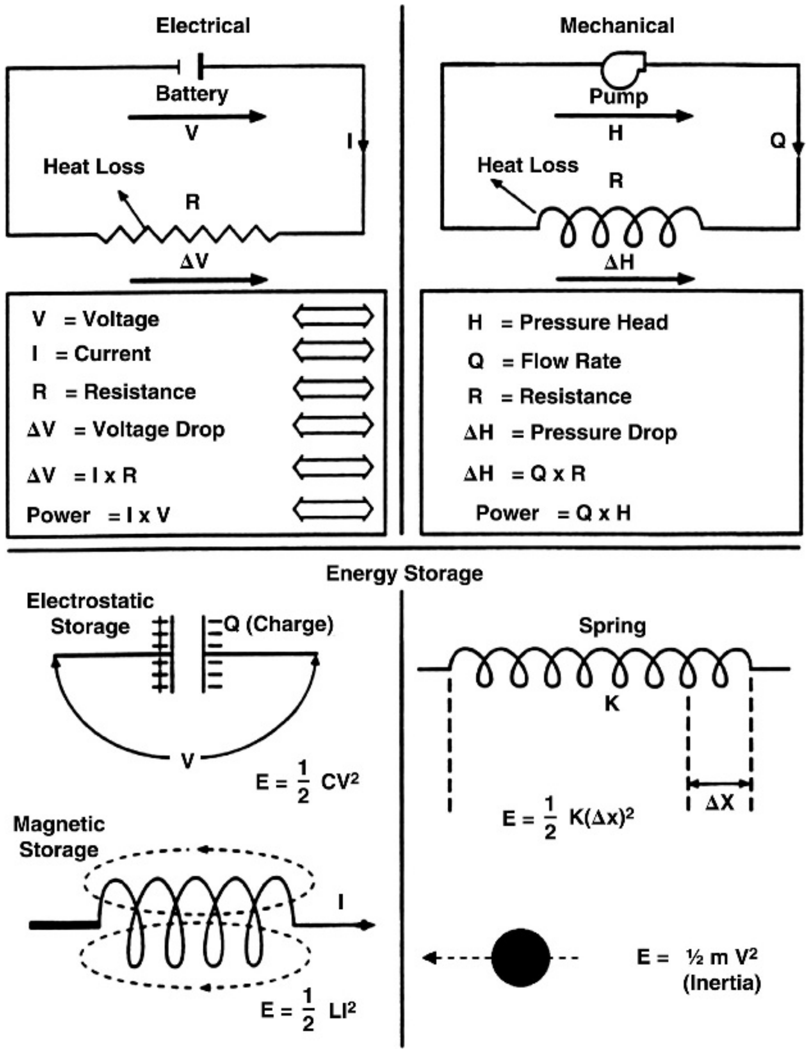


Fig. 1.9 Electrical–mechanical equivalence.

The frequency of an alternating circuit is measured by the number of times the currents and/or voltages change direction (polarity) in a unit of time. The hertz (Hz) is the universally accepted unit of frequency, and measures cycles per second. One Hz equals one cycle per second. Alternating currents and voltages encountered in the world of industrial electric power are for all practical purposes of constant frequency. This is important because *periodic* systems, namely, systems that have constant frequency, allow the currents and voltages to be represented by *phasors*.

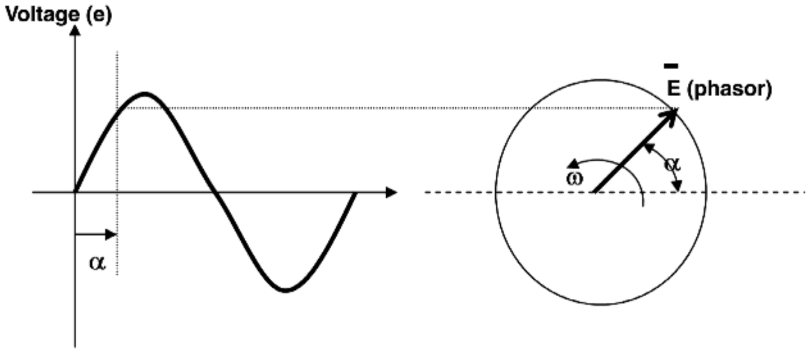


Fig. 1.10 A phasor **E** that can represent the voltage impressed on a circuit. The phasor is made of a vector with magnitude proportional to the magnitude of **E**, rotating at a constant rotational speed ω. The convention is that phasors rotate counterclockwise. The vertical projection of the phasor results in a sinusoidal, representing the instantaneous voltage *e* existing at any time. In the graph, $\alpha = \omega \times t$, where *t* is the time elapsed from its zero crossing.

A phasor is a rotating vector. The benefit of using phasors in electrical engineering analysis is that it greatly simplifies the calculations required to solve circuit problems.

Figure 1.10 depicts a phasor of magnitude **E**, and its corresponding sinusoidal trace represents the instantaneous value of the quantity *e*. The magnitude **E** represents the maximum value of *e*.

When a sinusoidal voltage is applied to a closed circuit, a current will flow in it. After a while, the current will have a sinusoidal shape (this is called the *steady-state* current component) and the same frequency as the voltage. An interesting phenomenon in periodic circuits is that the resulting angle between the applied voltage and the current depends on certain characteristics of the circuit. These characteristics can be classified as being *resistive, capacitive*, and *inductive*. The angle between the voltage and the current in the circuit is called the *power angle*. The cosine of the same angle is called the *power factor* of the circuit or, for short, the PF.

Note: As will be shown later, in synchronous machines the term power angle is used to identify a different concept. To avoid confusion, in this book the angle between the current and the voltage in the circuit will therefore be identified by its "power factor angle."

In the case of a circuit having only resistances, the voltages and currents are *in phase*, meaning that the angle between them equals zero. Figure 1.11 shows the various parameters encountered in a resistive circuit. It is important to note that resistances have the property of generating heat when a current flows through them. The heat generated equals the square of the current times the value of the

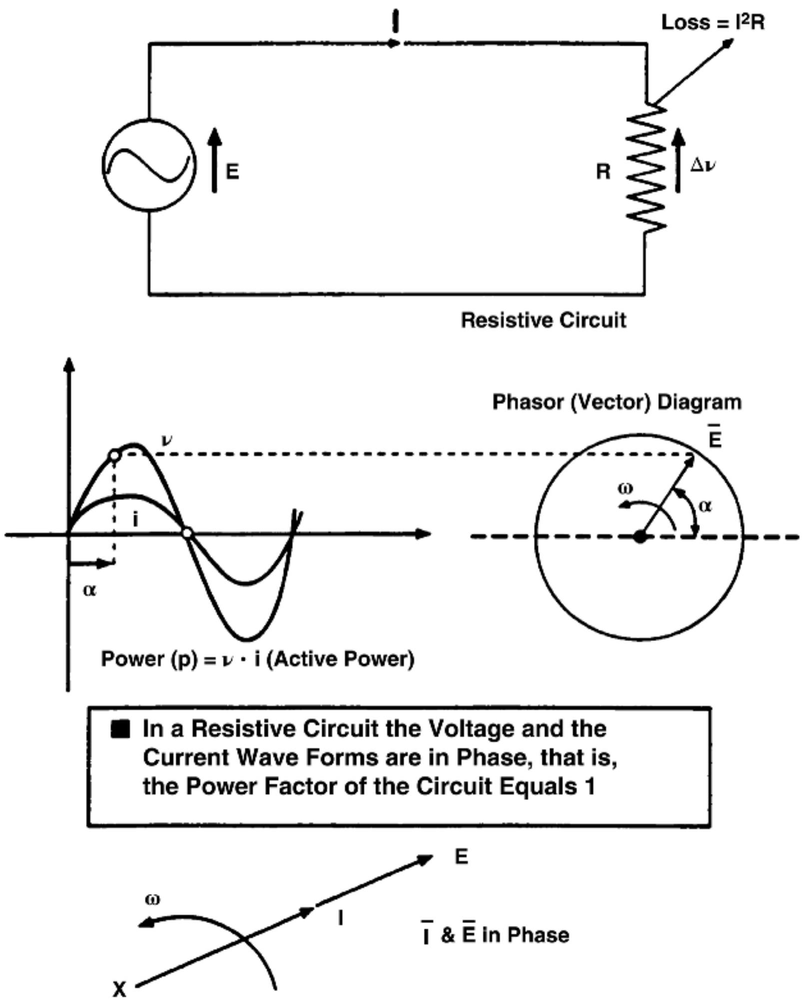


Fig. 1.11 Alternating circuits (resistive). Schematic representation of a sinusoidal voltage of magnitude **E** applied on a circuit with a resistive load *R*. The schematics show the resultant current *i* in phase with the voltage *v*. It also shows the phasor representation of the voltage and current.

resistance. When the current is measured in amperes and the resistance in ohms, the resulting power dissipated as heat is given in watts. In electrical machines, this heat represents a loss of energy. It will be shown later that one of the fundamental requirements in designing an electric machine is the efficient removal of these resistive losses, for the purpose of limiting the undesirable temperature rise of the internal components of the machine.

In resistive circuits, the instantaneous power delivered by the source to the load equals the product of the instantaneous values of the voltage and the current. When the same sinusoidal voltage is applied across the terminals of a circuit with capacitive or inductive characteristics, the steady-state current will exhibit an angular (or time) displacement vis-à-vis the driving voltage. The magnitude of the angle (or power factor) depends on how capacitive or inductive the load is. In a purely capacitive circuit, the current will lead the voltage by 90°, whereas in a purely inductive one, the current will lag the voltage by 90° (see Fig. 1.12).

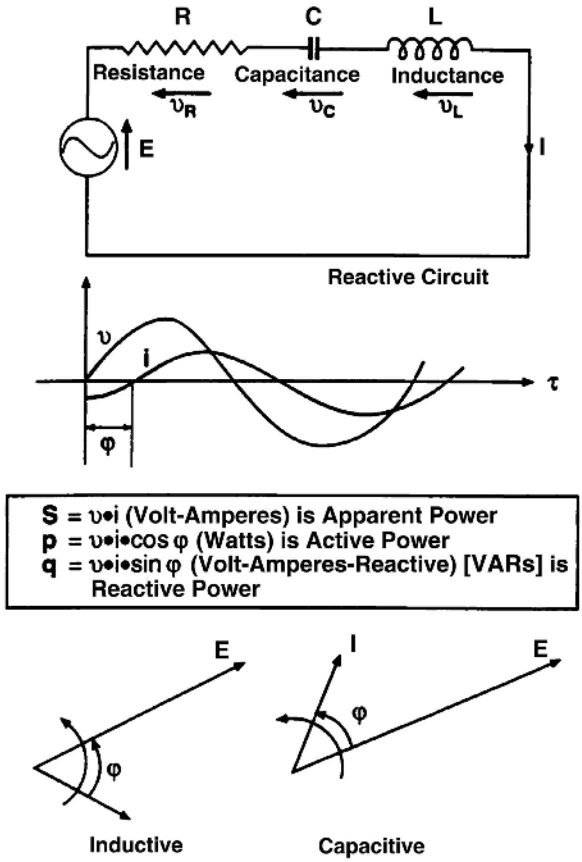


Fig. 1.12 Alternating circuits (resistive–inductive–capacitive). Here, the sinusoidal voltage **E** is applied to a circuit comprised of resistive, capacitive, and inductive elements. The resulting angle between the current and the voltage depends on the value of the resistance, capacitance, and inductance of the load.

A circuit that has capacitive or inductive characteristics is referred to as being a *reactive* circuit. In such a circuit, the following parameters are defined:

S: The *apparent power* — $\mathbf{S} = \mathbf{E} \times \mathbf{I}$, given in units of volt-amperes or VA.

P: The *active power* — $\mathbf{P} = \mathbf{E} \times \mathbf{I} \times \cos \Phi$, where Φ is the angle between the voltage and the current. **P** is given in units of watts.

Q: The *reactive power* — $\mathbf{Q} = \mathbf{E} \times \mathbf{I} \times \sin \Phi$, given in units of volt-amperes-reactive or VAR.

The active power **P** of a circuit indicates a real energy flow. This is power that may be dissipated on a resistance as heat, or may be transformed into mechanical energy, as will be shown later. However, the use of the word "power" in the definition of **S** and **Q** has been an unfortunate choice that has resulted in confounding most individuals without an electrical engineering background for many years. The fact is that *apparent power* and *reactive power* do not represent any measure of real energy. They do represent the reactive characteristic of a given load or circuit, and the resulting angle (power factor) between the current and voltage. This angle between voltage and current significantly affects the operation of an electric machine, as will be discussed later.

For the time being, let us define another element of ac circuit analysis: the *power triangle*. From the relationships shown above among **S**, **P**, **Q**, **E**, **I**, and Φ, it can be readily shown that **S**, **P**, and **Q** form a triangle. By convention, **Q** is shown as positive (above the horizontal), when the circuit is *inductive*, and vice versa when *capacitive* (see Fig. 1.13).

The power triangle can be easily related to the capability curve of a machine (see Figs. 1.14–1.20) In these figures, the relationship of "real" power out with changes in "reactive" loading can also be seen. The difference in output when the machine is operating at "unity," "leading," and "lagging" power factors is also shown in the series of graphs at constant MVA. Also, Figures 1.17 and 1.20 show the two points of operation if the generator were operating as a "synchronous condenser." One is when the machine is providing reactive power to the system and "boosting" terminal voltage (in the lagging range—Fig. 1.17) and the other when the machine is importing reactive power (in the leading range—Fig. 1.20) and helping to keep the voltage from rising.

To demonstrate the use of the power triangle within the context of large generators and their interaction with the power system, we need to consider a one-line schematic that includes the generator, transmission system, and the connected load at the end (see Fig. 1.21).

If we now consider an actual load for the simple system of Figure 1.21, we can calculate the current drawn by the load and the voltage required from the generator source to compensate for all the line losses and voltage drop across the line. Two cases are provided to illustrate the effect of a purely resistive load versus a load with a reactive component included (see Figs. 1.22 and 1.23).

