FUNDAMENTALS OF ELECTRIC POWER GENERATION

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Contents

Summary

Electric power for distribution and sale is generated as alternating current with a frequency of either 50 Hz or 60 Hz depending upon the standard adopted by the particular region of the world. Alternating current can be conveniently transformed to high voltage for transmission and to low voltage for consumption. For a given power flow, a higher voltage means a lesser current and lower transmission losses. Most generating and transmission systems are three-phase.

This allows a greater power output from a given size of generator and a larger power flow in a given size of transmission line conductor than does single-phase. The three phases may be connected in star or delta formation at each end of the transmission line, that is, at the generator and transformer or one transformer and another. A star connection allows for a ground connection at the centre point of the star. One such point is necessary in every transmission leg to ensure that the lines operate at the proper voltage relative to earth.

Generation of electric power is by a rotating magnetic field within static windings. Hence the electrically energized rotor with its magnetic poles rotates inside the stator where the electric current is generated at high voltage. This is subsequently stepped up to an even higher voltage by a transformer before long distance transmission.

The transformer consists of an iron core and primary and secondary windings.The alternating current in the primary winding produces an oscillating magnetic field in the iron core which in turn induces an alternating current in the secondary winding. The ratio of turns of the respective windings determines the ratio of current and voltage change. The winding with the greater number of turns produces the higher voltage and lower current.

Switching stations allow connections to be made to different transmission lines. Provision is made for some duplication of equipment so that, in the event of a failure or when maintenance is required, certain components can be isolated and power still supplied via parallel circuits.

1. Electrical Power Theory

1.1 Electrical Energy

Electrical energy is extremely versatile particularly as there are no inherent losses governed by the laws of nature when converting it into mechanical energy. Similarly the conversion of mechanical energy into electrical energy can theoretically be done without suffering losses. Heat energy, which is subject to the laws of thermodynamics, suffers some inherent loss when converted into mechanical energy and does not have this versatility.

There are of course small losses in any electrical process due largely to electrical resistance in the components so conversion efficiencies are not quite 100 percent. Overall, in the conversion of energy in thermal power plants, there are heat losses in the conversion of chemical or nuclear energy to heat energy, thermodynamic cycle losses in the conversion of heat energy to mechanical energy and electrical losses in the conversion of mechanical energy to electrical energy.

In addition, there are fluid friction losses in the thermodynamic cycle and mechanical friction losses in the turbine-generator. As energy losses occur through the entire process from fuel to electricity, the value of the remaining energy, expressed as cost per unit of energy, increases. Hence the final product, electricity, has the highest value.

This is a factor that has to be considered when comparing the cost of electricity with other forms of energy.

Previous articles have explained the thermal and thermodynamic processes in thermal power plants. Some of these processes are quite complex and the equipment quite extensive. Once, however, mechanical energy has been produced by the turbine, the conversion to electrical energy is fairly simple with relatively small components. This is not to say that the technology is any less sophisticated.

Compared with the rate of energy transfer per unit volume in a fossil fuel fired boiler, for example, the rate of energy transfer in an electrical generator or transformer is extremely high. This leads to the requirements for sophisticated fast acting protective devices on all major electrical components.

This article concentrates on electrical energy as the final product of thermal power plants and deals primarily with its generation and transmission. Key components covered are therefore the electrical generator itself and the electrical transformers required to increase the voltage to a level suitable for economic transmission to distant consumers.

Although all thermal power plants make extensive use of electrical distribution and control systems and use electrical motors for driving nearly all pumps and fans and other mechanical devices, these are not considered in this article. Generally between 5 percent and 7 percent of electrical power produced in a power plant is consumed in the plant to support pumping loads and to maintain all systems operational.

An equivalent amount of power may be lost in the transmission system depending upon its extent and configuration so somewhat less power than is sent out from the power plant is actually sold to the consumer.

Electrical losses lead directly to a loss in revenue so there is a need to design generators and transformers to minimize such losses and to operate the entire generation and transmission system in an optimal manner.

1.2 Direct and Alternating Current

An electric current flowing in one direction only is known as *direct current*. Simple circuits with fixed polarity such as those supplied from batteries operate on direct current. Small generators can also provide a source of direct current. A major limitation of such circuits is that voltage cannot readily be changed and the system must operate at the voltage at which the current is produced.

This problem can be overcome by the use of *alternating current*. Here the electric current reverses its flow many times a second. The advantage of this is that the repeated buildup and decay of current in the primary circuit of a transformer induces an oscillating electric field in the core which in turn generates reversing flows of current in the secondary circuit.

