

CHAPTER 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.

Chapter 1 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 the machine's 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 all turbogenerators belong to.

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 constituting 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 to 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.

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 “permanent magnets.” 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 is the subject of this book. Turbine-driven generators (for short: turbogenerators) take advantage of the fact that magnetic fields can be created by the flow of electric currents in conductors. See Figure 1.3.

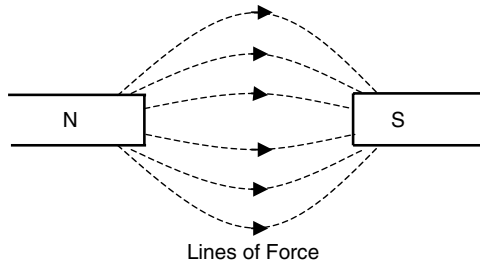


Fig. 1.1 Schematic representation of two magnetic poles of opposite polarity, and the magnetic field between them shown as “lines of force.”

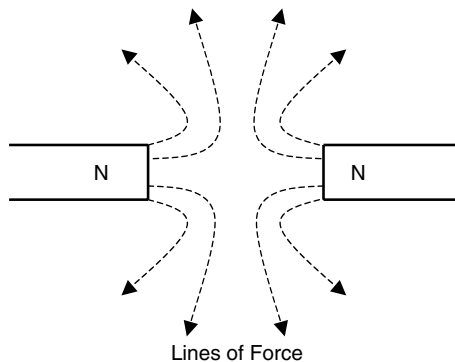


Fig. 1.2 Schematic representation of two north poles, and the magnetic field between them. South poles will create similar field patterns, but the lines of force will point toward the poles.

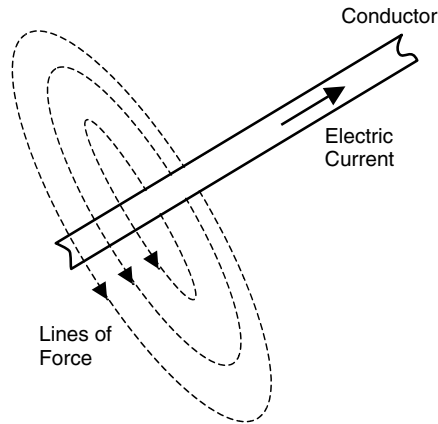


Fig. 1.3 Schematic representation of a magnetic field created by the flow of current in a conductor. The direction of the *lines of force* is given by the “law of the screwdriver”: mentally follow the movement of a screw as it is screwed in the same direction as that of the current; the lines of force will then follow the circular direction of the head of the screw. The magnetic lines of force are perpendicular to the direction of current.

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 Figure 1.4.

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

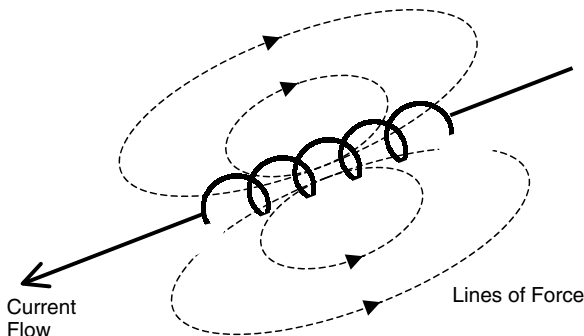


Fig. 1.4 Schematic representation of a magnetic field produced by the flow of electric current in a coil-shaped conductor.

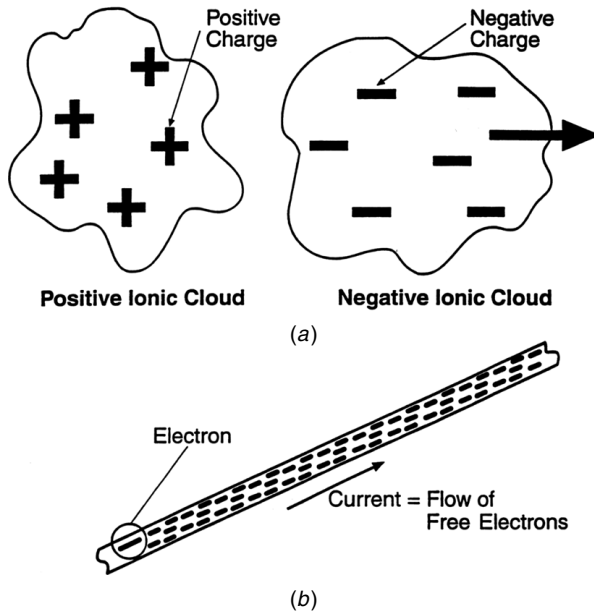


Fig. 1.5 Electricity. (a) Ionic clouds of positive and negative currents. The positive clouds are normally atoms that lost one or more electrons; the negative clouds are normally free electrons. (b) The flow of electrons inside a conductor material, for example, copper.

ions in space or within gases. As it will be shown in later chapters, both types of electrical conduction are found in turbogenerators. See Figure 1.5.

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 backgrounds find this equivalence useful to the understanding of the physical process in either form of energy. Figure 1.6 describes the various forms of electrical-mechanical equivalence.

1.3 ALTERNATED CIRCUITS (AC)

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

The frequency of an alternated circuit is measured by the number of times the currents and/or voltages change direction (polarity) in a unit of time. The Hertz is the universally accepted unit of frequency, and measures cycles per second. One

