ECL 4340

POWER SYSTEMS

LECTURE 1
INTRODUCTION

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ABOUT PROF. KWANG LEE

- Professional
  - BSEE from Seoul National University, MSEE from North Dakota State, Ph.D. from Michigan State
  - ROTC & Army Signal Corps for 2 years
  - Electric Industry (Han Young) for 1 year
  - Faculty at MSU, OSU, UH, Penn State doing teaching and research in electric power systems
  - Have been at Baylor since 2007 as ECE Chair
  - Doing research in power systems, power plants, fuel cell, intelligent systems
  - Teaching power systems, linear systems, optimal control, intelligent control

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ABOUT PROF. KWANG LEE

- Personal
  - Married to Sangwol
  - Have two sons & 6 grandchildren
    - Jonathan age 26
    - Owen age 23
    - Franziska age 19
    - Esme age 17
    - Jesse age 14
    - Teddy age 11
  - Live near campus on Hackberry Ave
  - Member of Fellowship Bible Church on Speegleville Road
  - Attend Bible Study Fellowship on Monday evenings

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Announcement

- Please read Chapters 1 and 2
- HW 1; Project 1 – due Wednesday 8/31, in Canvas
  - in-class quiz, randomly administered
  - For Project, you need to use the PowerWorld Software. You can download the software and cases at the link below; get version 19 (August 6, 2018) http://www.powerworld.com/gloveroberbyesarma.asp

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Simple Power System

- Every power system has three major components
  - generation: source of power, ideally with a specified voltage and frequency
  - load: consumes power; ideally with a constant resistive value
  - transmission system: transmits power; ideally as a perfect conductor

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Complications

- No ideal voltage sources exist
- Loads are seldom constant
- Transmission system has resistance, inductance, capacitance and flow limitations
- Simple system has no redundancy so power system will not work if any component fails

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Notation - Power

- Power: Instantaneous consumption of energy
- Power Units
  - Watts = voltage x current for dc (W)
  - kW – 1×10^3 Watt
  - MW – 1×10^6 Watt
  - GW – 1×10^9 Watt
- Installed U.S. generation capacity is about 1000 GW (about 3 kW per person)
- Maximum load of Greater Waco about 2 GW

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Notation - Energy

- Energy: Integration of power over time; energy is what people really want from a power system
- Energy Units
  - Joule = 1 Watt-second (J)
  - kWh = Kilowatthour (3.6×10^6 J)
  - Btu = 1055 J; 1 MBtu=0.292 MWh
  - One gallon of gas has about 0.125 MBtu (36.5 kWh);
- U.S. electric energy consumption is about 3600 billion kWh (about 13,333 kWh per person, which means on average we each use 1.5 kW of power continuously)

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Power System Examples

- Electric utility: can range from quite small, such as an island, to one covering half the continent
  - there are four major interconnected ac power systems in North American, each operating at 60 Hz ac; 50 Hz is used in some other countries.
- Airplanes and Spaceships: reduction in weight is primary consideration; frequency is 400 Hz.
- Ships and submarines
- Automobiles: dc with 12 volts standard
- Battery operated portable systems

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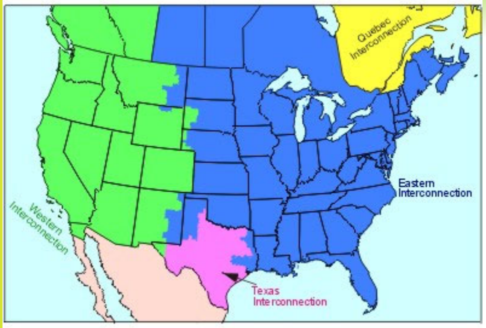
North America Interconnections



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Review of Phasors

Goal of phasor analysis is to simplify the analysis of constant frequency ac systems

$$v(t) = V_{max}\cos(\omega t + \theta_V)$$

$$i(t) = I_{max}\cos(\omega t + \theta_I)$$

Root Mean Square (RMS) voltage of sinusoid

$$\sqrt{\frac{1}{T}\int_0^T v(t)^2 dt} = \frac{V_{\max}}{\sqrt{2}}$$

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Phasor Representation

Euler's Identity: $e^{j\theta} = \cos\theta + j\sin\theta$

Phasor notation is developed by rewriting using Euler's identity

$$v(t) = \sqrt{2}|V|\cos(\omega t + \theta_V)$$

$$v(t) = \sqrt{2}|V|\operatorname{Re}\left[e^{j(\omega t + \theta_V)}\right]$$

(Note: $|V|$ is the RMS voltage)

