Introduction to Electrical Circuits

Final Term
Lecture - 01

<u>**Reference Book:**</u>

Introductory Circuit Analysis

Robert L. Boylestad, 11^{th} Edition

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W8	FC1	Chapter 15	15.2 IMPEDANCE AND THE PHASOR DIAGRAM Resistive Elements	15.1-15.6
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Instantaneous Value to Phasor or Polar form

Instantaneous Value	Phasor or Polar Form
$v(t) = V_m \sin(\omega t + \theta_v)$	$\boldsymbol{V} = \frac{V_m}{\sqrt{2}} \angle \theta_v = V_{rms} \angle \theta_v = V \angle \theta_v$ where, $V = V_{rms} = \frac{V_m}{\sqrt{2}}$
$v(t) = V_m \sin(\omega t - \theta_v)$	$\boldsymbol{V} = \frac{V_m}{\sqrt{2}} \angle -\theta_v = V_{rms} \angle -\theta_v = V \angle -\theta_v$ where, $V = V_{rms} = \frac{V_m}{\sqrt{2}}$
$i(t) = I_m \sin(\omega t + \theta_i)$	$\boldsymbol{I} = \frac{I_m}{\sqrt{2}} \angle \theta_i = I_{rms} \angle \theta_i = I \angle \theta_i$ where, $I = I_{rms} = \frac{I_m}{\sqrt{2}}$
$i(t) = I_m \sin(\omega t - \theta_i)$	$\boldsymbol{I} = \frac{I_m}{\sqrt{2}} \angle -\theta_i = I_{rms} \angle -\theta_i = I \angle -\theta_i$ where, $I = I_{rms} = \frac{I_m}{\sqrt{2}}$

Example

The following instantaneous voltage convert to (**i**) the phasor or polar form, (**ii**) the exponential form, and (**iii**) the Cartesian or rectangular form.

$$v(t) = 100\sin(\omega t + 45^{o})$$

Solution: **RMS value is:** $V = V_{rms} = \dfrac{V_m}{\sqrt{2}} = \dfrac{100}{\sqrt{2}} = 70.71$

Phasor or Polar form: $\vec{V} = \boldsymbol{V} = 70.71\angle 45^{\circ}$

Exponential form: $\vec{V} = \boldsymbol{V} = 70.71 e^{j45^{\circ}}$

Cartesian or Rectangular form:

$$\vec{V} = \boldsymbol{V} = 70.71(\cos 45^{\circ} + j\sin 45^{\circ}) = 70.71(0.7071 + j0.7071) = 50 + j50$$

Example

The following current convert to **(i)** the exponential form, (ii) **(i)** the Cartesian or rectangular form, and **(iii)** write the instantaneous expression.

$$\boldsymbol{I} = 90\angle\text{-}40^{o}$$

Solution: $I = I_{rms} = \dfrac{I_m}{\sqrt{2}} = 90 \ \text{A}$ $\qquad \theta_i = -40°$

Exponential form: $\vec{I} = \boldsymbol{I} = 90e^{-j40°}$

Cartesian or Rectangular form: $\vec{I} = \boldsymbol{I} = 90(\cos 40° - j\sin 40°) = 69 - j57.9$

Peak value: $I_m = \sqrt{2}I_{rms} = \sqrt{2} \times 90 = 127.28 \ \text{A}$

Instantaneous expression: $i(t) = \sqrt{2}I\sin(\omega t - 40°) = \sqrt{2}I_{rms}\sin(\omega t - 40°) \ \text{A}$

$$i(t) = 127.28\sin(\omega t - 40°) \ \text{A}$$

Impedance

According to ohm's Law, Impedance is the ratio of voltage to current. The unit of impedance is ohm [Ω].

$$\boldsymbol{Z} = \frac{v}{i} = \frac{V_m \sin(\omega t + \theta_v)}{I_m \sin(\omega t + \theta_i)} \ \text{ohm} \ [\Omega]$$

$$\boldsymbol{Z} = \frac{V_{rms}\angle\theta_v}{I_{rms}\angle\theta_i} = \frac{V_{rms}}{I_{rms}}\angle(\theta_v - \theta_i) = \frac{V}{I}\angle(\theta_v - \theta_i) = |Z|\angle\theta_z \quad \Omega$$

$$\boldsymbol{Z} = \frac{V_m}{I_m}\angle(\theta_v - \theta_i) = Z\angle\theta_z = R + jX = (\textbf{Resistance}) + j(\textbf{Reactance})$$

Magnitude of impedance, $Z = \frac{V_m}{I_m} = \frac{V_{rms}}{I_{rms}} = \frac{V}{I} \quad \Omega$

Angle of impedance, $\theta_z = \theta_v - \theta_i$

Resistance: $R = Z\cos\theta_z$

Reactance: $X = Z\sin\theta_z$

Example

The voltage and current of a circuit are given as follows: $v(t)=100\sin(314t+60^{o})$ V and $i(t)=10\sin(314t+30^{o})$ A. Calculate the magnitude of impedance and angle of impedance.

Solution: Here, $\omega=314$ rad/s, $V_m = 100$ V, $I_m = 10$ A, $\theta_v = 60^{o}$, and $\theta_i = 30^{o}$.

