CHAPTER 1

PRINCIPLES OF OPERATION OF SYNCHRONOUS MACHINES

The synchronous generator 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 these three. What is common to all the members of this family is the basic physical process involved in their operation, which is the conversion of electromagnetic energy to mechanical energy, and vice versa. Therefore, to gain an understanding of the physical principles governing the operation of electric rotating machines, one has to understand some rudiments of electrical and mechanical engineering.

Chapter 1 is for those who are involved in operating, maintaining, and trouble-shooting electrical generators. Specifically, those who want to acquire a better understanding of the principles governing the machines' design and operation, but lack 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 salient pole hydro generators belong.

1.1 INTRODUCTION TO BASIC NOTIONS ON ELECTRIC POWER

1.1.1 Magnetism and Electromagnetism

Certain materials found in nature exhibit a characteristic 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 will repel each

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Glenn Mottershead, Stefano Bomben, Isidor Kerszenbaum, and Geoff Klempner.

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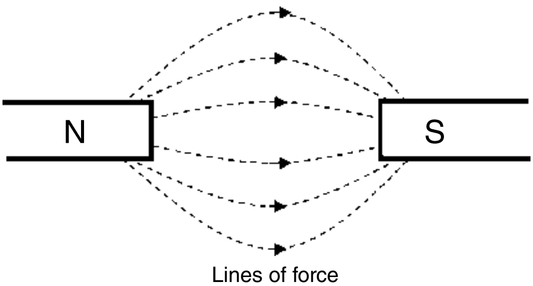


Figure 1.1-1 Representation of two magnetic poles of opposite polarity, with the magnetic field between them shown as “lines of force.”

other, as will two south poles. However, north and south poles will 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 1.1-1 and 1.1-2 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.” The magnetic field produced by the north and the south pole of a permanent magnet is directional from north to south as shown in Figure 1.1-3. 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 hydraulic (“hydro”) turbine-driven generators, which is the subject of this book. Hydro generators take advantage of the fact that magnetic fields can be created by the flow of electric currents in conductors, see Figure 1.1-4.

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

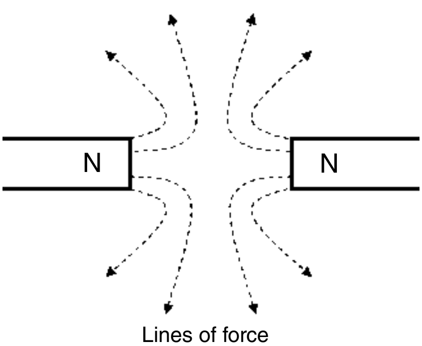


Figure 1.1-2 Representation of two north poles and the magnetic field between them. South poles will create similar field patterns, but the lines of force will point toward the poles.

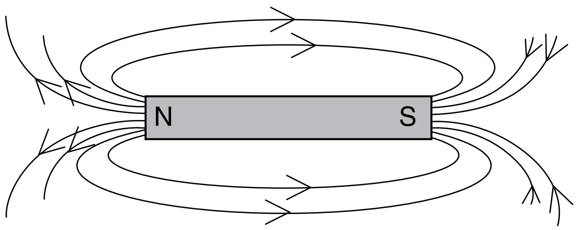


Figure 1.1-3 Representation of a "permanent magnet" showing the north and south poles and the magnetic field between them flowing from north to south outside the magnet.

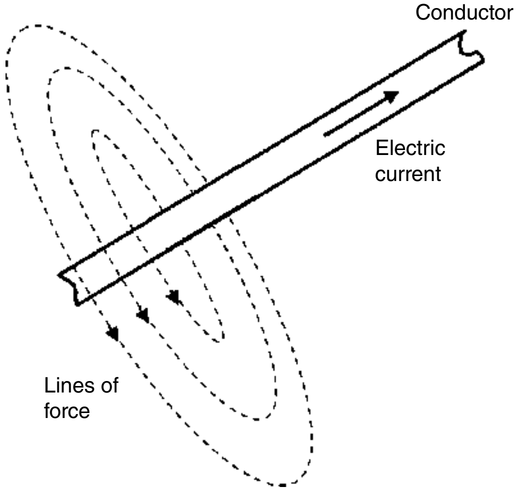


Figure 1.1-4 Representation of a magnetic field created by the flow of current in a conductor.

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 as shown in Figure 1.1-5.

The use of coils to amplify the magnetic field intensity requires them to be constructed in a very specific manner so that the resulting flux is produced in an effective way. When the coil is operating in air, the magnetic field direction, shape, and intensity depends 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* which 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 Figure 1.1-6). The

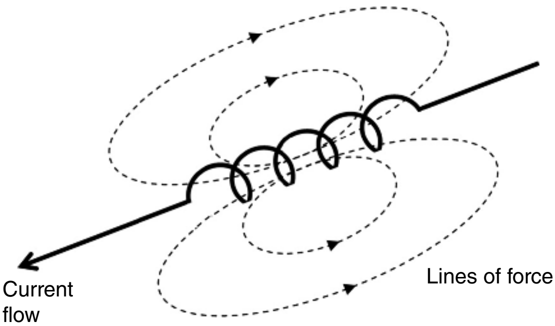


Figure 1.1-5 Representation of a magnetic field produced by the flow of electric current in a coil-shaped conductor.

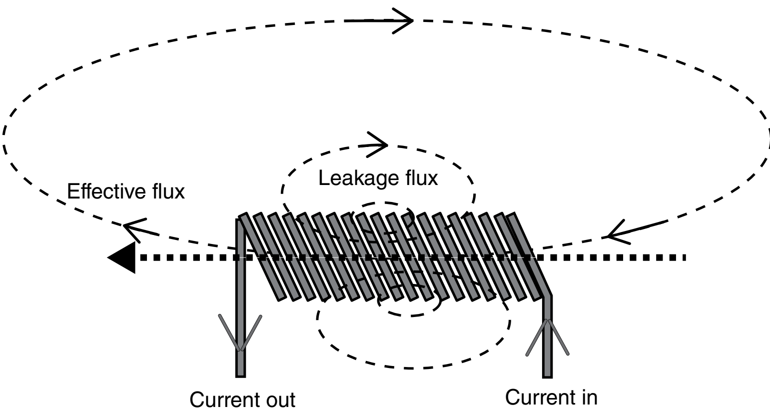


Figure 1.1-6 Representation of a magnetic field produced by the flow of electric current in a coil-shaped conductor operating in air, showing the effective and leakage flux components of the magnetic field produced.

principles illustrated here become very important later on as we discuss the magnetic field in the generator and stray losses.

To use the flux produced in a coil as effectively as possible, highly *permeable 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. It is structurally suitable, and cost-effective. 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 Figure 1.1-7). This is why stator cores and rotor poles of generators are made of steel, containing iron and a few small quantities of additional elements. The iron allows the principles discussed above to become a reality and is one of the reasons generators can be built to at least 97.5% efficiency.

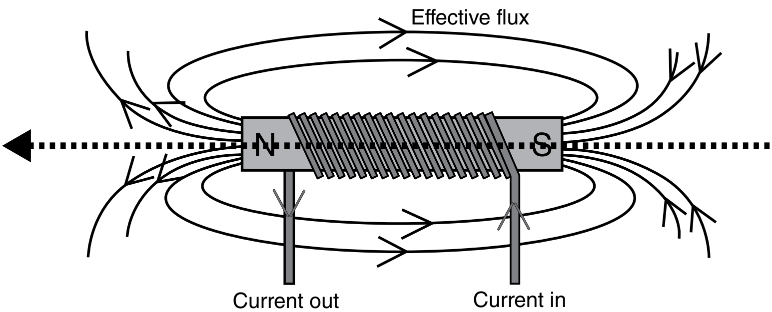


Figure 1.1-7 Representation of a magnetic field produced by the flow of electric current in a coil-shaped conductor with an "iron" core. The majority of the field produced is effective flux and the leakage field is reduced to a minimum.

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 hydro generators (see Figure 1.1-8).