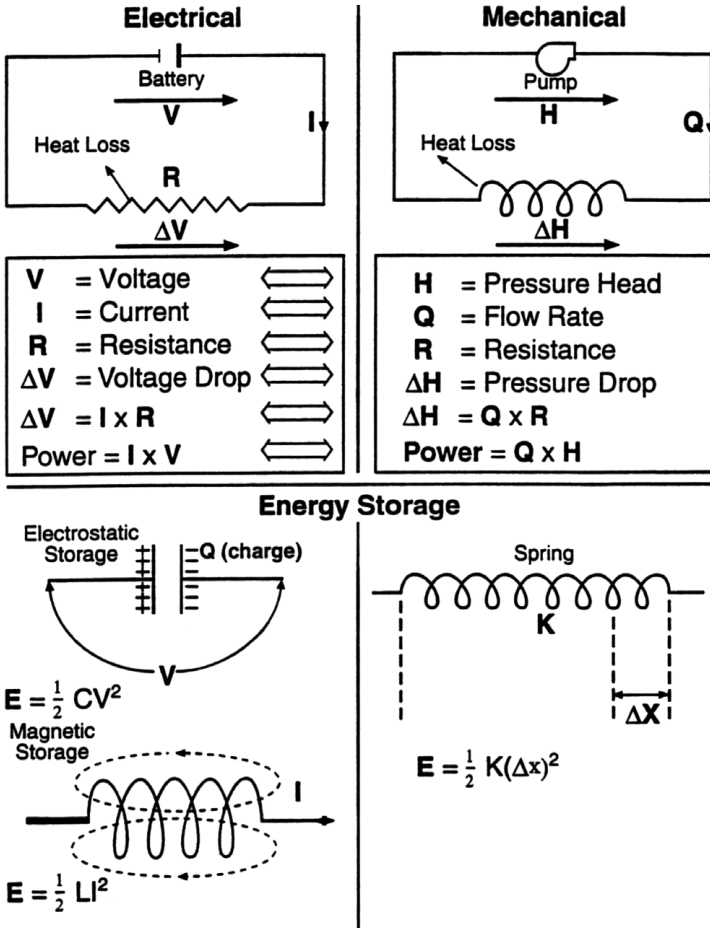


Fig. 1.6 Electrical-mechanical equivalence.

Hz equals one cycle per second. Alternated 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*.

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 1.7 depicts a phasor of magnitude **E**, and its corresponding sinusoidal trace representing 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

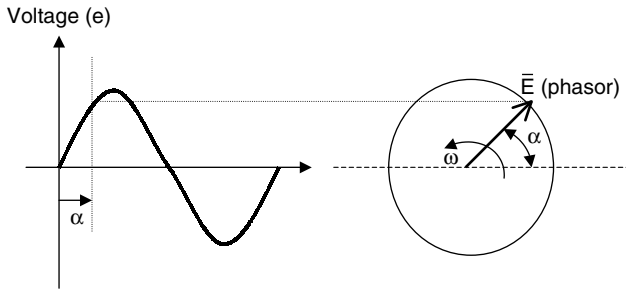


Fig. 1.7 A phasor \mathbf{E} , that can represent the voltage impressed on a circuit. The phasor is made of a vector with magnitude proportional to the magnitude of \mathbf{E} , rotating at a constant rotational speed ω . The convention is that phasors rotate counterclockwise. The vertical projection 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.

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 it 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 the “power factor.”

In the case of a circuit having only resistances, the voltages and currents are *in phase*, meaning the angle between them equals zero. Figure 1.8 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 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, with 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

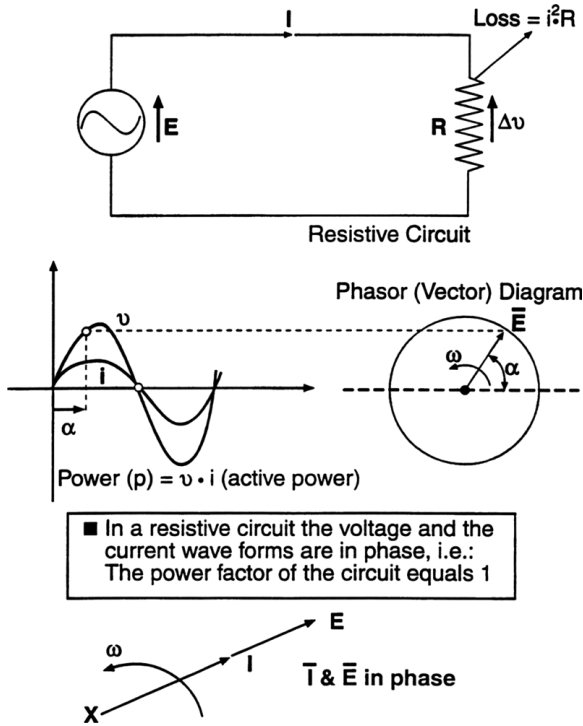


Fig. 1.8 Alternating circuits (resistive). Schematic representation of a sinusoidal voltage of magnitude E applied on a circuit with a resistive load R . The schematics shows the resultant current i in phase with the voltage v . It also shows the phasor representation of the voltage and current.

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° , while in a purely inductive one, the current will lag the voltage by 90° (see Fig. 1.9).

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* $\rightarrow S = E \times I$, given in units of *volt-amperes* or VA.
- P:** The *active power* $\rightarrow P = E \times I \times \cos \varphi$, where φ is the power angle of the circuit. **P** is given in units of watts.
- Q:** The *reactive power* $\rightarrow Q = E \times I \times \sin \varphi$, 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 it will be shown later. However, the use of the word “power” in the name of **S** and **Q** has been an unfortunate choice that has resulted in confounding