Magnitude of impedance, $Z = \dfrac{V_m}{I_m} = \dfrac{100}{10} = 10\ \Omega$

Angle of impedance, $\theta_z = \theta_v - \theta_i = 60° - 30° = 30°$

Impedance, $\boldsymbol{Z} = 10\angle 30° = 8.66 + j5\ \Omega$

Example

The voltage and current of a circuit are given as follows: $\boldsymbol{V}=15\angle 30^{o}$ V and $\boldsymbol{I}=1.2\angle 60^{o}$ A. Calculate the magnitude of impedance and angle of impedance.

Solution:

Impedance, $\boldsymbol{Z} = \dfrac{\boldsymbol{V}}{\boldsymbol{I}} = \dfrac{15\angle 30°}{1.2\angle 60°} = 12.5\angle -30° = 10.83 - j6.25\ \Omega$

Magnitude of impedance, $Z = 12.5\ \Omega$

Angle of impedance, $\theta_z = \theta_v - \theta_i = -30°$

Power (or Average or Real or Active or True or Wattfull Power)

Instantaneous power can be written as follows:

$$p(t) = P - P\cos 2\omega t + Q\sin 2\omega t \text{ [W]}$$

The average values of second and third terms of above equation are zero, so the average value of total instantaneous power equals to the constant term which is called power (or average power or real or active or true or wattfull power).

The unit of real power is called watt.

The real power is measured by wattmeter.

The power or real power or active power or true power or wattfull power can be written as follows:

$$\boxed{P = P_r = \frac{V_m I_m}{2}\cos\theta = V_{rms} I_{rms}\cos\theta = VI\cos\theta}$$

Physical Significance of Power or real power or average power:

The power (or average power or real or active or true or wattfull power) represents the power which is consumed by load (resistor).

The real power is the power which converts from electrical energy to other form of energy.

Reactive or imaginary or Quadrature or Wattless Power (or Reactive Volt-Ampere)

The maximum value of instantaneous reactive or imaginary or quadrature or wattless power (or instantaneous reactive volt-ampere) is called the reactive or imaginary or quadrature or wattless power (or reactive volt-ampere).

The unit of reactive power is called var (reactive volt-ampere).

The reactive power is measured by varmeter.

The instantaneous reactive or imaginary or quadrature or wattless power (or instanatneous reactive volt-ampere) can be written as follows:

$$Q = P_x = \frac{V_m I_m}{2}\sin\theta = V_{rms} I_{rms}\sin\theta = VI\sin\theta$$

Since the reactive power depends of the angle of sine, it may be positive (for capacitor) or negative (for inductor).

Volt-Ampere or Apparent Power

The volt-ampere or apparent power represents the maximum possible supply power by a source.

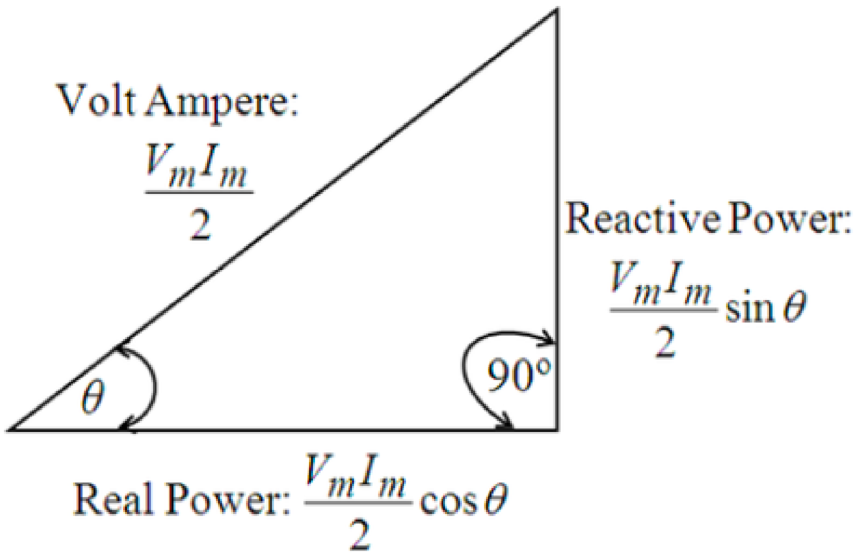
The apparent power can be obtained by combining the real and reactive power as follows:

$$S = \sqrt{P_r^2 + P_x^2} = \sqrt{P^2 + Q^2} = \frac{V_m I_m}{2} = V_{rms} I_{rms} = VI$$

The **unit** of apparent power is called **VA (volt-ampere)**.

Power Triangle

The power, reactive power and apparent power can be represented by graphically as shown in the following figure which is called **Power Triangle**.



Power Factor

Cosine θ (cosθ) which is a factor, by which volt-amperes are multiplied to give power, is called power factor. Power factor is always positive.

Power factor can be given by:

$$\text{Power Factor (pf)} = \cos\theta = \frac{P}{\frac{V_m I_m}{2}} = \frac{P}{V_{eff} I_{eff}} = \frac{P}{V_{rms} I_{rms}} = \frac{P}{S}$$

Physical Significance of Power Factor

Power factor represents how much of maximum possible supply power is utilized (or consumed by resistor).

Suppose 0.5 power factor (i.e. 50% pf) of a circuit means that it will utilize only 50% of the apparent power whereas 0.8 power factor means 80% utilization of apparent power.
For this reason, we wish that the power factor of the circuit to be near 1 (unity) as possible.

