ECE 330 POWER CIRCUITS AND ELECTROMECHANICS

LECTURE 1

COURSE INTRODUCTION AND REVIEW OF PHASORS

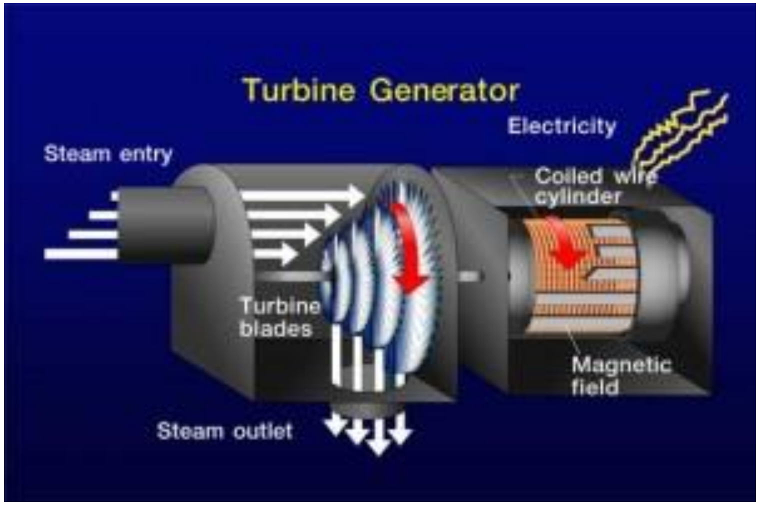
Acknowledgment-These handouts and lecture notes given in class are based on material from Prof. Peter Sauer's ECE 330 lecture notes. Some slides are taken from Ali Bazi's presentations.

Disclaimer- These handouts only provide highlights and should not be used to replace the course textbook.

WHY POWER CIRCUITS AND ELECTROMECHANICS?

Electromechanics combines electrical and mechanical processes and plays key roles at several levels:

- At generation level: synchronous machines convert mechanical energy to electric energy.



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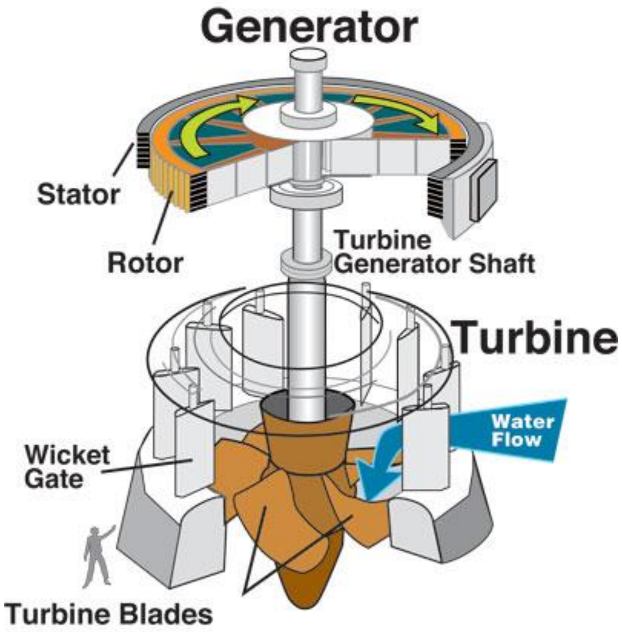
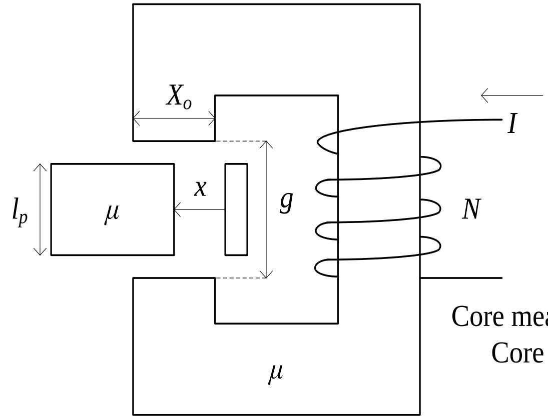


Source: water.usgs.gov

WHY POWER CIRCUITS AND ELECTROMECHANICS?

- At transmission-distribution level: Circuit breakers trip the faults in affected areas.

