

Module B3

3.1 Sinusoidal steady-state analysis (single-phase), a review

3.2 Three-phase analysis

Kirtley

Chapter 2: AC Voltage, Current and Power

2.1 Sources and Power

2.2 Resistors, Inductors, and Capacitors

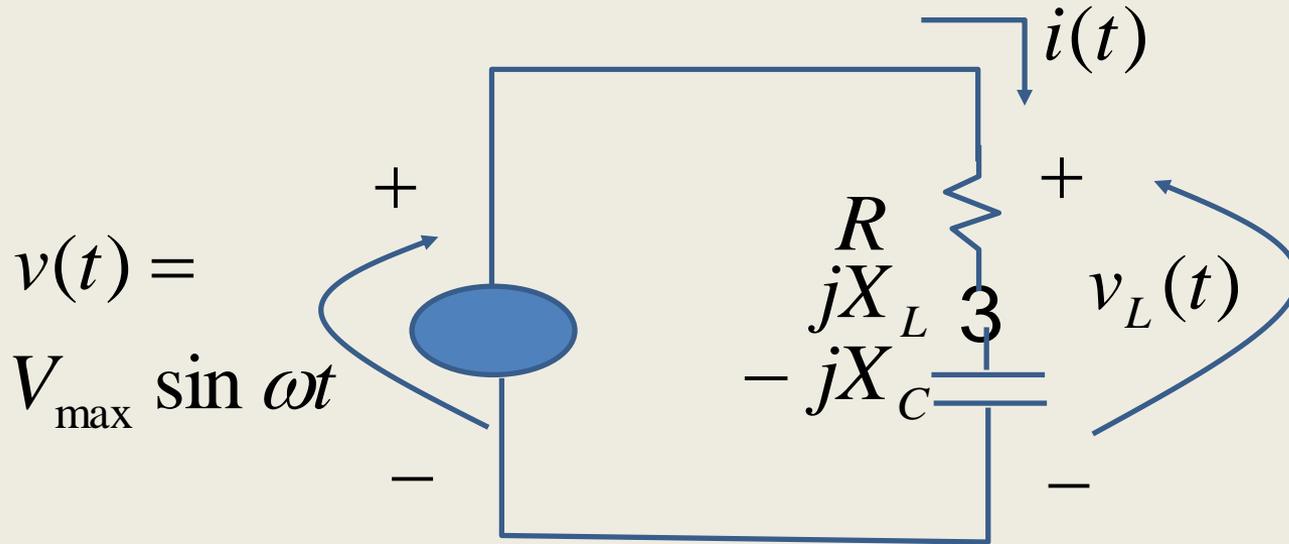
Chapter 4: Polyphase systems

4.1 Three-phase systems

4.2 Line-Line Voltages

Pop Quiz!!!

Let $R=2\Omega$, $C=0.001\text{farad}$, $L=0.01\text{henry}$, $V_{\max}=400$.

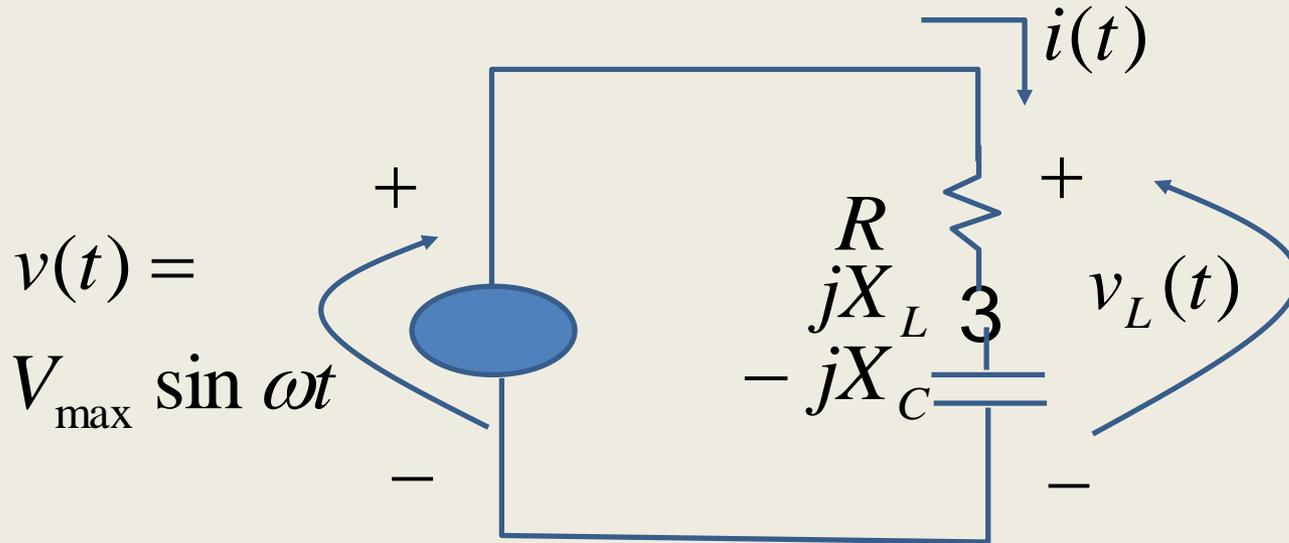


$$\omega = 377 \text{ rad / sec}$$

You have 3 mins to compute the current $i(t)$. If you don't know how, write down what you think are questions that, if answered, would enable you to do it.

Example 1

Let $R=2\Omega$, $C=0.001$ farad, $L=0.01$ henry, $V_{\max}=400$.



Compute the current $i(t)$

$$\begin{aligned} \text{Then } Z &= R + j\omega L - j/\omega C = 2 + j377 \times 0.01 - j/(377 \times 0.001) \\ &= 2 + j(3.77 - 2.6525) = 2 + j1.1048 \end{aligned}$$

The current will be

$$i(t) = \frac{v_L(t)}{Z} = \frac{V_{\max} \sin \omega t}{Z} = \frac{400 \sin \omega t}{2 + j1.1048}$$

Let's look into this a bit...

Basic concepts of electric power

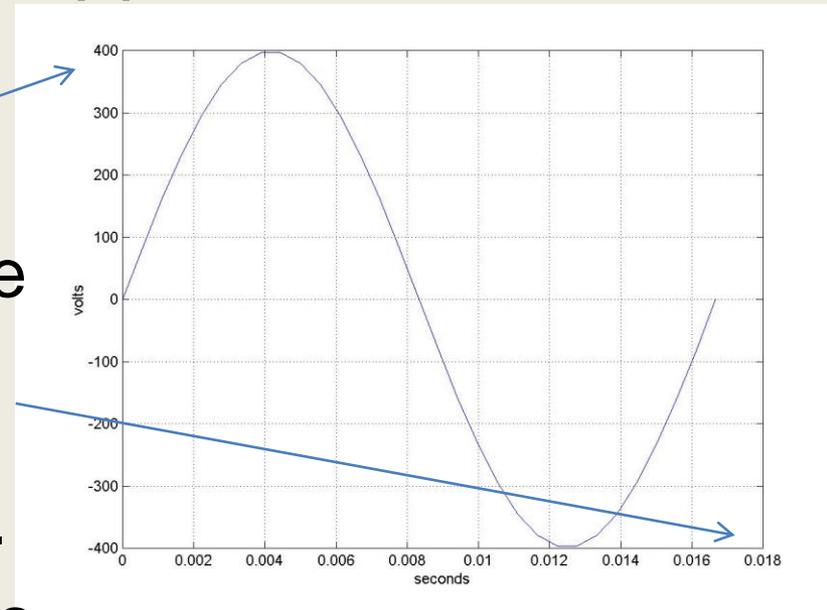
With exception of a few High Voltage DC circuits, the entire electric grid operates to deliver “alternating current” (AC). An “AC voltage” appears below.

The maximum value of the waveform is 400 volts.

The waveform completes one cycle in 0.0167 sec. This is the “period” of the waveform and is $1/f$. So, $f=1/0.0167=60\text{Hz}$ or 60 cycles/sec.

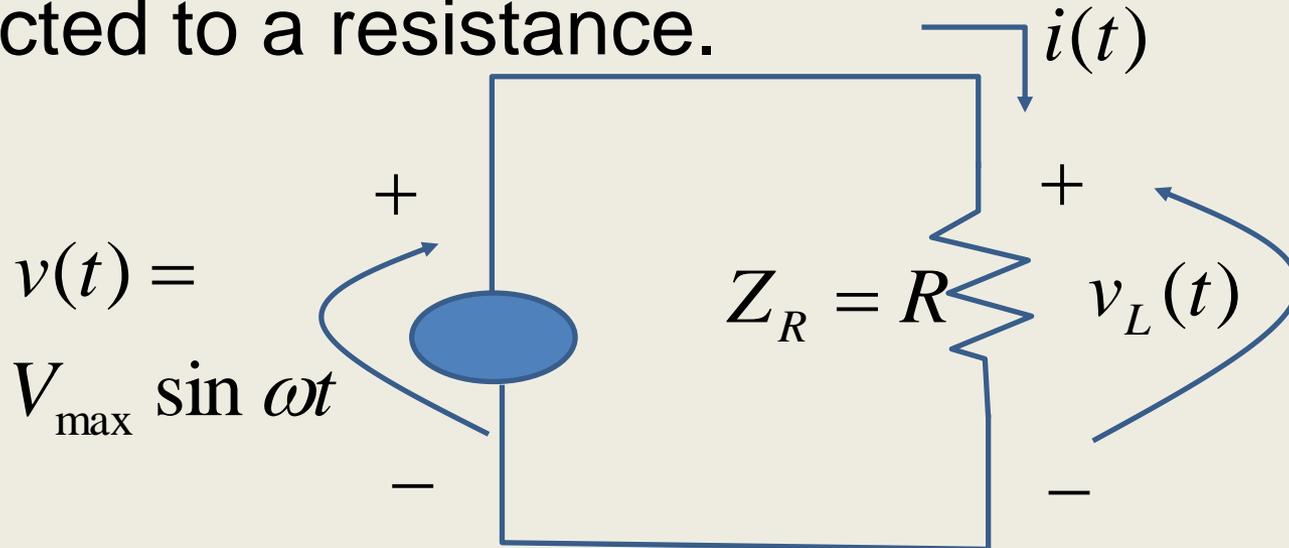
Since 1 cycle completes 2π radians, $\omega=(2\pi \text{ rad/cyc})\cdot 60\text{cyc/sec}=377\text{rad/sec}$.