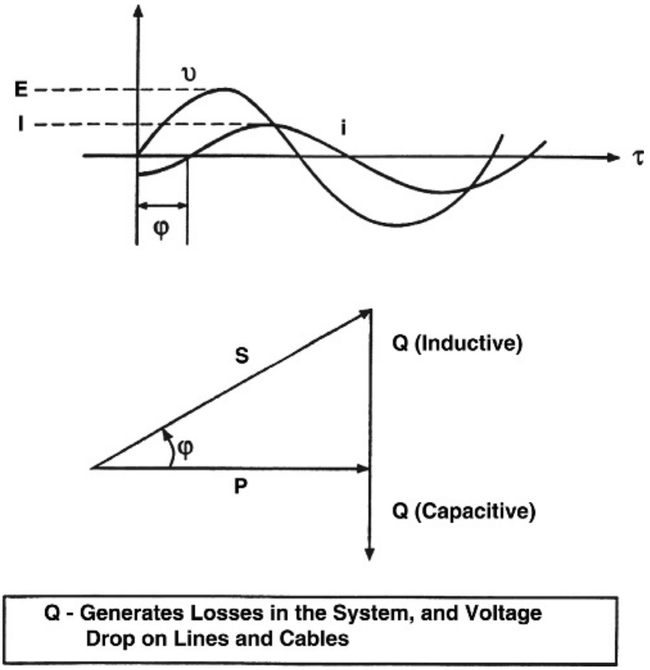


Fig. 1.13 Definition of the "power triangle" in a reactive circuit.

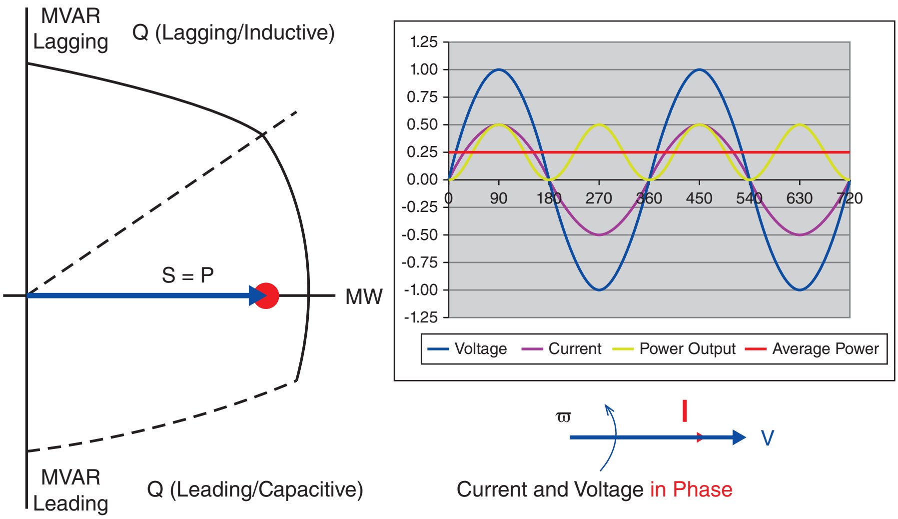


Fig. 1.14 In this figure, the output current and voltage are in phase and the generator is operating at "unity" power factor. Since there is no reactive component, the "real" power out (**P**) is at a maximum (the straight red line on the graph) and the power out is equal to the MVA (**S**). The generator is said to be operating in a "resistive" manner.

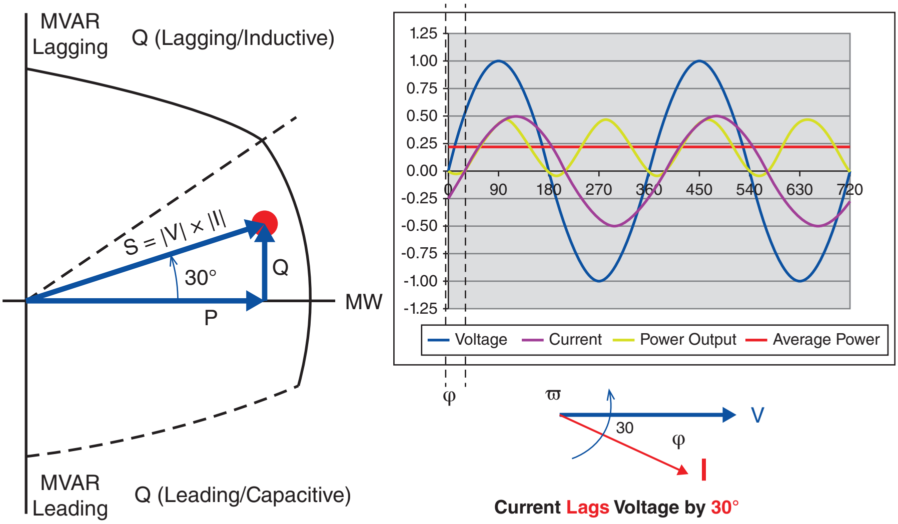


Fig. 1.15 In this figure, the output current lags the voltage by 30°. The generator is operating in the "lagging" power factor range and also producing reactive power (**Q**) delivered to the system.

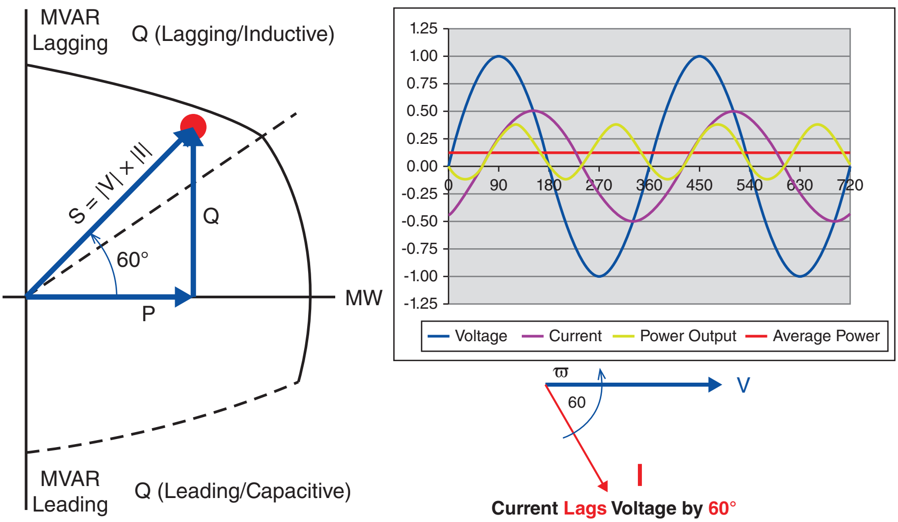


Fig. 1.16 In this figure, the output current lags the voltage by 60°. The generator is operating further into the "lagging" power factor range and producing more reactive power (**Q**) delivered to the system. The "real" power out (**P**) is reduced at this operating point to stay within the capability curve.

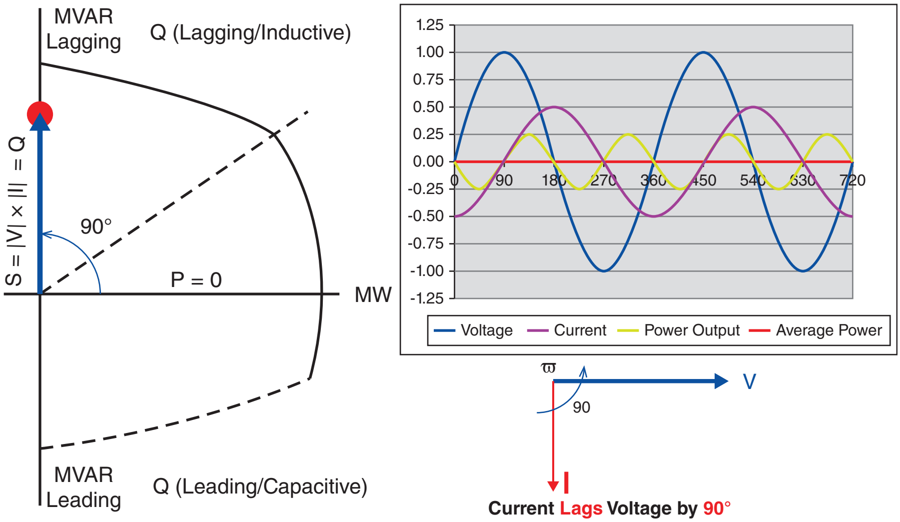


Fig. 1.17 In this figure, the output current lags the voltage by 90°. The generator is operating into the “lagging” power factor range with no real power output (**P**) and producing only reactive power (**Q**) delivered to the system. This type of operation is generally referred to as “synchronous condenser” mode, providing reactive power or VARs out to the system.

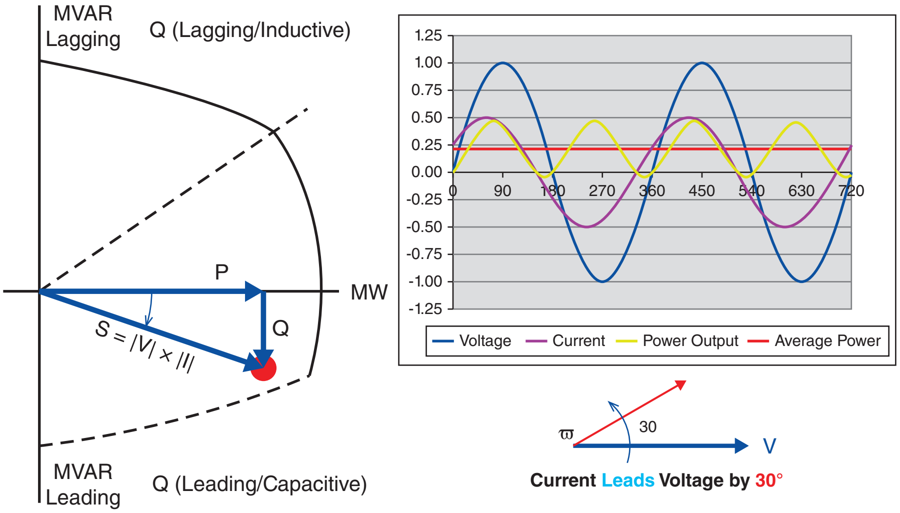


Fig. 1.18 In this figure, the output current now leads the voltage by 30°. The generator is operating into the “leading” power factor range and importing reactive power (**Q**) from the system into the generator.

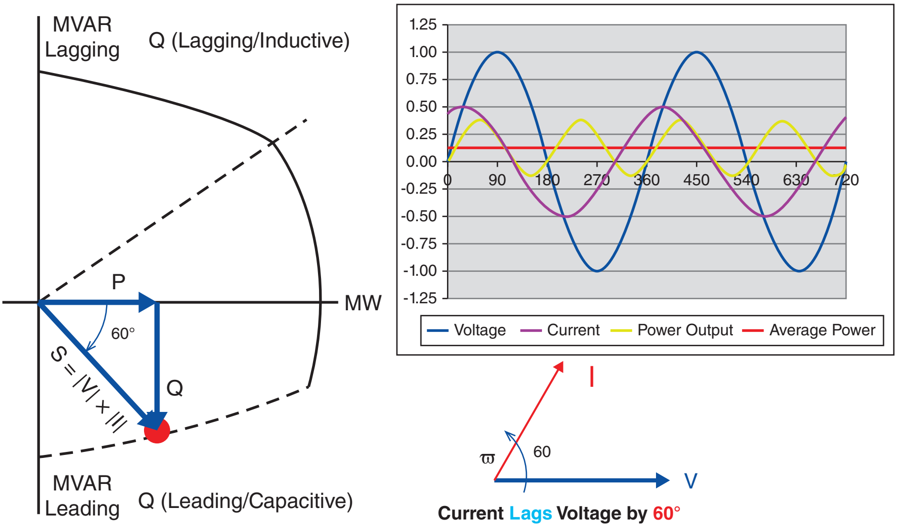


Fig. 1.19 In this figure, the output current now leads the voltage by 60°. The generator is operating further into the "leading" power factor range and importing more reactive power (**Q**) from the system into the generator. The "real" power out (**P**) is reduced at this operating point to stay within the capability curve.

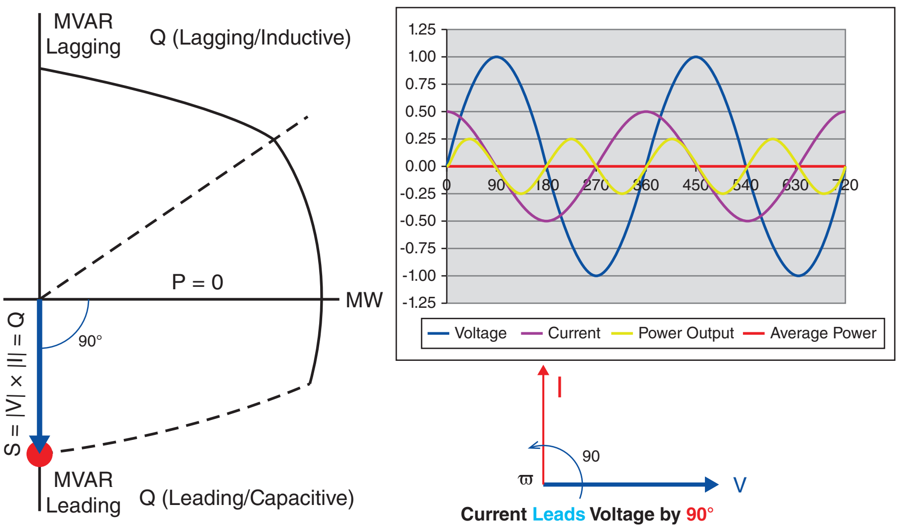
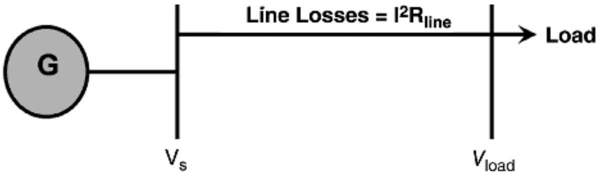


Fig. 1.20 In this figure, the output current leads the voltage by 90°. The generator is operating into the "leading" power factor range with no real power output (**P**) and importing only reactive power (**Q**) from the system into the generator. This type of operation is also referred to as "synchronous condenser" mode, but importing reactive power or VARs from the system.