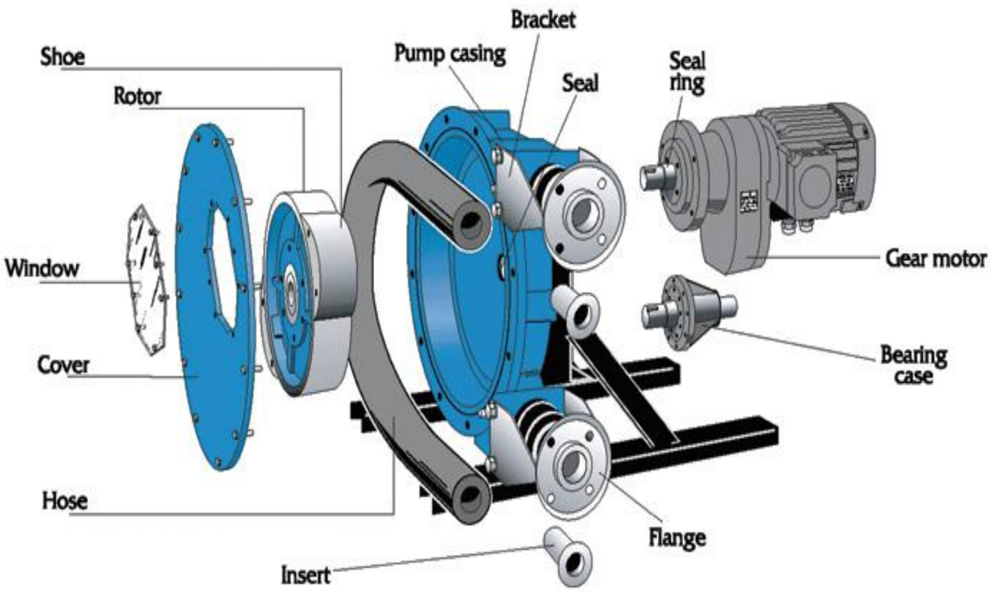


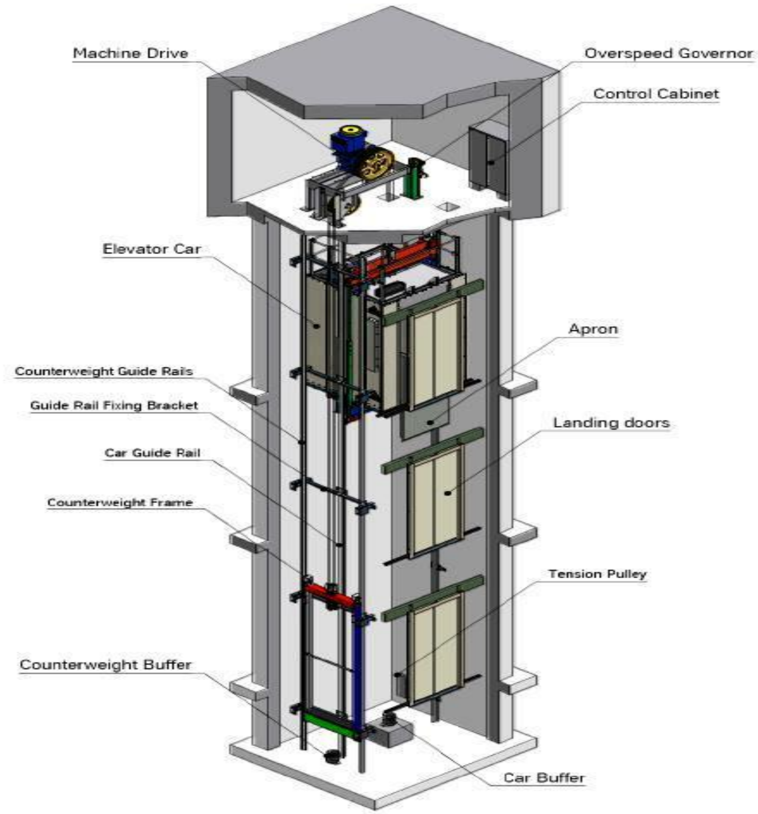

Source: abb.com


Source: engineeringtutorial.com

WHY POWER CIRCUITS AND ELECTROMECHANICS?