We can therefore express this voltage as $v(t) = V_{\max} \sin \omega t = 400 \sin(377t)$



KVL and Ohm's Law

The below is a circuit model of a voltage source connected to a resistance.



We apply Kirchoff's Voltage Law (KVL): the sum of voltages around the loop must be 0:

$$v(t) - v_L(t) = 0$$

$$\Rightarrow v_L(t) = v(t)$$

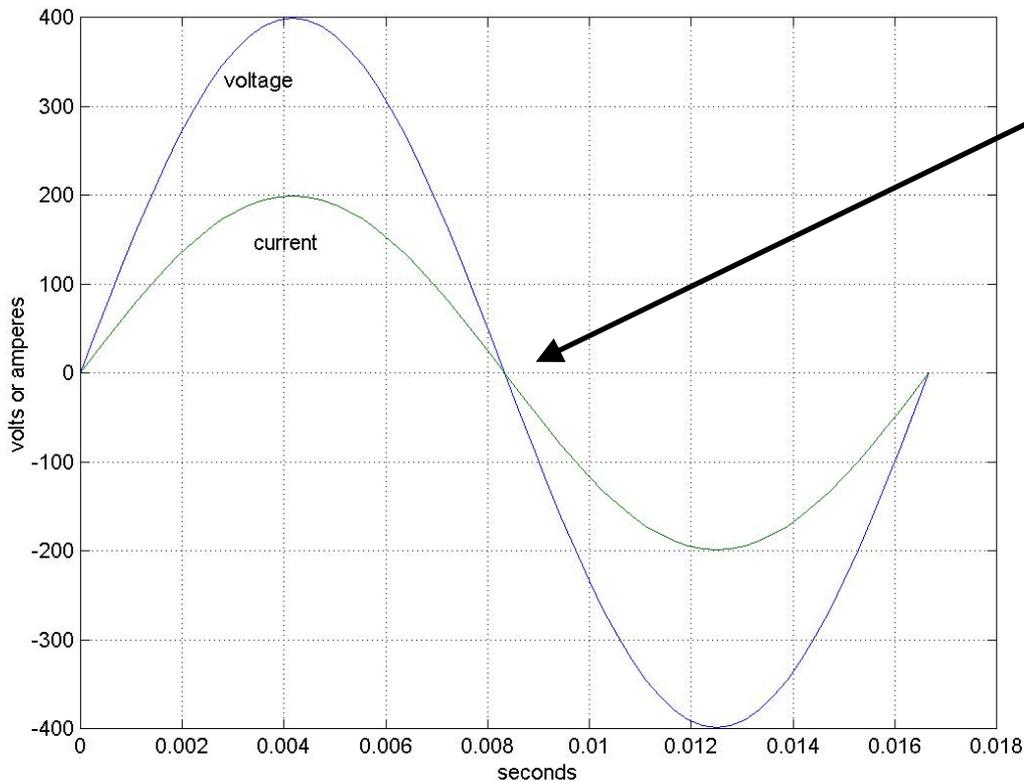
We may apply Ohm's Law to obtain the current:

$$i(t) = \frac{v_L(t)}{Z_R} = \frac{V_{\max}}{R} \sin \omega t$$

Voltage and current for resistive cct

Compare voltage & current. Assume $R=2$ ohms.

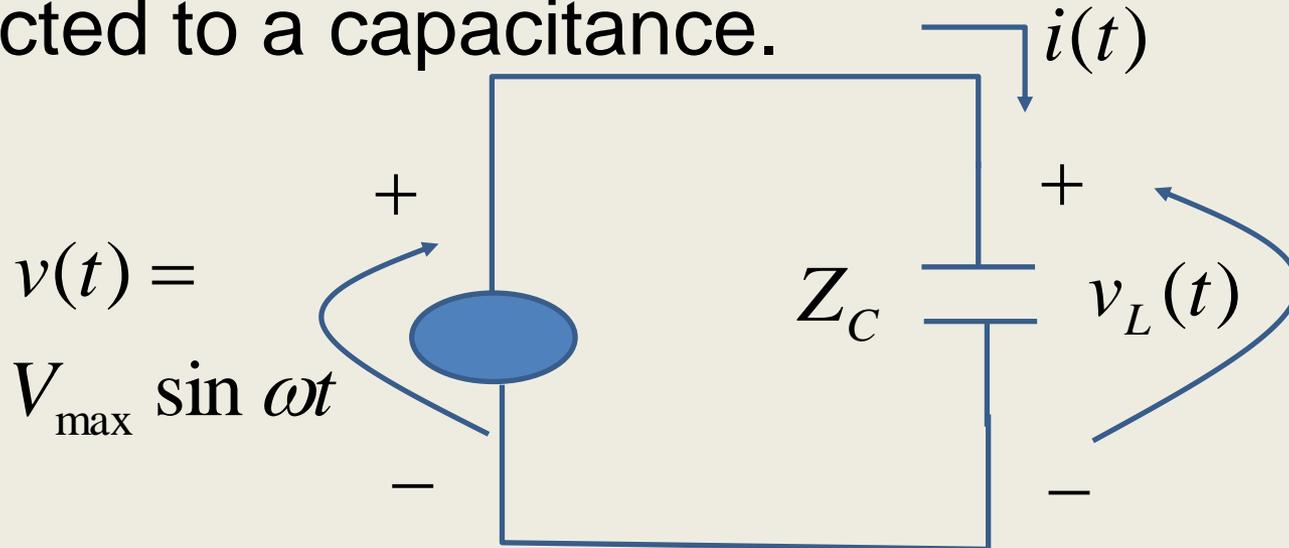
$$v_L(t) = V_{\max} \sin \omega t \qquad i(t) = \frac{V_{\max}}{R} \sin \omega t = \frac{400}{2} \sin 377t$$



Current & voltage
cross 0 simultaneously

Capacitance

The below is a circuit model of a voltage source connected to a capacitance.



Again, from KVL:

$$v(t) - v_L(t) = 0$$

$$\Rightarrow v_L(t) = v(t)$$

The current is given by:

$$i(t) = C \frac{dv_L(t)}{dt} = \omega C V_{\max} \cos \omega t$$

$$= \omega C V_{\max} \sin \left(\omega t + \frac{\pi}{2} \right)$$

$$= \frac{V_{\max}}{1/\omega C} \sin \left(\omega t + \frac{\pi}{2} \right)$$

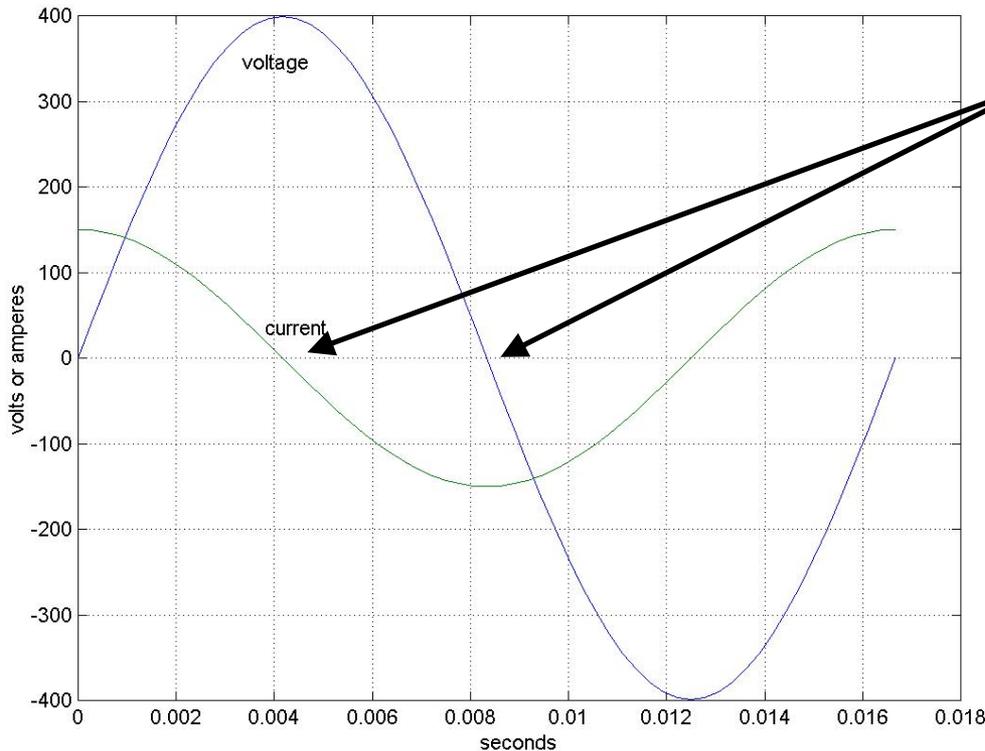
$\cos \omega t =$ $\sin(\omega t + \pi/2)$

Voltage and current for capacitive cct

Compare voltage & current. Assume $C=0.001$ farad.

$$v_L(t) = V_{\max} \sin \omega t \quad i(t) = C\omega V_{\max} \sin\left(\omega t + \frac{\pi}{2}\right) =$$

$$.001 \times 377 \times 400 \sin\left(\omega t + \frac{\pi}{2}\right) = 150.8 \sin\left(\omega t + \frac{\pi}{2}\right)$$