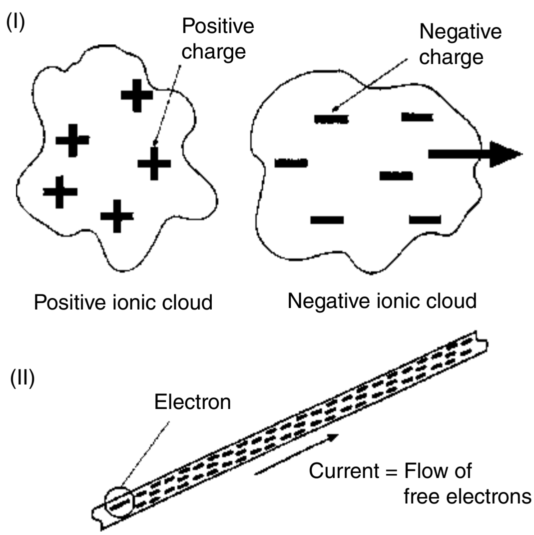


Figure 1.1-8 Electricity. (I) Ionic clouds of positive and negative currents. The positive clouds are normally atoms that lost one or more electrons; the negative clouds are normally free electrons. This effect can be found inside the generator as partial discharge in the stator winding. (II) The flow of electrons inside a conductor material, for example, the copper windings of the rotor and stator.

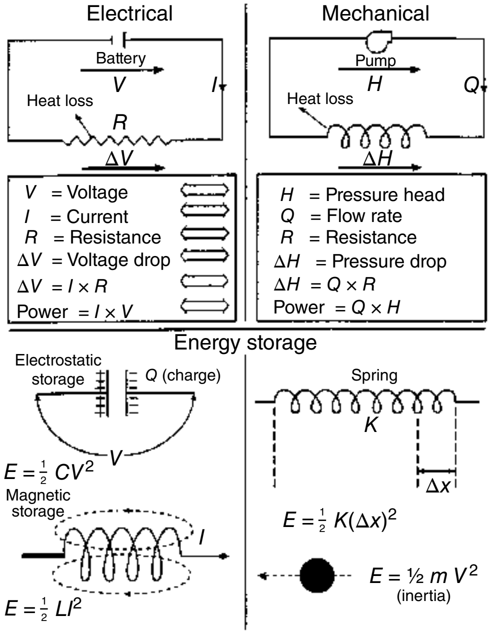


Figure 1.2-1 Electrical–mechanical equivalence.

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 1.2-1 describes the various forms of electrical–mechanical equivalence.

1.3 ALTERNATING CURRENT (AC)

Synchronous generators operate with both alternating-current (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 alternating circuit is a measure of 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 and sinusoidal signals, allow the currents and voltages to be represented by phasors.

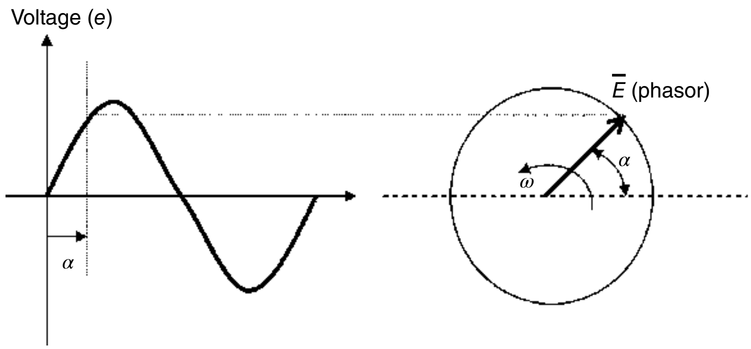


Figure 1.3-1 A phasor *E* that can represent the voltage impressed on a circuit.

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 1.3-1 depicts a phasor of magnitude *E*, and its corresponding sinusoidal trace representing the instantaneous value of the voltage quantity *e*. The magnitude *E* represents the maximum value of voltage (*e*).

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 sinusoid representing the instantaneous voltage (*e*) existing at any time. In Figure 1.3-1, $\alpha = \omega \times t$, where *t* is the time elapsed from its zero crossing.

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 combine into one representative parameter, impedance and are broken down into *resistive, capacitive,* and *inductive*. The angle between the voltage and the current in the circuit is called the *power factor angle* and is defined as φ. The cosine of the same angle is called the *power factor* of the circuit or, for short, the PF.

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 1.3-2 shows the various parameters encountered in a resistive circuit. This is a 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. 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

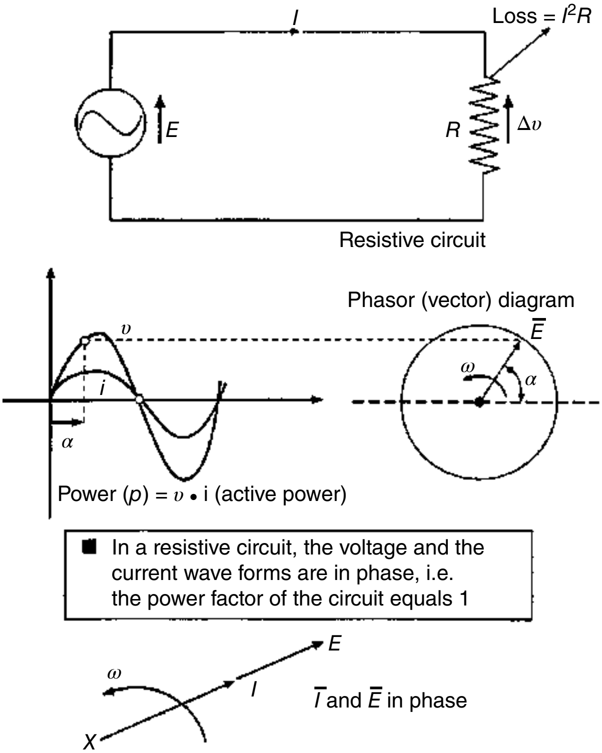


Figure 1.3-2 Alternating circuits (resistive).

in ohms, the resulting power dissipated as heat is given in watts. In electrical machines, this heat represents a loss of energy. One of the fundamental requirements in designing an electric machine is the efficient removal of the energy resulting from these resistive losses, with the purpose of limiting the 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 in relation to 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 Figure 1.3-3). 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:

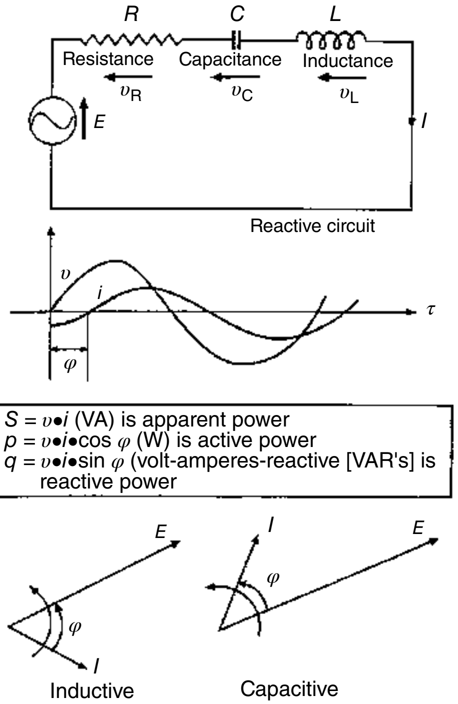


Figure 1.3-3 Alternating circuits (resistive-inductive-capacitive).

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

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

Q: The *reactive power* — $Q = E \times I \times \sin \varphi$, 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. 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.

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 Figure 1.3-4).

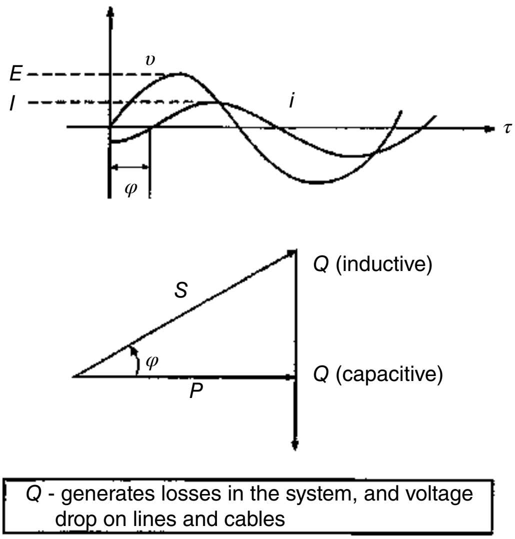
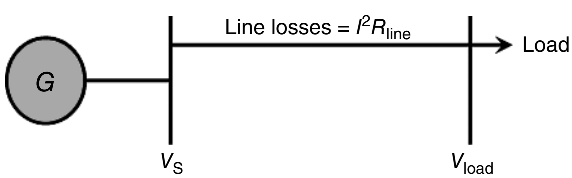


Figure 1.3-4 Definition of the "power triangle" in a reactive circuit.

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 Figure 1.3-5).

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. If we now consider an actual load for the simple system of Figure 1.3-5, 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



Simple power system showing a generator, bus, line, and load

V_{load} = 1 000 V

Line resistance (R) = 10 Ω (resistive)

Line reactance (X) = 10 Ω (inductive)

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

Figure 1.3-5 Schematic of a simple system in one-line form.