Simple Power System Showing a Generator, Bus, Line and Load.

V_{load} = 1000 Volts

Line Resistance (R) = 10 Ω (Resistive)

Line Reactance (X) = 10 Ω (Inductive)

Line Impedance (Z) = $\sqrt{(10^2 + 10^2)}$ = 14.14 Ω

Fig. 1.21 Schematic of a simple system in one-line form. The voltage required at the load (so that it will operate correctly) is given as 1000 V. The transmission line resistance and reactance are provided and the line impedance calculated as shown, using the power triangle approach.

Case 1 – Load = 100 kW (Unity Power Factor {i.e. Cos φ =1} **)**

$P = \sqrt{3} * I * V * \cos\varphi$

⇒ I = 100,000 Watts/1000 Volts/1.73 /1 = **57.8 Amperes**

Losses in the Line ($I^2 R_{line}$) = 57.8^2 Amperes * 10Ω = **33.4 kW / Phase**

Voltage Drop Along the Line = I*Z = $\sqrt{(I * R)^2 + (I * X)^2}$ = **817 Volts**

⇒The Required Delivery Voltage at the Source (V_S) is:

$Vs = \sqrt{(V_{Load} + IR)^2 + (IX)^2}$

$Vs = \sqrt{(1000 + 578)^2 + (578)^2}$ = **1680 Volts**

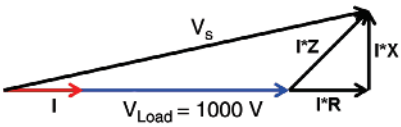


Fig. 1.22 Case 1. The load is purely resistive in this example, and the system is operating at the “unity” power factor.

Working out the required voltage from the generator for the two different loads by the power triangle method shows how reactive loads greatly affect the power system operation and the generation requirements. Reactive power compensation is a large part of generator operation and affects generator design in a significant way, as will be discussed in Chapter 2. There is a delicate balance between generation and load that is clearly shown by the two cases presented and the comparison of operational results (see Fig. 1.24).

Case 2 – Load = 100 kW and 50 kVAR-Inductive (Lagging Power Factor)

$S = \sqrt{3} * I * V = \sqrt{100{,}000^2 + 50{,}000^2} = 111{,}803$ VA (Volt-Amperes)

$\Rightarrow I = 111{,}803$ VA /1000 Volts /1.73 = **64.55 Amperes**

Losses in the Line ($I^2 R_{Line}$) = 64.55^2 Amperes * 10Ω = **41.6 kW / Phase**

Voltage Drop Along the Line = $I*Z = \sqrt{(I * R)^2 + (I * X)^2}$ = **913 Volts**

⇒The Required Delivery Voltage at the Source (V_s) is:

$$Vs = \sqrt{[V_{load} + IR(\sin\varphi+\cos\varphi)]^2 + [IX(\cos\varphi-\sin\varphi)]^2}$$

$$Vs = \sqrt{[1000+645.5(\sin\varphi+\cos\varphi)]^2 + [645.5(\cos\varphi-\sin\varphi)]^2} = \textbf{1892 Volts}$$

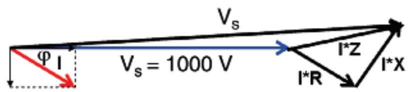


Fig. 1.23 Case 2. The load is resistive and inductive in this example, and the system is operating in the “lagging” power factor range.

Load	100 kW	100 kW and 50 kVAR
Power Consumed by the Load	100 kW	100 kW
Current	57.8 A	64.6 A
Line Losses Per Phase	33.4 kW	41.6 kW
Voltage Drop Along the Line	817 V	913 V
Required Delivery Voltage at Generating End	1680 V	1892 V

Fig. 1.24 A comparison of Case 1 and Case 2 shows that although the “real” power consumed is the same, the addition of the reactive component in Case 2 has caused an increase in current drawn from the generator, an increase in line losses, a higher volt drop across the line, and, therefore, a higher voltage required from the generator source.

The above examples show that there is a considerable demand placed on the generator to operate the various loads on a system. In reality, the generator terminal voltage **V** is constant at its nominal value, plus or minus 5% required by the standard, unless specified with a larger margin of variation. As the load increases or decreases, the current from the generator changes significantly and the voltage drop on the system $\mathbf{V}_{load}$ requires compensation (Fig. 1.25). Therefore, the second major function of the generator, after production of “real” power, is to produce “reactive” power to help control the grid’s voltage and frequency, which will also be discussed later in Chapter 4.

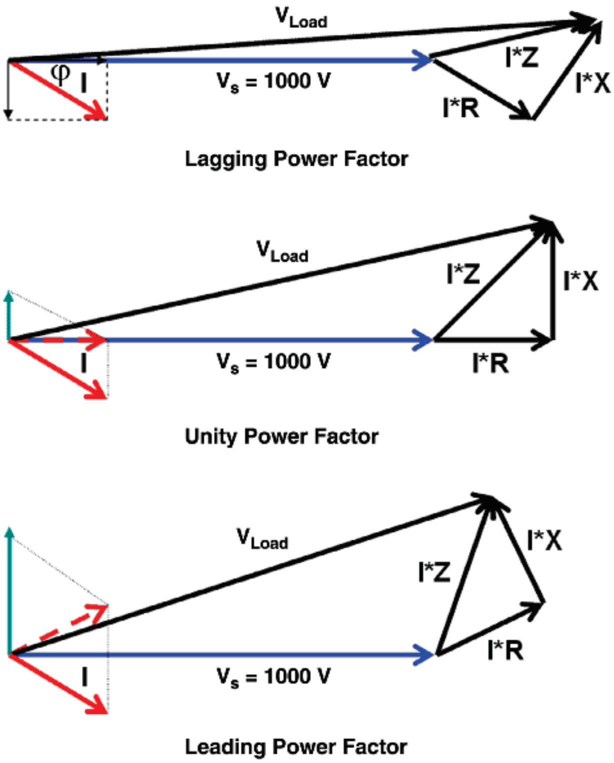


Fig. 1.25 The effect on the voltage drop as the circuit goes from lagging through unity to leading power factor operation is shown.

1.4 THREE-PHASE CIRCUITS

The two-wire ac circuits discussed above (called *single-phase* circuits or systems) are commonly used in residential, commercial, and low-voltage–low-power industrial applications. However, all electric power systems to which industrial generators are connected are *three-phase* systems. Therefore, any discussion in this book about the "power system" or the "grid" will refer to a three-phase system. Moreover, in industrial applications the voltage supplies are, for all practical reasons, balanced, meaning that all three-phase voltages are equal in magnitude and apart by 120 electrical degrees. In those events in which the voltages are unbalanced, the implications for the operation of the generator will be discussed in other chapters of this book.

Three-phase electric systems may have a fourth wire, called the "neutral." The "neutral" wire of a three-phase system will conduct electricity if the source and/or the load are unbalanced. In three-phase systems, two sets of voltages and currents can be identified. These are the *phase* and *line* voltages and currents.

Figure 1.26 shows the main elements of a three-phase circuit. Three-phase circuits can have their sources and/or loads connected in *wye* (*star*) or in *delta* forms (see Fig. 1.27 for a wye-connected source feeding a delta-connected load).

Almost without exception, turbine-driven generators have their windings connected in wye (star) form. Therefore, in this book the source (or generator) will be shown wye-connected. There are a number of important reasons why

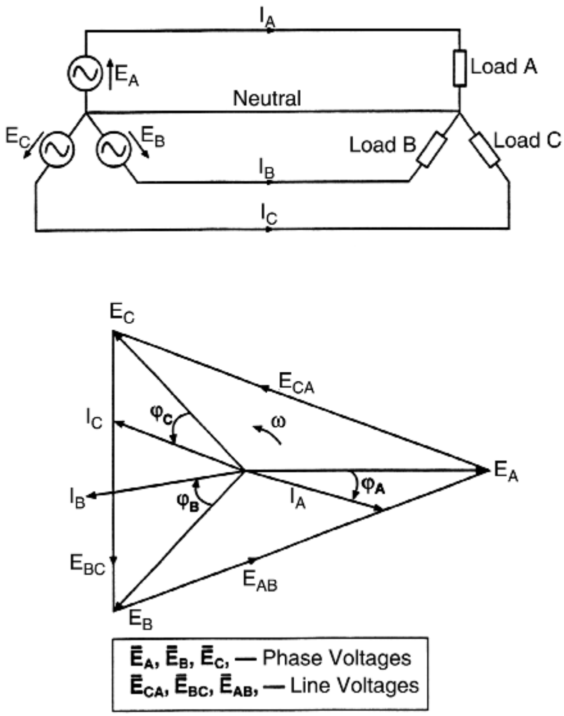


Fig. 1.26 Three-phase systems. Schematic depiction of a three-phase circuit and the vector (phasor) diagram representing the currents, voltages, and angles between them.

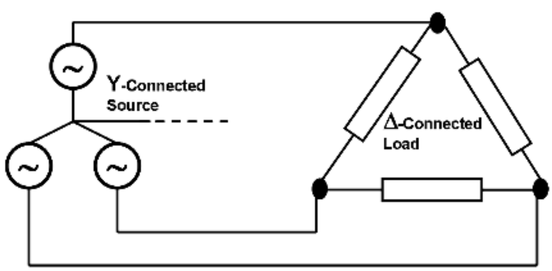


Fig. 1.27 A “wye-connected” source feeding a “delta-connected” load.

turbo-generators are wye-connected. They have to do with considerations about its effective protection as well as design (insulation, grounding, etc.). These will be discussed in the chapters covering stator construction and operations.

On the other hand, loads can be found connected in wye, delta, or a combination of the two. This book is not about circuit solutions; therefore, the type of load connection will not be brought up herein.

1.5 BASIC PRINCIPLES OF MACHINE OPERATION

In Section 1.1, basic principles were presented showing how a current flowing in a conductor produces a magnetic field. In this section, three important laws of electromagnetism will be presented. These laws, together with the law of energy conservation, constitute the basic theoretical foundation on which the operation of any electrical machine is based.

1.5.1 Faraday's Law of Electromagnetic Induction

This basic law, due to the genius of the great English chemist and physicist Michael Faraday (1791–1867), presents itself in two different forms:

1. A moving conductor cutting the lines of force (flux) of a constant magnetic field has a voltage induced in it.
2. A changing magnetic flux inside a loop made from a conductor material will induce a voltage in the loop.

In both instances, the *rate of change* is the critical determinant of the resulting differential of potential. Figure 1.28 illustrates both cases of electromagnetic induction, and also provides the basic relationship between the changing flux and the voltage induced in the loop, for the first case, and the relationship between the voltage induced in a wire moving across a constant field, for the second case. The figure also shows one of the simple rules that can be used to determine the direction of the induced voltage in the moving conductor.

1.5.2 Ampere–Biot–Savart's Law of Electromagnetic-Induced Forces

This basic law is attributed to the French physicists Andre Marie Ampere (1775–1836), Jean Baptiste Biot (1774–1862), and Victor Savart (1803–1862). In its simplest form, this law can be seen as the "reverse" of Faraday's law. Whereas Faraday's law predicts a voltage induced in a conductor moving across a magnetic field, the Ampere–Biot–Savart law establishes that a force is generated on a current-carrying conductor located in a magnetic field.

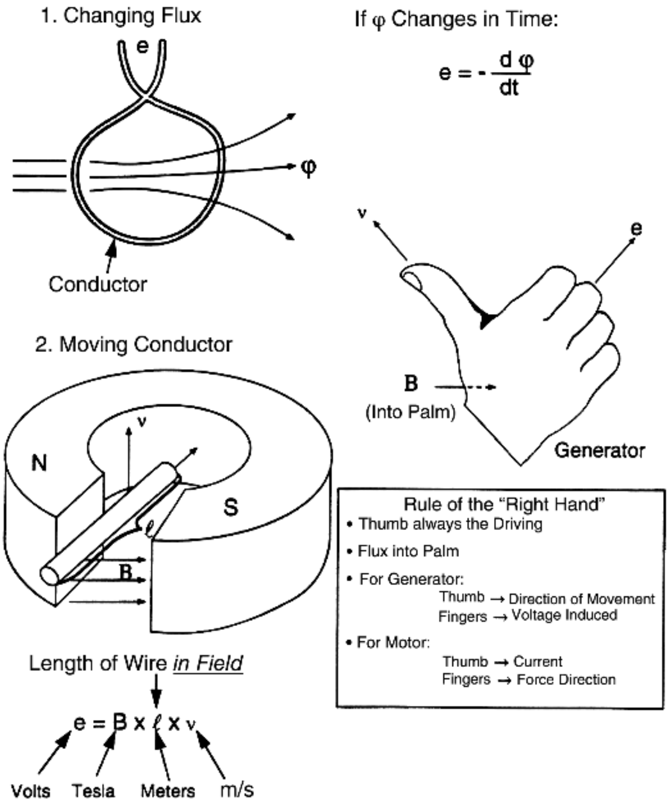


Fig. 1.28 Both forms of Faraday's basic law of electromagnetic induction. A simple rule (the "right-hand" rule) is used to determine the direction of the induced voltage in a conductor moving across a magnetic field at a given velocity.

Figure 1.29 presents the basic elements of Ampere–Biot–Savart's law as applicable to electric machines. The figure also shows the existing numerical relationships, and a simple hand rule to determine the direction of the resultant force.

1.5.3 Lenz's Law of Action and Reaction

Both Faraday's law and Ampere–Biot–Savart's law neatly come together in Lenz's law, written in 1835 by the Estonian-born physicist Heinrich Lenz (1804–1865). Lenz's law states that electromagnetic-induced currents and forces will try to cancel the originating cause.