Phase difference between voltage and current	Reactive factor	Sign in reactive power	Nature of power factor	Nature of load
$\theta = \theta_z = \theta_v - \theta_i = 0$	Zero	Zero	unity	Resistor
$\theta = \theta_z = \theta_v - \theta_i = 90^o$	1	$Q = S$	Zero lagging	Inductor
$\theta = \theta_z = \theta_v - \theta_i = -90^o$	-1	$Q = -S$	Zero leading	Capacitor
$\theta = \theta_z = \theta_v - \theta_i > 0$	Positive	Positive	Lagging	RL series
$\theta = \theta_z = \theta_v - \theta_i < 0$	negative	Negative	Leading	RC series

Example

The voltage and current of a circuit are given as follows: $v(t)=100\sin(314t+60^o)$ V and $i(t)=10\sin(314t+30^o)$ A.

(i) Calculate the apparent power, the power or active power, the reactive power, the power factor, the reactive factor. (ii) Write the expression of instantaneous real power, the expression of instantaneous reactive power, and the expression of instantaneous total power. (iii) Draw the power triangle.

Solution: Here, ω=314 rad/s, V_m = 100 V, I_m = 10 A, θ_v = 60^o, and θ_i = 30^o.

Thus $\theta = \theta_z = \theta_v - \theta_i = 60^o - 30^o = 30^o$.

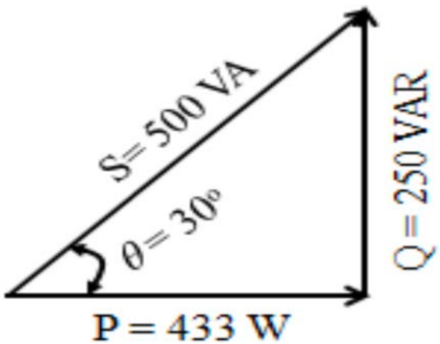
$$\text{Apparent power}: S = \frac{V_m I_m}{2} = \frac{100\times 10}{2} = 500 \text{ VA}$$

$$\text{Power factor, pf} = \cos\theta = \cos(30°) = 0.866$$

$$\text{Reactive factor, rf} = \sin\theta = \sin(30°) = 0.5$$

$$\text{Power}: P = \frac{V_m I_m}{2}\cos\theta = \frac{100\times 10}{2}\cos(30°) = 433 \text{ W}$$

$$\text{Reactive Power}: Q = \frac{V_m I_m}{2}\sin\theta = \frac{100\times 10}{2}\sin(30°) = 250 \text{ VAR}$$



Power Triangle

Example on Power Calculation

Example: The voltage of $v(t) = 100\sin(314t - 60°)\ V$ applied to an impedance of $\boldsymbol{Z} = (8.66 + j\,5)\Omega$. (i) Calculate the apparent power, the power or active power, the reactive power, the power factor, the reactive factor, (ii) Draw the power triangle.

Here, $\omega = 314$ rad/s, $V_m = 100\ V$, $\theta_v = -60°$

$\boldsymbol{V} = \frac{100}{\sqrt{2}}\angle -60° = 70.7\angle -60°\ V$

$\boldsymbol{Z} = (8.66 + j\,5)\Omega = 10\angle 30°\Omega$

$\boldsymbol{I} = \frac{V}{Z} = \frac{70.7\angle -60°}{10\angle 30°} = 7.07\angle -90°\ A$

$\theta = \theta_z = \theta_v - \theta_i = -60° - (-90°) = 30°$

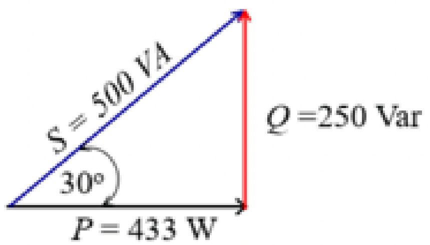
$\boldsymbol{S} = V_{rms}I_{rms} = 70.7 \times 7.07 = 500$ VA

$\boldsymbol{P} = V_{rms}I_{rms}\cos\theta = 70.7 \times 7.07\cos(30°) = 433$ W

$\boldsymbol{Q} = V_{rms}I_{rms}\sin\theta = 70.7 \times 7.07\sin(30°) = 250\ VAR$

$p.f. = \cos\theta = \cos(30°) = 0.866$

$r.f. = \sin\theta = \sin(30°) = 0.5$



Power Triangle

EXAMPLE 20.6 An electrical device is rated 5 kVA, 100 V at a 0.6 power-factor lag. What is the impedance of the device in rectangular coordinates?

Solution:

$$S = EI = 5000 \text{ VA}$$

Therefore,
$$I = \frac{5000 \text{ VA}}{100 \text{ V}} = 50 \text{ A}$$

For $F_P = 0.6$, we have

$$\theta = \cos^{-1} 0.6 = 53.13^\circ$$

Since the power factor is lagging, the circuit is predominantly inductive, and **I** lags **E**. Or, for $\mathbf{E} = 100 \text{ V} \angle 0^\circ$,

$$\mathbf{I} = 50 \text{ A} \angle -53.13^\circ$$

However,

$$\mathbf{Z}_T = \frac{\mathbf{E}}{\mathbf{I}} = \frac{100 \text{ V} \angle 0^\circ}{50 \text{ A} \angle -53.13^\circ} = 2\ \Omega \angle 53.13^\circ = \mathbf{1.2\ \Omega + j\,1.6\ \Omega}$$

which is the impedance of the circuit in Fig. 20.27.

