Electrical Power Engineering

By

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Lecture (3)

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System Protection

- In addition to generators, transformers and transmission lines, other devices are required for the satisfactory operation and protection of a power system.
- Some of the protective devices directly connected to the circuits are called switchgear.
- They include instrument transformers, circuit breakers, disconnect switches, fuses and lightning arresters.
- These devices are necessary to deenergize either for normal operation or on the occurrence of faults.
- The associate control equipment and protective relays are placed on switchboard in control houses.

Energy Control System

For reliable and economical operation of the power system it is necessary to monitor the entire system in a control center. The modern control center of today is called the *energy control center* (ECC). Energy control centers are equipped with on-line computers performing all signal processing through the remote acquisition system. Computers work in a hierarchical structure to properly coordinate different functional requirements in normal as well as emergency conditions. Every energy control center contains a control console which consists of a visual display unit (VDU), keyboard, and light pen. Computers may give alarms as advance warnings to the operators (dispatchers) when deviation from the normal state occurs. The dispatcher makes judgments and decisions and executes them with the aid of a computer. Simulation tools and software packages written in high-level language are implemented for efficient operation and reliable control of the system. This is referred to as SCADA, an acronym for "supervisory control and data acquisition."

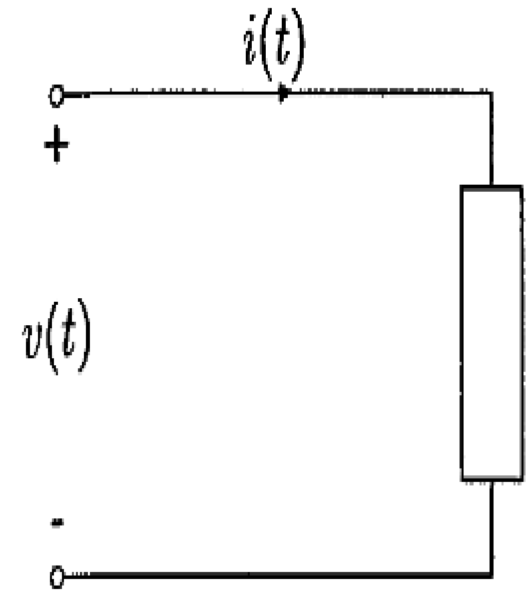
Computer Analysis

For a power system to be practical it must be safe, reliable, and economical. Thus many analyses must be performed to design and operate an electrical system. However, before going into system analysis we have to model all components of electrical power systems. Therefore, in this text, after reviewing the concepts of power and three-phase circuits, we will calculate the parameters of a multi-circuit transmission line. Then, we will model the transmission line and look at the performance of the transmission line. Since transformers and generators are a part of the system, we will model these devices. Design of a power system, its operation and expansion requires much analysis. This text presents methods of power system analysis with the aid of a personal computer and the use of *MATLAB*.

Basic Principles

Power in Single Phase AC Circuits

Figure 2.1 shows a single-phase sinusoidal voltage supplying a load.



Let the instantaneous voltage be

$$v(t) = V_m \cos(\omega t + \theta_v) \qquad (2.1)$$

and the instantaneous current be given by

$$i(t) = I_m \cos(\omega t + \theta_i) \qquad (2.2)$$

The instantaneous power $p(t)$ delivered to the load is the product of voltage $v(t)$ and current $i(t)$ given by

$$p(t) = v(t)\,i(t) = V_m I_m \cos(\omega t + \theta_v)\cos(\omega t + \theta_i) \qquad (2.3)$$

Power in Single Phase AC Circuits

It is informative to write (2.3) in another form using the trigonometric identity

$$\cos A \cos B = \frac{1}{2}\cos(A - B) + \frac{1}{2}\cos(A + B) \qquad (2.4)$$

which results in

$$\begin{aligned} p(t) &= \frac{1}{2}V_m I_m[\cos(\theta_v - \theta_i) + \cos(2\omega t + \theta_v + \theta_i)] \\ &= \frac{1}{2}V_m I_m\{\cos(\theta_v - \theta_i) + \cos[2(\omega t + \theta_v) - (\theta_v - \theta_i)]\} \\ &= \frac{1}{2}V_m I_m[\cos(\theta_v - \theta_i) + \cos 2(\omega t + \theta_v)\cos(\theta_v - \theta_i) \\ &\quad + \sin 2(\omega t + \theta_v)\sin(\theta_v - \theta_i)] \end{aligned}$$