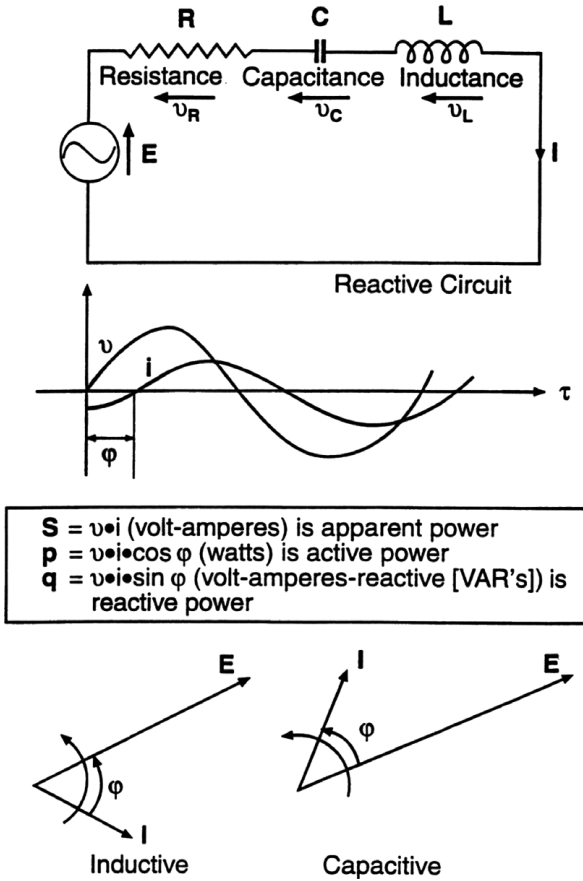


Fig. 1.9 Alternating circuits (resistive–Inductive–Capacitive). Here the sinusoidal voltage E is applied to a circuit comprised of resistive, capacitive, and inductive elements. The resulting angle between the current and the voltage depends on the value of the resistance, capacitance, and inductance of the load.

most individuals without an electrical engineering background for many years. The fact is that *apparent power* and *reactive power* does 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 it 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. 1.10).

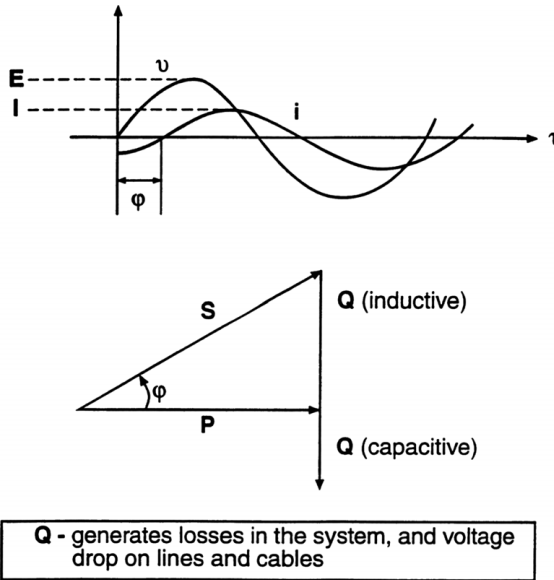


Fig. 1.10 Definition of the “power triangle” in a reactive circuit.

1.4 THREE-PHASE CIRCUITS

The two-wire ac circuits shown 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” will refer to a three-phase system. Moreover in industrial applications the voltage supplies are, for all practical reasons, balanced, meaning all three-phase voltages are equal in magnitude and apart by 120 electrical degrees. In those rare events where the voltages are unbalanced, its implication into the operation of the generator will be discussed in other chapters of this book.

Three-phase electric systems may have a fourth wire, called “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 1.11 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*. (See Fig. 1.12 for a wye-connected source feeding a delta-connected load.)

Almost without exception, turbine-driven generators have their windings connected in wye (*star*). Therefore in this book the source (or generator) will be shown wye-connected. There are a number of important reasons why turbogenerators are star-connected. They have to do with considerations about its effective

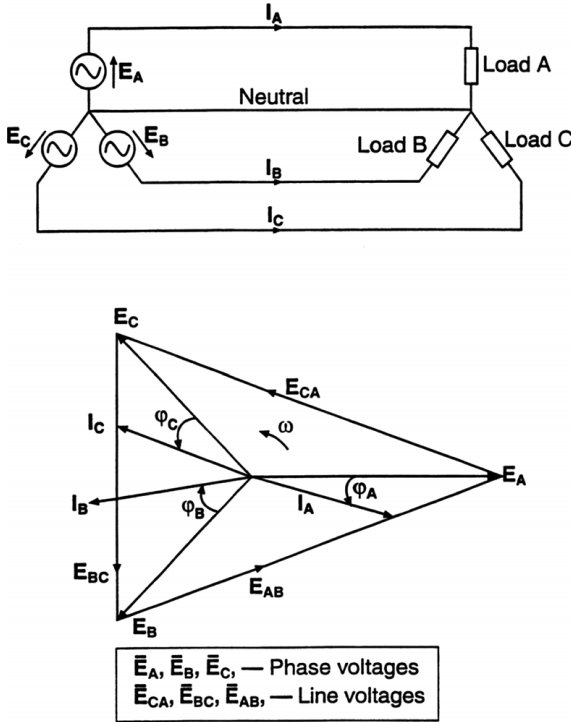


Fig. 1.11 Three phase systems. Schematic depiction of a three-phase circuit and the vector (phasor) diagram representing the currents, voltages, and angles between them.

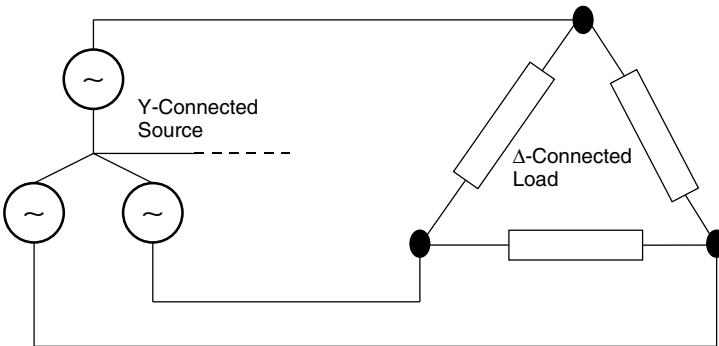


Fig. 1.12 A “Wye-connected” source feeding a “delta-connected” load.

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 star, 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 bricks on which the operation of any electrical machine can be explained.

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 1.13 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 induced voltage 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. While Faraday 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.

Figure 1.14 presents the basic elements of the 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.