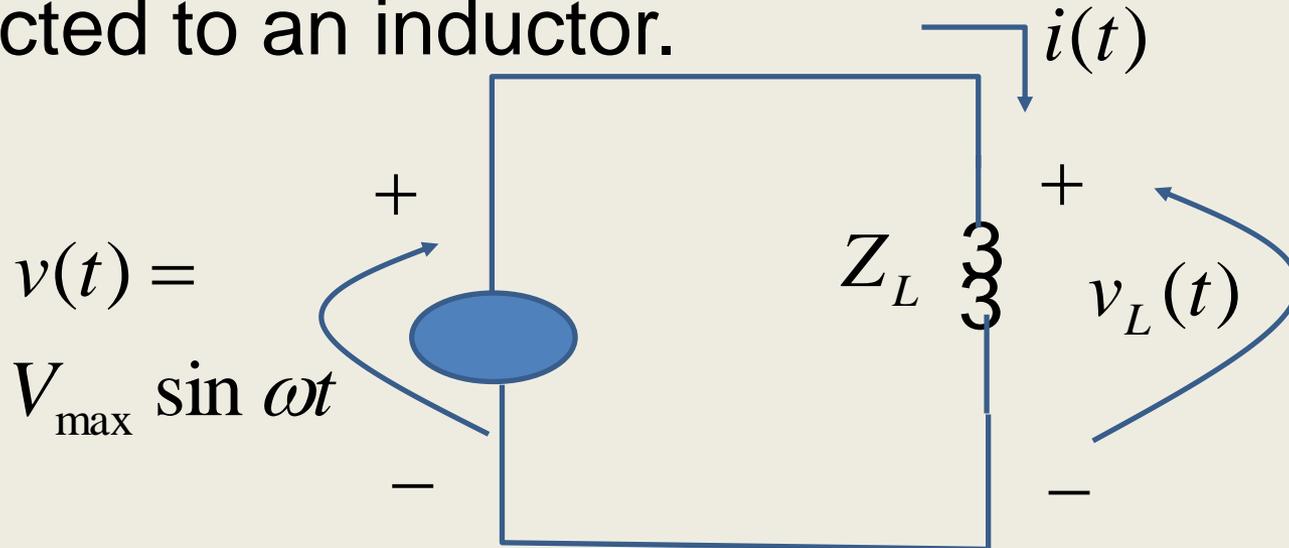


Current crosses 0 before voltage. We say “current leads voltage.”

If we multiply the time axis by $\omega=377$ rad/sec, we would see that current leads voltage by $\pi/2$ radians.

Inductance

The below is a circuit model of a voltage source connected to an inductor.



Again, from KVL:

$$v(t) - v_L(t) = 0$$

$$\Rightarrow v_L(t) = v(t)$$

The current is given by:

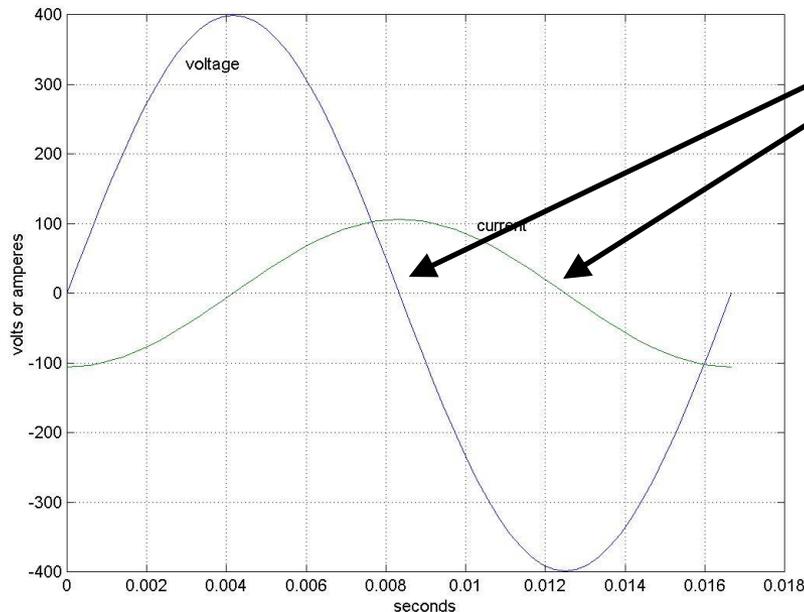
$$\begin{aligned} i(t) &= \frac{1}{L} \int v_L(t) = \frac{-V_{\max}}{\omega L} \cos \omega t \\ &= \frac{-V_{\max}}{\omega L} \sin\left(\omega t + \frac{\pi}{2}\right) = \frac{V_{\max}}{\omega L} \sin\left(\omega t - \frac{\pi}{2}\right) \end{aligned}$$

Voltage and current for inductive cct

Compare voltage & current. Assume $L=0.01$ henry.

$$v_L(t) = V_{\max} \sin \omega t \quad i(t) = \frac{V_{\max}}{\omega L} \sin \left(\omega t - \frac{\pi}{2} \right)$$
$$= \frac{400}{377 \times 0.01} \sin \left(\omega t - \frac{\pi}{2} \right) = 106.1 \sin \left(\omega t - \frac{\pi}{2} \right)$$

Current crosses 0 after voltage. We say “current lags voltage.”



If we multiply the time axis by $\omega=377$ rad/sec, we would see that current lags voltage by $\pi/2$ radians.

In the three expressions below, we use Ohm's law to express current in terms of impedance, then equate that expression to the one we found in the 5 previous slides.

$$v_L(t) = V_{\max} \sin \omega t \quad \text{Impedance}$$

RESISTIVE:
$$i(t) = \frac{v_L(t)}{Z_R} = \frac{V_{\max}}{R} \sin \omega t$$
 It is clear that $Z_R=R$.

CAPACITIVE:
$$i(t) = \frac{v_L(t)}{Z_C} = \frac{V_{\max}}{1/\omega C} \sin\left(\omega t + \frac{\pi}{2}\right)$$

INDUCTIVE:
$$i(t) = \frac{v_L(t)}{Z_L} = \frac{V_{\max}}{\omega L} \sin\left(\omega t - \frac{\pi}{2}\right)$$

Is $Z_C=1/\omega C$? Is $Z_L=\omega L$?

No, because we also need to take care of the phase shifts.

Impedance

To take care of phase shifts, let's utilize the imaginary unit "j" which has the following properties:

- It is the square root of -1: $j = \sqrt{-1}$
- From the Euler relation: $e^{j\phi} = \cos\phi + j\sin\phi$

With $\phi = \pi/2$, we obtain: $e^{j\pi/2} = \cos\pi/2 + j\sin\pi/2 = j$

Therefore, j has magnitude of "1" and angle $\pi/2$.

Therefore

$$j \sin \omega t = \sin\left(\omega t + \frac{\pi}{2}\right) \quad \frac{\sin \omega t}{j} = \sin\left(\omega t - \frac{\pi}{2}\right)$$

Then, with $Z_C = 1/j\omega C$, $Z_L = j\omega L$, we get correct current expressions.

Impedance

RESISTIVE:
$$i(t) = \frac{v_L(t)}{Z_R} = \frac{V_{\max}}{R} \sin \omega t$$

CAPACITIVE:
$$i(t) = \frac{v_L(t)}{Z_C} = \frac{V_{\max} \sin \omega t}{1/j\omega C} = V_{\max} j\omega C \sin \omega t = V_{\max} \omega C \sin \left(\omega t + \frac{\pi}{2} \right)$$

INDUCTIVE:
$$i(t) = \frac{v_L(t)}{Z_L} = \frac{V_{\max} \sin \omega t}{j\omega L} = \frac{V_{\max}}{\omega L} \frac{\sin \omega t}{j} = \frac{V_{\max}}{\omega L} \sin \left(\omega t - \frac{\pi}{2} \right)$$

Z, called impedance, is a generalization of resistance that accounts for the effects of capacitance & inductance.

Impedance

In a purely resistive circuit, $Z=Z_R=R$.

In a purely capacitive circuit, $Z=Z_C=1/j\omega C$.

In a purely inductive circuit, $Z=Z_L=j\omega L$.

We also define:

- Capacitive reactance: $X_C=1/\omega C$
- Inductive reactance: $X_L=\omega L$

In a purely resistive circuit, $Z=Z_R=R$.

In a purely capacitive circuit, $Z=Z_C=1/j\omega C=X_C/j$.

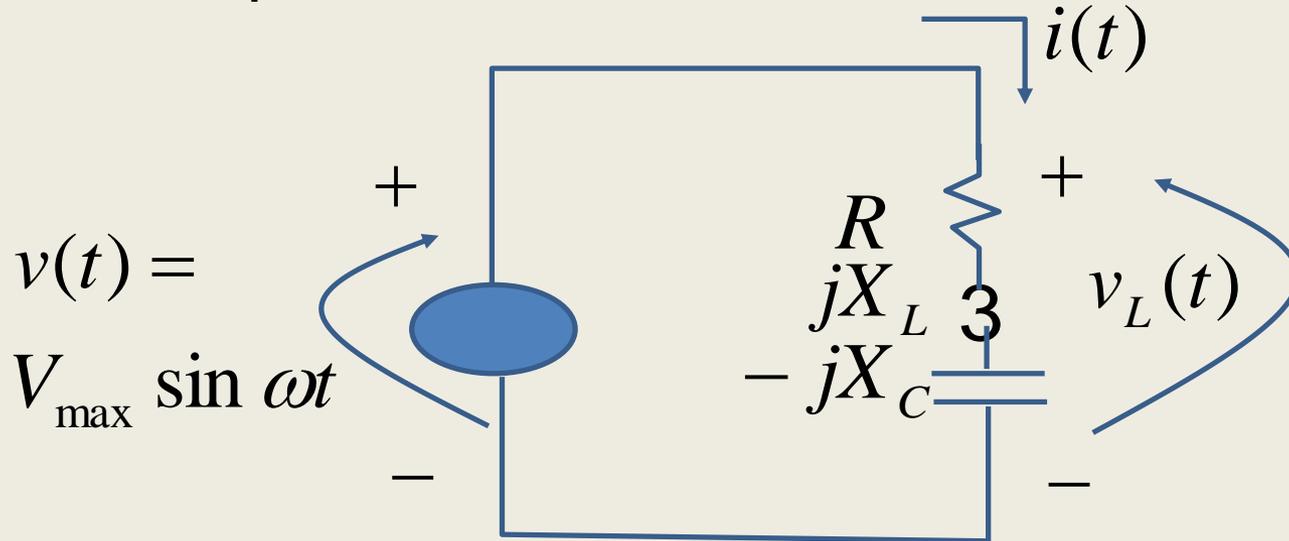
But recall $j=\sqrt{-1}$, then $j^2=-1$. So $(X_C/j)^*(j/j)=-jX_C$.