Power in Single Phase AC Circuits

The *root-mean-square* (rms) value of $v(t)$ is $|V| = V_m/\sqrt{2}$ and the rms value of $i(t)$ is $|I| = I_m/\sqrt{2}$. Let $\theta = (\theta_v - \theta_i)$. The above equation, in terms of the rms values, is reduced to

$$p(t) = \underbrace{|V||I|\cos\theta[1+\cos 2(\omega t+\theta_v)]}_{\substack{p_R(t) \\ \text{Energy flow into} \\ \text{the circuit}}} + \underbrace{|V||I|\sin\theta\sin 2(\omega t+\theta_v)}_{\substack{p_X(t) \\ \text{Energy borrowed and} \\ \text{returned by the circuit}}} \qquad (2.5)$$

where θ is the angle between voltage and current, or the impedance angle. θ is positive if the load is inductive, (i.e., current is lagging the voltage) and θ is negative if the load is capacitive (i.e., current is leading the voltage).

Power in Single Phase AC Circuits

The instantaneous power has been decomposed into two components. The first component of (2.5) is

$$p_R(t) = |V||I|\cos\theta + |V||I|\cos\theta\cos 2(\omega t + \theta_v)] \qquad (2.6)$$

The second term in (2.6), which has a frequency twice that of the source, accounts for the sinusoidal variation in the absorption of power by the resistive portion of the load. Since the average value of this sinusoidal function is zero, the average power delivered to the load is given by

$$P = |V||I|\cos\theta \qquad (2.7)$$

Power in Single Phase AC Circuits

This is the power absorbed by the resistive component of the load and is also referred to as the *active power* or *real power*. The product of the rms voltage value and the rms current value $|V||I|$ is called the *apparent power* and is measured in units of volt ampere. The product of the apparent power and the cosine of the angle between voltage and current yields the real power. Because $\cos\theta$ plays a key role in the determination of the average power, it is called *power factor*. When the current lags the voltage, the power factor is considered lagging. When the current leads the voltage, the power factor is considered leading.

Power in Single Phase AC Circuits

The second component of (2.5)

$$p_X(t) = |V||I| \sin\theta \sin 2(\omega t + \theta_v) \quad (2.8)$$

pulsates with twice the frequency and has an average value of zero. This component accounts for power oscillating into and out of the load because of its reactive element (inductive or capacitive). The amplitude of this pulsating power is called *reactive power* and is designated by Q.

$$Q = |V||I| \sin\theta \quad (2.9)$$

Power in Single Phase AC Circuits

Both P and Q have the same dimension. However, in order to distinguish between the real and the reactive power, the term "var" is used for the reactive power (var is an acronym for the phrase "volt-ampere reactive"). For an inductive load, current is lagging the voltage, $\theta = (\theta_v - \theta_i) > 0$ and Q is positive; whereas, for a capacitive load, current is leading the voltage, $\theta = (\theta_v - \theta_i) < 0$ and Q is negative.

Power in Single Phase AC Circuits

A careful study of Equations (2.6) and (2.8) reveals the following characteristics of the instantaneous power.

- For a pure resistor, the impedance angle is zero and the power factor is unity (UPF), so that the apparent and real power are equal. The electric energy is transformed into thermal energy.
- If the load is purely capacitive, the current leads the voltage by 90°, and the average power is zero, so there is no transformation of energy from electrical to nonelectrical form. In a purely capacitive circuit, the power oscillates between the source and the electric field associated with the capacitive elements.

Power in Single Phase AC Circuits

- If the circuit is purely inductive, the current lags the voltage by 90° and the average power is zero. Therefore, in a purely inductive circuit, there is no transformation of energy from electrical to nonelectrical form. The instantaneous power at the terminal of a purely inductive circuit oscillates between the circuit and the source. When $p(t)$ is positive, energy is being stored in the magnetic field associated with the inductive elements, and when $p(t)$ is negative, energy is being extracted from the magnetic fields of the inductive elements.