For example, if a conductor is forced to move, cutting lines of magnetic force, a voltage is induced in it (Faraday's law). Now, if the conductors' ends are closed together so that a current can flow, this induced current will produce (according to

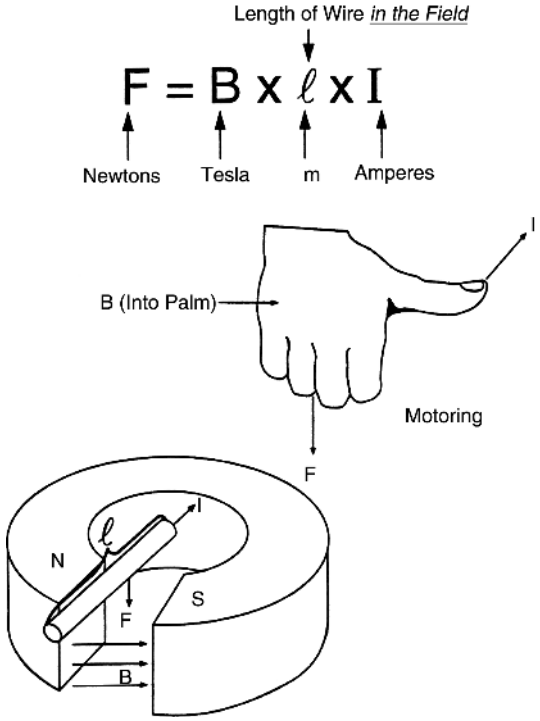


Fig. 1.29 The Ampere–Biot–Savart law of electromagnetic-induced forces as it applies to electric rotating machines. Basic numerical relationships and a simple rule are used to determine the direction of the induced force.

Ampere–Biot–Savart's law) a force acting upon the conductor. Lenz's law states that this force will act to oppose the movement of the conductor in its original direction.

Here, in a nutshell, is the explanation for the *generating* and *motoring* modes of operation of an electric rotating machine! This law explains why, when a generator is loaded (more current flows in its windings, cutting the magnetic field in the gap between rotor and stator), more force is required from the driving turbine to counteract the induced larger forces and keep supplying the larger load. Similarly, Lenz's law explains the increase in the supply current of a motor as its load increases.

Figure 1.30 neatly captures the main elements of Lenz's law as it applies to electric rotating machines.

1.5.4 Electromechanical Energy Conversion

The fourth and final physical law that captures, together with the previous three, all the physical processes occurring inside an electric machine is the "principle of

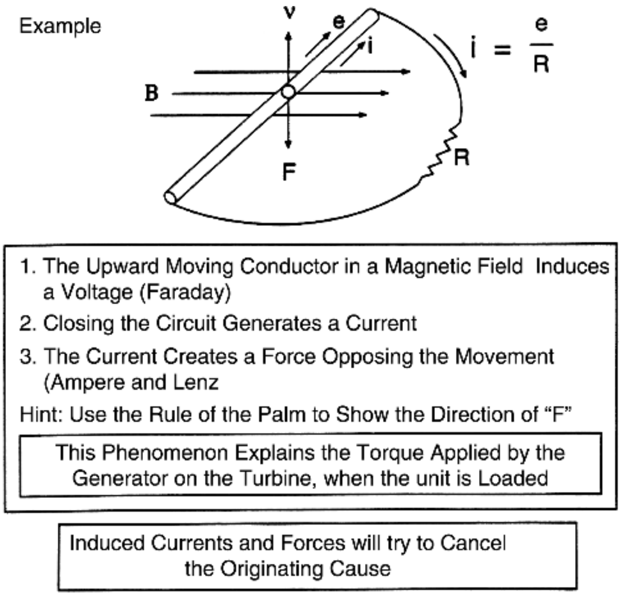


Fig. 1.30 Lenz's law as it applies to electric rotating machines. Basic numerical relationships and a simple rule are used to determine the direction of the induced forces and currents.

energy conversion." Within the domain of the electromechanical world of an electric rotating machine, this principle states that

> "All the electrical and mechanical energy flowing into the machine, less all the electrical and mechanical energy flowing out of the machine and stored in the machine, equals the energy dissipated from the machine as heat."

It is important to recognize that although mechanical and electrical energy can go into or out of the machine, the heat generated within the machine always has a negative sign, that is, heat generated in the machine is always released during the conversion process. A *plus* sign indicates energy going in; a *minus* indicates energy going out. In the case of the stored energy (electrical and mechanical), a plus sign indicates an increase of stored energy, whereas a minus sign indicates a reduction in stored energy.

The balance between the various forms of energy in the machine will determine its efficiency and cooling requirements, both critical performance and construction parameters in a large generator. Figure 1.31 depicts the principle of energy conversion as applicable to electric rotating machines.

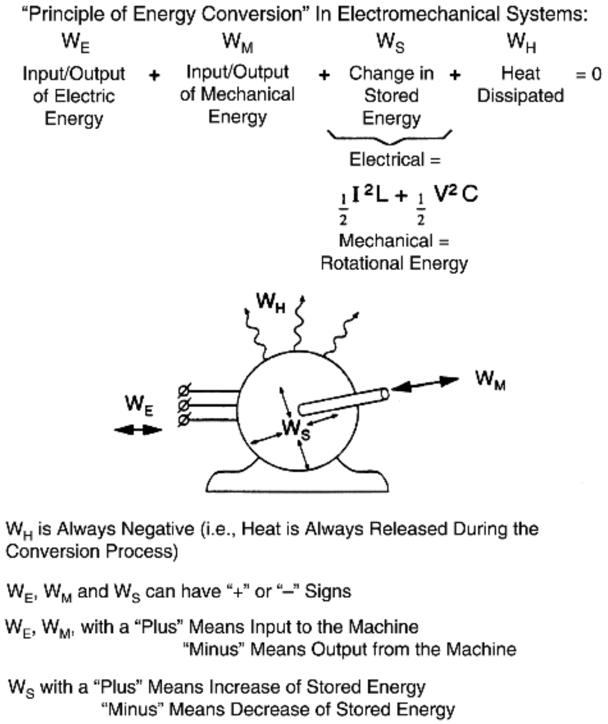


Fig. 1.31 Principle of energy conversion as applicable to electric rotating machines.

1.6 THE SYNCHRONOUS MACHINE

At this point, the rudiments of electromagnetism have been presented, together with the four basic laws of physics describing the inherent physical processes coexisting in any electrical machine. Therefore, it is the right time to introduce the basic configuration of the synchronous machine, which, as mentioned before, is the type of electric machine that all large turbine-driven generators belong to.

1.6.1 Background

The commercial birth of the alternator (synchronous generator) can be dated back to August 24, 1891. On that day, the first large-scale demonstration of transmission of ac power was carried out. The transmission extended from Lauffen, Germany, to Frankfurt, about 110 miles away. The demonstration was carried out during an international electrical exhibition in Frankfurt. This demonstration was so convincing about the feasibility of transmitting ac power over long distances that the city of Frankfurt adopted it for their first power plant,

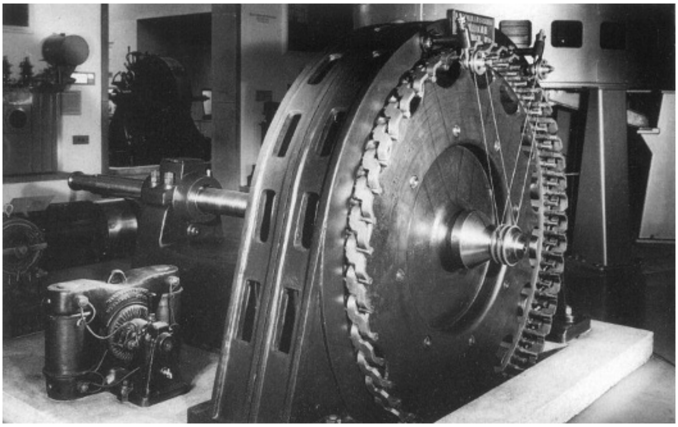


Fig. 1.32 The hydroelectric generator from Lauffen, now in the Deutches Museum, Munich. (Reprinted with permission from *The Evolution of the Synchronous Machine* by Gerhard Neidhofer, 1992, Asea Brown Boveri.)

commissioned in 1894. This happened about 127 years before the writing of this the third edition of the book (see Fig. 1.32).

The Lauffen–Frankfurt demonstration and the consequent decision by the city of Frankfurt to use ac power delivery were instrumental in the adoption by New York's Niagara Falls power plant of the same technology. The Niagara Falls power plant became operational in 1895. For all practical purposes, the great dc versus ac duel was over. Southern California Edison's history book reports that its Mill Creek hydro plant is the oldest active polyphase (three-phase) plant in the United States. Located in San Bernardino County, California, its first units went into operation on September 7, 1893, placing it almost 2 years ahead of the Niagara Falls project. One of those earlier units is still preserved and displayed at the plant.

It is interesting to note that although tremendous development in machine ratings, insulation components, and design procedures has occurred for over 100 years, the basic constituents of the machine have remained practically unchanged. The concept that a synchronous generator can be used as a motor followed suit. Although Tesla's induction motor replaced the synchronous motor as the choice for the vast majority of electric motor applications, synchronous generators remained the universal machines of choice for the generation of electric power. The world today is divided between countries generating their power at 50 Hz and others (e.g., North America) at 60 Hz. Additional frequencies (e.g., 25 Hz) can still be found in some locations, but they constitute the rare exception.

Synchronous generators have continuously grown in size over the years (see Fig. 1.33). The justification is based on simple economies of scale: the output rating of the machine per unit of weight increases as the size of the unit increases. Thus, it is not uncommon to see machines with ratings reaching up to 2000 MVA

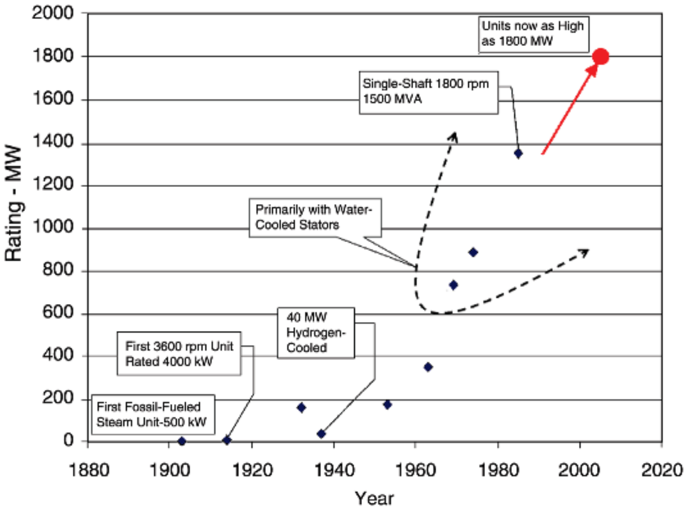


Fig. 1.33 "Growth" graph, depicting the overall increase in size over the last century, of turbine-driven generators.

in the most recent times, with the largest normally used in nuclear power stations. These are generally four-pole machines (see Figs. 1.34 and 1.35).

One of the key issues restricting the size of a generator is transport to site. Building a very large and heavy machine is not very useful if you cannot get to the site by rail, road, or other means. In addition, transmission system stability considerations also place an upper limit on the rating of a single generator. The sudden loss of a very large machine can easily put the local system into an unstable condition. And worse, if the instability cascades to neighboring systems, a major power outage may occur, and actually has in various locations in the not too recent past.

Interestingly enough, the present ongoing shift from large steam turbines as prime movers to more efficient gas turbines is resulting in a reverse of the trend toward larger and larger generators, at least for the time being.

1.6.2 Principles of Construction

Chapter 2 includes a description of the design criteria leading to the construction of the modern turbo-generator, as well as a detailed description of all components most commonly found in such a machine. This section is limited to the presentation of the elementary components comprising a synchronous machine, with the purpose of describing its basic operating theory.

Synchronous machines come in all sizes and shapes, from the miniature permanent magnet synchronous motor found in wall clocks to the largest steam-turbine-driven generators of up to about 2000 MVA. Synchronous machines are one of two types: stationary field or rotating dc magnetic field.

Fig. 1.34 Large modern generator stator with a rating of 2000 MVA or 1800 MW at 0.90 power factor. The weight of the stator is over 500 tons. The person standing in the bore gives perspective of the stator size.

Fig. 1.35 Large 1600 MVA generator rotor. The weight of the rotor is approximately 250 tons. Note the person standing to the left of the photo who gives perspective as to the size of the rotor.

The stationary field synchronous machine has salient poles mounted on the stator—the stationary member. The poles are magnetized either by permanent magnets or by a dc current. The armature, normally containing a three-phase winding, is mounted on the shaft. The armature winding is fed through three slip rings (collectors) and a set of brushes sliding on them. This arrangement can be found in machines up to about 5 kVA in rating. For larger machines—all those covered in this book—the typical arrangement used is the rotating magnetic field.

The rotating magnetic field (also known as revolving field) synchronous machine has the field winding wound on the rotating member (the *rotor*) and the *armature* wound on the stationary member (the *stator*). A dc current, creating a magnetic field that must be rotated at synchronous speed, energizes the rotating field winding. The rotating field winding can be energized through a set of slip rings and brushes (external excitation) or from a diode bridge mounted on the rotor (self-excited). The rectifier bridge is fed from a shaft-mounted alternator, which is itself excited by the pilot exciter. In externally fed fields, the source can be a shaft-driven dc generator, a separately excited dc generator, or a solid-state rectifier. Several variations on these arrangements exist.

The stator core is made of insulated steel laminations. The thickness of the laminations and the type of steel are chosen to minimize eddy current and hysteresis losses, while maintaining required effective core length and minimizing costs. The core is mounted directly onto the frame or in large two-pole machines, through a vibration damping type of construction. The core is slotted (the slots are normally open), and the coils making up the winding are placed in the slots. There are several types of armature windings, such as concentric windings of several types, cranked coils, split windings of various types, wave windings, and lap windings of various types. Modern large machines typically are wound with double-layer lap windings. (Details on stator cores, frames, and winding types are provided in Chapter 2.)

The rotor field is either of salient-pole (Fig. 1.36) or nonsalient-pole construction, also known as round rotor or cylindrical rotor (Fig. 1.37). Figure 1.38 shows a schematic comparison of the arrangement of a two-pole salient-pole generator versus a two-pole round rotor arrangement. Figure 1.39 shows a schematic comparison of the arrangement of a four-pole round rotor generator versus a four-pole salient-pole generator. The basic difference between salient-pole and round rotor generator construction is in the rotor construction and winding arrangement.