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Phasor Representation

The RMS, cosine-referenced voltage phasor is:

$$V = |V| e^{j\theta_V} = |V| \angle \theta_V$$

$$v(t) = \text{Re}\sqrt{2}\, V e^{j\omega t} e^{j\theta_V}$$

$$V = |V| \cos\theta_V + j|V| \sin\theta_V$$

$$I = |I| \cos\theta_I + j|I| \sin\theta_I$$

(Note: Some texts use "boldface" type for complex numbers, or "bars on the top")

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Advantages of Phasor Analysis

Device	Time Analysis	Phasor
Resistor	$v(t) = Ri(t)$	$V = RI$
Inductor	$v(t) = L\dfrac{di(t)}{dt}$	$V = j\omega LI$
Capacitor	$\dfrac{1}{C}\int_0^t i(t)dt + v(0)$	$V = \dfrac{1}{j\omega C} I$

Z = Impedance $= R + jX = |Z| \angle \phi$

R = Resistance

X = Reactance

$|Z| = \sqrt{R^2 + X^2}$ $\quad \phi = \arctan(\dfrac{X}{R})$

(Note: **Z** is a complex number but not a phasor)

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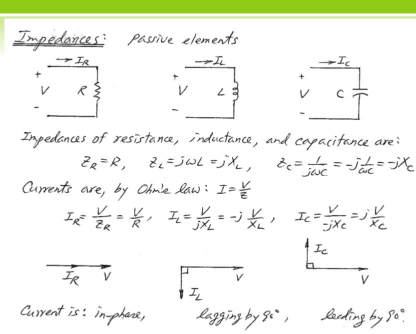
BASIC PRINCIPLES



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BASIC PRINCIPLES

In general, we have a combination of R, L, C

$Z = |Z| \angle \theta = R + jX$

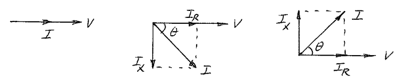
$\theta > 0, \quad X > 0$: inductive reactance

$\theta < 0, \quad X < 0$: capacitive reactance

$I = \frac{V}{Z} = \frac{V}{|Z|} \angle -\theta$

$\theta > 0$, inductive : lagging current

$\theta < 0$, capacitive : leading current



lagging current inductive

leading current capacitive

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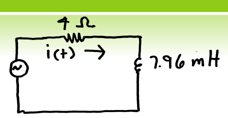
RL CIRCUIT EXAMPLE



$$
\begin{aligned}
V(t) &= \sqrt{2}\,100\cos(\omega t + 30°) \\
f &= 60\text{Hz} \\
\text{R} &= 4\Omega \qquad X = \omega L = 3 \\
|Z| &= \sqrt{4^2 + 3^2} = 5 \quad \phi = 36.9° \\
I &= \frac{V}{Z} = \frac{100\angle 30°}{5\angle 36.9°} \\
&= 20\angle -6.9° \text{ Amps} \\
i(\text{t}) &= 20\sqrt{2}\cos(\omega t - 6.9°)
\end{aligned}
$$

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COMPLEX POWER

Power

$p(t) = v(t) \cdot i(t)$

$v(t) = V_{\max} \cos(\omega t + \theta_V)$

$i(t) = I_{\max} \cos(\omega t + \theta_I)$

$\cos \alpha \cos \beta = \frac{1}{2}[\cos(\alpha - \beta) + \cos(\alpha + \beta)]$

$p(t) = \frac{1}{2} V_{\text{Max}} I_{\text{Max}} [\cos(\theta_V - \theta_I) + \cos(2\omega t + \theta_V + \theta_I)]$

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Complex Power

Average Power

$p(t) = \frac{1}{2} V_{max} I_{max} [\cos(\theta_V - \theta_I) + \cos(2\omega t + \theta_V + \theta_I)]$

$P_{avg} = \frac{1}{T} \int_0^T p(t) dt$

$= \frac{1}{2} V_{max} I_{max} \cos(\theta_V - \theta_I)$

$= |V||I| \cos(\theta_V - \theta_I)$

Power Factor Angle $= \phi = \theta_V - \theta_I$

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Complex Power

$S = |V||I|[\cos(\theta_V - \theta_I) + j \sin(\theta_V - \theta_I)]$

$= P + j\, Q$

$= V\, I^*$

(Note: S is a complex number but not a phasor)

$P =$ Real Power (W, kW, MW)

$Q =$ Reactive Power (var, kvar, Mvar)

$S =$ Complex power (VA, kVA, MVA)

Power Factor (pf) $= \cos \phi$

If current leads voltage then pf is leading

If current lags voltage then pf is lagging

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Complex Power

Relationships between real, reactive and complex power

$P = |S| \cos \phi$

$Q = |S| \sin \phi = \pm |S| \sqrt{1 - pf^2}$

Ex: A load draws 100 kW with a leading *pf* of 0.85. What are ϕ (power factor angle), Q and $|S|$?