Complex Power

$$v(t) = V_m \cos(\omega t + \theta_v) \quad (2.1)$$

$$i(t) = I_m \cos(\omega t + \theta_i) \quad (2.2)$$

The rms voltage phasor of (2.1) and the rms current phasor of (2.2) shown in Figure 2.3 are

$$V = |V|\angle\theta_v \text{ and } I = |I|\angle\theta_i$$

The term VI^* results in

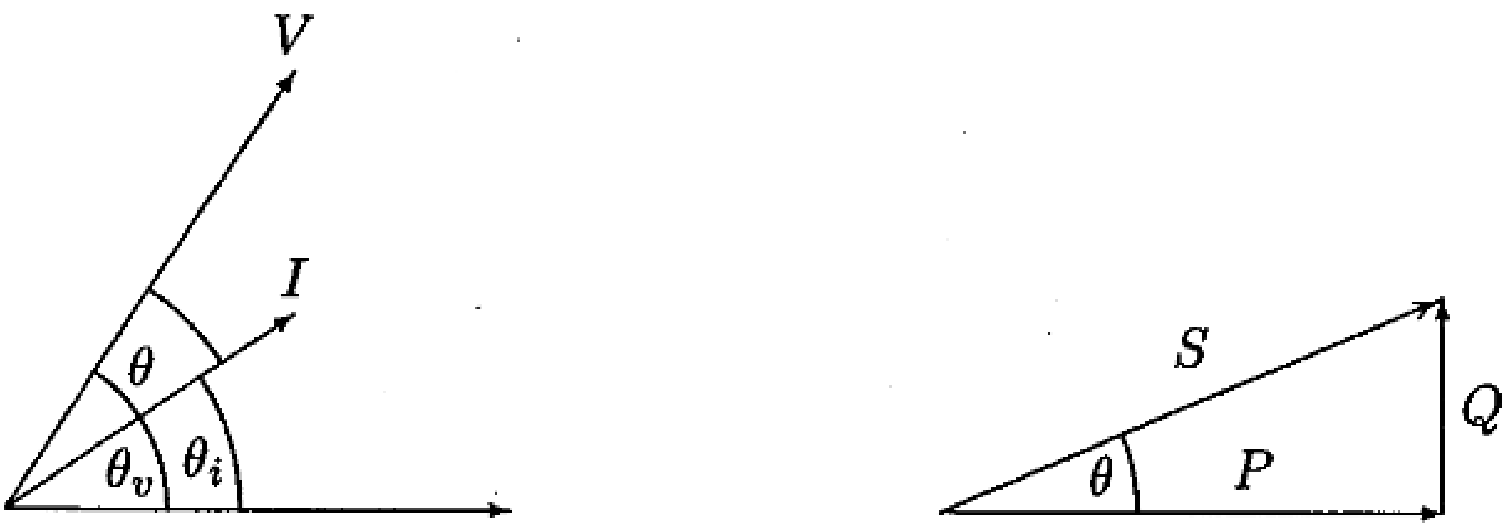


FIGURE 2.3
Phasor diagram and power triangle for an inductive load (lagging PF).

Complex Power

$$VI^* = |V||I|\angle\theta_v - \theta_i = |V||I|\angle\theta$$

$$= |V||I|\cos\theta + j|V||I|\sin\theta$$

The above equation defines a complex quantity where its real part is the average (real) power P and its imaginary part is the reactive power Q. Thus, the complex power designated by S is given by

$$S = VI^* = P + jQ \tag{2.10}$$

The magnitude of S, $|S| = \sqrt{P^2 + Q^2}$, is the apparent power;

Complex Power

The reactive power Q is positive when the phase angle θ between voltage and current (impedance angle) is positive (i.e., when the load impedance is inductive, and I lags V). Q is negative when θ is negative (i.e., when the load impedance is capacitive and I leads V) as shown in Figure 2.4.

In working with Equation (2.10) it is convenient to think of P, Q, and S as forming the sides of a right triangle as shown in Figures 2.3 and 2.4.