Nonsalient-pole (cylindrical) rotors are utilized in two- or four-pole machines, and very seldom in six-pole machines. These are typically driven by steam or combustion turbines. The vast majority of salient-pole machines have six or more poles. They include all synchronous hydrogenerators, almost every synchronous condenser, and the overwhelming majority of synchronous motors. In later years, some generators with nonsalient-pole rotors have been converted to synchronous condensers, upon their retirement.

Nonsalient-pole rotors are typically machined out of a solid steel forging. The winding is placed in slots machined out of the rotor body and retained against the

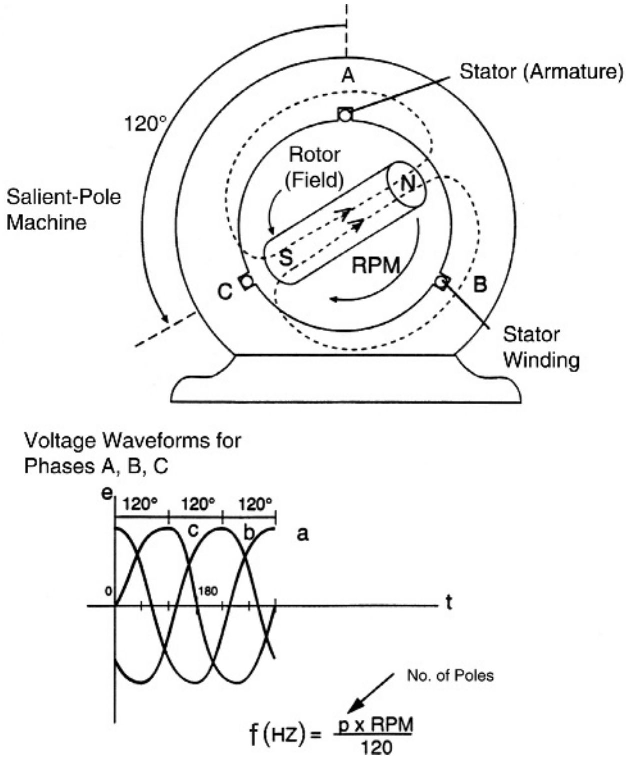


Fig. 1.36 Synchronous machine construction. Schematic cross section of a salient-pole synchronous machine. In a large generator, the rotor is magnetized by a coil wrapped around it. The figure shows a two-pole rotor. Salient-pole rotors normally have many more than two poles. When designed as a generator, large salient-pole machines are driven by water turbines. The bottom part of the figure shows the three-phase voltages obtained at the terminals of the generator, and the equation relates the speed of the machine, the number of poles, and the frequency of the resulting voltage.

large centrifugal forces by metallic wedges, normally made of aluminum or steel. The *retaining rings* restrain the end part of the windings (end windings). In the case of large machines, the retaining rings are made out of steel.

Large salient-pole rotors are made of laminated poles retaining the winding under the pole head. The poles are keyed onto the shaft (spider-and-wheel structure). Salient-pole machines have an additional winding in the rotating member. This winding, made of copper bars short-circuited at both ends, is embedded in the head of the pole, close to the face of the pole. The purpose of this winding is to start the motor or condenser under its own power as an induction motor, and take it unloaded to almost synchronous speed, when the rotor is "pulled in" by the synchronous torque. The winding also serves to damp the

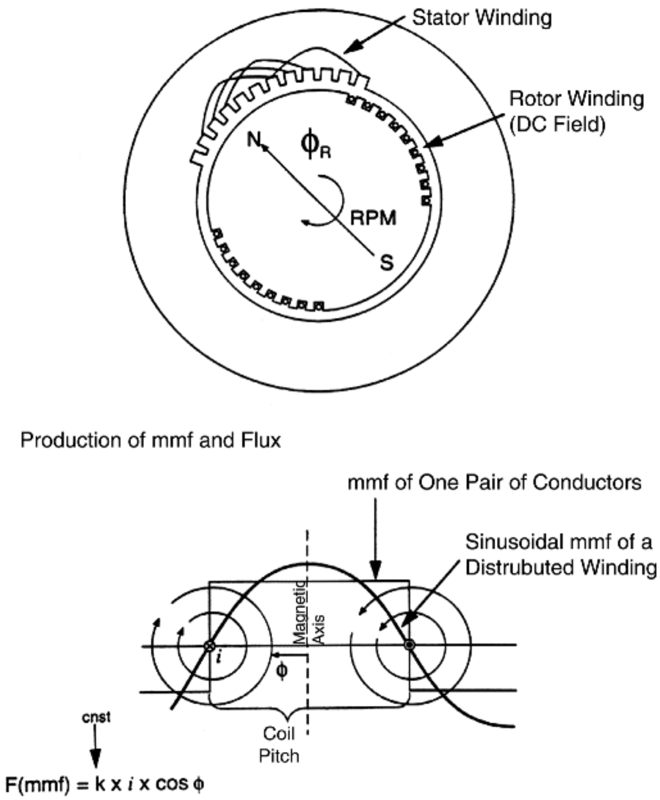


Fig. 1.37 Schematic cross section of a synchronous machine with a cylindrical round-rotor. This is the typical design for all large turbo-generators. Here, both the stator and rotor windings are installed in slots, distributed around the periphery of the machine. The lower part shows the resulting waveforms of a pair of conductors and that of a distributed winding. The formula gives the magneto-motive force (mmf) created by the windings.

oscillations of the rotor around the synchronous speed and is, therefore, named the *damping winding* (also known as *amortisseur*).

This book focuses on large turbine-driven generators. These are always two- or four-pole machines having cylindrical rotors. The discussion of salient-pole machines can be found in other books. (See the Additional Reading section at the end of this chapter.)

1.6.3 Rotor Windings

In turbo-generators, the rotor winding (which produces the magnetic field) is made of a number of coils connected in a single circuit and installed in slots machined into the rotor forging main body. It is then energized with dc power fed

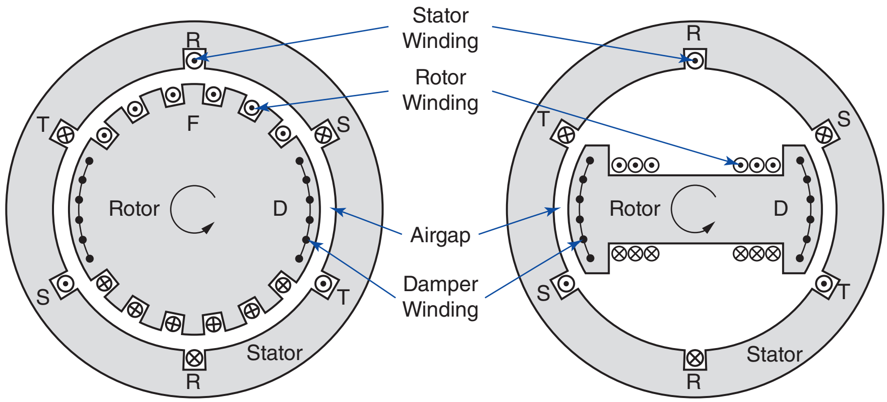


Fig. 1.38 This figure shows a schematic comparison of the arrangement of a two-pole round-rotor generator (left) versus a two-pole salient-pole generator (right). The basic difference is in the rotor construction and winding arrangement. Also shown on the rotor pole faces of each configuration is where a *damper-winding* or*amortisseur* winding is installed.

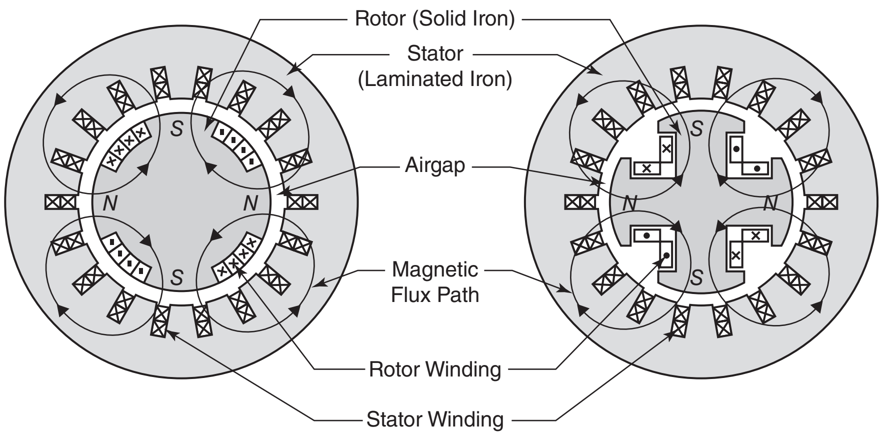


Fig. 1.39 This figure shows a schematic comparison of the arrangement of a four-pole round-rotor generator (left) versus a four-pole salient-pole generator (right). Again, the basic difference is in the rotor construction and winding arrangement.

via the shaft from the collector rings riding on the shaft, and positioned outside the main generator bearings. Figure 1.40 shows a basic series connection for a simple two-pole rotor winding with eight coils per pole. The number of turns in each coil will vary, depending on the size of the machine and its design. However, seven to eight turns per coil are not uncommon in larger rotors with ratings in the hundreds of megawatt range. For example, if this rotor had 8 turns per coil, it would produce a total number of ampere-turns equal to 16 coils times 8 turns per coil times the

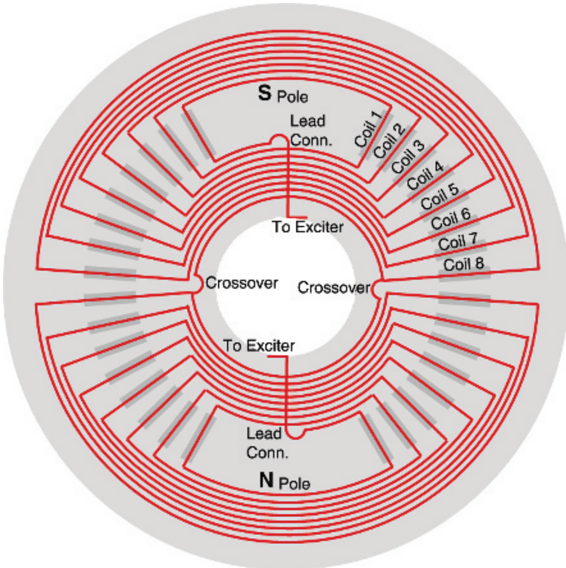


Fig. 1.40 This diagram shows the winding connection for a two-pole rotor with eight coils per pole. By tracing the winding connection, one can see that it is connected in series through both poles, giving a total number of turns to be 16 coils times the number of turns that would be in each coil. (Courtesy of Mr. Relu Ilie, Israel Electric Co.)

amount of field current applied. If the field current were 1000 A, then the total ampere-turns would be $(16 \times 8 \times 1000) = 128{,}000$ ampere-turns. The principles discussed at the beginning of Section 1.1.1 are put into practice here to maximize the amount of flux produced by using a coiled conductor and a steel forging to minimize leakage flux and maximize the amount of useful flux.

In *self-excited* generators, the shaft-mounted exciter and rectifier (diodes) generate the required field current. The shaft-mounted exciter is itself excited from a stationary winding. The fact that, unlike the stator, the rotor field is fed from a relatively low-power, low-voltage circuit has been the main reason why these machines have the field mounted on the rotating member and not the other way around. Moving high currents and high power through the collector rings and brushes (with a rotating armature) would represent a serious technical challenge, making the machine that much more complex and expensive.

Older generators have field supplies of 125 V dc. Excitation voltages of 500 V or higher are common in newer machines. A much more elaborate discussion of rotor winding design and construction can be found in Chapter 2.

1.6.4 Stator Windings

The magnitude of the voltage induced in the stator winding is, as shown above, a function of the magnetic field intensity, the rotating speed of the rotor, and the number of turns in the stator winding. An actual description of individual coil design and construction, as well as how the completed winding is distributed around the stator, is meticulously described in Chapter 2. In this section, a very elementary description of the winding arrangement is presented to facilitate the understanding of the basic operation of the machine.

As stated above, coils are distributed in the stator in a number of forms, each with its own advantages and disadvantages. The basic goal is to obtain three balanced and sinusoidal voltages having very little harmonic content (harmonic voltages and currents are detrimental to the machine and other equipment in a number of ways). To achieve a desired voltage and MVA rating, the designer may vary the number of slots and the manner in which individual coils are connected, producing different winding patterns. The most common winding arrangement is the lap winding, shown in Figure 1.41 for a four-pole machine and in Figure 1.42 for a two-pole machine.

A connection scheme that allows great freedom of choice in designing the windings to accommodate a given terminal voltage is one that allows connecting sections of the winding in parallel, series, and/or a combination of the two. Figure 1.43 shows two typical winding arrangements for a two-pole generator.

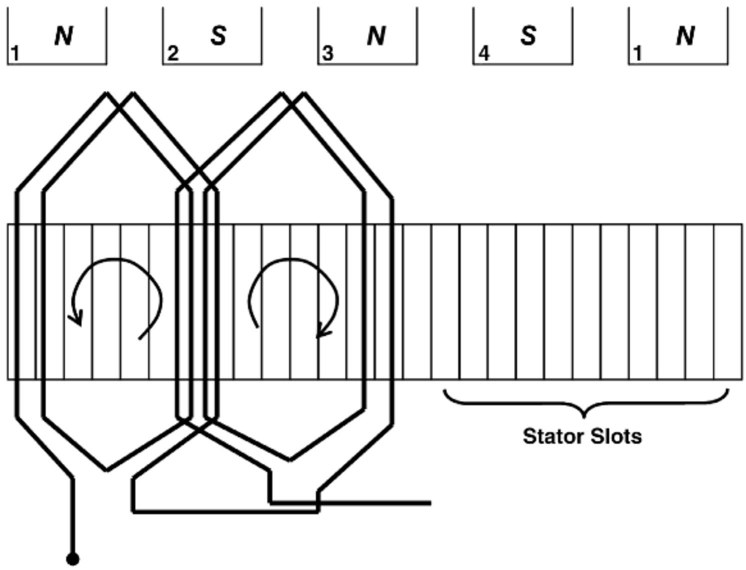


Fig. 1.41 "Developed" view of a four-pole stator, showing the slots, the poles, and a section of the winding. The section shown is of one of the three phases. It can be readily seen that the winding runs clockwise under a north pole, and counterclockwise under a south pole. This pattern repeats itself until the winding covers the four poles. A similar pattern is followed by the other two phases, but located at 120 electrical degrees apart.