The secondary circuit is designed to generate current at a voltage different from that of the primary and hence the desired voltage may be obtained from a given source. In a well designed transformer electrical losses are minimal, so an increase in voltage reduces the current to maintain the same flow of power. Reduced current in turn lowers electrical resistance losses. Thus it is desirable to transmit electric power at high voltage to minimize loss but to generate and utilise it at lower voltages to reduce insulation requirements.

Generally the relationship between voltage and current is given by Ohm's law which states that the voltage E between the ends of a conductor is proportional to the steady current I flowing in it.

$$E = I\,R \tag{1}$$

R is the electrical resistance which, if increased, requires a higher voltage to drive the same current. The power P produced by the flow of an electric current is equal to the product of the voltage and the current.

$$P = E\,I \tag{2}$$

It follows from these equations that the power is also given by the square of current multiplied by the resistance.

$$P = I^2\,R \tag{3}$$

This is important with respect to power losses in various circuits. A small reduction in current can have a significant effect in reducing power losses.

With regard to alternating current circuits, these equations require some elaboration since the alternating current has oscillating values of current and voltage. Generally these periodic values are expressed by a simple harmonic function where the amplitude y is given in terms of the angular frequency ω and time t.

$$y = A \sin \omega\, t \tag{4}$$

Here A is the amplitude and the angular frequency ω is a circular function of the linear frequency f.

$$\omega = 2\,\pi\, f \tag{5}$$

The linear frequency in turn is the inverse of the period T of one complete cycle.

$$f = 1\,/\,T \tag{6}$$

Usually, in alternating current circuits, the current and voltage are not in phase with each another. This is due to the inductive and capacitive effects of the reversing flow. In an *inductive circuit* the rising voltage induces an increasing electric field which retards the current buildup due to self inductance. This causes the current to lag the voltage. In a *capacitive circuit* the current must flow first before the voltage can build up causing the current to lead the voltage. Most power transmission and distribution circuits have inductive loads due to transformers and motors so operate with the current lagging the voltage or voltage leading the current. This gives rise to the following relationships for instantaneous current i and instantaneous voltage e.

$$i = I_m \sin \omega t \tag{7}$$

$$e = E_m \sin (\omega t + \varphi) \tag{8}$$

Here I_m and E_m are the maximum values of the current and voltage and φ is the angular difference between the current and voltage peaks. This is illustrated in Figure 1.

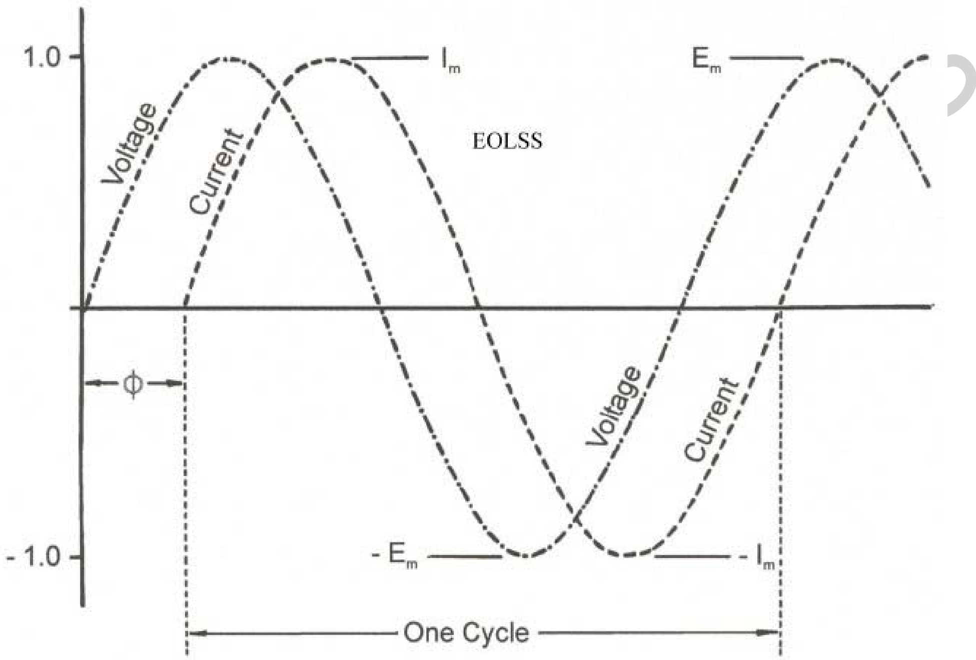

Figure 1. Voltage and current in an inductive circuit

The instantaneous power in such a circuit is the product of instantaneous voltage and instantaneous current.