$\phi = -\cos^{-1} 0.85 = -31.8°$

$|S| = \frac{100kW}{0.85} = 117.6 \text{ kVA}$

$Q = 117.6 \sin(-31.8°) = -62.0 \text{ kVar}$

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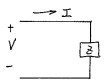
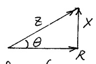
Complex Power

Impedance & Power:



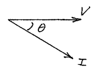
$Z = R + jX = |Z| \angle \theta$



$V = IZ$, $\quad V = |V| \angle 0°$, reference, $\delta = 0°$

$\Rightarrow I = \frac{V}{Z} = \frac{|V| \angle 0°}{|Z| \angle \theta} = \frac{V}{|Z|} \angle -\theta$

$P = |V||I| \cos\theta = (|I||Z|)|I| \cos\theta$
$= |I|^2 \underbrace{|Z| \cos\theta} = |I|^2 R$



$Q = |V||I| \sin\theta = (|I||Z|)(|I|) \sin\theta$
$= |I|^2 |Z| \sin\theta = |I|^2 X$

$$P = I^2 R \qquad Q = I^2 X$$

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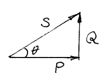
Complex Power

Note: $\sqrt{P^2 + Q^2} = \sqrt{(|V||I|)^2 \cos^2\theta + (|V||I|)^2 \sin^2\theta}$
$= |V||I| \triangleq |S|$, "apparent power"

Power factor & Power factor angle:

$\frac{Q}{P} = \frac{|V||I| \sin\theta}{|V||I| \cos\theta} = \tan\theta$



$pf = \cos\theta = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{P}{|S|} = \frac{P}{|V||I|}$

Note: The impedance angle θ is preserved in the power triangle!

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Complex Power

Complex Power: Let $V = |V| \angle \delta$
$I = |I| \angle \beta$

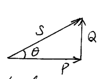
Define

$S = VI^* = (|V| \angle \delta)(|I| \angle -\beta) = |V||I| \angle \delta - \beta = |S| \angle \delta - \beta$

$= \underbrace{|V||I| \cos(\delta - \beta)}_{P} + j \underbrace{|V||I| \sin(\delta - \beta)}_{Q}$

$|S| = |V||I|$: apparent power [VA]

$\theta = \delta - \beta$: power factor angle



$\delta > \beta$: $\theta > 0$, $Q > 0$, I lagging, inductive load

$\delta < \beta$: $\theta < 0$, $Q < 0$, I leading, capacitive load

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Complex Power

Impedance & Complex power:

$$S = VI^* = (IZ)(I^*) = |I|^2 Z$$
$$= |I|^2 |Z| \angle\theta = |S| \angle\theta$$
$$= |I|^2 (R + jX) = \underbrace{|I|^2 R}_{P} + j \underbrace{|I|^2 X}_{Q}$$

Alternatively,

$$S = VI^* = V\left(\frac{V}{Z}\right)^* = \frac{|V|^2}{Z^*} = |V|^2 Y^*$$
$$= \frac{|V|^2}{|Z|} \angle\theta = |S| \angle\theta$$
$$= |V|^2 |Y| \angle\theta = |V|^2 (G + jB)$$
$$= \underbrace{|V|^2 G}_{P} + j \underbrace{|V|^2 B}_{Q}$$

Here, $Y = \frac{1}{Z}$, admittance
$$= G - jB$$

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Conservation of Power

- At every node (bus) in the system
  - Sum of real power into node must equal zero
  - Sum of reactive power into node must equal zero
- This is a direct consequence of Kirchhoff's current law, which states that the total current into each node must equal zero.
  - Conservation of power follows since $S = VI^*$

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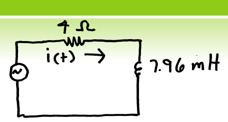
RL Circuit Example



$$V(t) = \sqrt{2}\,100\cos(\omega t + 30°)$$
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$$R = 4\Omega \qquad X = \omega L = 3$$
$$|Z| = \sqrt{4^2 + 3^2} = 5 \quad \phi = 36.9°$$
$$I = \frac{V}{Z} = \frac{100\angle 30°}{5\angle 36.9°}$$
$$= 20\angle -6.9° \text{ Amps}$$
$$\text{i(t)} = 20\sqrt{2}\cos(\omega t - 6.9°)$$

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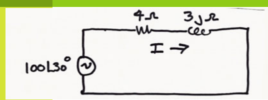
Conservation of Power



Earlier we found
$I = 20\angle{-6.9°}$ amps

Find complex power, real power and reactive power of the source and line components.