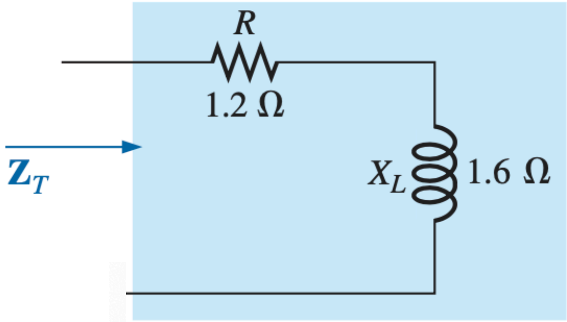
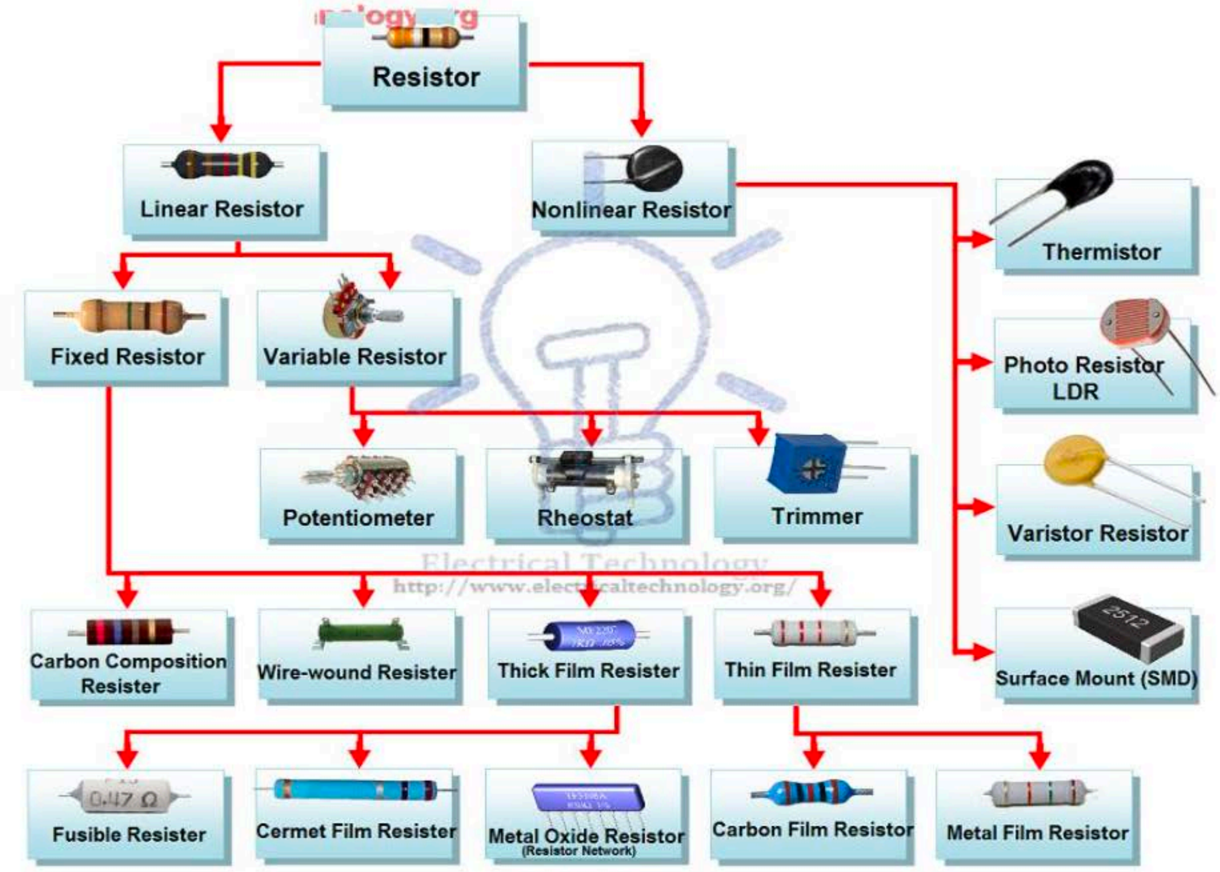
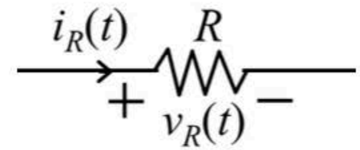


FIG. 20.27
Example 20.6.

Pure Resistive Circuit

Response of Basic Resistor Element to a Sinusoidal Voltage or Current





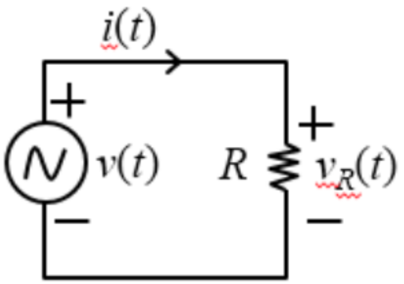
Voltage and current relation in a resistor:

$$v_R(t) = R i_R(t)$$

$$i_R(t) = \frac{v_R(t)}{R}$$

Let, the input is $v(t) = V_m \sin \omega t$ V, according to KVL, we have: $v(t) = v_R(t) = V_m \sin \omega t$

For a resistance the relation of voltage and current is: $v_R(t) = Ri(t)$



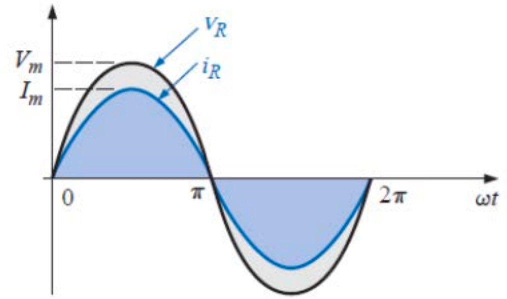
$$Ri(t) = V_m \sin \omega t$$

$$i(t) = \frac{V_m}{R} \sin \omega t = I_m \sin \omega t$$

Magnitude of impedance, $Z = \dfrac{V_m}{I_m} = R \quad \Omega$

Angle of impedance, $\theta_z = \theta_v - \theta_i = 0°$

Impedance of a Resistor, $\boldsymbol{Z} = \boldsymbol{Z}_R = R\angle 0° = R\ \Omega$



The phase difference between voltage across and current through a resistor is zero.