So $Z=Z_C=-jX_C$.

In a purely inductive circuit, $Z=Z_L=j\omega L=jX_L$.

Impedance

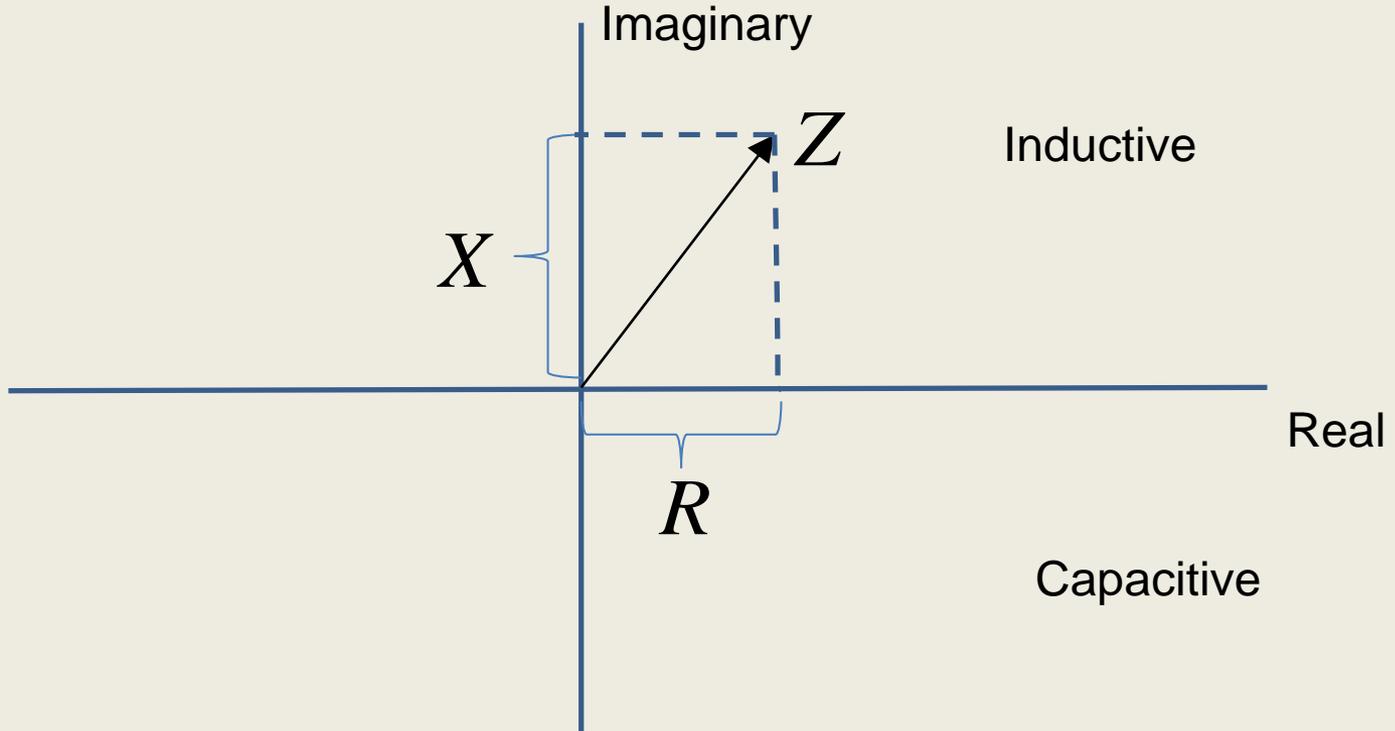
It is possible to have an impedance that is a combination of resistance, capacitance, and inductance.



Then
$$Z = R + jX_L - jX_C = R + j(X_L - X_C) = R + jX$$

The impedance, Z , can be thought of as a vector on the complex plane.

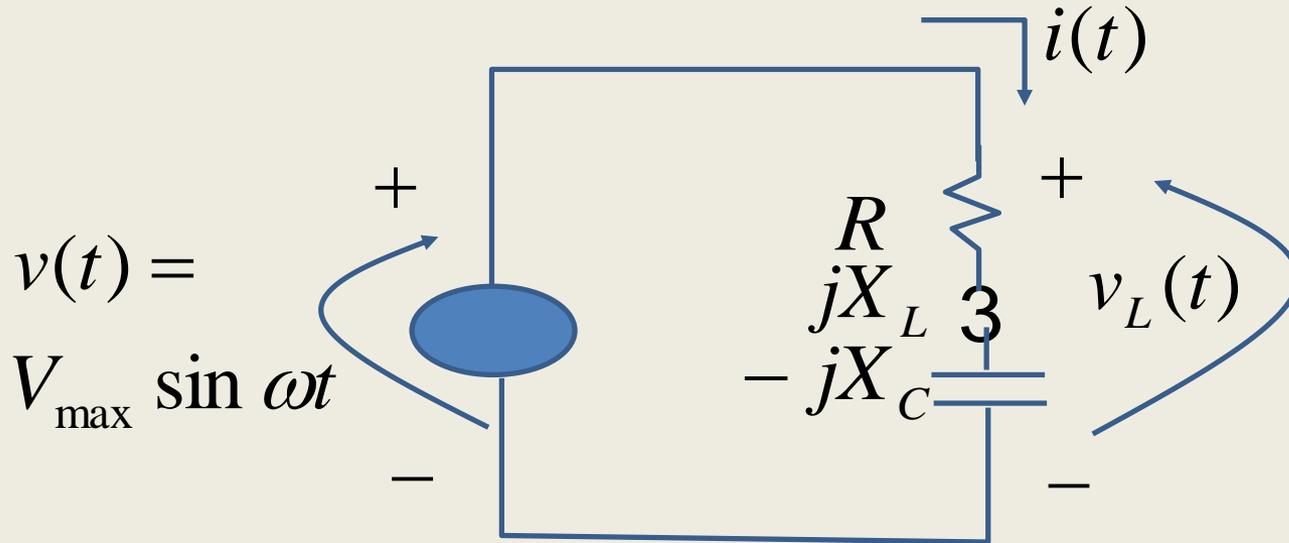
Impedance



$$Z = R + jX_L - jX_C = R + j(X_L - X_C) = R + jX$$

Example 1

Let $R=2\Omega$, $C=0.001$ farad, $L=0.01$ henry, $V_{\max}=400$.



Compute the current $i(t)$

$$\begin{aligned} \text{Then } Z &= R + j\omega L - j/\omega C = 2 + j377 \times 0.01 - j/(377 \times 0.001) \\ &= 2 + j(3.77 - 2.6525) = 2 + j1.1048 \end{aligned}$$

The current will be

$$i(t) = \frac{v_L(t)}{Z} = \frac{V_{\max} \sin \omega t}{Z} = \frac{400 \sin \omega t}{2 + j1.1048}$$

But how to evaluate this?

Example 1

$$i(t) = \frac{400 \sin \omega t}{2 + j1.1048}$$

You can divide each numerical point in the sinusoidal numerator by the complex denominator, then take the magnitude and angle of each resulting complex number.

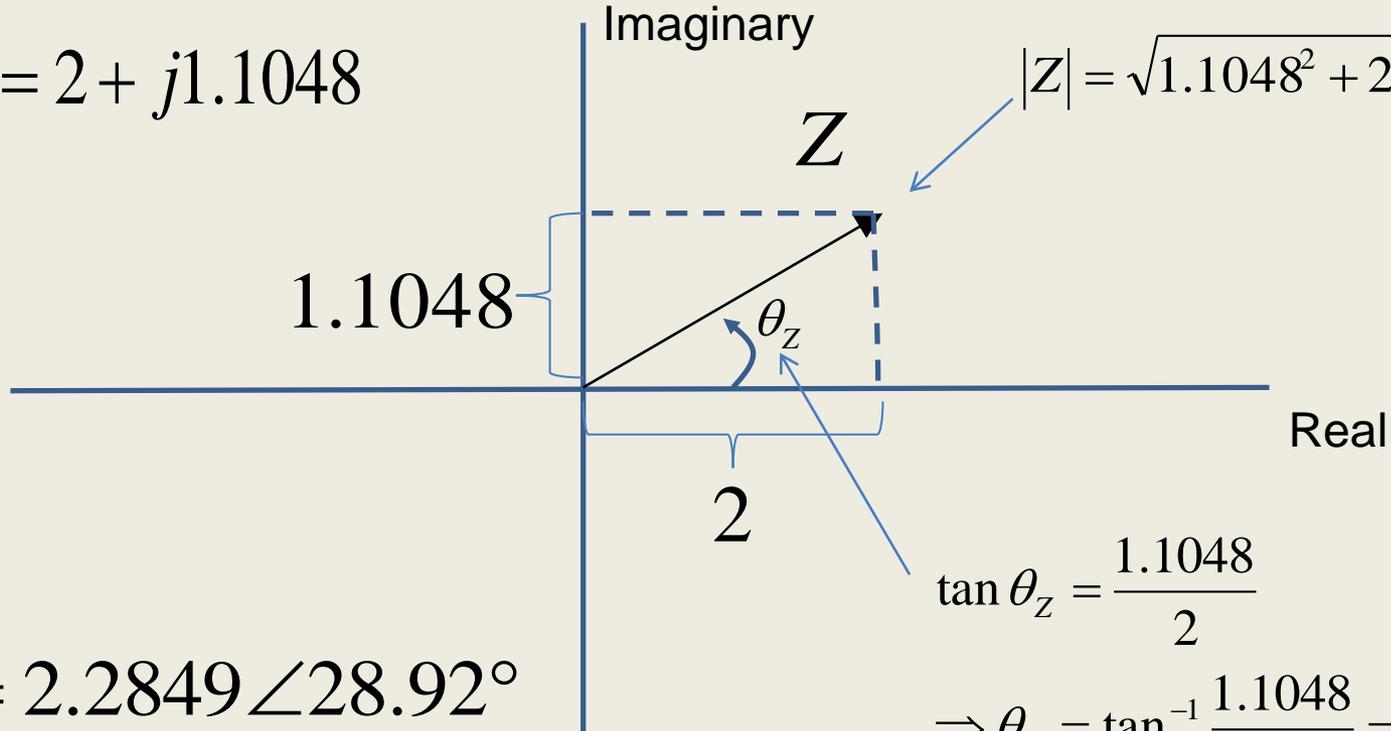
But observe that only the magnitude changes as t increases. This is because the “phasor angle” of the numerator (0°) and the vector angle of the denominator both remain constant with t . That is:

$$i(t) = \frac{400 \sin \omega t}{2 + j1.1048} = \frac{400 \angle 0 \sin \omega t}{\underbrace{|Z| \angle \theta_Z}}$$

→ But what is $|Z| \angle \theta_Z$?

Impedance

$$|Z| \angle \theta_z = 2 + j1.1048$$



$$|Z| = \sqrt{1.1048^2 + 2^2} = 2.2849$$

$$\tan \theta_z = \frac{1.1048}{2}$$

$$\Rightarrow \theta_z = \tan^{-1} \frac{1.1048}{2} =$$

$$0.5047 \text{ radians} = 28.92^\circ$$

So:

$$|Z| \angle \theta_z = 2.2849 \angle 28.92^\circ$$

And from the previous slide:

$$i(t) = \frac{400 \angle 0 \sin \omega t}{|Z| \angle \theta_z} = \frac{400}{|Z|} (\angle (0 - \theta_z)) \sin \omega t$$

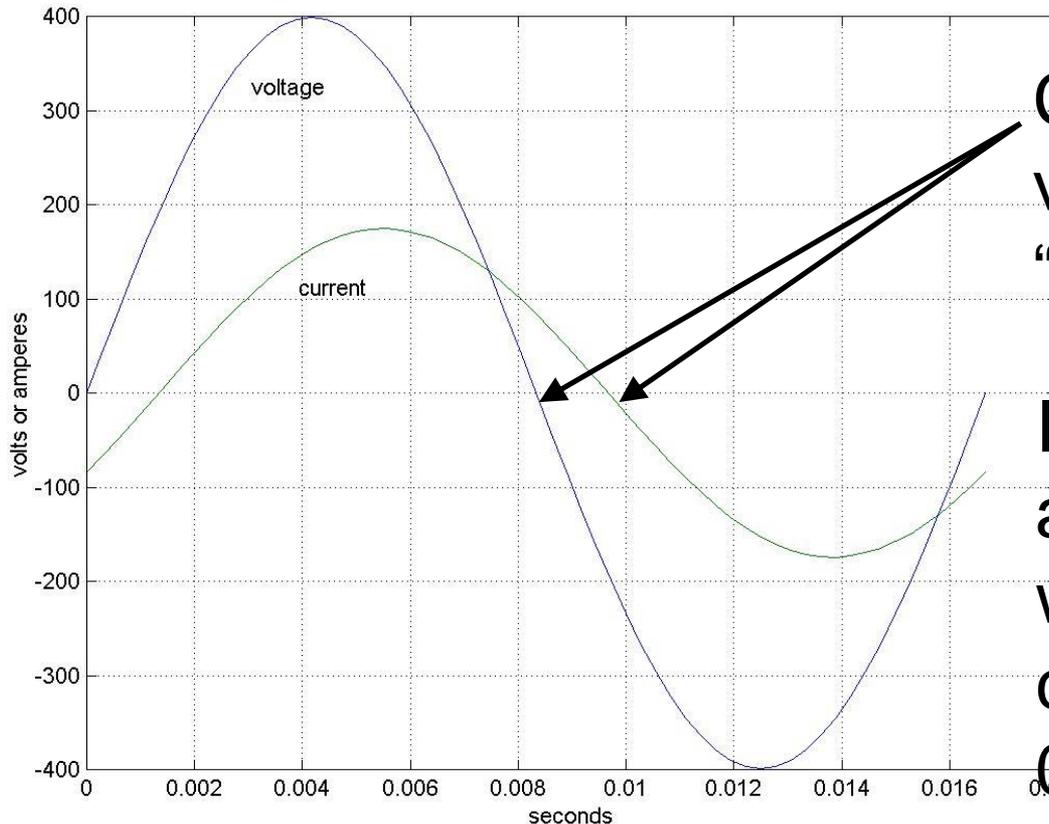
$$= \frac{400}{2.2849} (\angle -28.92^\circ) \sin \omega t = 175.06 \angle -28.92^\circ \sin \omega t$$

Impedance

$$\text{So } i(t) = 175.06 \angle -28.92^\circ \sin \omega t$$

Recalling that $28.92^\circ = 0.5047$ radians, we write the above as:

$$i(t) = 175.06 \sin(\omega t - 0.5047) \quad \rightarrow \text{We can plot this:}$$



Current crosses 0 after voltage. We say “current lags voltage.”

If we multiply the time axis by $\omega = 377$ rad/sec, we would see that current lags voltage by 0.5047 radians.

Phasors

Let's review what we just did:

$$\begin{aligned}
 i(t) &= \frac{\overset{\text{Ohm's Law}}{v_L(t)}}{Z} = \frac{V_{\max} \overset{\text{Express } v_L(t)}{\sin \omega t}}{Z} = \frac{\overset{\text{Express numerically}}{400 \sin \omega t}}{2 + j1.1048} \\
 &= \frac{\overset{\text{Express in "polar" notation}}{400 \angle 0 \sin \omega t}}{|Z| \angle \theta_Z} = \frac{\overset{\text{Separate magnitude \& angle calculations}}{400}}{|Z|} (\angle(0 - \theta_Z)) \sin \omega t = \frac{\overset{\text{Express numerically}}{400}}{2.2849} (\angle -28.92^\circ) \sin \omega t \\
 &= \overset{\text{Do the arithmetic}}{(175.06 \angle -28.92^\circ)} \overset{\text{Convert from polar notation to trigonometric notation}}{\sin \omega t} = 175.06 \sin(\omega t - 0.5047)
 \end{aligned}$$

Notice that nothing ever happened to the ωt part. Nor did the sinusoidal function change. This means that the frequency of the current is the same as the frequency of the voltage. If this is the case, then why do we need to carry the $\sin \omega t$ through the calculations? Why not just drop it? This is what we do when we use phasor notation, as in the next slide.

Phasors

Define:

Phasor for source voltage:

Phasor for load voltage:

Phasor for current:

Also recall the impedance:

Then...

$$\hat{\mathbf{V}}_S = V_S \angle \phi_{V_S}$$

$$\hat{\mathbf{V}}_L = V_L \angle \phi_{V_L}$$

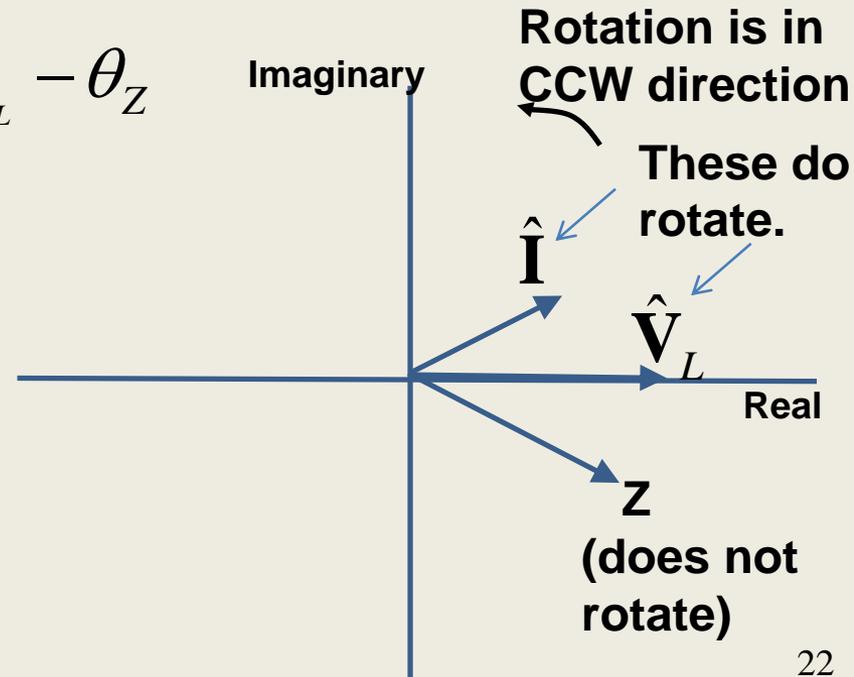
$$\hat{\mathbf{I}} = I \angle \phi_I$$

$$\mathbf{Z} = |\mathbf{Z}| \angle \theta_Z$$

There is an implicit $\sin\omega t$ that we are not writing. This $\sin\omega t$ gives rotation to the vectors which make them phasors.