Case 1– Load = 100 kW (Unity power factor {i.e. cos φ =1})

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

$\Rightarrow I = 100\,000 \text{ W}/1\,000 \text{ V}/1.73/1 = 57.8 \text{ A}$

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

Voltage drop along the line = $I*Z = \sqrt{(I * R)^2 + (I * X)^2} = 817$ V

⇒The required delivery voltage at the source (V_s) is:

$V_s = \sqrt{(V_{load} + IR)^2 + (IX)^2}$

$V_s = \sqrt{(1000 + 578)^2 + (578)^2} = 1\,680$ V

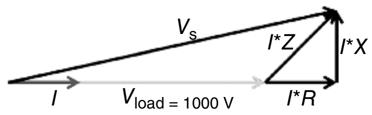


Figure 1.3-6 Case 1. The load is purely resistive in this example, and the system is operating at the "unity" power factor.

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

$\Rightarrow I = 111\,803 \text{ VA}/1\,000 \text{ V}/1.73 = 64.55 \text{ A}$

Losses in the line ($I^2 R_{line}$) = 64.55^2 A * 10 Ω = 41.6 kW

Voltage drop along the line = $I*Z = \sqrt{(I * R)^2 + (I * X)^2} = 913$ V

⇒ The required delivery voltage at the source (V_s) is:

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

$V_s = \sqrt{(1\,000 + 645.5\,(\sin\varphi + \cos\varphi))^2 + [645.5(\cos\varphi - \sin\varphi)]^2} = 1\,892$ V

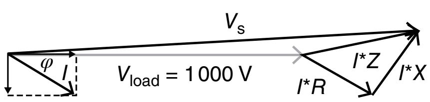


Figure 1.3-7 Case 2. The load is resistive and inductive in this example, and the system is operating in the "lagging" power factor range.

a reactive component include (see Figures 1.3-6 and 1.3-7). 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 synchronous generator operation and affects generator design in a significant way, as will be discussed later on 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 Table 1.3-1).

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.

TABLE 1.3-1 A comparison of Case 1 and Case 2

Load	100 kW	100 kW and 50 kVAR
Power consumed by the load (kW)	100	100
Current (A)	57.8	64.6
Line losses (kW)	33.4	41.6
Voltage drop along line (V)	817	913
Required delivery voltage at generating end (V)	1680	1892

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_s is constant, plus or minus 5% by design. As the load increases or decreases, the current from the generator changes significantly and the voltage drop on the system V_{load} requires compensation (Figure 1.3-8). Therefore, the second major function of the generator, after production of “real” power, is to produce “reactive” power to help control the voltage on the grid, which will also be discussed later in Chapter 4.

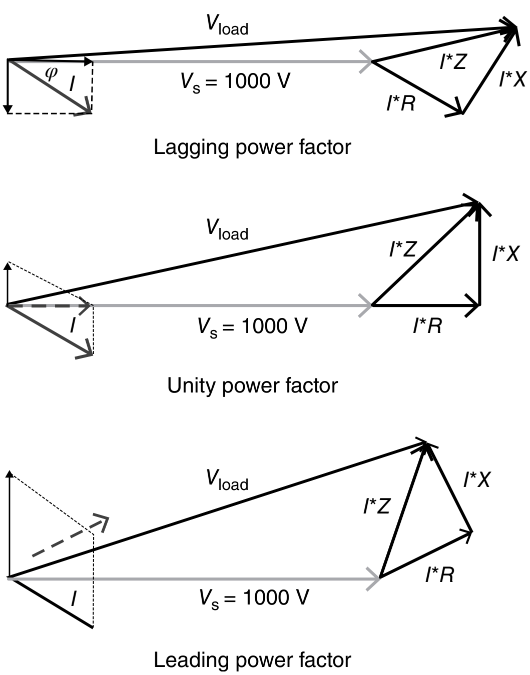


Figure 1.3-8 The effect on the voltage drop as the circuit goes from lagging through unity to leading power factor operation.

1.4 THREE-PHASE CIRCUITS

The two-wire AC circuits discussed above (called *single-phase* circuits or systems), are commonly used in residential, commercial, low voltage, and 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 that all three-phase voltages are equal in magnitude and apart by 120 electrical degrees. In those rare 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 "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 1.4-1 shows the main elements of a three-phase circuit. Three-phase circuits can have their sources and/or loads connected in *wye (also known as "star")* or in *delta* forms. (See Figure 1.4-2 for a wye-connected source feeding a delta-connected load.)

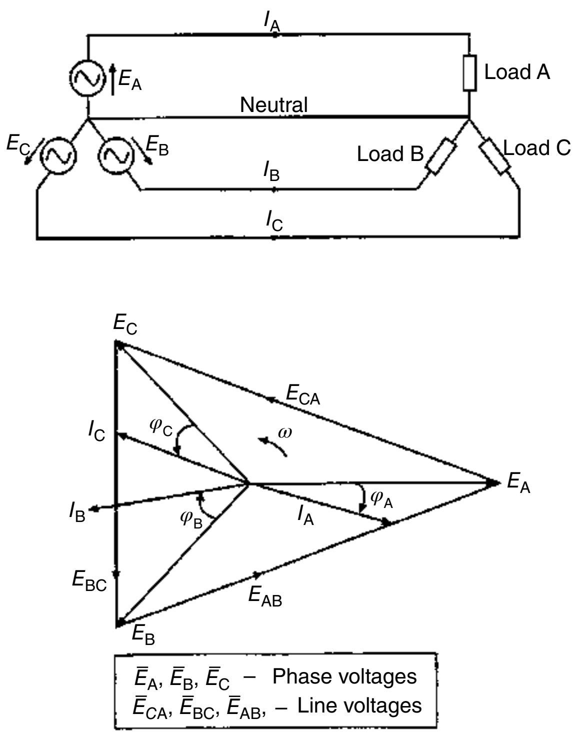


Figure 1.4-1 Three-phase systems. Schematic depiction of a three-phase circuit and the vector (phasor) diagram representing the currents, voltages, and angles between them.

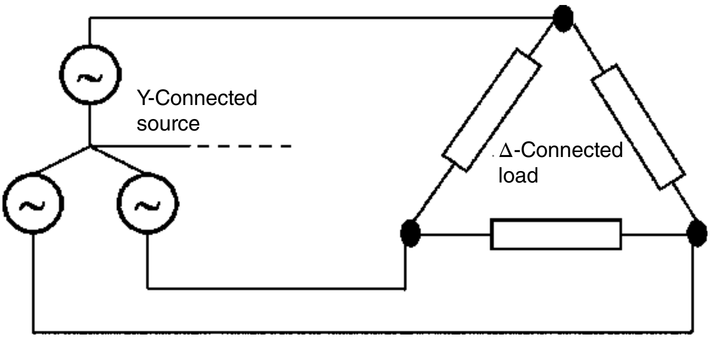


Figure 1.4-2 A “wye-connected” source feeding a “delta-connected” load.

Almost without exception, hydro 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 hydro 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 bricks on which the operation of an electrical machine is based.

1.5.1 Faraday's Law of Electromagnetic Induction

This basic law of Electromagnetic Induction, derived by 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* of the magnetic field is the critical determinant of the resulting voltage potential. Figure 1.5-1 illustrates both cases of

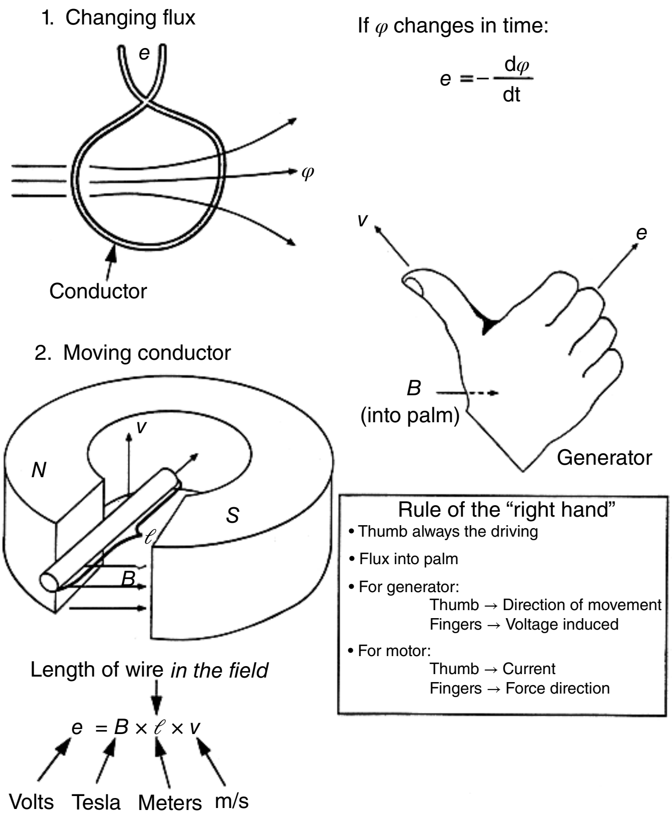


Figure 1.5-1 Both forms of Faraday's basic law of electromagnetic induction. A simple rule (the "right-hand" rule) is used to determine the direction of the induced voltage in a conductor moving across a magnetic field at a given velocity.

electromagnetic induction and also provides the basic relationship between the changing flux and the voltage induced in the loop. The first case shows the relationship between the induced voltage in a wire moving across a constant field. The second case 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

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.