For a purely resistive element, the voltage across and the current through the element are in phase.

Power of Resistive Load

The power of a resistive load:

$$p(t) = (V_m \sin \omega t)(I_m \sin \omega t) = V_m I_m \sin^2 \omega t = \frac{V_m I_m}{2} - \frac{V_m I_m}{2}\cos 2\omega t$$

$$p(t) = V_{rms} I_{rms} - V_{rms} I_{rms} \cos 2\omega t$$

Power Factor :

$$\text{pf} = \cos(\theta_Z) = \cos(0) = 1$$

Reactive Factor :

$$\text{rf} = \sin(\theta_Z) = \sin(0) = 0$$

For resistive load, the power factor is 1 which called **unity power factor**.

Average or Real Power :

$$P = P_{ave} = V_{rms} I_{rms} = \frac{V_{rms}^2}{R} = I_{rms}^2 R \quad \text{W}$$

Reactive Power :

$$Q = P_x = V_{rms} I_{rms} \sin \theta_Z = 0 \quad \text{VAR}$$

Apparent Power :

$$S = \sqrt{P_r^2 + P_x^2} = \sqrt{P^2 + Q^2} = P = \frac{V_m I_m}{2} = V_{rms} I_{rms} = VI \quad \text{VA}$$

EXAMPLE 15.1 Using complex algebra,

a. Find the current i_R for the circuit in Fig. 15.3.
b. Sketch the waveforms of i_R and V_R.

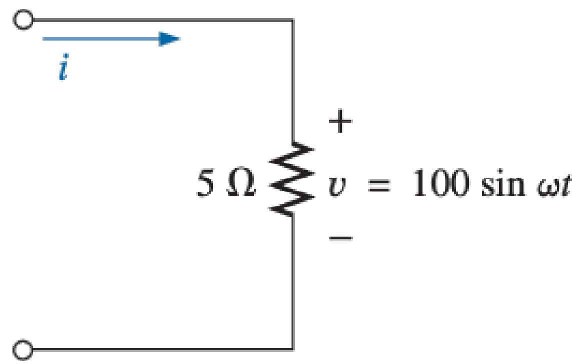


FIG. 15.3
Example 15.1.

Solution:

a. $$v = 100 \sin \omega t \Rightarrow \text{phasor form } \mathbf{V} = 70.71 \text{ V} \angle 0^\circ$$

$$\mathbf{I}_R = \frac{\mathbf{V}_R}{\mathbf{Z}_R} = \frac{V \angle \theta}{R \angle 0^\circ} = \frac{70.71 \; V \angle 0^\circ}{5 \; \Omega \angle 0^\circ} = 14.14 \text{ A} \angle 0^\circ$$

and $$i_R = \sqrt{2}(14.14) \sin \omega t = \mathbf{20 \sin \omega t}$$

b. Note Fig. 15.4.

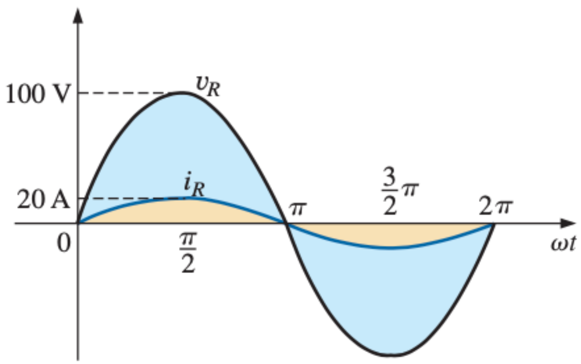
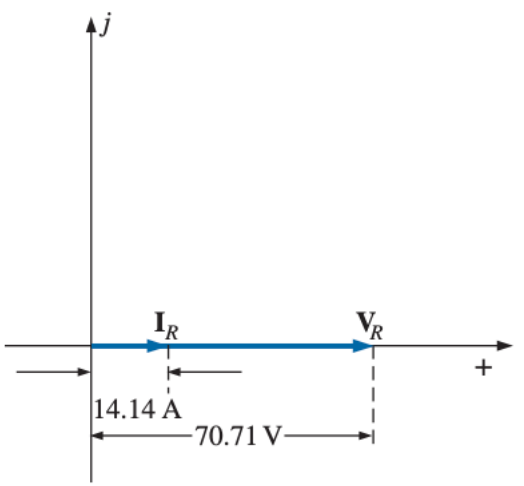


FIG. 15.4
Waveforms for Example 15.1.



EXAMPLE 15.2 Using complex algebra,

a. Find the voltage v_R for the circuit in Fig. 15.5.
b. Sketch the waveforms of v_R and i_R.