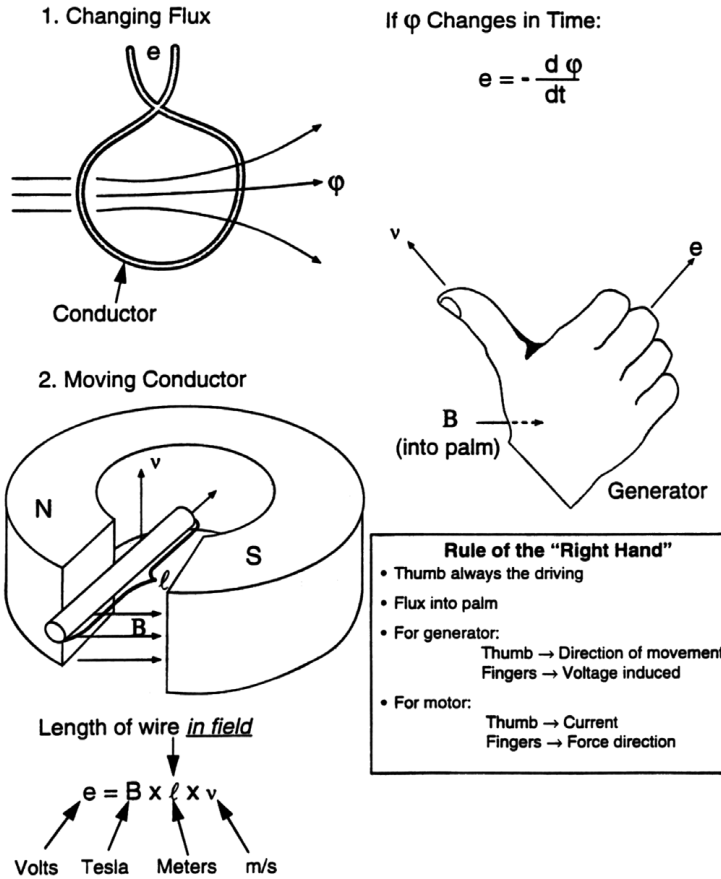


Fig. 1.13 Both forms of Faraday’s basic law of electromagnetic induction. A simple rule (the “right-hand” rule) is used to determine the direction of the induced voltage in a conductor moving across a magnetic field at a given velocity.

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 Ampere-Biot-Savart’s law) a force acting upon the conductor. What Lenz’s law states is 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.

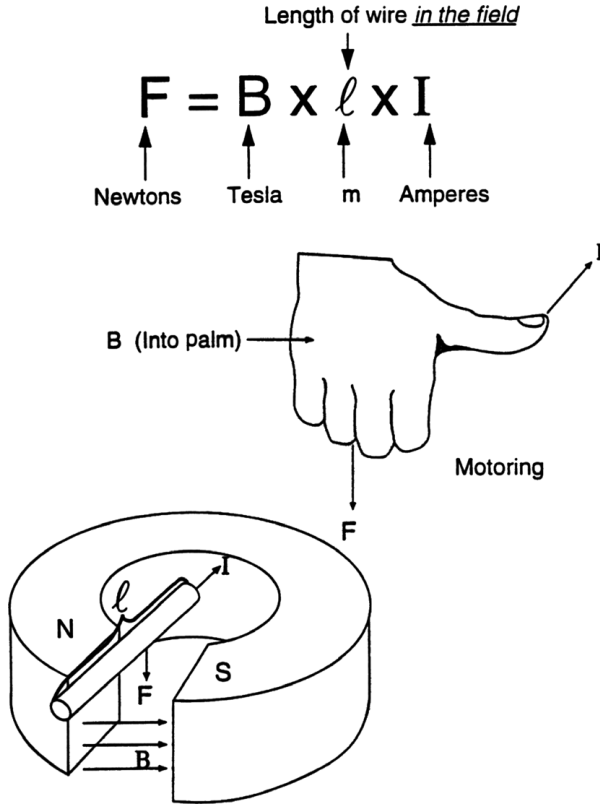


Fig. 1.14 The Ampere-Biot-Savart law of electromagnetic induced forces as it applies to electric rotating machines. Basic numerical relationships and a simple rule are used to determine the direction of the induced force.

Figure 1.15 neatly captures the main elements of Lenz’s law as it applies to electric rotating machines.

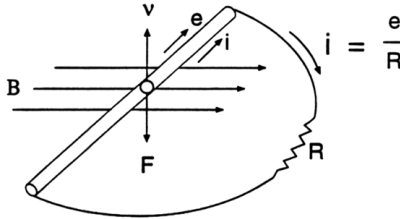
1.5.4 Electromechanical Energy Conversion

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 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 the machine and stored in the machine, equals the energy dissipated from the machine as heat.

It is important to recognize that while mechanical and electrical energy can go in or out the machine, the heat generated within the machine always has a

Example



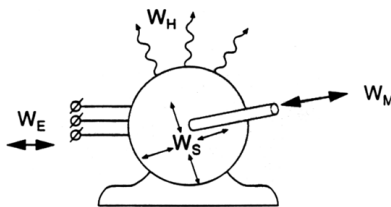
1. The upward moving conductor in a magnetic field induces a voltage (Faraday)
 2. Closing the circuit generates a current
 3. The current creates a force opposing the movement (Ampere and Lenz)
- Hint: Use the rule of the palm to show the direction of "F"**

This phenomenon explains the torque applied by the generator on the turbine, when the unit is loaded

Induced currents and forces will try to cancel the originating cause

Fig. 1.15 The Lenz 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.

$$\begin{array}{ccccccc}
 W_E & & W_M & & W_S & & W_H \\
 \text{Input/output} & + & \text{Input/output} & + & \text{Change in} & + & \text{Heat} \\
 \text{of electric} & & \text{of mechanical} & & \text{stored} & & \text{dissipated} \\
 \text{energy} & & \text{energy} & & \text{energy} & & \\
 & & & & \underbrace{\hspace{2cm}} & & = 0 \\
 & & & & \text{Electrical} = & & \\
 & & & & \frac{1}{2} I^2 L + \frac{1}{2} V^2 C & & \\
 & & & & \text{Mechanical} = & & \\
 & & & & \text{Rotational energy} & &
 \end{array}$$



W_H is always negative (i.e., heat is always released during the conversion process)

W_E , W_M and W_S can have "+" or "-" signs

W_E and W_M with a "plus" means input to the machine
 "minus" means output from the machine

W_S with a "plus" means increase of stored energy
 "minus" means decrease of stored energy

Fig. 1.16 Principle of energy conversion, as applicable to electric rotating machines.

negative sign: namely 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, while a *negative* 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 1.16 depicts the 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, commissioned in 1894. This happened about one hundred and eight years before the writing of this book (see Fig. 1.17).