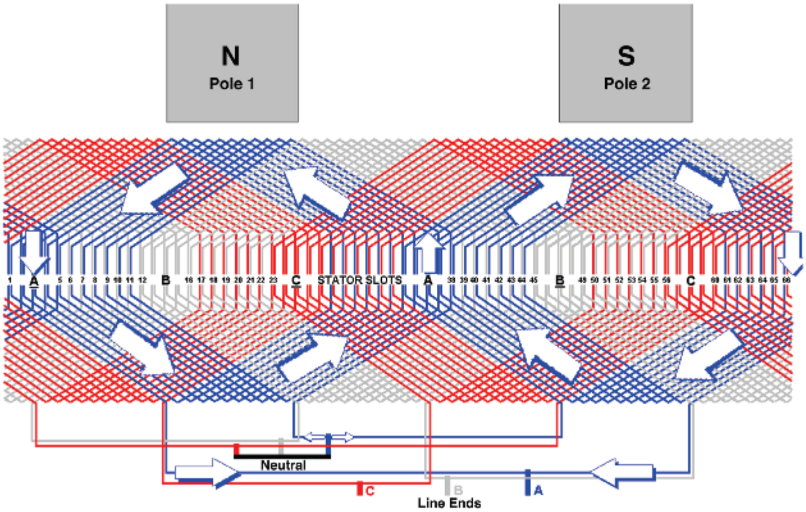


Fig. 1.42 "Developed" view of a two-pole stator, showing the slots, the poles, and the three winding phases. It can be readily seen that the winding runs clockwise under a north pole and counterclockwise under a south pole. A similar pattern is followed by the other two phases, but located 120 electrical degrees apart.

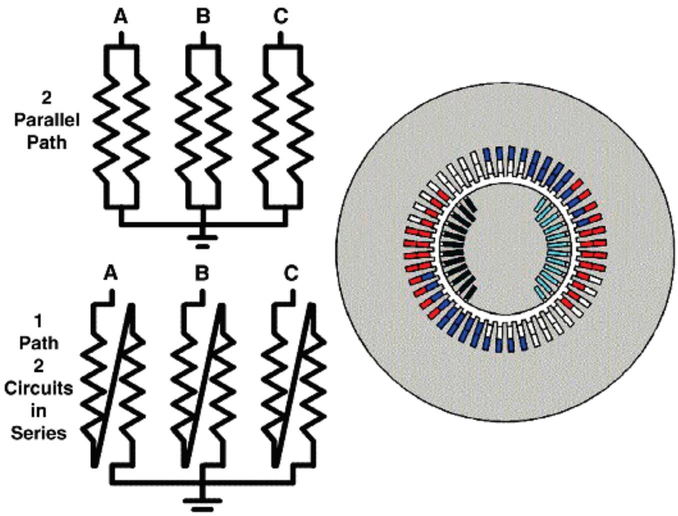


Fig. 1.43 Schematic view of a two-pole generator with two possible winding configurations: (1) a two parallel circuits winding and (2) a two series-connected circuits winding, per phase. On the right, the three phases are indicated by different colors. Note that some slots only have coils belonging to the same phase, whereas in others coils belonging to two phases share the slot.

1.7 BASIC OPERATION OF THE SYNCHRONOUS MACHINE

For a more in-depth discussion of the operation and control of large turbo-generators, the reader is referred to Chapter 4. In this chapter, the most elementary principles of operation of synchronous machines will be presented. As mentioned above, all large turbo-generators are three-phase machines. Thus, the best place to start describing the operation of a three-phase synchronous machine is a description of its magnetic field.

Earlier, we described how a current flowing through a conductor produces a magnetic field associated with that current. It was also shown that by coiling the conductor, a larger field is obtained without increasing the current's magnitude. Recall that if the three phases of the winding are distributed at 120 electrical degrees apart, three balanced voltages are generated, creating a three-phase system.

Now, a new element can be brought into the picture. By a simple mathematical analysis, it can be shown that if three balanced currents (of equal magnitudes and 120 electrical degrees apart) flow in a balanced three-phase winding, a magnetic field of constant magnitude is produced in the airgap of the machine. This magnetic field revolves around the machine at a frequency equal to the frequency of the currents flowing through the winding (see Fig. 1.44). The importance of a three-phase system creating a constant field cannot be stressed enough. The constant magnitude flux allows hundreds of megawatts of power to be transformed inside an electric machine from electrical to mechanical power, and vice versa, without major mechanical limitations. It is important to remember that a constant-magnitude flux produces a constant-magnitude torque. Now, try to imagine the same type of power being transformed under a pulsating flux (and, therefore, pulsating torque), which is tremendously difficult to achieve.

It is difficult to envision how the three balanced currents in a three-phase generator can create the three-phase flux vectors and their resultant flux vector in Figure 1.44. At this point, it is useful to describe this process as it will make operation of the generator much clearer. The starting point for this is to take the two-pole stator representation of Figure 1.44 and show the flux vectors on the stator representation, and include the three-phase currents, synchronized in time and rotation. Initially we can look at this in Figure 1.45*a* showing the A-phase current and flux vectors. One can see that the A-phase current is at a maximum value in the positive direction and the A-phase flux, which is always in phase with the current, points to the positive side of phase A inside the machine, and has a maximum value. Next, we include the B-phase current and flux vectors, in Figure 1.45*b*. In this diagram, we see the B-phase current at 120° to the A-phase current, and at the same overall magnitude. But when we resolve this current in terms of its value at the same point in time by projecting it onto the reference axis, we get a negative value at half of the magnitude of the A-phase current. And since the current is negative, the flux vector for the B-phase must be in the negative or B (hat) direction on the flux vector diagram. We can now see why the A and B flux vectors are 60° apart, as shown in Figure 1.44, and of different magnitudes. In

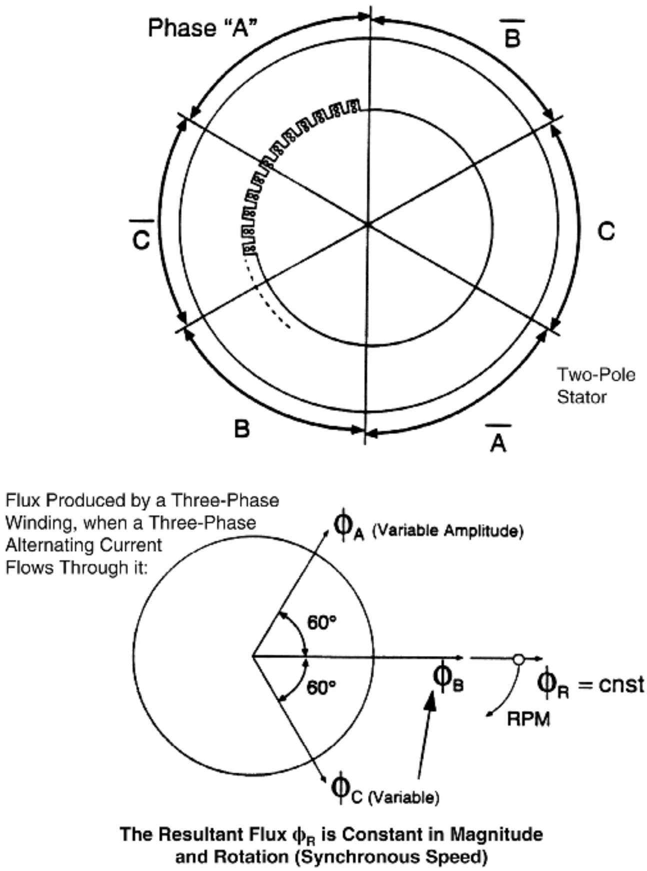


Fig. 1.44 Production of stator rotating field. A constant magnitude and constant rotational speed magnetic flux is created when three-phase balanced currents flow through a three-phase symmetrical winding. The sketch is for a two-pole winding; however, similar result applies for any number of pairs of poles.

Figure 1.45*c* we now include the C-phase current and flux vectors, using the same principles. This produces the C-phase current at 120° to both the A- and B-phase currents and the C-phase flux vector at 60° to the A-phase flux vector and in the negative or C (hat) direction. This gives the basic representation as shown in Figure 1.44. If we now sum all the flux vectors in Figure 1.45*c*, we get the representation in Figure 1.45*d* and finally the resultant flux vector shown in Figure 1.45*e*.

With the basic theory now shown for determining the resultant flux vector at a single point in time, we need to see what happens as the machine operates in time, as rotation of the currents and vectors occurs. This is shown in the series of Figure 1.46*a–m*. For this purpose, the diagrams are constructed to show points in

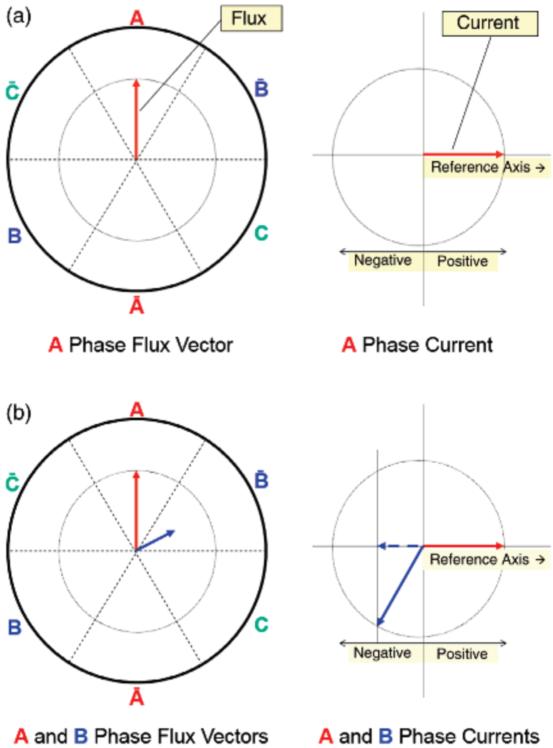


Fig. 1.45 (a–e) These diagrams show the principle of how the three-phase flux vectors (produced by three-phase balanced stator currents) are summed in relation to one another to produce a total and constant resultant flux vector.

a. The peak red phase current is shown at zero degrees, with the corresponding maximum red phase flux in phase with the current in the A phase coil.
b. The blue (B) phase current is shown as the dashed blue current vector for the same point in time as (a). However, the "peak" red and blue phase currents are 120° apart. The red and blue phase flux vectors are 60° apart. Since the B phase current is "negative," the B phase flux vector direction is toward B (hat) or the negative polarity of B. It is also reduced in magnitude when related to the current value for the same point in time as the A phase current when it is at its peak.
c. The white (C) phase current is also shown as a dashed white current vector for the same point in time as (a). Again, all "peak" three-phase currents are 120° apart (i.e. balanced), but the blue and white phase flux vectors are 60° separated from the red phase vector and at half the magnitude, in the negative direction. The same reasoning in (b) applies here.
d. This diagram shows the vector addition of all three flux components that produces the resultant total flux vector for the 3 balanced phase currents.
e. The resulting total flux vector of the three-phase currents is shown. This vector will remain a constant value as the phase currents and flux vectors change with rotation.

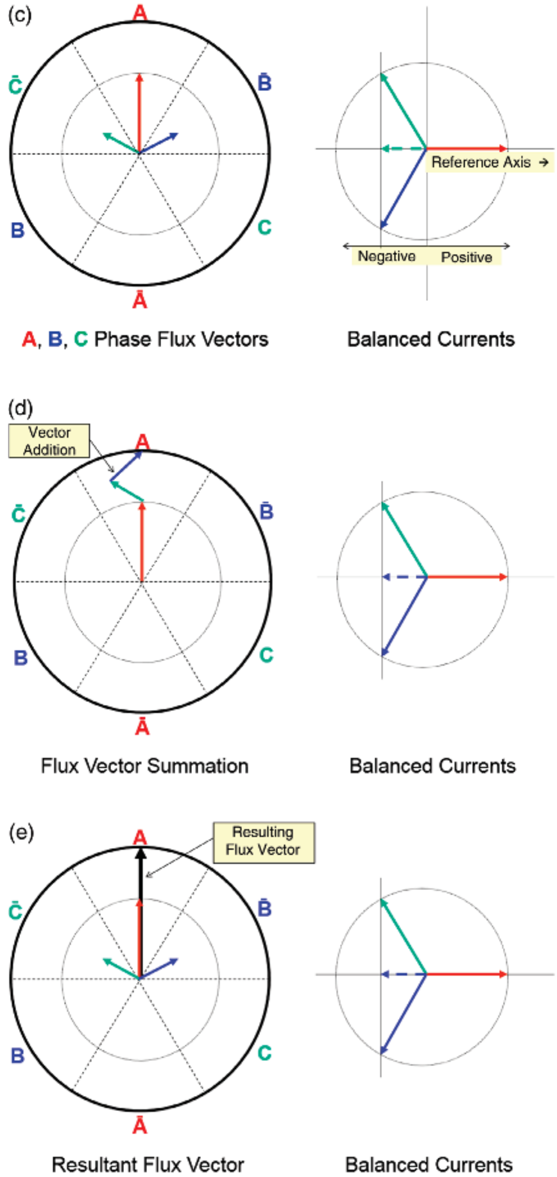


Fig. 1.45 (*Continued*)