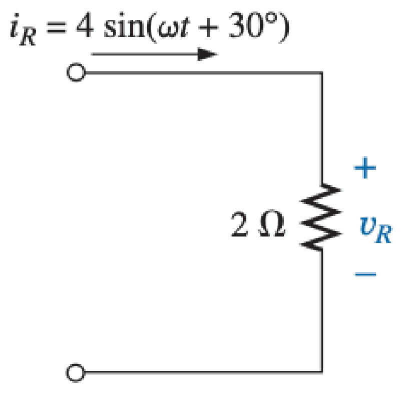


FIG. 15.5
Example 15.2.

Solution:

a.
$$i_R = 4 \sin(\omega t + 30°) \Rightarrow \text{phasor form } \mathbf{I}_R = 2.828 \text{ A} \angle 30°$$
$$\mathbf{V} = \mathbf{I}_R \mathbf{Z}_R = (I \angle \theta)(R \angle 0°) = (2.828 \text{ A} \angle 30°)(2\ \Omega \angle 0°)$$
$$= 5.656 \text{ V} \angle 30°$$
and
$$v_R = \sqrt{2}(5.656) \sin(\omega t + 30°) = \mathbf{8.0 \sin(\omega t + 30°)}$$

b. Note Fig. 15.6.

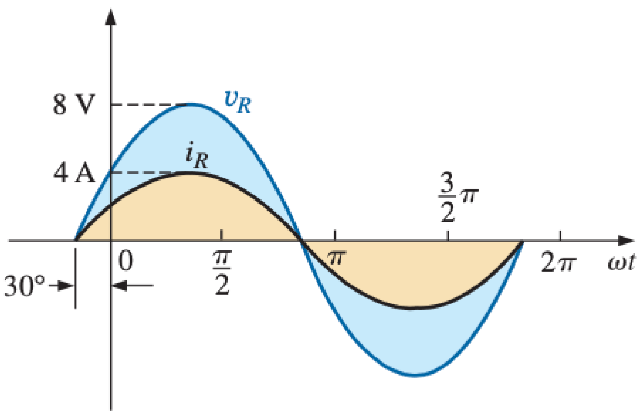
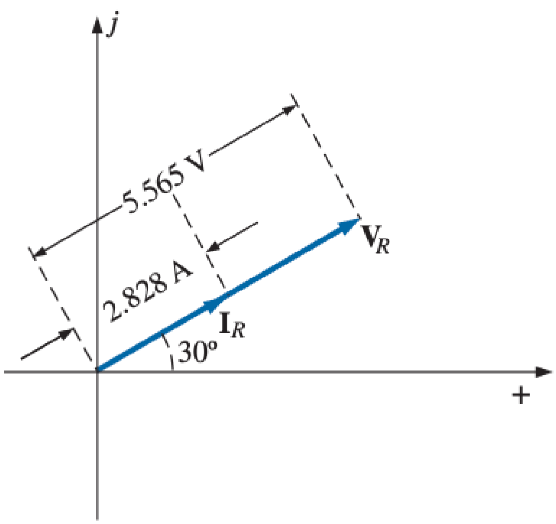


FIG. 15.6
Waveforms for Example 15.2.



Summary For a Resistive Load

Magnitude of impedance, $Z = \dfrac{V_m}{I_m} = R \quad \Omega$ $\qquad \theta_i = \theta_v = 0$

Angle of impedance, $\theta_z = \theta_v - \theta_i = 0°$

Impedance of a Resistor, $\boldsymbol{Z} = \boldsymbol{Z}_R = R\angle 0° = R + j0\ \Omega$

The phase difference between voltage across and current through a resistor is zero.

That means, the voltage across and the current through the element are in phase.

The power factor is 1 that means **unity**.

The reactive factor is 0 that means **zero**.

The reactive power is 0 that means **zero**.

The apparent power equals to real power.

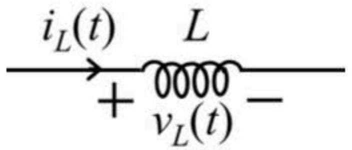
Home Work

Problem 1: The current $i(t) = 4\sin(\omega t - 20^{\circ})$ A flows through a 8 Ω resistor. (*i*) What is the sinusoidal expression for the voltage? (*ii*) Calculate the real power, reactive power, power factor, reactive factor. (*iii*) write the expression of instantaneous power. (*iv*) Sketch the v and i sinusoidal waveforms on the same axis. (*v*) Draw the phasor diagram.

Problem 2: The voltage $v(t) = 20\sin(\omega t + 30^{\circ})$ V is applied to a 4 Ω resistor. (*i*) What is the sinusoidal expression for the current? (**ii**) Calculate the real power, reactive power, power factor, reactive factor. (**iii**) write the expression of instantaneous power. (**iv**) Sketch the v and i sinusoidal waveforms on the same axis. (**v**) Draw the phasor diagram.

Pure Inductive Circuit

Response of Basic Inductor or Choke or Reactor Element to a Sinusoidal Voltage or Current



Voltage and current relation in a inductor:

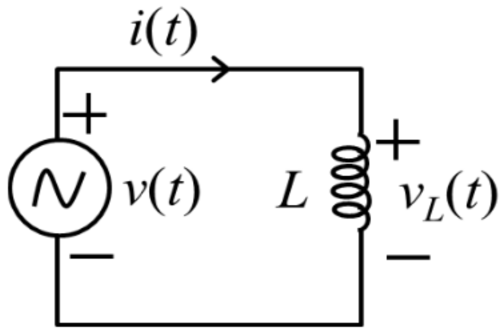
$$v_L(t) = L\frac{di_L(t)}{dt}$$

$$i_L(t) = \frac{1}{L}\int v_L(t)dt$$

Inductance opposes the rate of change current, and for this reason it is sometimes called *electrical inertia*.