The Lauffen-Frankfurt demonstration—and the consequent decision by the city of Frankfurt to use alternating 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 two 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 now for over one hundred years, the basic constituents of the machine have remained practically unchanged.

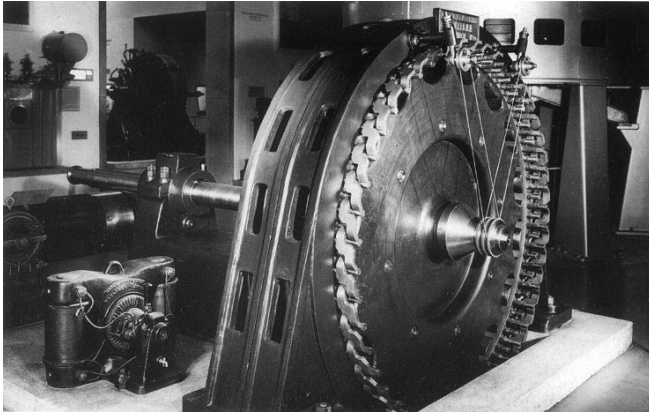


Fig. 1.17 The hydroelectric generator from Lauffen, now in the Deutsches Museum, Munich. (Reprinted with permission from *The Evolution of the Synchronous Machine* by Gerhard Neidhofer, 1992, ABB)

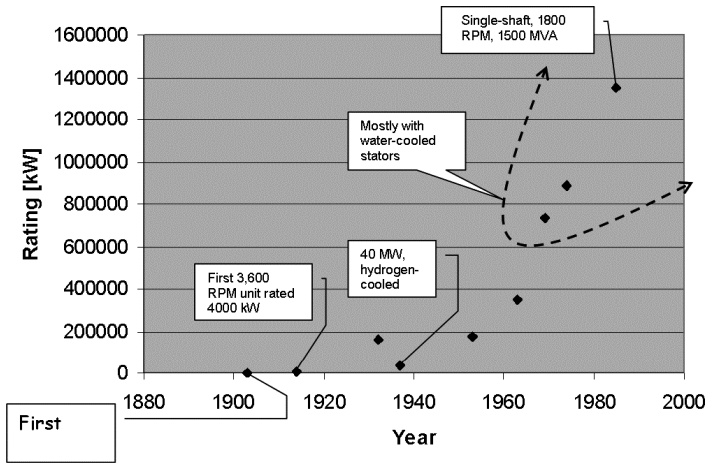


Fig. 1.18 “Growth” graph, depicting the overall increase in size over the last century, of turbine-driven generators.

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., the United States) 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. 1.18). 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 1500 MVA, with the largest normally used in nuclear power stations. 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. Transmission system stability considerations also place an upper limit on the rating of a single generator.

1.6.2 Principles of Construction

Chapter 2 includes a description of the design criteria leading to the construction of a modern turbogenerator, as well as contains a detailed description of all components most commonly found in such a machine. This section is limited to the presentation of the basic 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 in wall-clocks, to the largest steam-turbine-driven generators of up to about 1500 MVA. Synchronous machines are one of two types: the stationary field or the rotating dc magnetic field.

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 sliprings (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 to 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 spring bars. The core is slotted (normally open slots), and the coils making 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 (more about these winding types in Chapter 2).

The rotor field is either of salient-pole (Fig. 1.19) or non-salient-pole construction, also known as round rotor or cylindrical rotor (Fig. 1.20). Non-salient-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.

Non-salient-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 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 or spider-and-wheel

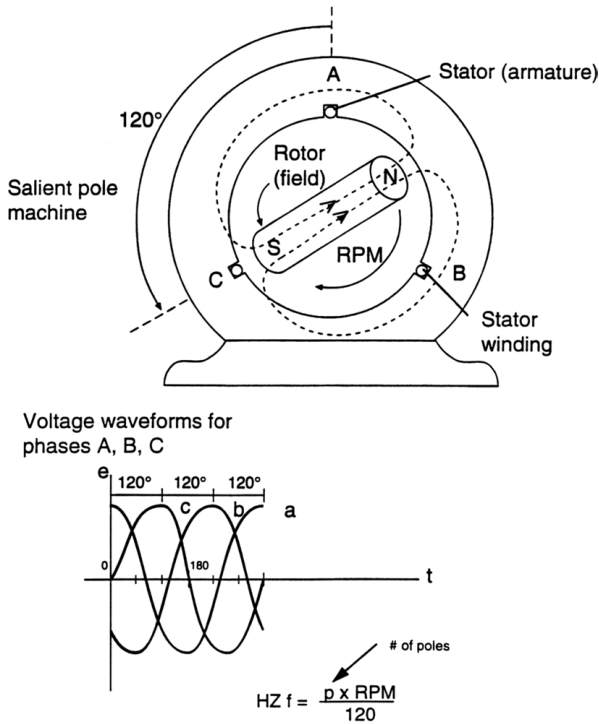
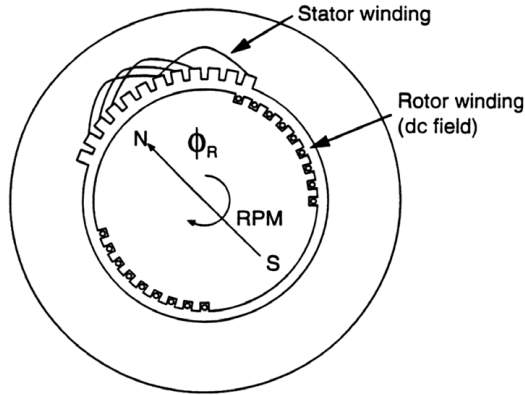


Fig. 1.19 Synchronous machine construction. Schematic cross section of a salient-pole synchronous machine. In a large generator, the rotor is magnetized by a coil wrapped around it. The figure shows a two-pole rotor. Salient-pole rotors normally have many more than two poles. When designed as a generator, 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, its number of poles, and the frequency of the resulting voltage.