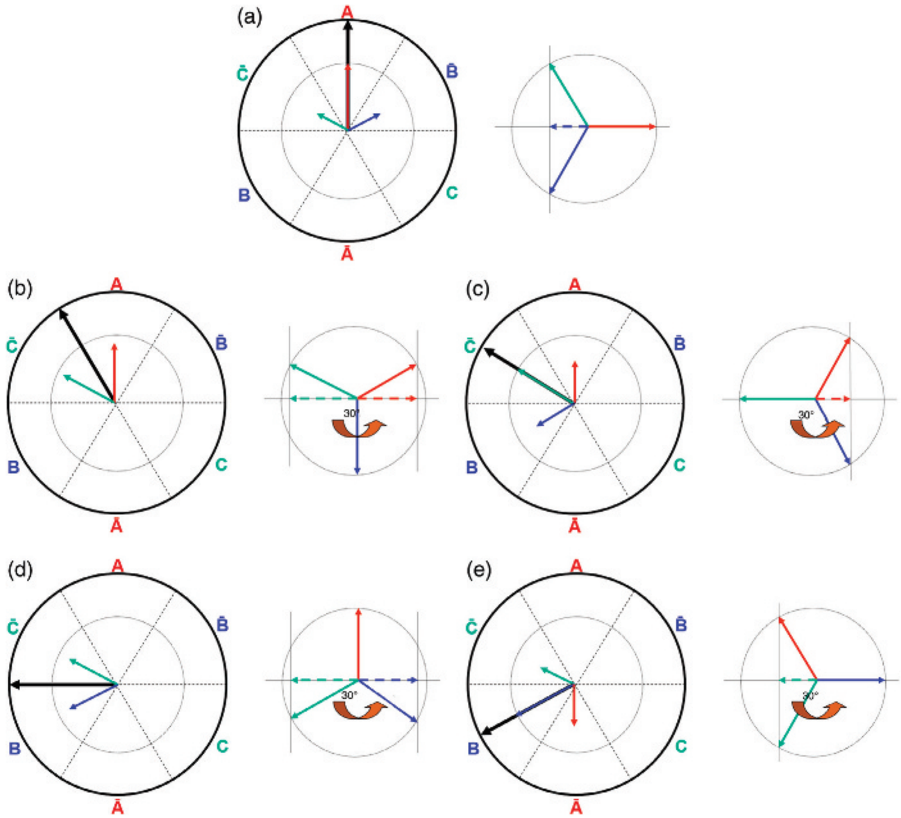


Fig. 1.46 (a–m) This series of diagrams shows the relation of the three-phase flux vectors to the three-phase balanced currents, at 30° rotational increments. From this, one can see how the flux vectors change in magnitude and phase relation to one another as the rotation progresses from 0 to 360°.

a. Three-phase generator: flux vector representation (left diagram), with the corresponding three-phase balanced currents (right diagram), starting with the red phase at peak current and zero degrees, and therefore peak red phase flux in phase with the current, pointing in the direction of phase A.
b. The flux vectors when the phase currents are advanced by 30°. Note there is no blue phase flux component as the blue phase current is at the zero crossing of the sinusoidal wave.
c. (up to m) The flux vectors as the phase currents are advanced by 30° increments from 0 to 360°, or back to the starting point with the red phase current at zero degrees. The resultant flux vector is always constant.

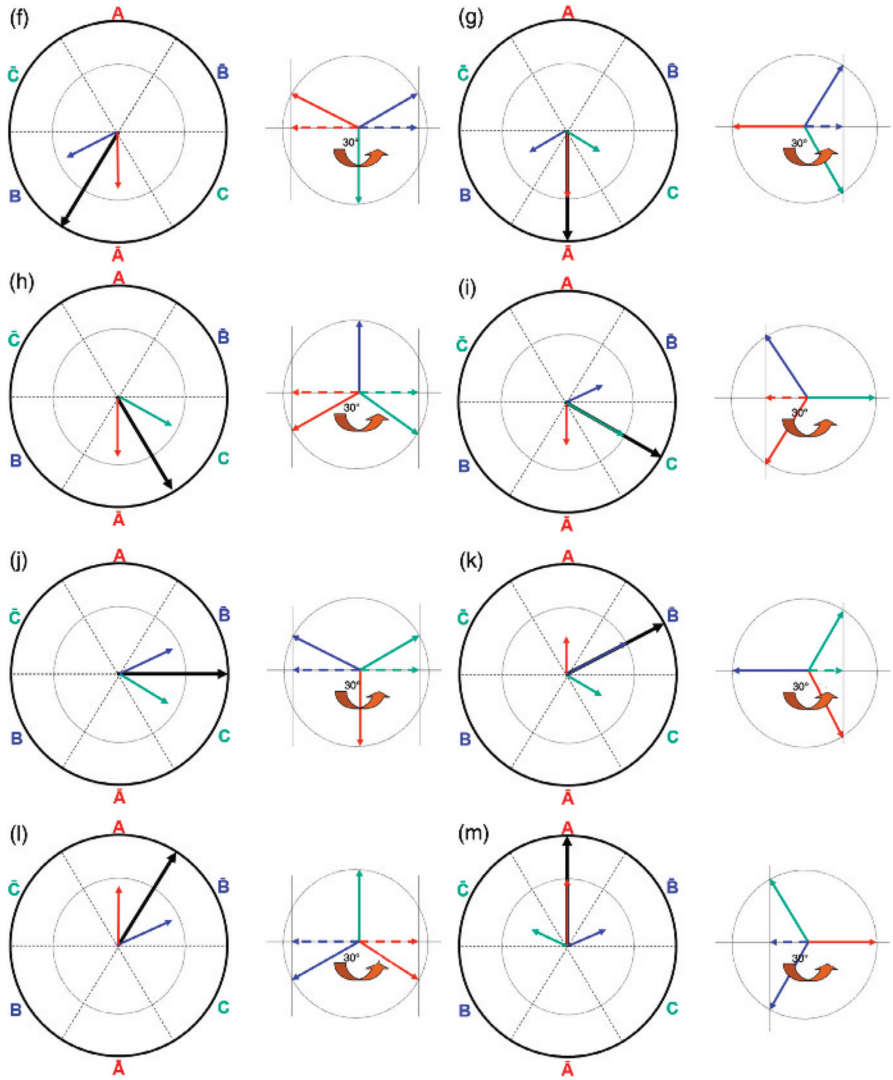


Fig. 1.46 (*Continued*)

time that are rotated in steps of 30°, for one full revolution or cycle. The main point to take away from this series of diagrams is that the *resultant* flux vector is always at the same magnitude (i.e., the constant magnitude flux vector in the airgap). It should be noted, however, that all of these diagrams are based on three-phase "balanced" currents.

As a final representation of effect of three-phase operation, Figure 1.47 shows a *real-time* representation of the information presented in Figures 1.45 and 1.46, at a

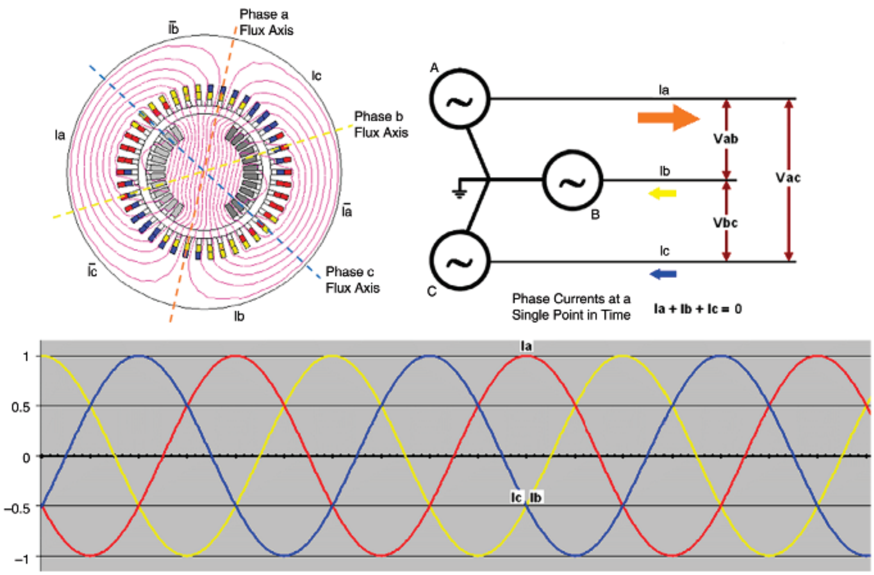


Fig. 1.47 This diagram is a depiction of generator three-phase operation. The generator cross section diagram in the top left corner shows the relation of the rotor and stator windings at a single point in time. The position of the machine flux in relation to the stator currents and flux axes are shown. The diagram in the top right corner shows the three-phase generator schematic and the relative current magnitudes and directions at a single point in time. The diagram on the bottom is the sin wave representation of the currents in the schematic. It shows that the three-phase currents always sum to zero at any single point in time.

single point in time in three specific ways. The machine cross section is shown in operation connected to the system, with the rotor flux pattern included. The flux pattern is shown as related to the same point in time of the three flux axis's and stator and rotor currents. At the same point in time, the three-phase currents are shown on the three-phase generator schematic, in terms of magnitude and direction. And finally, the corresponding sin wave pattern for the three-phase currents is shown. The magnitude of the resultant flux vector will be dependent on the MVA output of the generator, but the resultant flux vector will be constant in magnitude.

It is now convenient to introduce the fundamental principles describing the operation of a synchronous machine in terms of an *ideal* cylindrical-rotor machine connected to an *infinite* bus. The infinite bus represents a bus bar of constant voltage, which can deliver or absorb active and reactive power without any limitations. The ideal machine has zero resistance and leakage reactance, infinite permeability, and no saturation, as well as zero reluctance torque.

The production of torque in the synchronous machine results from the natural tendency of two magnetic fields to align themselves. The magnetic field produced by the stationary armature is denoted as $\mathbf{\Phi_s}$. The magnetic field produced by the rotating field is $\mathbf{\Phi_f}$. The resultant magnetic field is

$$\mathbf{\Phi_r} = \mathbf{\Phi_s} + \mathbf{\Phi_f}$$

The flux $\mathbf{\Phi}_r$ is established in the airgap (or gas gap) of the machine. (Bold symbols indicate vector quantities.)

When the torque applied to the shaft equals zero, the magnetic fields of the rotor and the stator become perfectly aligned. The moment torque is introduced to the shaft, either in a generating mode or in a motoring mode; a small angle is created between the stator and rotor fields. This angle (λ) is called the torque angle of the machine.

1.7.1 No-Load Operation

When the ideal machine is connected to an infinite bus, a three-phase balanced voltage $\mathbf{V}_1$ is applied to the stator winding (within the context of this work, three-phase systems and machines are assumed). As described above, it can be shown that a three-phase balanced voltage applied to a three-phase winding evenly distributed around the core of an armature will produce a rotating (revolving) magneto-motive force (mmf) of constant magnitude $\mathbf{F_s}$. This mmf, acting upon the reluctance encountered along its path, results in the magnetic flux $\mathbf{\Phi}_s$ previously introduced. The speed at which this field revolves around the center of the machine is related to the supply frequency and the number of poles by the following expression:

$$n_s = 120\left(\frac{f}{p}\right)$$

where
f = electrical frequency in Hz
p = number of poles of the machine
n_s = speed of the revolving field in revolutions per minute (rpm)

If no current is supplied to the dc field winding, no torque is generated, and the resultant flux $\boldsymbol{\phi}_r$, which in this case equals the stator flux $\boldsymbol{\phi}_s$, magnetizes the core to the extent the applied voltage $\mathbf{V}_1$ is exactly opposed by a counterelectromotive force (cemf) ($\mathbf{E}_1$). If the rotor's excitation is slightly increased, and no torque is applied to the shaft, the rotor provides some of the excitation required to produce $\mathbf{E}_1$, causing an equivalent reduction of $\boldsymbol{\phi}_s$. This situation represents the under-excited condition shown in condition *no load* in Figure 1.48*a*. When operating under this condition, the machine is said to behave as a *lagging condenser*, meaning it absorbs reactive power from the network. If the field excitation is

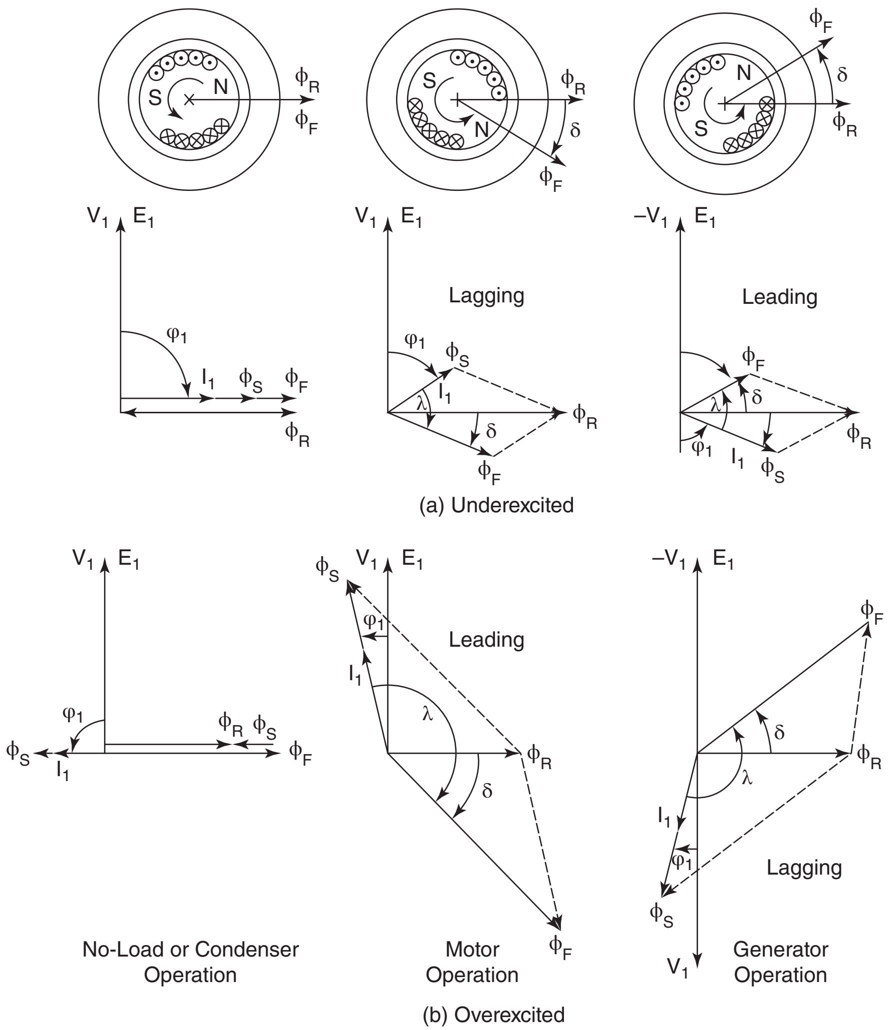


Fig. 1.48 Phasor diagrams for a synchronous cylindrical-rotor ideal machine.

increased over the value required to produce $\mathbf{E}_1$, the stator currents generate a flux that counteracts the field-generated flux. Under this condition, the machine is said to be overexcited, shown as condition *no-load* in Figure 1.48*b*. The machine is behaving as a leading condenser; that is, it is delivering reactive power to the network.