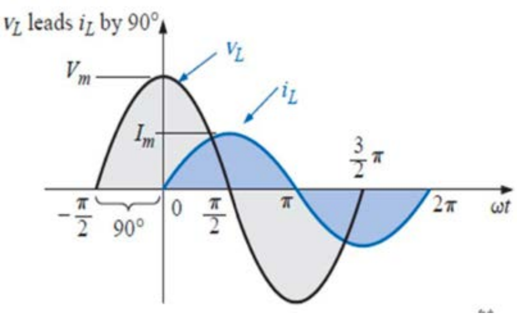
Let, the input is $v(t) = V_m \sin\omega t$ V, according to KVL, we have: $v(t) = v_L(t) = V_m \sin\omega t$

For an inductance the relation of voltage and current is:



$$i_L(t) = \frac{1}{L}\int v_L(t)dt = \frac{V_m}{L}\int \sin\omega t dt = -\frac{V_m}{\omega L}\cos\omega t$$

$$i_L(t) = \frac{V_m}{\omega L}\sin(\omega t - 90°) = I_m \sin(\omega t + \theta_i)$$



Magnitude of impedance, $Z = \dfrac{V_m}{I_m} = \omega L = X_L \quad \Omega$

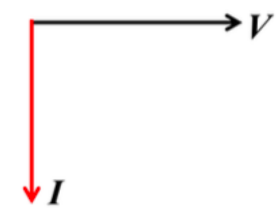
Inductive reactance, $X_L = \omega L = 2\pi f L \quad \Omega$

Angle of impedance, $\theta_Z = \theta_v - \theta_i = 90°$

Impedance of Inductor, $Z = Z_L = X_L \angle 90° = j\, X_L \ \Omega$

The phase difference between voltage across and current through an inductor is 90º .

For a purely inductive element, the voltage leads the current through the inductive element by 90º . Or, the current lags the voltage in an inductive element by 90º.



Phasor Diagram

EXAMPLE 15.3 Using complex algebra,

a. Find the current i_L for the circuit in Fig. 15.9.
b. Sketch the v_L and i_L curves.

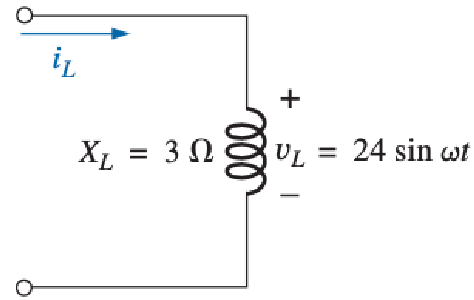


FIG. 15.9
Example 15.3.

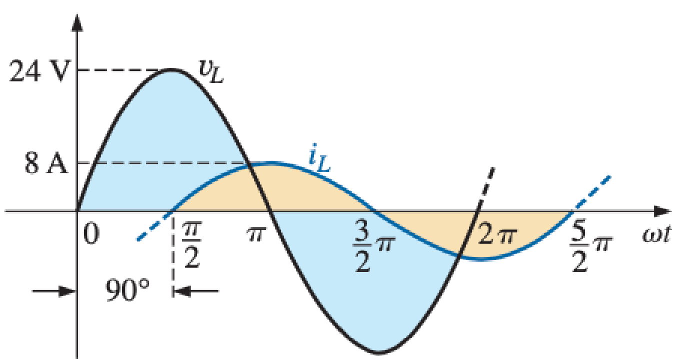
Solution:

a. $$v_L = 24 \sin \omega t \Rightarrow \text{phasor form } \mathbf{V}_L = 16.968 \text{ V} \angle 0°$$

$$\mathbf{I} = \frac{\mathbf{V}_L}{\mathbf{Z}_L} = \frac{V \angle \theta}{X_L \angle 90°} = \frac{16.968 \text{ V} \angle 0°}{3\ \Omega \angle 90°} = 5.656 \text{ A} \angle -90°$$

and $$i = \sqrt{2}(5.656) \sin(\omega t - 90°) = \mathbf{8.0 \sin(\omega t - 90°)}$$

b. Note Fig. 15.10.



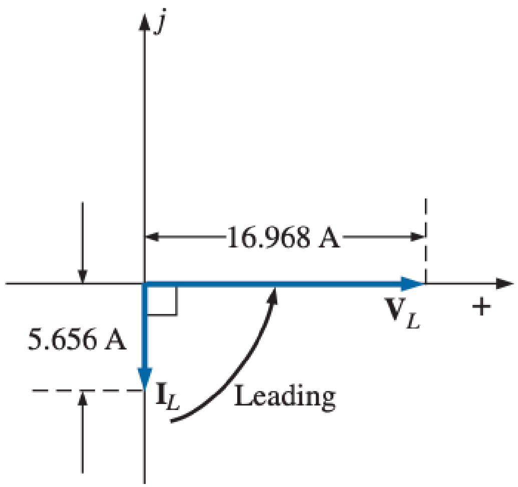


FIG. 15.10
Waveforms for Example 15.3.

EXAMPLE 15.4 Using complex algebra,

a. Find the voltage v_L for the circuit in Fig. 15.11.
b. Sketch the v_L and i_L curves.