Production of mmf and flux

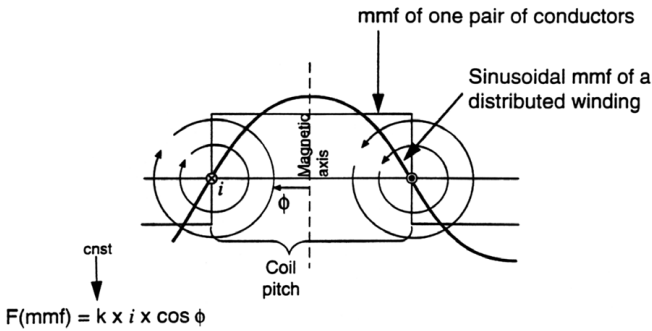


Fig. 1.20 Schematic cross section of a synchronous machine with a cylindrical round-rotor (turbogenerator). This is the typical design for all large turbogenerators. Here both the stator and rotor windings are installed in slots, distributed around the periphery of the machine. The lower part shows the resulting waveforms of a pair of conductors, and that of a distributed winding. The formula giving the magneto-motive force (mmf) created by the windings.

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 oscillations of the rotor around the synchronous speed, and is therefore named the *damping-winding* (also known as *amortisseurs* or *dampers-windings*).

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 turbogenerators, the winding producing the magnetic field is made of a number of coils, single-circuit, energized with dc power fed via the shaft from the collector rings riding on the shaft and positioned outside the main generator bearings. In *self-excited* generators, 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 volts dc. Later ones have supplies of 250 volts and higher. Excitation voltages of 500 volts or higher are common in newer machines. A much more elaborated 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 has 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, and it shown in Figure 1.21.

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 1.22 shows two typical winding arrangements for a four-pole generator.

1.7 BASIC OPERATION OF THE SYNCHRONOUS MACHINE

For a more in-depth discussion of the operation and control of large turbogenerators, the reader is referred to Chapter 4. In this chapter the most elementary principles of operation of synchronous machines will be presented. As it was

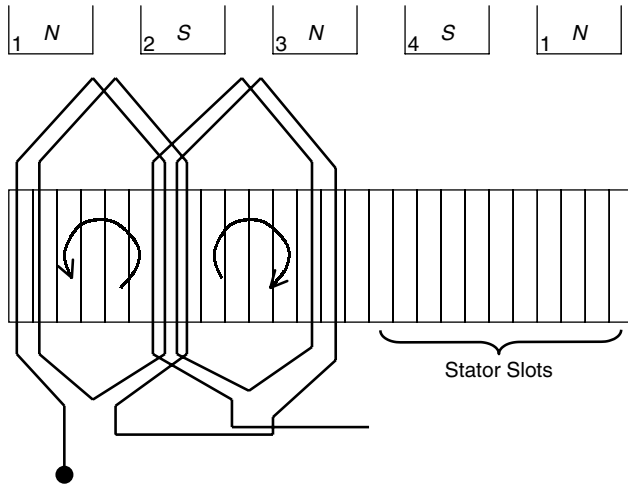


Fig. 1.21 “Developed” view of a four-pole stator, showing the slots, the poles, and a section of the winding. The section shown is of one of the three phases. It can be readily seen that the winding runs clockwise under a north pole, and counterclockwise under a south pole. This pattern repeats itself until the winding covers the four poles. A similar pattern is followed by the other two phases, but located at 120 electrical degrees apart.

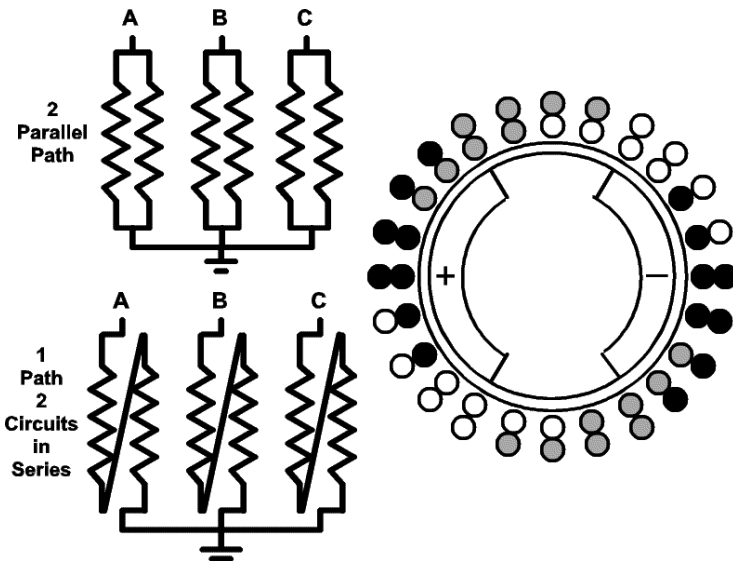


Fig. 1.22 Schematic view of a two-pole generator with two possible winding configurations: (1) A two parallel circuits winding, (2) A two series connected circuits per phase. On the right, the three phases are indicated by different tones. Note that, some slots only have coils belonging to the same phase, while in others, coils belonging to two phases share the slot.

mentioned above, all large turbogenerators 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 (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. 1.23). The importance of a three-phase system creating a constant field cannot be stressed enough. The constant magnitude flux allows hundred of megawatts of power to be transformed