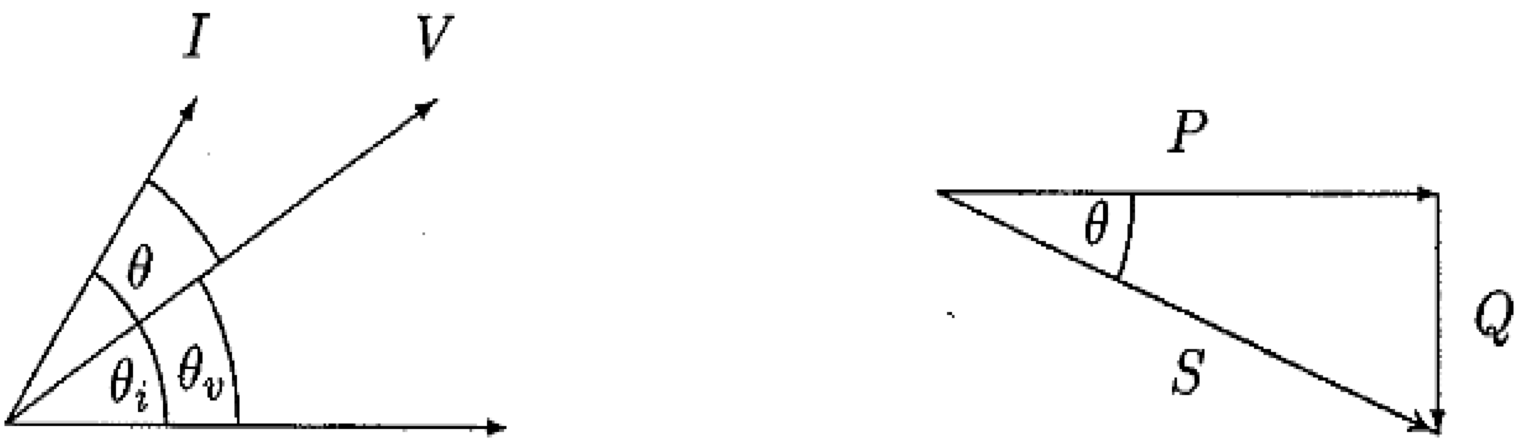


FIGURE 2.4

Phasor diagram and power triangle for a capacitive load (leading PF).

Complex Power

If the load impedance is Z then

$$V = ZI \tag{2.11}$$

substituting for V into (2.10) yields

$$S = VI^* = ZII^* = R|I|^2 + jX|I|^2 \tag{2.12}$$

From (2.12) it is evident that complex power S and impedance Z have the same angle. Because the power triangle and the impedance triangle are similar triangles, the impedance angle is sometimes called the *power angle*.

Similarly, substituting for I from (2.11) into (2.10) yields

$$S = VI^* = \frac{VV^*}{Z^*} = \frac{|V|^2}{Z^*} \tag{2.13}$$

From (2.13), the impedance of the complex power S is given by

$$Z = \frac{|V|^2}{S^*} \tag{2.14}$$

The Complex Power Balance

From the conservation of energy, it is clear that real power supplied by the source is equal to the sum of real powers absorbed by the load. At the same time, a balance between the reactive power must be maintained. Thus the total complex power delivered to the loads in parallel is the sum of the complex powers delivered to each. Proof of this is as follows:

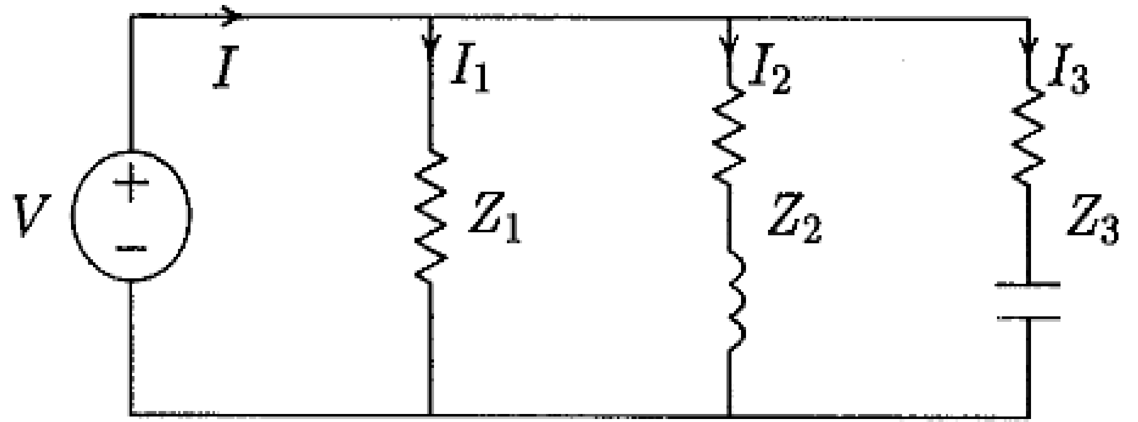


FIGURE 2.5
Three loads in parallel.

For the three loads shown in Figure 2.5, the total complex power is given by

$$S = VI^* = V[I_1 + I_2 + I_3]^* = VI_1^* + VI_2^* + VI_3^* \qquad (2.15)$$

Activity (4)

Thank You For Your Attention

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