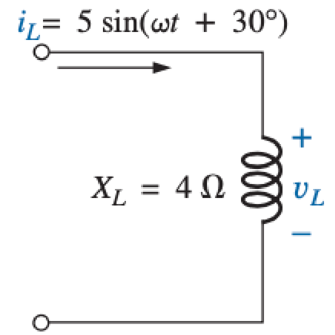


FIG. 15.11
Example 15.4.

Solution:

a.
$$i_L = 5 \sin(\omega t + 30°) \Rightarrow \text{phasor form } \mathbf{I}_L = 3.535\text{ A} \angle 30°$$
$$\mathbf{V}_L = \mathbf{I}\mathbf{Z}_L = (I \angle \theta)(X_L \angle 90°) = (3.535\text{ A} \angle 30°)(4\ \Omega \angle +90°)$$
$$= 14.140\text{ V} \angle 120°$$
and $v_L = \sqrt{2}(14.140) \sin(\omega t + 120°) = \mathbf{20 \sin(\omega t + 120°)}$

b. Note Fig. 15.12.

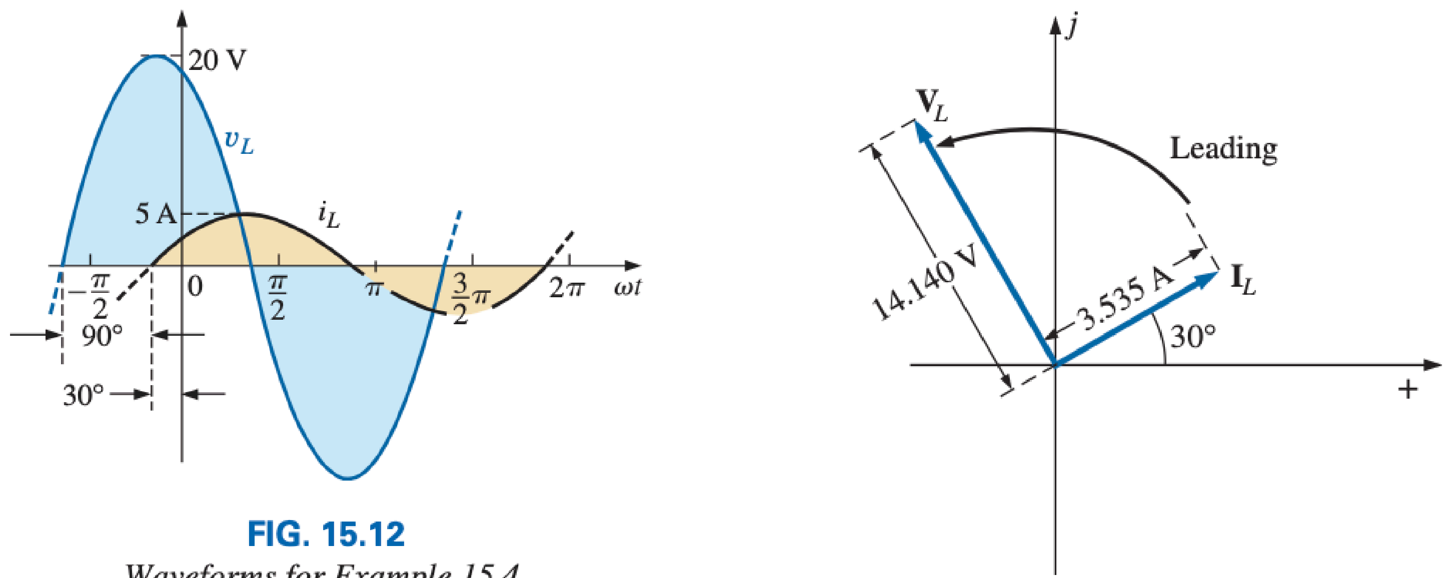


FIG. 15.12
Waveforms for Example 15.4.

Summary For a pure Inductive Load

Magnitude of impedance, $Z = \frac{V_m}{I_m} = X_L \quad \Omega$ $\qquad \theta_i = \theta_v - 90° \qquad \theta_v = \theta_i + 90°$

Angle of impedance, $\theta_z = \theta_v - \theta_i = 90°$

Impedance of a Resistor, $\boldsymbol{Z} = \boldsymbol{Z}_L = X_L \angle 90° = jX_L \ \Omega$

The phase difference between voltage across and current through an inductor is 90°.

The voltage leads the current in an inductor by 90°.

The current lags the voltage in an inductor by 90°.

The power factor is 0 which is called **zero lagging power factor**.

The reactive factor is 1.

The active power is 0 that means **zero**.

The apparent power equals to reactive power.

Inductor consumed the reactive power.

Home Work

Problem 4: The current $i(t)=5\sin(\omega t+30^{\circ})$ A flows through a 4 Ω inductive reactance. (***i***) What is the sinusoidal expression for the voltage? (***ii***) Calculate the real power, reactive power, power factor, reactive factor. (***iii***) write the expression of instantaneous power. (***iv***) Sketch the v and i sinusoidal waveforms on the same axis. (***v***) Draw the phasor diagram.

Problem 5: The voltage $v(t)=24\sin\omega t$ V is applied to a 3 Ω inductive reactance. (***i***) What is the sinusoidal expression for the current? (**ii**) Calculate the real power, reactive power, power factor, reactive factor. (**iii**) write the expression of instantaneous power. (**iv**) Sketch the v and i sinusoidal waveforms on the same axis. (**v**) Draw the phasor diagram.

Thank You