There is no implicit $\sin\omega t \rightarrow$ impedance is a vector, not a phasor!

$$\hat{\mathbf{I}} = I \angle \phi_I = \frac{\hat{\mathbf{V}}_L}{\mathbf{Z}} = \frac{V_L \angle \phi_{V_L}}{|\mathbf{Z}| \angle \theta_Z} = \frac{V_L}{|\mathbf{Z}|} \angle \phi_{V_L} - \theta_Z$$



Instantaneous Power

Instantaneous power is given by $p(t) = v(t)i(t)$

Let $v(t) = V_{\max} \cos(\omega t + \theta_v)$ $i(t) = I_{\max} \cos(\omega t + \theta_i)$

Then $p(t) = v(t)i(t) = V_{\max} \cos(\omega t + \theta_v) I_{\max} \cos(\omega t + \theta_i)$
 $= V_{\max} I_{\max} \cos(\omega t + \theta_v) \cos(\omega t + \theta_i)$

Apply trig identity: $\cos a \cos b = \frac{1}{2} [\cos(a - b) + \cos(a + b)]$

$$p(t) = \frac{V_{\max} I_{\max}}{2} [\cos(\omega t + \theta_v - \omega t - \theta_i) + \cos(\omega t + \theta_v + \omega t + \theta_i)]$$

$$= \frac{V_{\max} I_{\max}}{2} [\cos(\theta_v - \theta_i) + \cos(2\omega t + \theta_v + \theta_i)] = \frac{V_{\max} I_{\max}}{2} [\cos(\theta_v - \theta_i) + \cos(2\omega t + \underbrace{2\theta_v - \theta_v + \theta_i}_{\theta_v})]$$

Gathering terms in the argument of the second cos function:

$$p(t) = \frac{V_{\max} I_{\max}}{2} [\cos(\theta_v - \theta_i) + \cos(2(\omega t + \theta_v) - (\theta_v - \theta_i))]$$

Instantaneous Power

$$p(t) = \frac{V_{\max} I_{\max}}{2} \left[\cos(\theta_v - \theta_i) + \cos(2(\omega t + \theta_v) - (\theta_v - \theta_i)) \right]$$

Apply trig identity to last term: $\cos(a - b) = \cos a \cos b + \sin a \sin b$

$$p(t) = \frac{V_{\max} I_{\max}}{2} \left[\cos(\theta_v - \theta_i) + \cos 2(\omega t + \theta_v) \cos(\theta_v - \theta_i) + \sin 2(\omega t + \theta_v) \sin(\theta_v - \theta_i) \right]$$

Rearrange and distribute:

$$p(t) = \frac{V_{\max} I_{\max}}{2} \cos(\theta_v - \theta_i) + \frac{V_{\max} I_{\max}}{2} \cos(\theta_v - \theta_i) \cos 2(\omega t + \theta_v) + \frac{V_{\max} I_{\max}}{2} \sin(\theta_v - \theta_i) \sin 2(\omega t + \theta_v)$$

Then: $p(t) = P + P \cos 2(\omega t + \theta_v) + Q \sin 2(\omega t + \theta_v)$

where: $P = \frac{V_{\max} I_{\max}}{2} \cos(\theta_v - \theta_i), \quad Q = \frac{V_{\max} I_{\max}}{2} \sin(\theta_v - \theta_i)$

↑
Real power
Active power
Watts

↑
Imaginary power
Reactive power
VARs

Example 2

Consider example 1, where $V_{\max}=400$, $\theta_v=0$,

$$v(t) = V_{\max} \sin(\omega t + \theta_v)$$

and we computed that $I_{\max}=175.06$, $\theta_i = -.5047\text{rad}$,

$$i(t) = I_{\max} \sin(\omega t + \theta_i)$$

Then:

$$P = \frac{V_{\max} I_{\max}}{2} \cos(\theta_v - \theta_i) = \frac{400 \times 175.06}{2} \cos(0 + .5047) = 30647 \quad \text{watts}$$

$$Q = \frac{V_{\max} I_{\max}}{2} \sin(\theta_v - \theta_i) = \frac{400 \times 175.06}{2} \sin(0 + .5047) = 16930 \quad \text{vars}$$

$$\begin{aligned} p(t) &= P + P \cos 2(\omega t + \theta_v) + Q \sin 2(\omega t + \theta_v) \\ &= 30647 + 30647 \cos 2(377t) + 16930 \sin 2(377t) \end{aligned}$$

TERM1

TERM2

TERM3

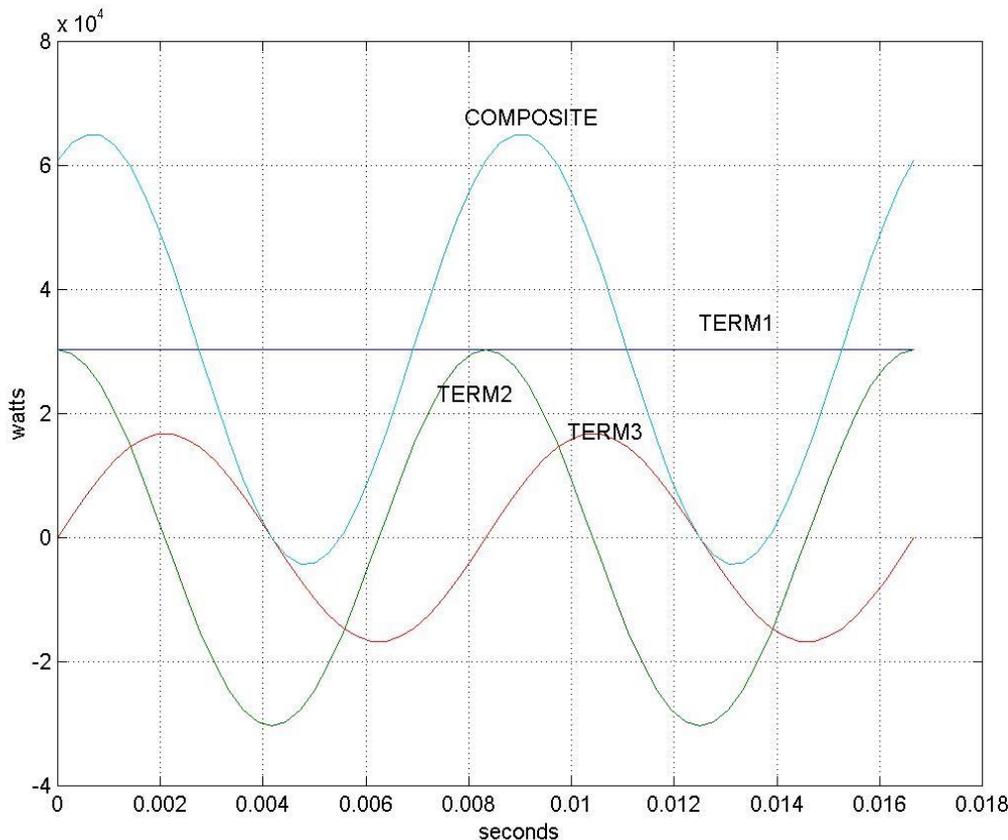
Example 2

$$p(t) = P + P \cos 2(\omega t + \theta_v) + Q \sin 2(\omega t + \theta_v)$$
$$= 30647 + 30647 \cos 2(377t) + 16930 \sin 2(377t)$$

TERM1

TERM2

TERM3



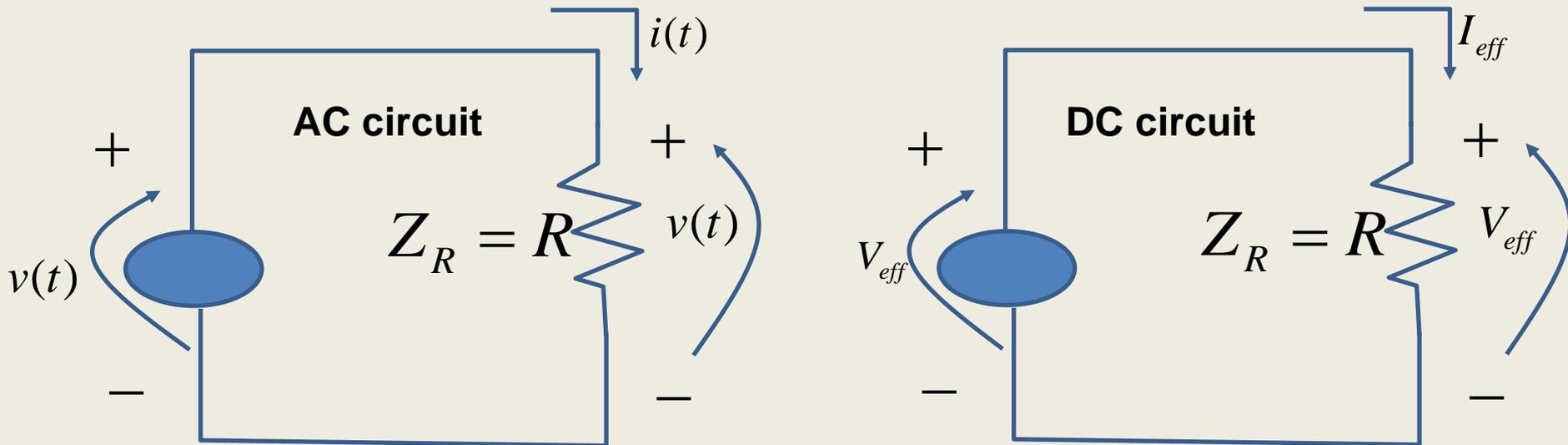
The average of a periodic signal $x(t)$ is given by:

$$X_{avg} = \frac{1}{T} \int_T x(t) dt$$

- Power delivered is the avg of $p(t)$; power is delivered only if the avg of $p(t)$ is not 0.
- The average value of term2 and term3 is 0. These terms are not responsible for power delivery.
- Average value of the composite [the composite is instntns power, $p(t)$] is term1, P .
- Interesting side note: instntns power varies at twice the nominal frequency.