- At the level of loads: Electric energy is consumed by mechanical loads through motors, mostly induction (three-phase and single-phase)



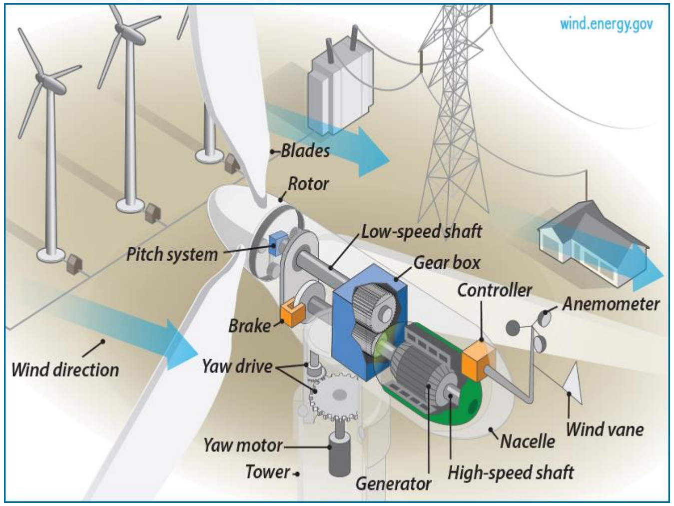


- Source: pumpsandsystem.com

Source: electrical-know-how.com

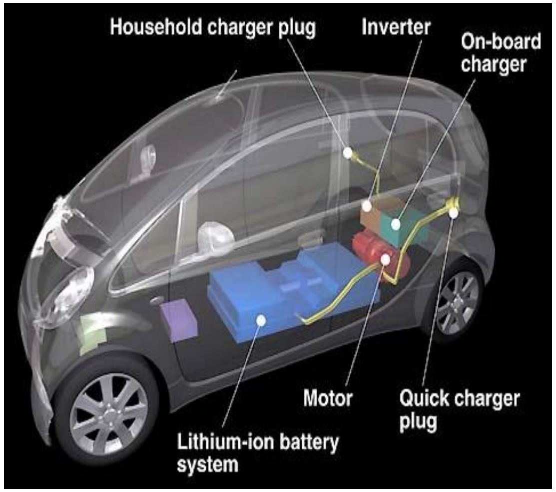
WHY POWER CIRCUITS AND ELECTROMECHANICS ?

- In advanced technology: renewable energy, electric cars, robots,….. etc. contain electromechanic systems.



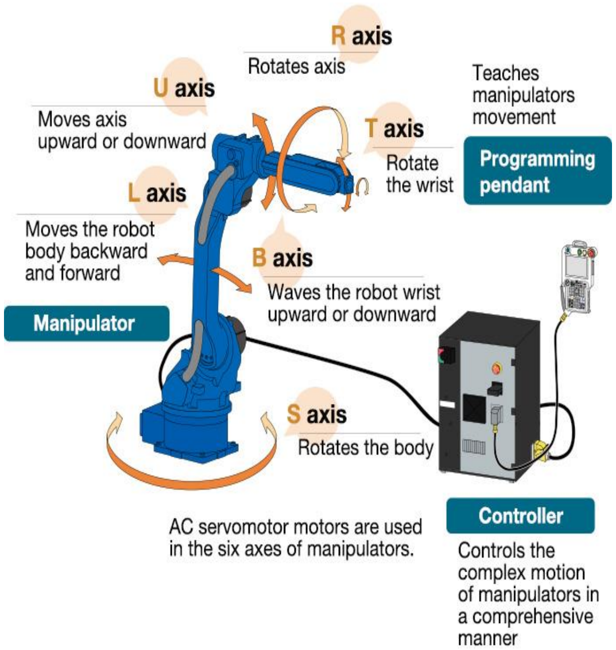
Wind Turbine

Source: energy.gov



Electric Vehicle

Source: exchangeev.aaa.co m



Robot

Source: yaskawa.co.jp

POWER CIRCUITS AND ELECTROMECHANICS

Goals:

To impart basics of three-phase power circuits, transformers, electromechanical systems, and rotating machines.

Objectives:

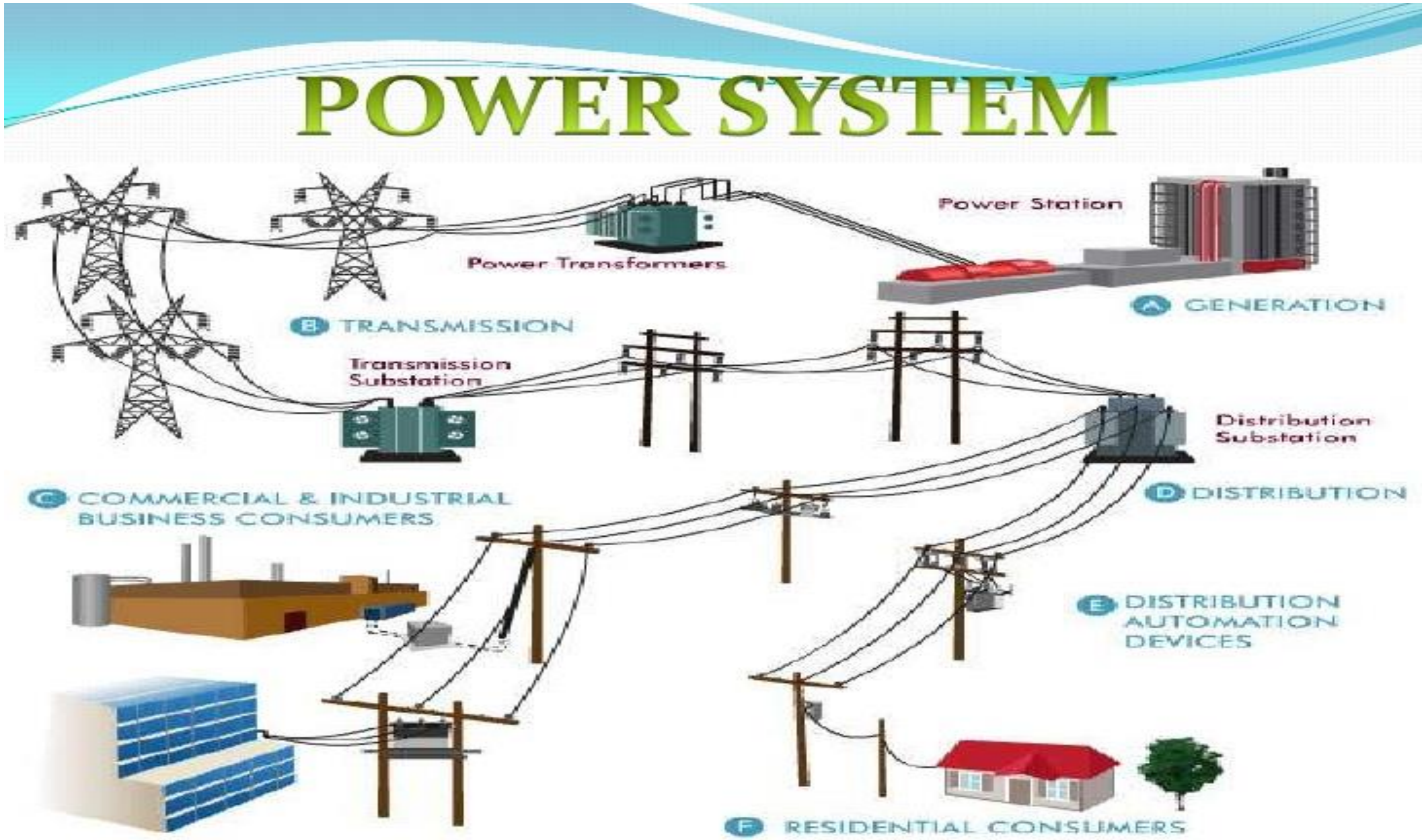
To build cognitive skills, such as analytical thinking and problem solving. The course integrates fundamentals of advanced math and science to enhance the ability to design a system and meet desired needs.

COURSE OUTLINE

- Review of phasors, complex power
- Three-phase circuits, three-phase power, wye-delta conversion
- Magnetic circuits, self and mutual inductance, Maxwell's equations
- Ideal transformers, practical transformers, equivalent circuits
- Electromechanical systems, energy, co-energy, energy cycles, computation of forces and torques.
- Dynamic equations, numerical integration of electromechanical systems
- Equilibrium points, linearization, stability
- Synchronous machines
- Induction machines
- Other machines

STRUCTURE OF POWER SYSTEMS

- Power system's main components: generation, transmission, distribution, and loads.



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STRUCTURE OF POWER SYSTEMS

Generating System:

- The generating system consists of a fuel source such as coal, water, natural gas or nuclear power.
- Hydropower accounts for about 8%, and nuclear power 20%, renewable energy 14% of electric energy production in the US.
- The turbine acting as the prime-mover converts mechanical energy into electric energy through a three-phase synchronous machine.
- The three-phase voltages of the generators range from 13.8 kV to 24 kV.

STRUCTURE OF POWER SYSTEMS

Transmission System:

- A three-phase transformer at each generator steps up the voltage to a high value ranging from 138 kV to 765 kV.
- The transmission lines carry power over these lines to load centers and, where appropriate, step it down to lower voltages up to 34 kV at the bulk-power substations.
- Some industrial customers are supplied from these substations. This is known as the transmission—sub-transmission system.