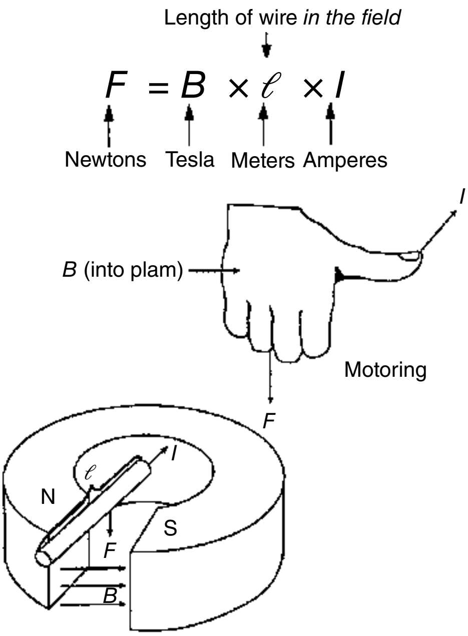


Figure 1.5-2 The Ampere–Biot–Savart law of electromagnetic-induced forces as it applies to electric rotating machines. Basic numerical relationships and a simple rule are used to determine the direction of the induced force.

Figure 1.5-2 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 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 the load in a generator is increased (i.e. more current flows in its windings, cutting the magnetic field in the gap between rotor and stator), more force is required from the

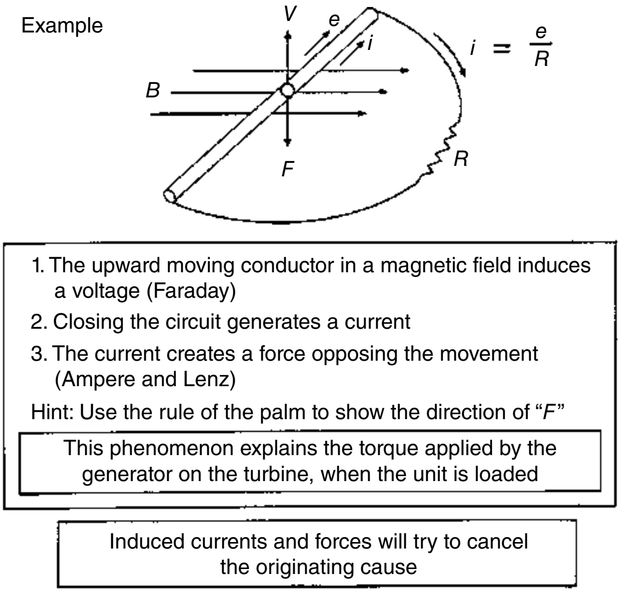


Figure 1.5-3 Lenz's law as it applies to electric rotating machines. Basic numerical relationships and a simple rule are used to determine the direction of the induced forces and currents.

turbine to counteract the increase in 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 1.5-3 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 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

"Principle of energy conversion" in electromechanical systems:

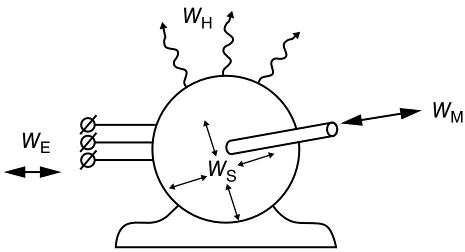
W_E + W_M + W_S + W_H = 0

Input/Output of electric energy + Input/Output of mechanical energy + Change in stored energy + Heat dissipated = 0

Change in stored energy:

Electrical = $\frac{1}{2} I^2 L + \frac{1}{2} V^2 C$

Mechanical = rotational energy



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 "+" means input to the machine
"–" means output from the machine

W_S with a "+" means increase of stored energy
"–" means decrease of stored energy

Figure 1.5-4 Principle of energy conversion as applicable to electric rotating machines.

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, as well as its critical performance and construction parameters. Figure 1.5-4 depicts the principle of energy conversion as applicable to electric rotating machines.

1.6 THE SYNCHRONOUS MACHINE

The rudiments of electromagnetism have been presented along with the four basic laws of physics describing the physical processes existing in any electrical machine. Therefore, it is the right time to introduce the basic synchronous machine, which, is the type of electric machine used for all large hydro turbine driven generators.

1.6.1 Background

The birth of commercial alternating current (AC) hydro generation dates back to June 1891 with the delivery of AC power in Colorado USA from the Ames Hydro Power Station to the Gold King Mine 4.2 km away. The generator for the power plant and the motor for the mill were identical Westinghouse synchronous single-phase machines rated 73.5 kW, 3,000 volts, 133 Hz. Later in 1891 an Oerlikon synchronous 3-phase hydro generator at 180 kW, 55 volts, 40 Hz, with transformer extended power transmission 160 km from Lauffen to Frankfurt Germany during an international electrical exhibition in Frankfurt, see Figure 1.6-1. These pioneering concepts happened more than 125 years before the writing of this book and the basic principles of the hydro electrical power system are the same today.

These very early power generation experiments were instrumental in the adoption by New York's Niagara Falls Power Company to use this technology at their Niagara Falls Adams Hydro Station. This pioneering power plant started a rapid and continuing increase of unit ratings at these falls by operating their first of ten Westinghouse 3,677 kW, 2,000 volt, 25 Hz hydro generators in August of 1895. For all practical purposes, the great DC (Edison) versus AC (Westinghouse) duel was over. It is interesting to note that although tremendous development in generator structural, magnetic and insulating materials, and manufacturing methods has occurred over the years, the basic design elements of these electric machines have remained practically unchanged. The very earliest concept was that a synchronous generator is used to drive a synchronous motor but Tesla's induction motor quickly replaced the synchronous motor for the vast majority of electric

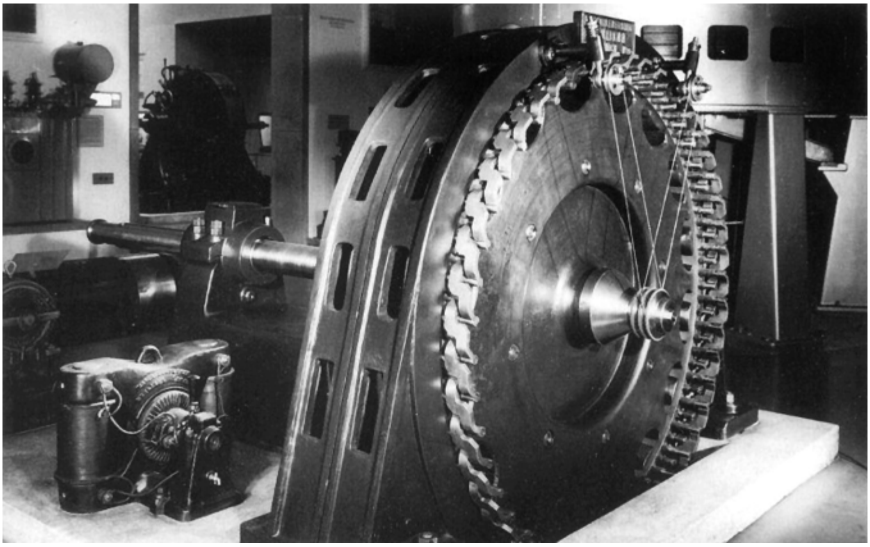


Figure 1.6-1 The hydroelectric generator from Lauffen, now in the Deutches Museum, Munich. *Source:* Reprinted with permission from Neidhofer [3].