$$
\begin{aligned}
S &= V\,I^* = 100\angle 30° \times 20\angle 6.9° = 2000\angle 36.9° \ \text{VA} \\
\phi &= 36.9° \quad \text{pf} = 0.8 \text{ lagging} \\
S_R &= V_R\,I^* = 4 \times 20\angle{-6.9°} \times 20\angle 6.9° \\
P_R &= 1600W = |I|^2 R \quad (Q_R = 0) \\
S_L &= V_L\,I^* = 3j \times 20\angle{-6.9°} \times 20\angle 6.9° \\
Q_L &= 1200\,\text{var} = |I|^2 X \quad (P_L = 0)
\end{aligned}
$$

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Power Consumption in Devices

Resistors only consume real power

$$P_{\text{Resistor}} = |I_{\text{Resistor}}|^2 R$$

Inductors only consume reactive power

$$Q_{\text{Inductor}} = |I_{\text{Inductor}}|^2 X_L$$

Capacitors only generate reactive power

$$Q_{\text{Capacitor}} = -|I_{\text{Capacitor}}|^2 X_C \qquad X_C = \frac{1}{\omega C}$$

$$Q_{\text{Capacitor}} = -\frac{|V_{\text{Capacitor}}|^2}{X_C} \quad \text{(Note-some define } X_C \text{ negative)}$$

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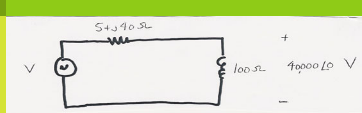
Example



First solve basic circuit:

$$
\begin{aligned}
I &= \frac{40000\angle 0°\ V}{100\angle 0°\ \Omega} = 400\angle 0° \ \text{Amps} \\
V &= 40000\angle 0° + (5 + j40)\,400\angle 0° \\
&= 42000 + j16000 = 44.9\angle 20.8° \ \text{kV} \\
S &= V I^* = 44.9\text{k}\angle 20.8° \times 400\angle 0° \\
&= 17.98\angle 20.8° \ \text{MVA} \ = 16.8 + j6.4 \ \text{MVA}
\end{aligned}
$$

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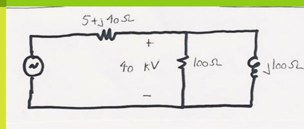
Example



Now add additional reactive power load & resolve:

$$Z_{Load} = 70.7\angle 45^\circ \quad pf = 0.7 \text{ lagging}$$
$$I = 564\angle -45^\circ \text{ Amps}$$
$$V = 59.7\angle 13.6^\circ \text{ kV}$$
$$S = 33.7\angle 58.6^\circ \text{ MVA} \quad = 17.6 + j28.8 \text{ MVA}$$

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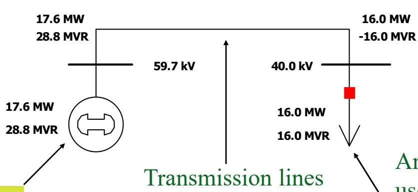
Power System Notation

Power system components are usually shown as "one-line diagrams." Previous circuit redrawn



Generators are shown as circles

Transmission lines are shown as a single line

Arrows are used to show loads

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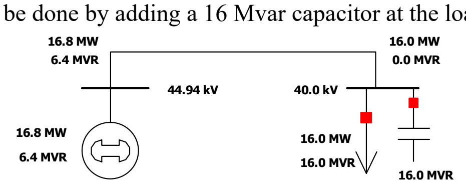
Reactive Compensation

Key idea of reactive compensation is to supply reactive power locally. In the previous example this can be done by adding a 16 Mvar capacitor at the load.



Compensated circuit is identical to the first example with just real power load.

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Reactive Compensation, cont'd

- Reactive compensation decreased the line flow from 564 Amps to 400 Amps. Advantages:
  - Lines losses, which are equal to $I^2 R$ decrease
  - Lower current allows utility to use small wires, or alternatively, supply more load over the same wires
  - Voltage drop on the line is less
- Reactive compensation is used extensively by utilities
- Capacitors can be used to "correct" a load's power factor to an arbitrary value.

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Power Factor Correction Example

Assume we have 100 kVA load with pf=0.8 lagging, and would like to correct the *pf* to 0.95 lagging

$$S = 80 + j60 \text{ kVA} \qquad \phi = \cos^{-1} 0.8 = 36.9°$$

$$pf \text{ of } 0.95 \text{ requires } \phi_{\text{desired}} = \cos^{-1} 0.95 = 18.2°$$

$$S_{new} = 80 + j(60 - Q_{cap})$$

$$\frac{60 - Q_{cap}}{80} = \tan 18.2° \quad \Rightarrow \quad 60 - Q_{cap} = 26.3 \text{ kvar}$$

$$Q_{cap} = 33.7 \text{ kvar}$$

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Distribution System Capacitors

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