Under no-load condition, both the torque angle (λ) and the load angle (δ) are zero. The *load angle* is defined as the angle between the rotor's mmf ($\mathbf{F}_f$) or flux ($\boldsymbol{\phi}_f$) and the resultant mmf ($\mathbf{F}_r$) or flux ($\boldsymbol{\phi}_r$). The load angle (δ) is the most commonly used because it establishes the torque limits the machine can attain in a simple manner (discussed later). One must be aware that in many texts, the name *torque angle* is used to indicate the load angle. The name *torque angle* is also sometimes given to indicate the angle between the terminal voltage ($\mathbf{V}_1$) and the excitation voltage ($\mathbf{E}_1$). This happens because the leakage reactance is generally very much smaller than the magnetizing reactance, and therefore the load angle (δ) and the angle between $\mathbf{V}_1$ and $\mathbf{E}_1$ are very similar. In this book the more common name *power angle* is used for the angle between $\mathbf{V}_1$ and $\mathbf{E}_1$. In Figure 1.48, the power angle is always shown as zero because the leakage impedance has been neglected in the ideal machine.

It is important at this stage to introduce the distinction between electrical and mechanical angles. In studying the performance of the synchronous machine, all the electromagnetic calculations are carried out based on electric quantities; that is, all angles are electrical angles. To convert the electrical angles used in the calculations to the physical mechanical angles, we observe the following relationship:

$$\text{Mechanical angle} = \left(\frac{2}{p}\right)\text{Electrical angle}$$

1.7.2 Motor Operation

The subject of this book is turbo-generators. These units seldom operate as motors. The term "motoring" is used when generators operate as a motor, and infers absorbing rather than producing megawatt. This is an abnormal (sometimes even dangerous) operating regime for a generator, as detailed later in the book. (One such example is when the main generator is used for a short period of time as a motor fed from a variable speed converter. The purpose of this operation is for starting its own prime-mover combustion turbine). However, this section presents an introductory discussion of the synchronous machine, and thus the motor mode of operation is also covered. If a breaking torque is applied to the shaft, the rotor starts falling behind the revolving-armature-induced mmf $\mathbf{F}_s$. In order to maintain the required magnetizing mmf $\mathbf{F}_r$, the armature current changes. If the machine is in the underexcited mode, the condition *motor* in Figure 1.48*a* represents the new phasor diagram.

On the other hand, if the machine is overexcited, the new phasor diagram is represented by *motor* in Figure 1.48*b*. The active power consumed from the network under these conditions is given by

$$\text{Active power} = V_1 \times I_1 \times \cos\varphi_1 \qquad \text{(per phase)}$$

If the breaking torque is increased, a limit is reached in which the rotor cannot keep up with the revolving field. The machine then stalls. This is known as "falling out of step," "pulling out of step," or "slipping poles." The maximum torque limit is reached when the angle δ equals $\pi/2$ electrical. The convention is to define δ as negative for motor operation and positive for generator operation. The torque is also a function of the magnitude of $\boldsymbol{\phi}_r$ and $\boldsymbol{\phi}_f$. When overexcited, the value of $\boldsymbol{\phi}_f$ is larger than in the underexcited condition. Therefore, synchronous motors are capable of greater mechanical output when overexcited. Likewise, underexcited operation is more prone to result in an "out-of-step" situation.

1.7.3 Generator Operation

Let us assume that the machine is running at no load and a positive torque is applied to the shaft; that is, the rotor flux angle is advanced ahead of the stator flux angle. As in the case of motor operation, the stator currents will change to create the new conditions of equilibrium shown in Figure 1.48, under *generator*. If the machine is initially underexcited, condition in Figure 1.48*a* results. On the other hand, if the machine is overexcited, condition in Figure 1.48*b* results.

It is important to note that when "seen" from the terminals, with the machine operating in the underexcited mode, the power factor angle (φ_1) is leading (i.e., $\mathbf{I}_1$ leads $\mathbf{V}_1$). This means the machine is absorbing reactive power from the system. The opposite occurs when the machine is in the overexcited mode. As for the motor operation, an overexcited condition in the generating mode also allows for greater power deliveries.

As generators are normally called to provide VARs together with watts, they are almost always operated in the overexcited condition.

1.7.4 Equivalent Circuit

When dealing with three-phase balanced circuits, electrical engineers use the *one-line* or *single-line* representation. This simplification is allowed because in three-phase balanced circuits, all currents and voltages, as well as circuit elements are symmetrical. Thus, by "showing" only one phase, it is possible to represent the three-phase system, as long as care is taken in using the proper factors. For instance, the three-phase balanced system of Figure 1.26 or Figure 1.27 can be represented as shown in Figure 1.49. Hereinafter, when describing a three-phase generator by an electrical diagram, the one-line method will be used.

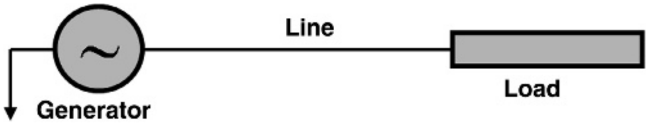


Fig. 1.49 One-line representation of the circuit shown in Figures 1.26 and 1.27.

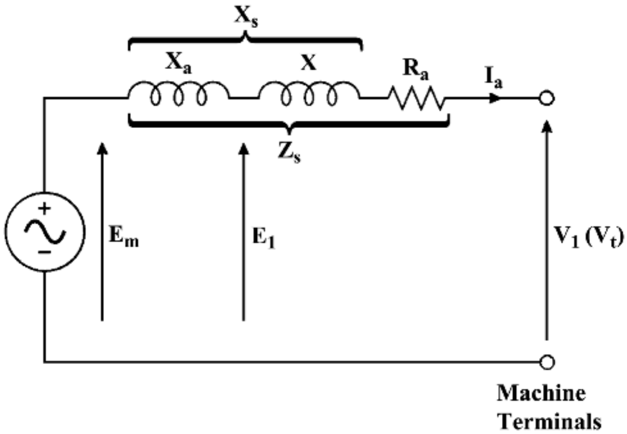


Fig. 1.50 Steady-state equivalent circuit of a synchronous machine. X = leakage reactance, X_a = armature reaction reactance, $X_s = X_a + X$ = synchronous reactance, R_a = armature resistance, Z_s = synchronous impedance, $V_1(V_t)$ = terminal voltages, and E_m = magnetizing voltage.

The most convenient way to determine the performance characteristics of synchronous machines is by means of equivalent circuits. These equivalent circuits can become very elaborate when saturation, armature reaction, harmonic reactance, and other nonlinear effects are introduced. However, the simplified circuit in Figure 1.50 is conducive to obtaining the basic performance characteristics of the machine under steady-state conditions.

In Figure 1.50 the reactance X_a represents the magnetizing or demagnetizing effect of the stator windings on the rotor. It is also called the *magnetizing reactance*. R_a represents the effective resistance of the stator. The reactance X represents the stator leakage reactance. The sum of X_a and X is used to represent the total reactance of the machine, and is called the *synchronous reactance* (X_s). Z_s is the *synchronous impedance* of the machine. It is important to remember that the equivalent circuit described in Figure 1.50 represents the machine only under steady-state condition.

The simple equivalent circuit of Figure 1.51 suffices to determine the steady-state performance parameters of the synchronous machine connected to a power grid. These parameters include voltages, currents, power factor, and load angle. The *regulation* of the machine can be easily found from the equivalent circuit for different load conditions by using the regulation formula:

$$\mathfrak{R}(\%) = 100(V_{\text{no-load}} - V_{\text{load}})/V_{\text{load}}$$

For a detailed review of the performance characteristics of the synchronous machine, in particular the turbo-generator, the reader is referred to Chapter 4.

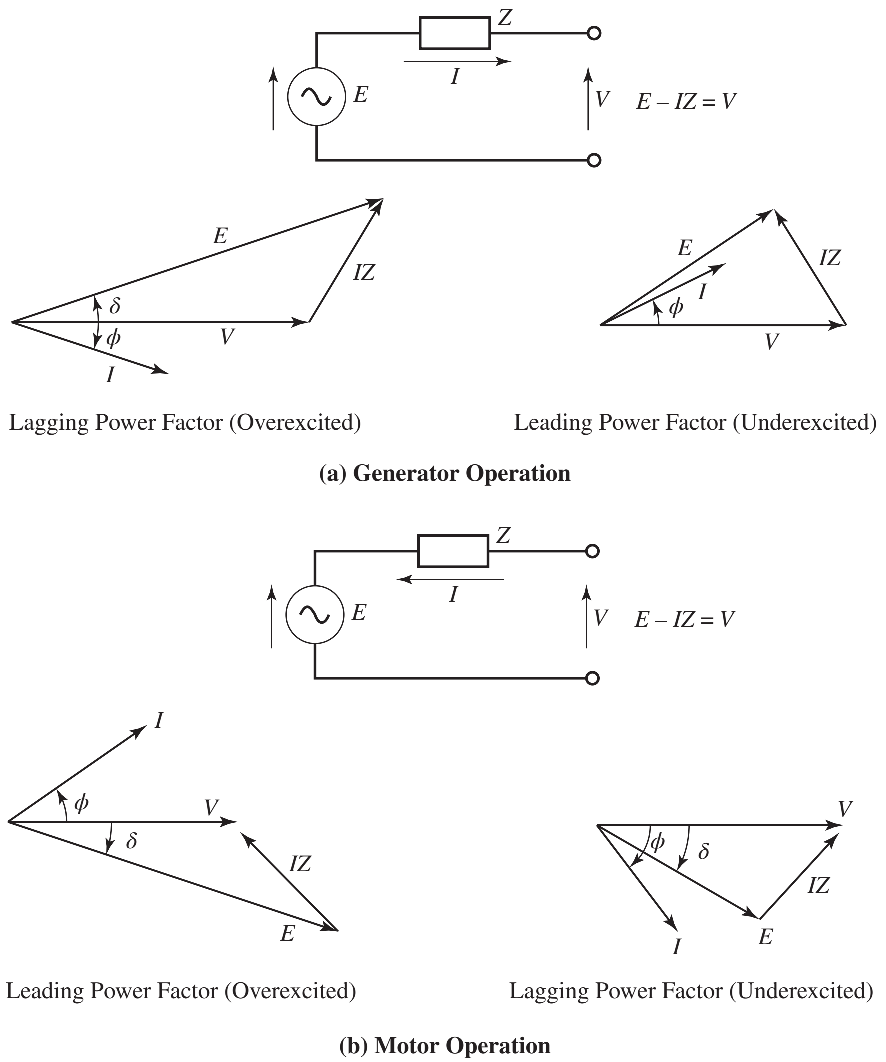


Fig. 1.51 Steady-state equivalent circuit and vector diagram.

Note: Regulation in a generator indicates how the terminal voltage of the machine varies with changes in load. When the generator is connected to an infinite bus (i.e., a bus that does not allow the terminal voltage to change), a change in load will affect the machine's output in a number of ways (see Chapter 4 for a discussion on this topic).

1.7.5 Machine Losses

In Section 1.5.4, the balance of energy in an electric machine was discussed. As part of the discussion, reference was made to the fact that current flows through the machine's conductors generating heat (a loss). However, there are a number of other sources within a working alternator that produce heat and, thus, losses. The following is a list of some of those sources of losses:

Winding Losses (Copper Losses)

- I^2R stator loss
- I^2R rotor loss
- Eddy and circulating current loss in windings (parasitic currents induced in the windings)

Iron Losses

- Mainly stator losses due to hysteresis loss and eddy current loss in stator laminations

Parasitic Eddy Losses

- Induced currents in all metallic components (bolts, frame, etc.)

Mechanical Losses

- Friction and windage loss
- Losses in fans and rotor and stator cooling vents
- Losses in bearings

Exogenous Losses

- Losses in auxiliary equipment
  - Excitation
  - Lubrication oil pumps
  - H_2 seal oil pumps
  - H_2 and water cooling pumps
- Isophase or lead losses

In the following chapters, these losses and their origin, control, and consequences to the machine's design and operation will be covered in detail.

ADDITIONAL READING

A wealth of literature exists for the reader interested in a more in-depth understanding of synchronous machine theory. The following is only but a very short list of readily available classic textbooks describing the operation and design of synchronous machines in a manner accessible to the uninitiated.

1. D. Zorbas, *Electric Machines: Principles, Applications, and Control Schematics*, West, 1989.
2. M. G. Say, *Alternating Current Machines*, Pitman Publishing, 1978.
3. T. Wildi, *Electrical Machines, Drives and Power Systems*, Prentice-Hall, 2005.
4. V. del Toro, *Electric Machines and Power Systems*, Prentice-Hall, 1985.
5. M. Liwschitz-Garik and C. C. Whipple, *Electric Machinery*, Vols. 1–2, Van Nostrand, 1947.
6. A. E. Fitzgerald, C. Kingsley, and S. Umans, *Electric Machinery*, McGraw-Hill, 1990.
7. For a text describing the practical issues related to operation and maintenance of both turbo-generators and hydrogenerators, see I. Kerszenbaum, *Inspection of Large Synchronous Machines*, IEEE Press, 1996.