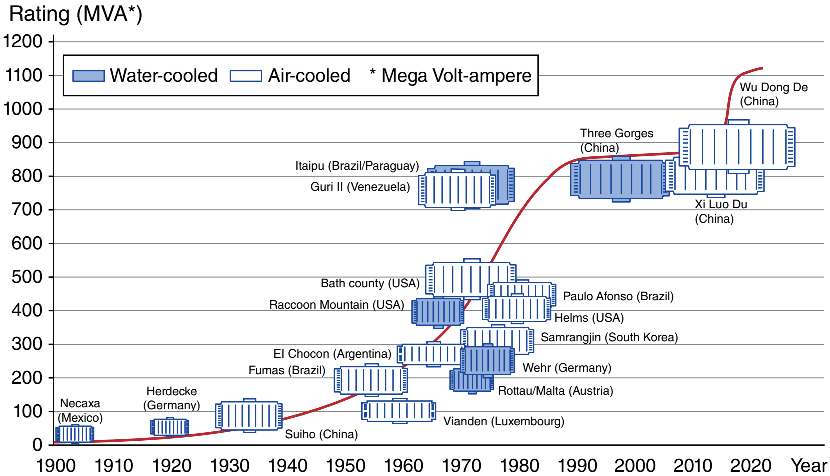


Figure 1.6-2 "Growth" graph, depicting the overall increase in size over the last century, of hydro generators. *Source:* Courtesy of Voith.

motor applications. However the synchronous generator remained the universal machine of choice for the large-scale generation of hydroelectric power.

The world today is divided almost exclusively between utility systems generating their power at either 50 Hz or 60 Hz and these synchronous generators have continuously grown in size over the years. Today, it is now possible to see these hydro machines with terminal voltages over 20,000 volts and ratings over 900 MVA as shown in Figure 1.6-2.

1.6.2 Principles of Construction

Synchronous machines come in all sizes and shapes, from the miniature permanent magnet synchronous motor in wall clocks, to the largest hydro generators of up to about 944.5 MVA. Synchronous machines are one of two types: stationary field or 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 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 sliprings and brushes (external excitation) or from a diode bridge mounted on the rotor. The rectifier bridge is fed from a shaft-mounted synchronous generator, which is itself excited by the pilot exciter. In externally supplied fields, the source can be a shaft-driven DC generator, a separately excited DC generator, or a solid-state rectifier. Several variations or combinations of these variations are used.

The stator core is made of insulated silicon-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. The core is slotted (the slots are normally open), and the coils making up the winding are placed in the slots. The most popular arrangements are lap and wave windings of various types. Modern large machines typically are wound with double-layer lap windings.

A rotor field of salient pole construction is as shown in Figure 1.6-3.

In a large generator, the rotor magnetic field is generated by a coil wrapped around it with current passing through the coil. For simplicity, this figure shows a

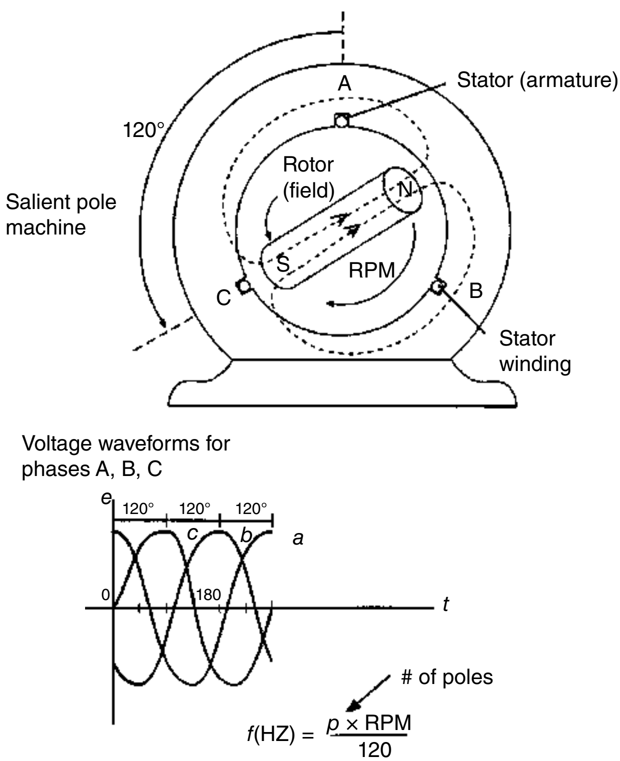


Figure 1.6-3 Synchronous machine construction.

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 this 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.

This figure includes all synchronous hydro generators, almost every synchronous condenser, and the overwhelming majority of synchronous motors.

Large salient pole rotors are typically made of laminated poles retaining the winding under the pole head. The poles are keyed or bolted onto the shaft (spider-and-wheel structure). The majority of salient pole machines have an additional winding on the rotating member. This winding, made mostly of copper bars short-circuited at both ends, is embedded in the head of the pole, close to the face of the pole at its airgap. In synchronous generators this winding serves to dampen the oscillations of the rotor around synchronous speed and is, therefore, named the *damping or damper winding* (also known as *amortisseur*). In synchronous motor applications, this winding can be used to start the motor or condenser as an induction motor, and take it to almost synchronous speed, when the rotor is "pulled in" by the synchronous torque.

1.6.3 Rotor Windings

In hydro generators, the winding producing the magnetic field is made of a number of coils connected in a series circuit, energized with DC power typically supplied through the shaft from slip or collector rings on the shaft. In *self-excited* generators, the shaft-mounted exciter and rectifier (diodes/commutators) generate the required field current. The shaft mounted exciter is itself excited from a stationary winding. Alternately, static excitation eliminates the need for shaft driven exciters. This method is commonly applied to modern generators or as an upgrade for older machines where maintenance and performance are issues. Generators typically have field supplies of 125 or 250 V DC, and in some machines even higher depending on the design. A 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 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

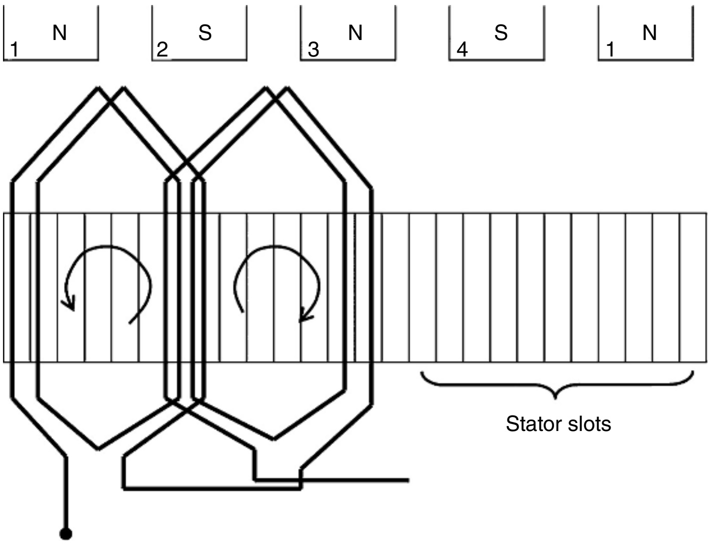


Figure 1.6-4 “Developed” view showing four-poles, slots, and a section of the winding.

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 1.6-4, for salient pole machines. The section shown is a portion 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 number of pole groups in a parallel. A similar pattern is followed by the other two phases, but located at 120 electrical degrees apart. 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 as shown in Figure 1.6-5.

1.7 SYNCHRONOUS MACHINE: BASIC OPERATION

For a more in depth discussion of the operation and control of hydro 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, hydro generators are almost always 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.

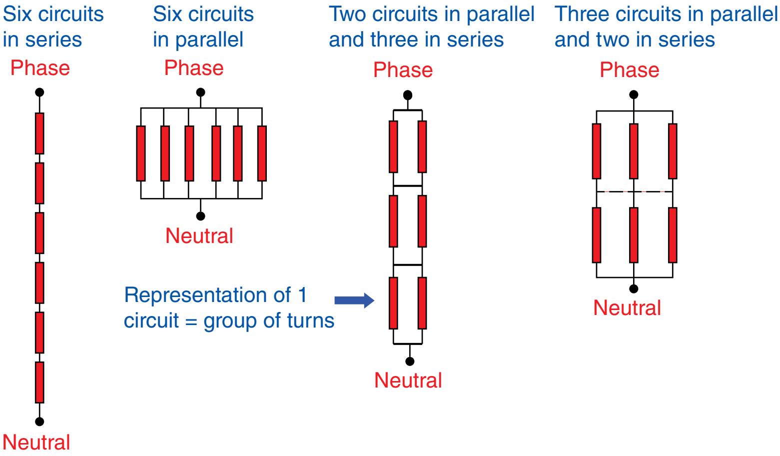


Figure 1.6-5 Typical winding configurations. *Source:* Courtesy of Voith.