STRUCTURE OF POWER SYSTEMS

Distribution System:

- Transformers step down the voltage to a range of 2.4 kV to 69 kV.
- Power is carried by main feeders to specific areas where there are lateral feeders to step it down further to customer levels, such as 208, 240, or 600 volts.
- The distribution transformers serve anywhere from 1 to 10 customers.

STRUCTURE OF POWER SYSTEMS

The classes of entities in the electricity market are:

- Generator companies (GENCOs), also called independent power producers (IPPs).
- Transmission companies TRANSCOs, Their primary responsibility is to transport power from generators to customers and make the transmission system available to all.

STRUCTURE OF POWER SYSTEMS

- Distribution companies DISCOs,

  owning and operating the local distribution network.

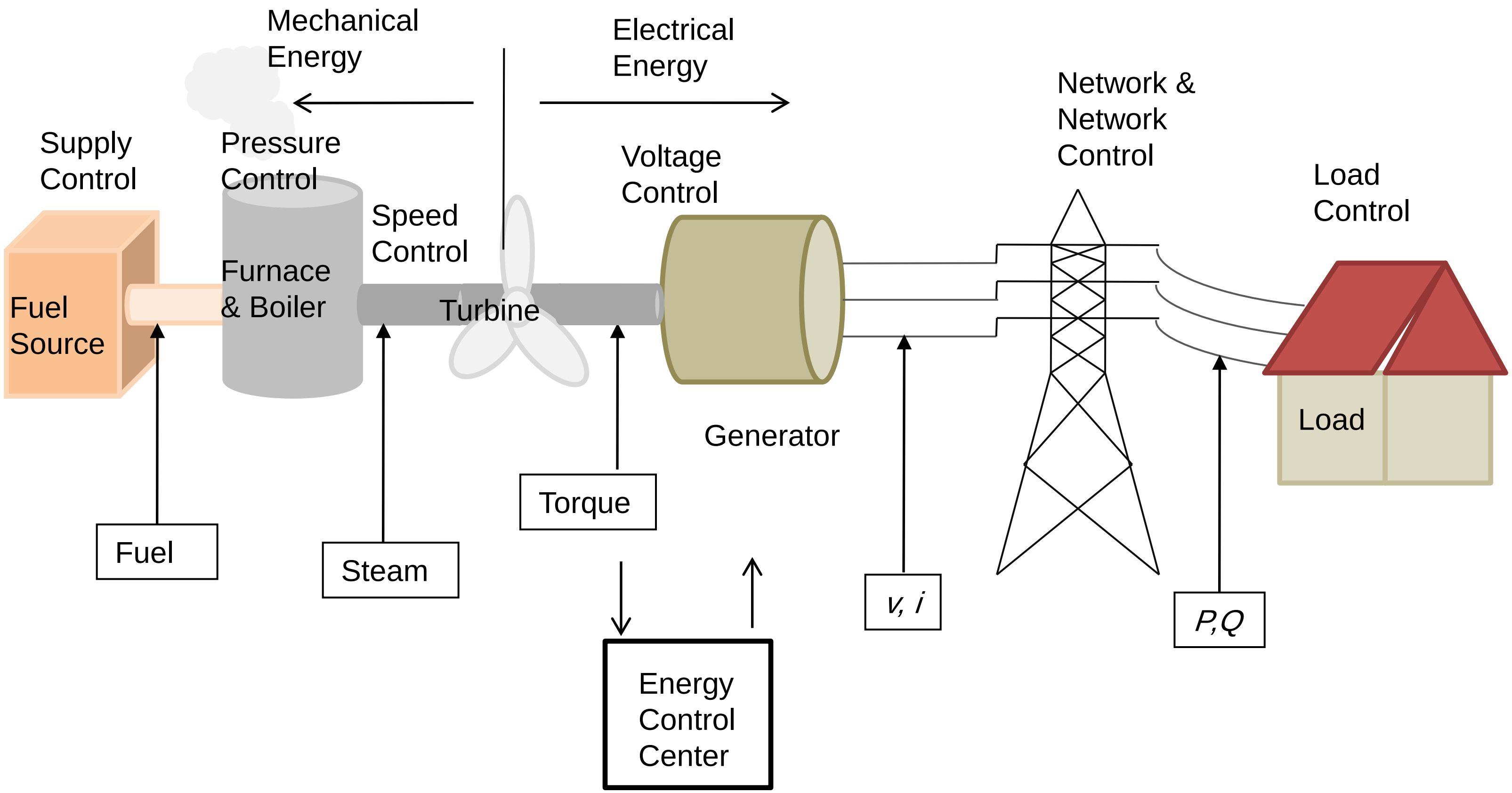
- Independent system operator (ISO)

  The ISO is charged with ensuring the reliability and security of the entire system.