$$e\, i = E_m I_m \sin (\omega t + \varphi) \sin \omega t \tag{9}$$

If this expression is analyzed it is found that there is a constant term and an oscillating term. The constant term is thus the mean value of the expression. This mean value then represents the average power P being produced.

$$P = \tfrac{1}{2} E_m I_m \cos \varphi \tag{10}$$

This is illustrated in Figure 2 which is an elaboration of Figure 1 with instantaneous power shown as well.

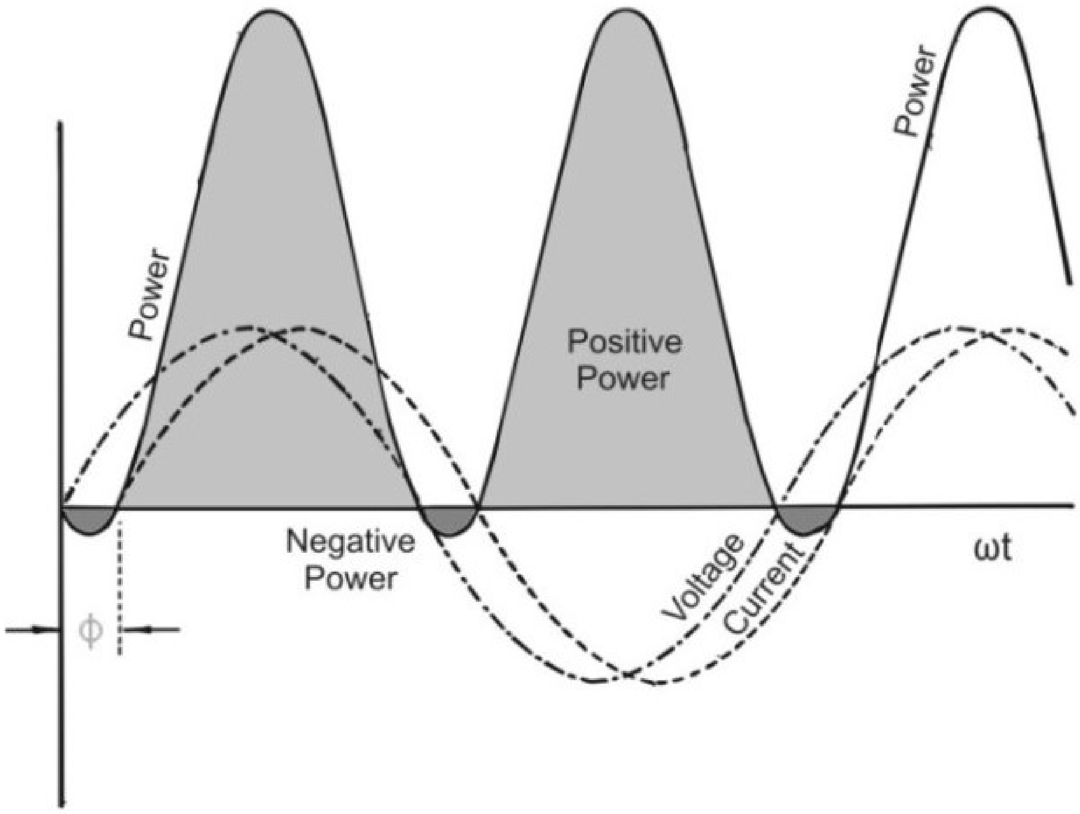

Figure 2. Power in an inductive circuit (small φ)

It is evident from this figure that the power oscillates with a frequency twice that of the current and voltage. This is given by the oscillating term from Equation 9 and apparent from Figure 2 since the current and voltage are both positive and both negative during part of each cycle.

Also evident from the figure is that some negative power is also developed twice each cycle. This cancels some of the positive power and leads to the concept of *reactive power* as opposed to the net positive or *real power* produced. The reactive power Q also known as *vars* (volts-amps-reactive) is given by:

$$Q = \tfrac{1}{2} E_\mathrm{m} I_\mathrm{m} \sin\varphi \qquad (11)$$

Referring to Figure 2 it can be seen that as angle φ decreases to zero the real power P reaches a maximum and the reactive power Q goes to zero. Conversely as angle φ increases to $\pi/2$ the real power goes to zero since the average power decreases to zero from Equation 10.