It was also shown that by coiling the conductor, a larger field is obtained for the same current 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.

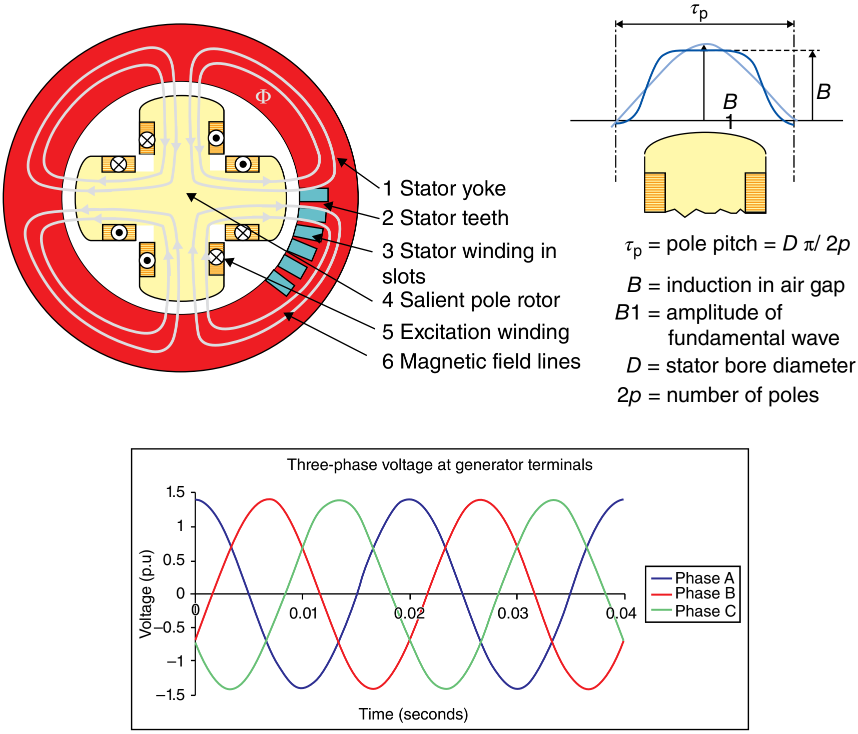
Now, a new element can be brought into the picture. By a simple mathematical analysis, it can be shown that three balanced currents (of equal magnitudes and 120 electrical degrees apart) flow in a balanced three-phase winding when a magnetic field of constant magnitude is produced in the airgap of the machine.

This magnetic field revolves around the machine at a frequency equal to the frequency of the currents flowing through the winding (see Figure 1.7-1). As shown, 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 four pole winding, however, similar result applies for any number of pairs of poles.

The importance of a three-phase system creating a constant field cannot be stressed enough. The constant magnitude flux allows power, megawatts, to be transformed inside an electric machine from electrical to mechanical power, and vice versa. It is important to remember that a constant-magnitude flux produces a constant-magnitude torque.

1.7.1 Magnetic Representation

To describe the fundamental principles describing the operation of a synchronous machine, it is convenient to use the constructs of an *ideal* salient pole rotor machine connected to an *infinite* bus. The infinite bus represents a bus which can deliver or absorb active and reactive power without any limitations and whose voltage and frequency are essentially constant. The ideal machine has zero resistance and leakage reactance, infinite permeability, and no saturation, as well as zero reluctance torque.



- Three-phase system: voltage or current waves 120°
    - Phase A voltage: $U = U_{max} \cdot \cos(w.t)$
    - Phase B voltage: $U = U_{max} \cdot \cos(w.t - 120°)$
    - Phase C voltage: $U = U_{max} \cdot \cos(w.t + 120°)$

Figure 1.7-1 Production of stator rotating field. *Source:* Courtesy of Voith.

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_f. The resultant magnetic field is

$$\boldsymbol{\Phi}_r = \boldsymbol{\Phi}_f + \boldsymbol{\Phi}_s$$

The flux, Φ_r, is established in the airgap 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 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, the angle (ψ) is called the internal power factor angle, and (β) is

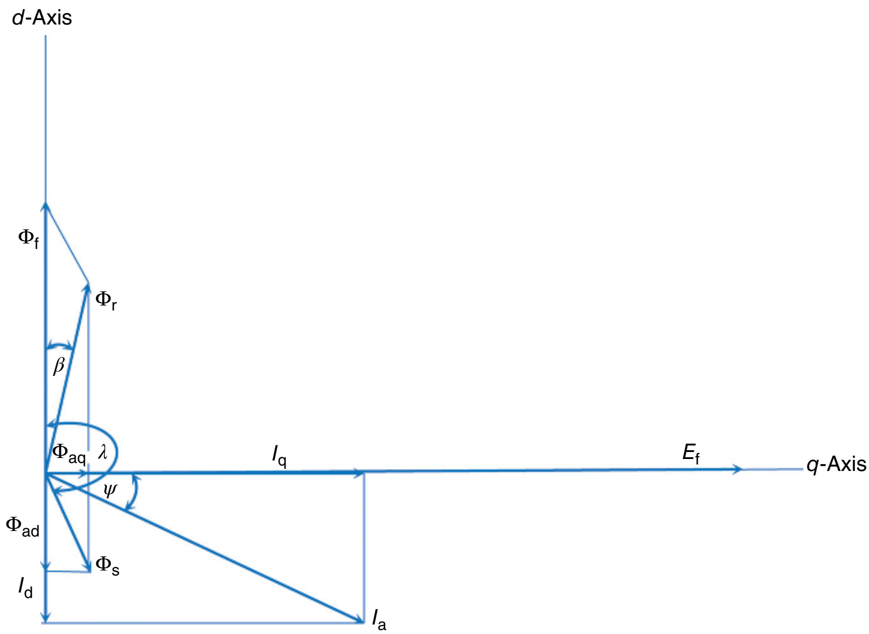


Figure 1.7-2 Phasor diagram of an unsaturated salient pole generator (lagging pf).

the space angle between the fundamentals of the $\mathbf{\Phi_f}$ and $\mathbf{\Phi_r}$ waves (see Figure 1.7-2) [1].

Due to saliency, the reactance measured at the terminals of the generator is a function of rotor positon and thus the two reactance theory can be applied [1]. The armature current $\mathbf{I_a}$ can be resolved into two components, namely, $\mathbf{I_d}$ and $\mathbf{I_q}$ representing direct and quadrature axis currents. $\mathbf{I_d}$ is in time quadrature with the internal excitation voltage $\mathbf{E_f}$, where $\mathbf{I_q}$ is in time phase with $\mathbf{E_f}$. The direct axis component of the armature $\mathbf{I_d}$ produces an armature reaction flux $\mathbf{\Phi_{ad}}$ along the axis of the field poles. $\mathbf{I_q}$ however produces an armature reaction flux $\mathbf{\Phi_{aq}}$ in space quadrature with the field poles. The magnetic effect of $\mathbf{\Phi_{ad}}$ is centered on the axis of the field pole where the magnetic effect of $\mathbf{\Phi_{aq}}$ is centered on the inter polar axis. The armature reaction flux $\mathbf{\Phi_s}$ is the space phasor sum of the components $\mathbf{\Phi_{ad}}$ and $\mathbf{\Phi_{aq}}$. It follows that the resultant flux $\mathbf{\Phi_r}$ is a result of the space phasor sum of the main field flux $\mathbf{\Phi_f}$ and armature reaction flux $\mathbf{\Phi_s}$.

1.7.2 Generator Mode: Steady State Using Vectors

This section describes various practical use diagrams of a salient pole machine that is operating under steady-state conditions [2].

Most generators in operation are in the mode of supplying real power and either supplying or absorbing reactive power. A machine is said to have a lagging power factor when supplying reactive power and a machine is said to have a

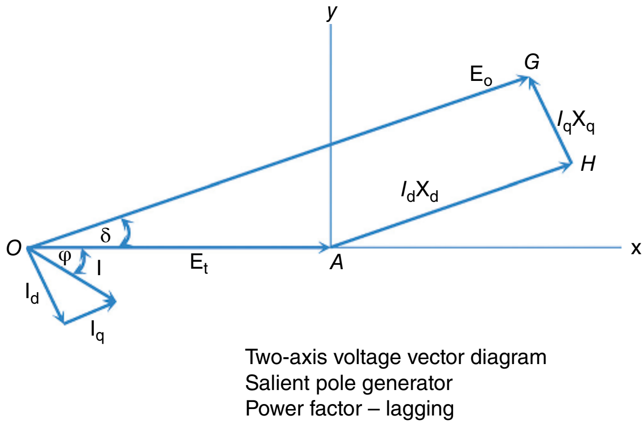


Figure 1.7-3 Vector diagram of generator with a lagging power factor.

leading power factor when absorbing reactive power. It is also common to have the machine supply just real power and the machine is said to be at unity power factor. Figure 1.7-3 shows a diagram of a generator suppling power to the system with a lagging power factor and Figure 1.7-4 shows a diagram of the same generator with a leading power factor. When looking at these diagrams a few assumptions need to be kept in mind. First, the machine is in steady-state operation, second, the machine is connected to an "infinite bus," and lastly, magnetic saturation is neglected. The following explanation does not discuss how to develop these curves in detail and is left to the reader by referencing [2].