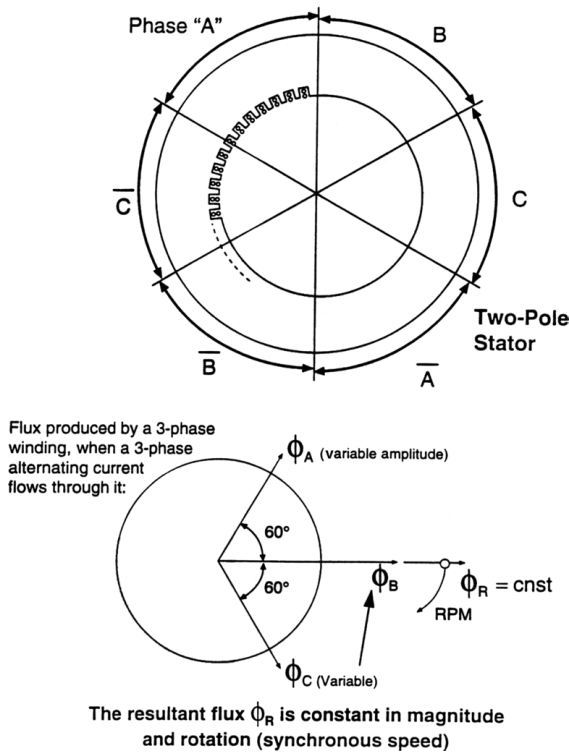


Fig. 1.23 Production of stator rotating field. A constant magnitude and constant rotational speed magnetic flux is created when three-phase balanced currents flow through a three-phase symmetrical winding. In a two-pole winding, however, any the same result applies for any number of pairs of poles.

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 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 busbar 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 Φ_s . The magnetic field produced by the rotating field is Φ_r . The resultant magnetic field is

$$\Phi_r = \Phi_s + \Phi_f$$

The flux Φ_r is established in the airgap (or gasgap) 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 instant 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 (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 (F_s). This mmf, acting upon the reluctance encountered along its path, results in the magnetic flux (Φ_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)

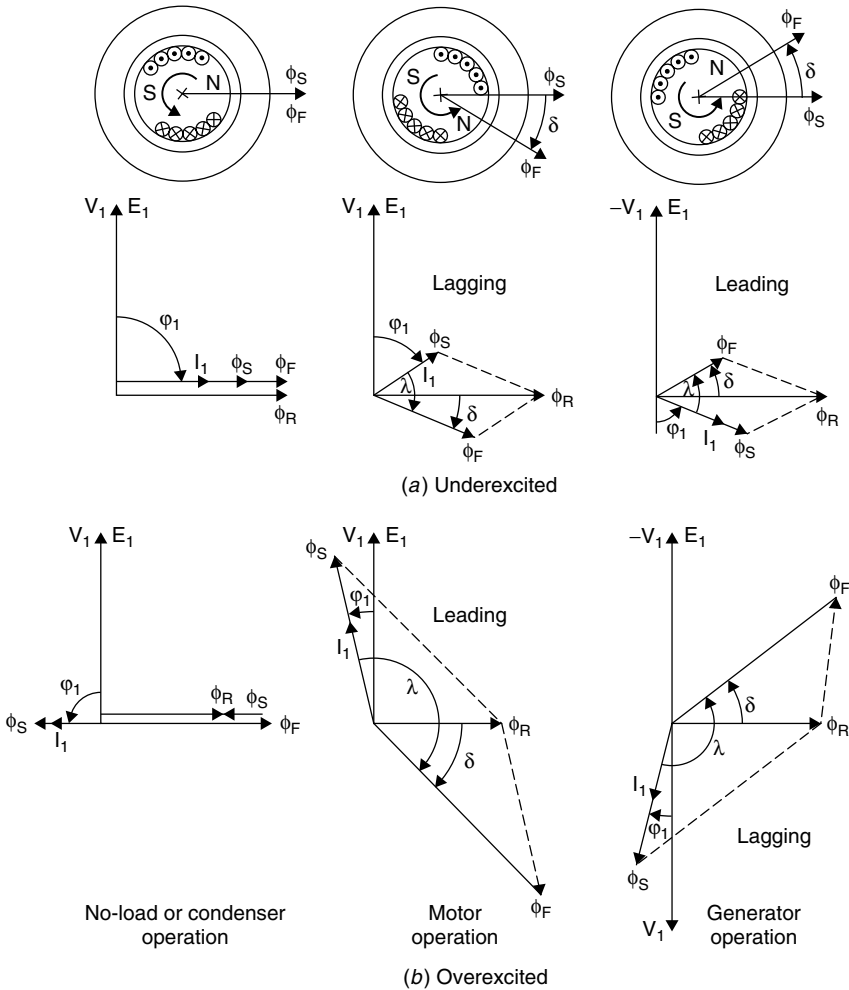


Fig. 1.24 Phasor diagrams for a synchronous cylindrical-rotor *ideal* machine.

If no current is supplied to the dc field winding, no torque is generated, and the resultant flux (ϕ_r), which in this case equals the stator flux (ϕ_s), magnetizes the core to the extent the applied voltage (V_1) is exactly opposed by a counter-electromotive force (cemf) (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 (E_1), causing an equivalent reduction of (ϕ_s). This situation represents the underexcited condition shown in condition *no load* (a) in Figure 1.24. 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 increased over the value required to produce (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* (b) in Figure 1.24. 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}_r) or flux (Φ_r) and the resultant mmf (\mathbf{F}_r) or flux (Φ_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 1.24, 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 turbogenerators. These units seldom operate as a motor. (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 braking torque is applied to the shaft, the rotor starts falling behind the revolving-armature-induced magnetomotive force (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 1.24a represents the new phasor diagram.

On the other hand, if the machine is overexcited, the new phasor diagram is represented by *motor* in Figure 1.24b. The active power consumed from the network under these conditions is given by

$$\text{Active power} = V_1 \times I_1 \times \cos \phi_1 \quad (\text{per phase})$$

If the braking 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 ϕ_r and ϕ_f . When overexcited, the value of ϕ_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’s 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 1.24, under *generator*. If the machine is initially underexcited, condition (a) in Figure 1.24 obtains. On the other hand, if the machine is overexcited, condition (b) in Figure 1.24 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, “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 1.11 or Figure 1.12 can be represented as shown in Figure 1.25. Hereinafter, when describing a three-phase generator by an electrical diagram, the one-line method will be applied.