Effective or RMS value

We want to obtain the constant (or DC) value of a current which delivers the same average power to a resistor.



The power delivered is:

$$P = \frac{1}{T} \int_T i^2(t) R dt$$

The power delivered is:

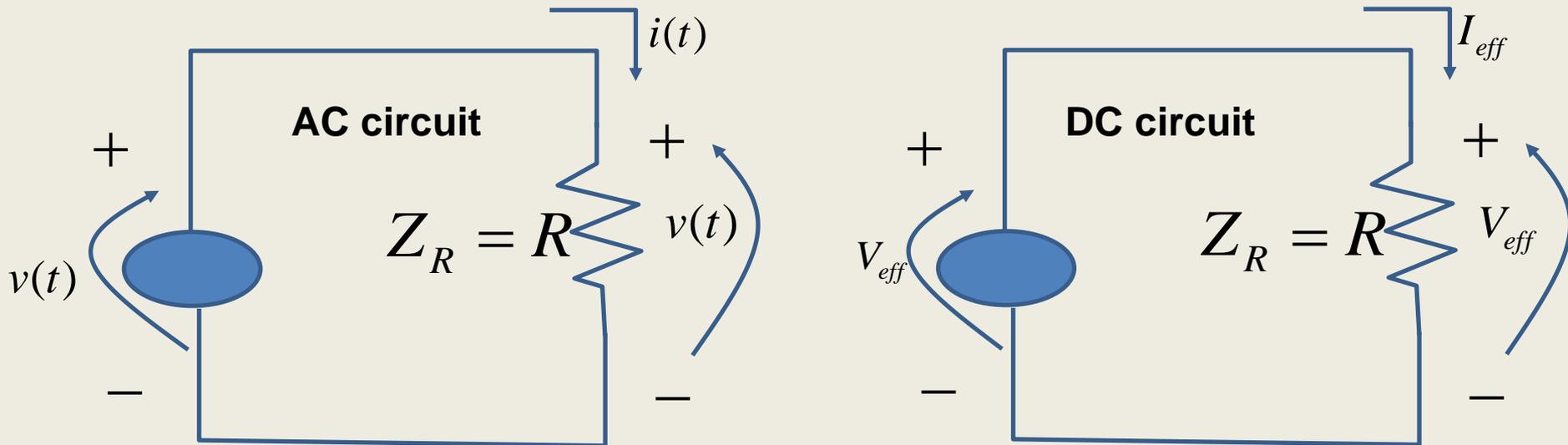
$$P = I_{eff}^2 R$$

← Equate →

$$\frac{1}{T} \int_T i^2(t) R dt = I_{eff}^2 R \Rightarrow I_{eff} = \sqrt{\frac{1}{T} \int_T i^2(t) dt}$$

Effective or RMS value

We want to obtain the constant (or DC) value of a voltage which delivers the same average power to a resistor.



The power delivered is:

$$P = \frac{1}{T} \int_T v^2(t) / R dt$$

The power delivered is:

$$P = V_{eff}^2 / R$$

← Equate →

$$\frac{1}{T} \int_T v^2(t) / R dt = V_{eff}^2 / R \Rightarrow V_{eff} = \sqrt{\frac{1}{T} \int_T v^2(t) dt}$$

Effective or RMS value

The root-mean-square value of any periodic signal $x(t)$ is:

$$X_{eff} = \sqrt{\frac{1}{T} \int_T x^2(t) dt}$$

Let $x(t)$ be $v(t)$: $v(t) = V_{\max} \sin(\omega t + \theta_v)$

$$V_{eff} = \sqrt{\frac{1}{T} \int_T v^2(t) dt} = \sqrt{\frac{1}{T} \int_T V_{\max}^2 \sin^2(\omega t + \theta_v) dt}$$

Apply trig identity: $\sin^2 a = \frac{1}{2}[1 - \cos(2a)]$

$$V_{eff} = \sqrt{\frac{V_{\max}^2}{2T} \int_T 1 - \cos(2(\omega t + \theta_v)) dt} = \sqrt{\frac{V_{\max}^2}{2T} t \Big|_0^T} = \sqrt{\frac{V_{\max}^2 T}{2T}} = \frac{V_{\max}}{\sqrt{2}}$$

Current may be similarly treated, resulting in $I_{eff} = \frac{I_{\max}}{\sqrt{2}}$

Power and Phasor notation

We previously derived power expressions for P and Q in terms of V_{\max} and I_{\max} . We may now express these in terms of rms (effective) values:

$$P = \frac{V_{\max} I_{\max}}{2} \cos(\theta_v - \theta_i) = \frac{\sqrt{2}V_{\text{eff}} \sqrt{2}I_{\text{eff}}}{2} \cos(\theta_v - \theta_i) = V_{\text{eff}} I_{\text{eff}} \cos(\theta_v - \theta_i)$$

$$Q = \frac{V_{\max} I_{\max}}{2} \sin(\theta_v - \theta_i) = \frac{\sqrt{2}V_{\text{eff}} \sqrt{2}I_{\text{eff}}}{2} \sin(\theta_v - \theta_i) = V_{\text{eff}} I_{\text{eff}} \sin(\theta_v - \theta_i)$$

This simplifies our power expressions. Commercial voltages and currents are always specified as rms values.

Phasor magnitudes may be rms or maximum. Unless it is otherwise specified, we assume phasor magnitudes are rms, and we will drop the subscript “eff.” Thus,

$$P = VI \cos(\theta_v - \theta_i); \quad Q = VI \sin(\theta_v - \theta_i)$$

Power factor

Power factor angle, defined θ , is the angle by which voltage across an element leads current through the element, i.e., $\theta = \theta_v - \theta_i$. It is also the angle of the load Z , i.e., $Z = |Z| \angle \theta$. One observes from the P , Q expressions that it is also the argument of the trig functions of P and Q . Therefore:

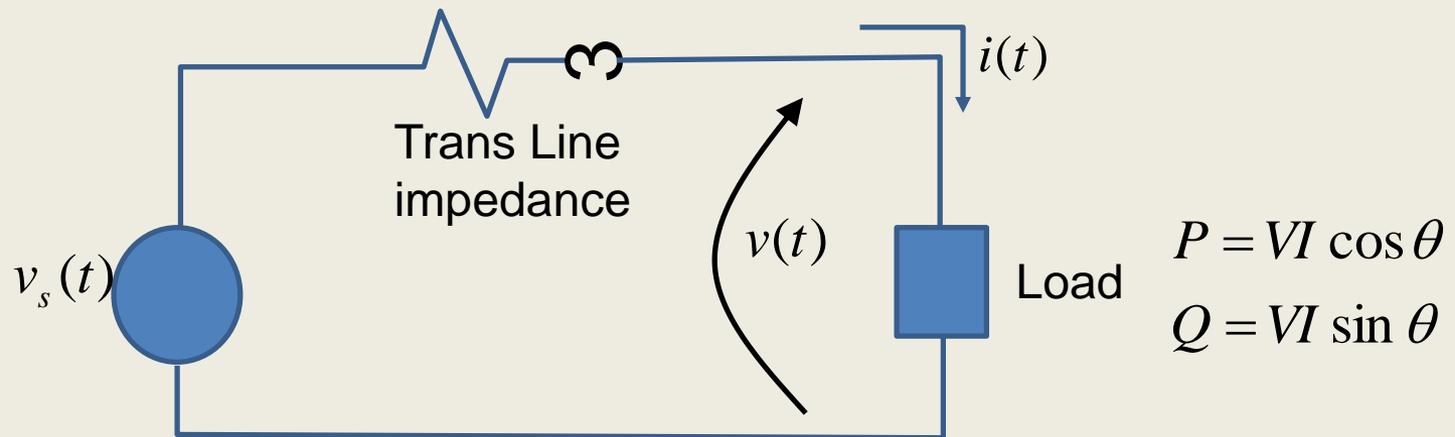
$$P = VI \cos(\theta_v - \theta_i) = VI \cos \theta; \quad Q = VI \sin(\theta_v - \theta_i) = VI \sin \theta$$

The power factor is given as $\text{pf} = \cos \theta$. It is always positive, therefore we usually indicate pf with either the word “leading” (for capacitive load) or “lagging” (for inductive load). The following table summarizes important relations.

Load, Z	$\text{Im}\{Z\}$	θ_i ($\theta_v=0$)	θ ($\theta_v=0$)	pf	Q sign	Q Load
R only	0	0	0	1.0	0	0 vars
R and L	+	-	+	0 to 1, lagging	+	Absorbing vars
R and C	-	+	-	0 to 1, leading	-	Supplying vars

Power factor

Consider a load at the end of a transmission line. Assume the load is highly inductive. This means current is lagging, $\theta_i < 0$, and $\theta > 0$ (with $\theta_v = 0$).



Assume V is constant, and we must supply P (this is the real power of the load). With V and P constant, from $P = VI \cos \theta$, $I \cos \theta = P/V$ must be constant. What do we want pf to be?