Referring to Figure 1.7-3, the line *OA* represents the terminal voltage $\mathbf{E_t}$, *OG* represents the internal generated voltage $\mathbf{E_o}$, and **I** is the armature current lagging behind the terminal voltage by the angle φ which is the power factor angle. The armature current **I** can be represented by the direct and quadrature currents $\mathbf{I_d}$

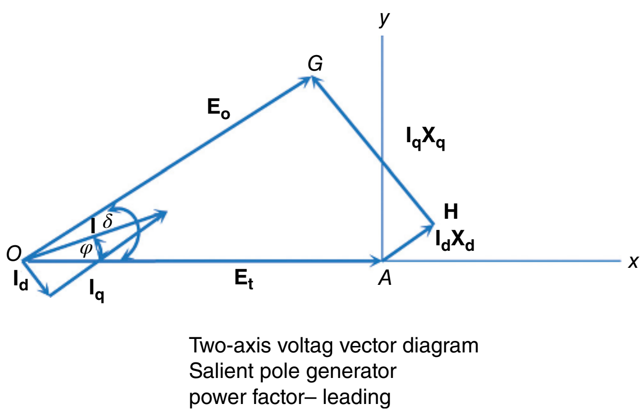


Figure 1.7-4 Vector diagram of generator with a leading power factor.

and $\mathbf{I_q}$, respectively. The vectors $\mathbf{I_d X_d}$ (parallel to $\mathbf{E_o}$) and represented by *AH* and $\mathbf{I_q X_q}$ (perpendicular to $\mathbf{E_o}$) and represented by *HG* are also mutually perpendicular. The angle (δ) is the torque or power angle. The diagram demonstrates the internal generated voltage is higher than the terminal voltage during lagging power factor operation. This makes sense as the generator must push out the reactive power and requires the higher internal potential voltage of $\mathbf{E_o}$ in order to accomplish this.

Referring to Figure 1.7-4, there are some key differences worth noting while operating at a leading power factor. The armature current **I** is now leading the terminal voltage $\mathbf{E_t}$ by the angle φ. The quadrature axis components $\mathbf{I_q}$ and $\mathbf{I_q X_q}$ are now larger in magnitude than when the machine was lagging. The takeaway from this diagram is that the terminal voltage is higher than the internal generated voltage. This also makes sense as the generator is now absorbing reactive power so the terminal voltage must be higher to push the power back into the machine.

It is important to recognize that as soon as the internal generated voltage is higher or lower than the terminal voltage, even by the smallest amount, reactive power will be supplied or absorbed by the machine accordingly.

1.7.3 System Support: Reactive Power

For all intents and purposes, during reactive power support operation, there is no water flowing through the turbine, thus no MW are being supplied to the system. However, by adjusting the excitation higher (over excitation), the machine can deliver reactive power and by decreasing the excitation (under excited), the machine can absorb reactive power. This mode of operation for a conventional generator (that normally supplies MW as well) is only during times where there may be an abnormal system condition and the generator will need to provide this reactive support or there is system emergency and extreme reactive support is required.

On one end of extreme operation, there is almost no current supplied to the DC field winding of the rotor and large amounts of reactive power (MVARS) are being absorbed by the generator. The capability curve, which is discussed later in the book, will have limits set as to how many MVARS the generator may absorb on a continuous basis without damaging effects. This mode of operation is not far from operating with a loss of excitation. Protections are put in place to prevent migration into this potentially damaging area of operation. Depending on the design of the generator and excitation system, rotating or static, the minimum excitation value can approach 10 A or less before the excitation system bottoms out and/or protections operate.

On the other end of extreme operation, the generator will need to supply large amounts of reactive power (MVARS) to the system, again, for abnormal system events or emergencies. Again, the capability curve from the manufacturer will outline what the maximum capability is and over excitation limits can be put in place to protect the generator from damaging effects from rotor overheating.

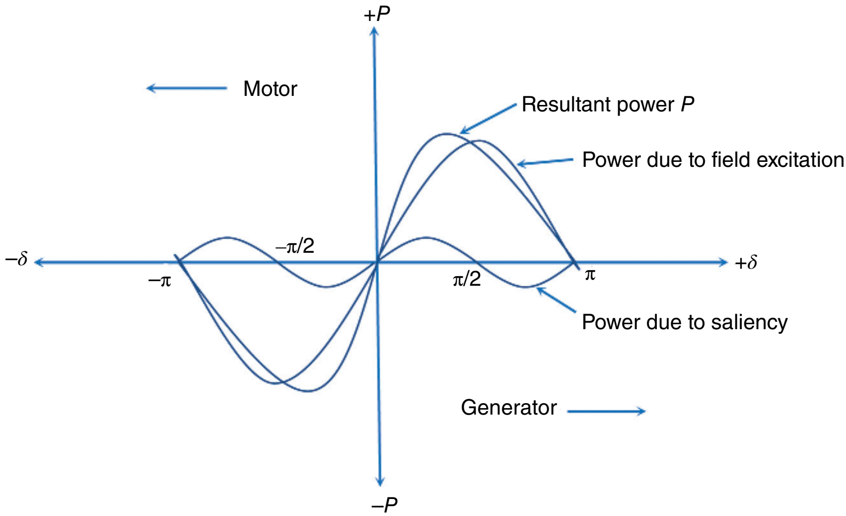


Figure 1.7-5 Steady-state power angle characteristic of a salient pole synchronous machine (with negligible armature resistance).

It is now appropriate to expand on the effects of “saliency” on generator operation. Power developed in a salient pole machine can be written as Equation (1.1) [1]:

$$P = (E_t E_o / X_d) \sin \delta + \frac{1}{2} E_t^2 \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\delta \tag{1.1}$$

The term on the left-hand side of the “+” sign is the power developed due to the field excitation. The term on the right-hand side of the “+” sign is the power developed due to saliency. A graphic representation of the resultant power is shown in Figure 1.7-5 [1].

Even if no current is supplied to the DC field winding, there is a torque generated known as reluctance torque, due to the saliency effect. It is this torque which keeps the rotor in synchronism with the system, and prevents the machine from slipping poles.

1.7.4 Motor Operation

The electric machine can be specifically designed to operate as a pump motor so it performs useful physical work. In this particular arrangement, the motor pumps water through the penstock for irrigation or as storage when power is abundant to be used later to generate when power is in short supply. Synchronous pump motors are designed to operate at a fixed speed without any slip between the armature frequency and the fields rotating frequency. To bring the motor to synchronous speed, it must be accelerated by a method consistent with its design. A separate induction starting motor dedicated to accelerating the synchronous rotor is a common starting method. Other methods incorporating variable frequency sources or across-the-line inductive starting by the rotor damper windings are also used. In the situation, where across-the-line starting is used, the damper windings will get very hot quickly and the machine must be synchronized within the recommended time by the manufacturer. Failed synchronization attempts must allow for cooling of the damper circuit before an attempt to start the machine is made again. This cooling off period will also be specified by the manufacturer. Failure to follow these set procedures can result in overheated and even melted damper assemblies which in turn will affect starting performance and may require repair depending on the severity. If a known excursion from these procedures has occurred, it is highly recommended that a visual inspection of the damper assembly by a knowledgeable person be performed.

1.7.5 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 1.4-1 or Figure 1.4-2 can be represented as shown in Figure 1.7-5. Hereinafter, when describing a three-phase generator by an electrical diagram, the one-line method will be used.

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 1.7-6 is conducive to obtaining the basic performance characteristics of the machine under steady-state conditions.