The most convenient way to determine the performance characteristics of synchronous machines is by means of equivalent circuits. These equivalent circuits

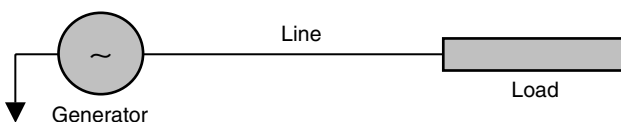


Fig. 1.25 One-line representation of circuit shown in Figure 1.10 and 1.11.

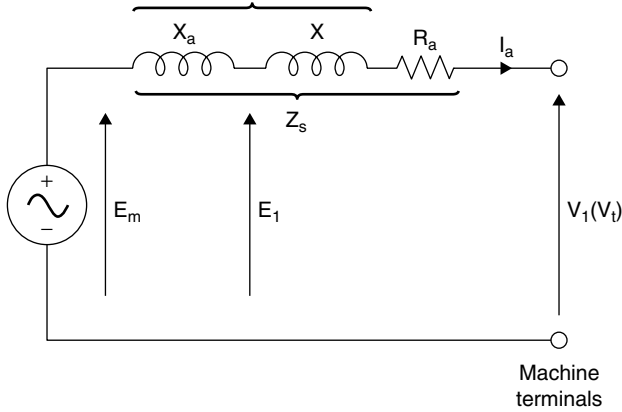


Fig. 1.26 Steady-state equivalent circuit of a synchronous machine. X = leakage reactance, X_a = armature reaction reactance, $X_s = X_a + X$ = synchronous reactance, R_a = armature resistance, Z_s = synchronous impedance, $V_1 (V_t)$ = terminal voltages, and E_m = magnetizing voltage.

can become very elaborate when saturation, armature reaction, harmonic reactance, and other nonlinear effects are introduced. However, the simplified circuit in Figure 1.26 is conducive to obtaining the basic performance characteristics of the machine under steady-state conditions.

In Figure 1.26 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 1.26 represents the machine only under steady-state condition.

The simple equivalent circuit of Figure 1.27 (a) 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 (see Fig. 1.27b). The *regulation* of the machine can be easily found from the equivalent circuit for different load conditions by using the regulation formula:

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

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

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

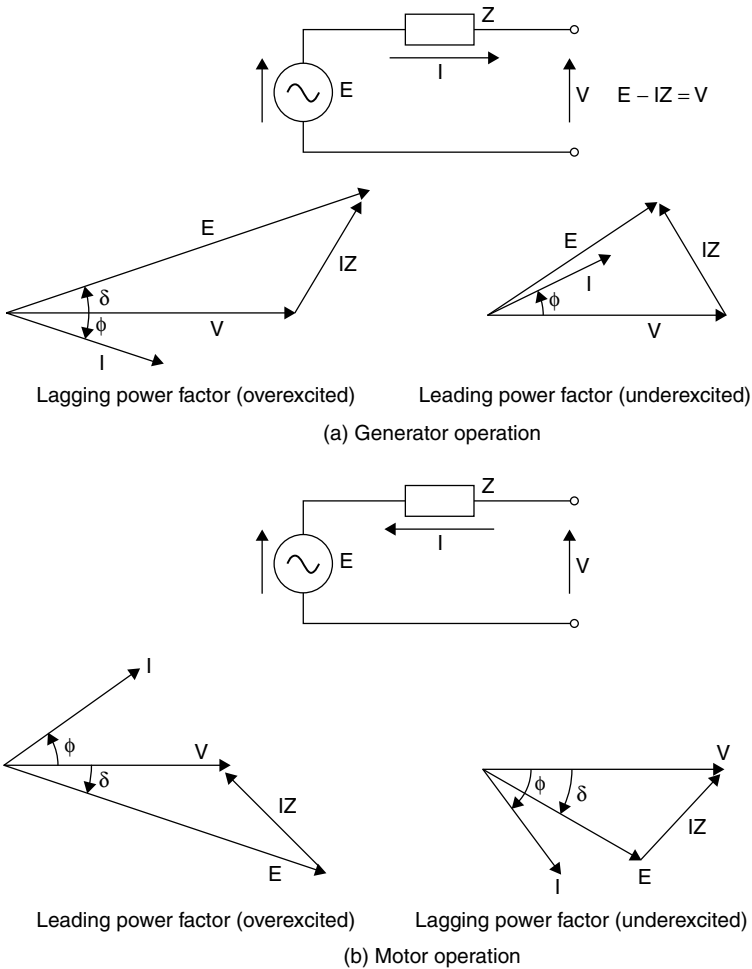


Fig. 1.27 Steady-state equivalent circuit and vector diagram.

load will affect the machine’s output in a number of ways. (See Chapter 4 for a discussion of this topic.)

1.7.5 Machine Losses

In Item 1.5.4 above the balance of energy in an electric machine was discussed. As part of the discussion reference was made to the fact that the current that flow through the machine’s conductors generate heating (a loss). However, there are a number of other sources within a working alternator that produced heat and, thus, losses. The following is a list of those sources of losses. In the following chapters these losses, their origin, control, and consequences to the machine’s design and operation will be covered in detail.

Machine Losses.*Winding Losses (Copper Losses).*

- I^2R stator loss
- I^2R rotor loss
- Eddy and circulating current loss in winding (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 component (bolts, frame, etc.)
- Friction and windage loss
- Losses in fans, rotor and stator cooling vents
- Losses in bearings

Exogenous Losses.

- Losses in auxiliary equipment
 - Excitation
 - Lubrication oil pumps
 - H₂ seal oil pumps
 - H₂ and water cooling pumps
 - And so on . . .
- Iso-phase or lead losses

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 classic textbooks readily available 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.
4. V. del Toro, *Electric Machines and Power Systems*. Prentice Hall, 1985.
5. M. Liwshitz-Garik and C. C. Whipple, *Electric Machinery*, Vols. 1–2. Van Nostrand.

6. A. E. Fitzgerald and C. Kingsley, *Electric Machinery*. McGraw-Hill, 1971.
7. For a text describing the practical issues related to operation and maintenance of both turbogenerators and hydrogenerators, see Isidor Kerszenbaum, *Inspection of Large Synchronous Machines*. IEEE-Press, 1996.