Power factor

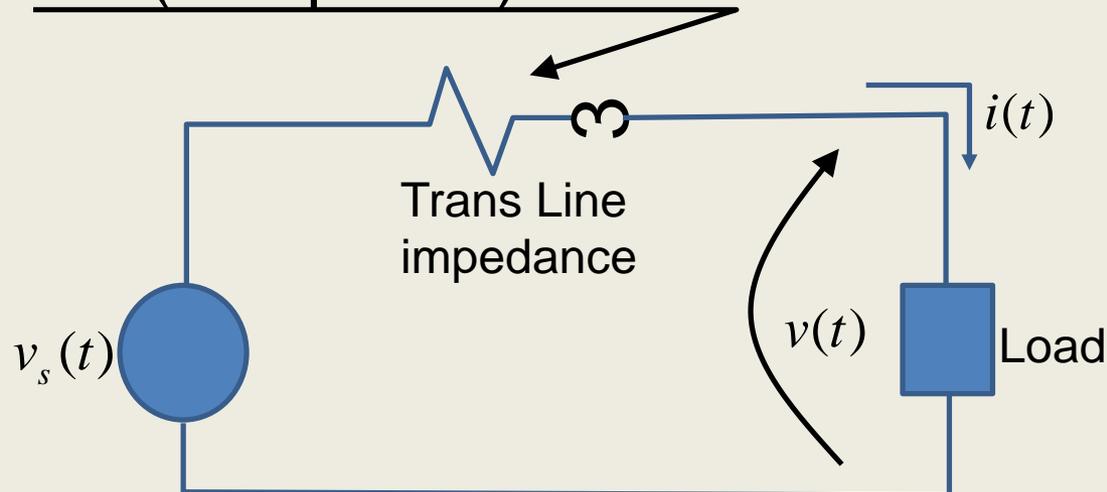
Assume $P=33\text{MW}$, $V=39.84\text{kV}$. This means that

$$P = VI \cos \theta \Rightarrow I \cos \theta = P/V = 33E6/39.84E3 = 828.3$$

Here are a few possibilities for $I \cos \theta = I \times \text{pf}$.

I (amperes)	828.3	871.9	920.3	1035.4
Pf (leading)	1	0.95	0.9	0.8

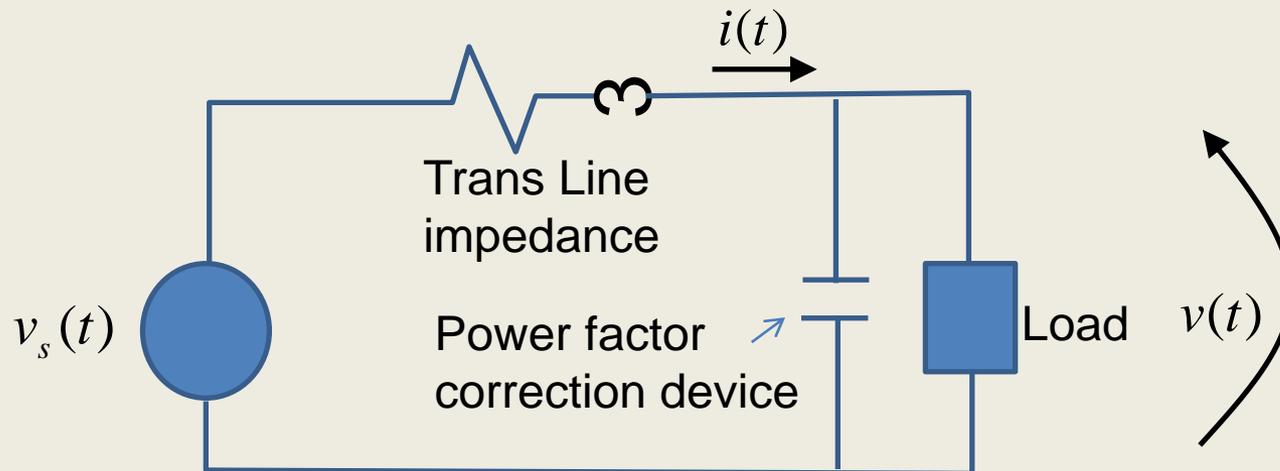
For a given P , we need higher pf to obtain lower current. Lower current is desired in order to minimize I^2R (real power) losses in the transmission line.



Power factor correction (PFC)

So what do you do if your load has a power factor of 0.85 but your provider requires that you have 0.95 ?

→ Install a PFC device at the load's point of interconnection with the grid.



The least expensive PFC device is a switched capacitor, or several switched capacitors. These are static devices, however. Dynamic devices are also available but are more expensive (and you get dynamic responsiveness as well).

What is reactive power?

1. It is given by: $Q = VI \sin(\theta_v - \theta_i)$
2. It occurs as the coefficient of the double frequency “sin” term in $p(t)$:

$$p(t) = P + P \cos 2(\omega t + \theta_v) + Q \sin 2(\omega t + \theta_v)$$

3. It is the maximum value of the rate of energy flowing alternately into the reactive component of the load (away from the source) and away from the reactive component of the load (toward the source). It is only present when there is a stored energy device (C or L) in the circuit.
4. Its units are “volt-amperes-reactive” or “vars.”
Dimensionally, vars are the same as watts and volt-amperes.
5. Three attributes of reactive power:
 - a. It does no useful work (its average value is 0).
 - b. Its presence increases current magnitude for a given P and V.
 - c. Derivatives of Q “flow” equations (not shown in these slides) indicate that Q is closely related to voltage magnitudes.

Complex power

Complex power is defined as:

$$S = \hat{\mathbf{V}}\hat{\mathbf{I}}^* = P + jQ$$

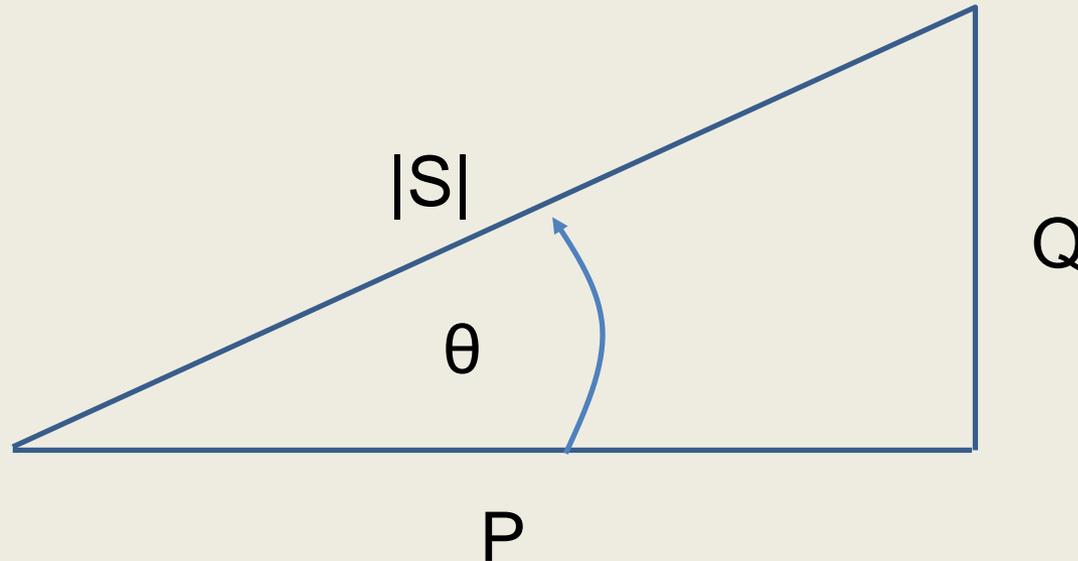
where:

$$\hat{\mathbf{V}} = V \angle \theta_v \quad \hat{\mathbf{I}} = I \angle \theta_i$$

The asterisk next to the “I” phasor indicates conjugation:

$$\hat{\mathbf{I}}^* = I \angle -\theta_i$$

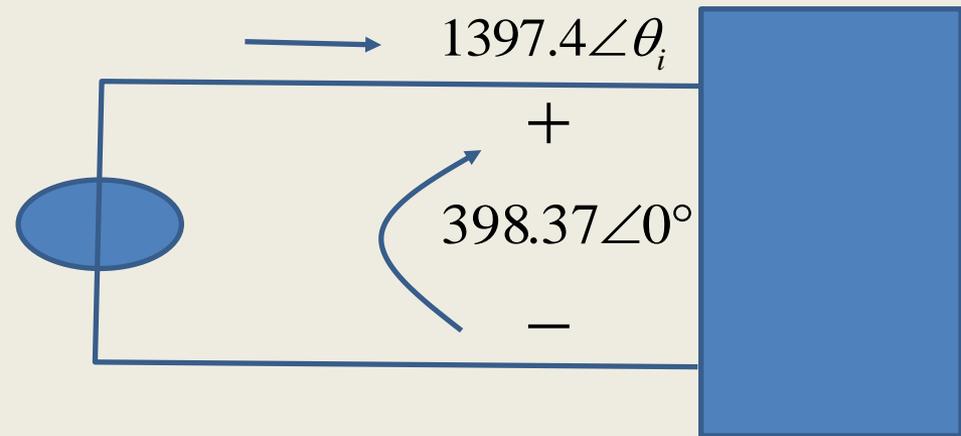
Power triangle



$$S = P + jQ \Rightarrow |S| = \sqrt{P^2 + Q^2}$$

Example 3

The below represents one of the phases of a generator supplying a load. The box to the right represents the load. The current flowing into the load is 1397.4 A at 0.866 pf leading, with 398.37 volts at its terminals. What complex power is delivered to the load from this phase alone?



Solution: $\theta = -\cos^{-1}(.866) = -30^\circ$.
 $\rightarrow \theta_i = -\theta = 30^\circ$.

$$\begin{aligned} S &= \hat{\mathbf{v}}\hat{\mathbf{i}}^* = 398.37\angle 0^\circ \times (1397.4\angle 30^\circ)^* \\ &= 398.37\angle 0^\circ \times (1397.4\angle -30^\circ) = 556680\angle -30^\circ \\ &= 556680(\cos 30^\circ - j \sin 30^\circ) = 482100 - j278340 \end{aligned}$$

Thus, $P = 0.482100\text{MW}$,
 $Q = -0.27834\text{MVARs}$

We also define the apparent power $|S|$, the magnitude of S :

$$S = P + jQ \Rightarrow |S| = \sqrt{P^2 + Q^2} = \sqrt{.4821^2 + .27834^2} = 0.5567$$