However the reactive power is now a maximum from Equation 11. Although current still circulates in the system as before, it is not possible to produce useful or real power. Figure 3 shows the situation as angle φ approaches $\pi/2$.

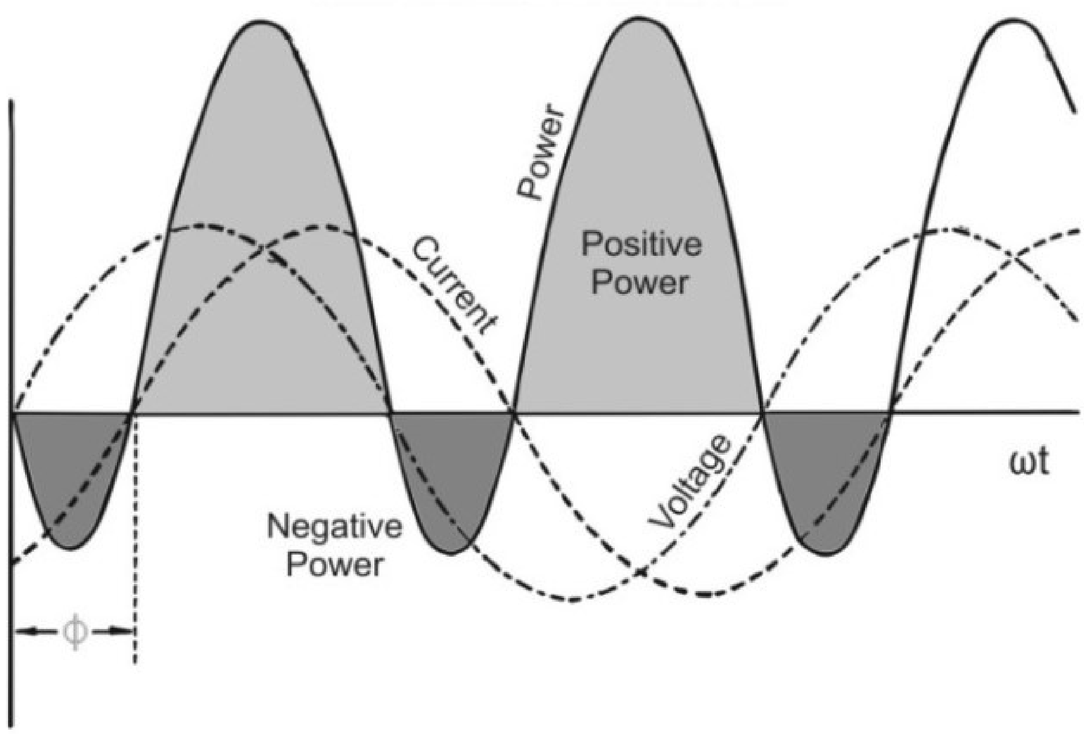

Figure 3 Power in an inductive circuit (large φ)

The factor cos φ appearing in Equation 10 is known as the *power factor*. This defines the amount of real power in an alternating current circuit with respect to the current and voltage in that circuit and is an important concept in the design of generators and transformers which must bear the load of reactive power while meeting real power demands.

In the above equations the maximum voltage E_m and maximum current I_m have been used to derive expressions for real power P and reactive power Q. Actual measurements of these values however will indicate an average value of the effect of the voltage and current on the measuring device.

This effect is proportional to the square of the fluctuating value. Hence the measured quantity will be equal to the mean value of the square of the voltage or current. This leads to the term *root-mean-square* (RMS) value when applied to the measurement of sinusoidal alternating currents and to the following relationships.

$$I^2 = \tfrac{1}{2} I_m^2 \qquad (12)$$

$$E^2 = \tfrac{1}{2} E_m^2 \qquad (13)$$

Equation 10 and Equation 11 can hence be modified to reflect actual root-mean-square or RMS measurements for real power and reactive power respectively.

$$P = E\, I \cos\varphi \qquad (14)$$

$$Q = E\, I \sin\varphi \qquad (15)$$

Finally these equations can be combined using standard trigonometric relationships

$$E\,I = [P^2 + Q^2]^{½} \qquad (16)$$

The value *EI* is sometimes referred to as the *apparent power*.

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained a M.Sc. in nuclear engineering from Imperial College of London University. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.