In Figure 1.7-7, the reactance X_a, represents the magnetizing or demagnetizing effect of the stator windings on the rotor. It is also called the *magnetizing reactance or armature reaction reactance*. R_a represents the effective resistance of the stator. The reactance X_l represents the stator leakage reactance. The sum of X_a and X_l 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. The internal generated voltage is represented by E_o, the airgap voltage by E_r, and finally the terminal voltage of the machine by E_t. It is important to remember that the

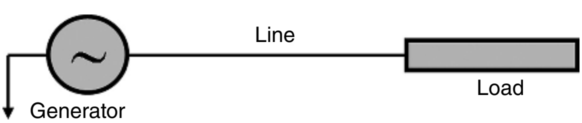


Figure 1.7-6 One-line representation of the circuit shown in Figures 1.4-1 and 1.4-2.

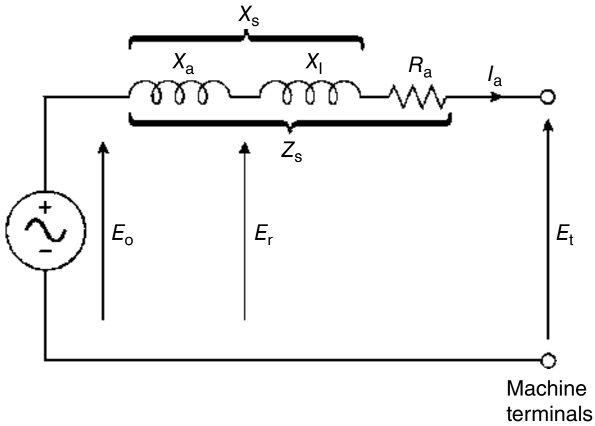


Figure 1.7-7 Steady-state equivalent circuit of a synchronous machine.

equivalent circuit described in Figure 1.7-7 represents the machine only under steady-state conditions.

The simple equivalent circuits of Figure 1.7-8 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 power angle. The *regulation* of the machine can be easily found from the equivalent circuit for different load conditions by using the regulation formula:

$$\text{Percent regulation} = 100(V_{\text{no load}} - V_{\text{load}})/V_{\text{load}}$$

For a detailed review of the performance characteristics of the synchronous machine, in particular the hydro generator, 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 load will affect the machine's output in a number of ways. (See Chapter 4 for a discussion of this topic.)

1.7.6 Machine Losses [4]

Current flows through the machines conductors generating heat (a loss). However, there are a number of other sources within a working synchronous generator that produce heat and, thus, losses. The following is a list of some of those sources of losses:

- I^2R losses of stator winding
- I^2R losses of rotor winding
- Core loss
- Stray load loss
- Excitation system loss

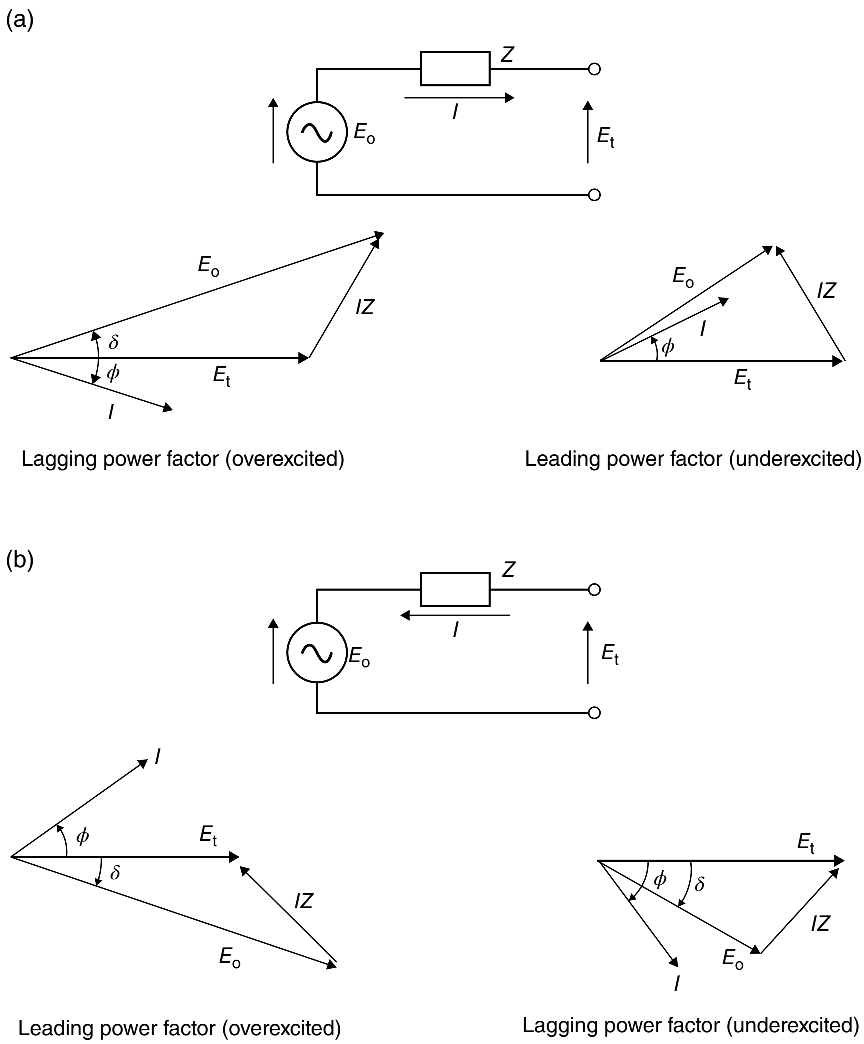


Figure 1.7-8 Steady-state equivalent circuit and vector diagram. (a) Generator operation and (b) motor operation.

- Windage and Friction loss
- Ventilation and cooling loss

In determining I^2R losses, the resistance of windings should be corrected to the reference temperature. During the commissioning tests for a generator, the OEM may use a common reference temperature of 75 °C. When calculating the actual losses at a specific temperature, then the resistance at 75 °C must be converted to the resistance at the desired temperature.

1.7.6.1 Stator Winding I^2R Loss

The stator winding I^2R loss is the sum of the I^2R losses in all of the stator winding current paths. The I^2R loss in each current path shall be the product of its resistance in ohms as measured with direct current and the square of its current in amperes.

1.7.6.2 Rotor I^2R Loss

The rotor winding I^2R loss shall be the product of the measured resistance in ohms of the rotor winding and the square of rotor current in amperes.

1.7.6.3 Core Loss

The core loss shall be taken as the difference in power required to drive the machine at normal speed when separately excited to produce a voltage at the terminals corresponding to the rated voltage at open circuit, and the power required to drive the unexcited machine at the same speed.

1.7.6.4 Stray Load Loss

The stray load loss is determined by subtracting the stator winding I^2R loss at a specific value of stator current from the short circuit loss at the same value of stator current. The short circuit loss shall be taken as the difference in power required to drive the machine at normal speed, when separately excited to circulate current in the stator winding with its terminals shorted, and the power required to drive the unexcited machine at the same speed. The stator winding I^2R loss shall be calculated for the temperature of the winding during the short circuit test.

1.7.6.5 Excitation System Losses

These losses are the total of electrical and mechanical losses in the equipment supplying excitation. They shall include the exciter, voltage regulator, and associated devices comprising the excitation system of the synchronous machine. Where common equipment is provided in the excitation system for two or more machines, the common equipment loss shall not be included in the evaluation of the synchronous machine efficiency. Motor loss shall be included if a unit motor-generator exciter set is used; if a unit rectifier is used, the rectifier and rectifier transformer losses shall be included. Include collector electrical brush contact voltage drop loss if applicable.

1.7.6.6 Friction and Windage Loss

The friction and windage loss, including brush mechanical friction, is the power required to drive the unexcited machine at rated speed with the brushes in contact, deducting that portion of the loss which results from

- **a.** forcing the air through any part of the ventilating system that is external to the machine and cooler (if used);
- **b.** the driving of direct-connected flywheels or other direct-connected apparatus.
- **c.** In the case of machines furnished with a complete set of bearings, only that portion of the friction and windage loss produced by the bearing load due to

the generator or generator/motor itself shall be included. In the case of machines not furnished with a complete set of bearings, only that portion of the friction and windage loss associated with the equipment supplied with the generator or generator/motor shall be included. Where losses are apportioned between equipment or between manufacturers, the method of allocation of the losses shall be subject to agreement between the manufacturer and purchaser.

1.7.6.7 Ventilating and Cooling Loss

This loss includes any power required to circulate the cooling medium through the machine and cooler (if used) by fans or pumps that are driven by external means (such as a separate motor), so that their power requirements are not included in the friction and windage loss. The power consumption of a separate blower system used for a specific unit and necessary for continuous operation of the unit shall be included.

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

1.8 REFERENCES

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1.9 FURTHER READING

Say, M. G. (1978). *Alternating Current Machines*, Pitman Publishing.