DYNAMICS OF POWER SYSTEMS AND COMPONENTS

- The power system is a dynamic one, it is described by a set of vector of differential equations $\dot{x} = f(x + u)$
- The time scales in the response of this equation range from milliseconds, in the case of electromagnetic transients, to a few seconds in the control of frequency, and a few hours in the case of boiler dynamics.
- Therefore, we analyze such equations for time-domain response, steady-state sinusoidal behavior, equilibrium points, stability, etc.

DYNAMICS OF POWER SYSTEMS AND COMPONENTS



Power system dynamic structure

DYNAMICS OF POWER SYSTEMS AND COMPONENTS

- Diagram does not show all the complex dynamic interaction between components and their controls.
- Electrical side contains mechanical dynamics(TCUL)
- Mechanical side contains components with electrical dynamics (electrical valves)
- After the model is derived we put it in the state-space form.

REVIEW OF PHASORS

- Phasors represent quantities with magnitude and angle with respect to a reference and are commonly used in energy systems.
- Example: $v(t) = V_m \cos(\omega t + \theta_v)$

  Euler's expansion: $e^{j\alpha} = \cos(\alpha) + j\sin(\alpha)$

  Then, $v(t)$ can be written as

$$v(t) = \mathrm{Re}\{V_m e^{j(\omega t + \theta_v)}\} = \mathrm{Re}\{V_m e^{j\omega t} e^{j\theta_v}\} = \mathrm{Re}\{\sqrt{2}\bar{V} e^{j\omega t}\}$$

where $\bar{V} = \frac{V_m}{\sqrt{2}} e^{j\theta_v} = V_{rms} \angle \theta_v$ is the RMS phasor with cosine reference.

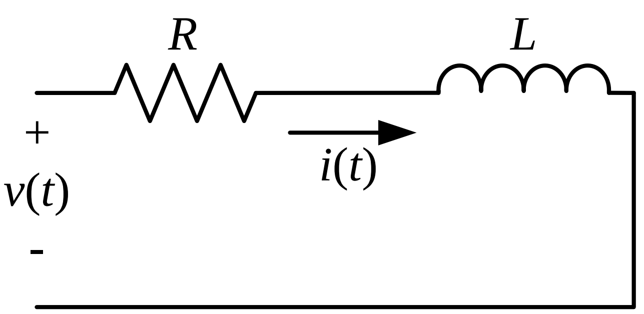
REVIEW OF PHASORS

- Recall: RMS (root-mean square) where v is a function of time, t_0 is the initial time, and T is the period of v.

$$V_{rms} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} v^2(t)dt} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} V_m^2 \cos^2(\omega t + \theta_v)dt} = \frac{V_m}{\sqrt{2}}$$

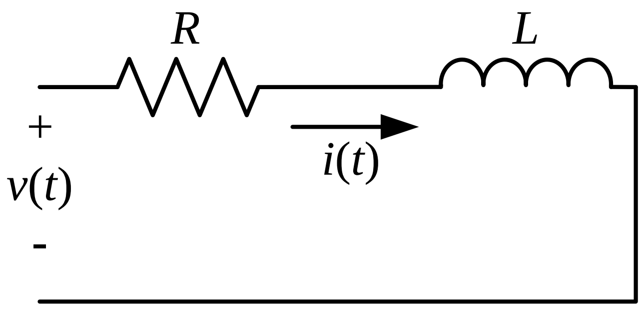
- How do phasors apply in electric circuits?
- Example:

Find $v(t)$ for $i(t) = I_m \sin(\omega t)$ A



REVIEW OF PHASORS

- Time-domain approach:



$$v(t) = Ri(t) + L\frac{di(t)}{dt}$$

$$v(t) = RI_m \sin(\omega t) + L\omega I_m \cos(\omega t)$$

$$v(t) = \sqrt{(RI_m)^2 + (L\omega I_m)^2}\cos\left(\omega t - \tan^{-1}\left(\frac{RI_m}{L\omega I_m}\right)\right)$$

For $R = 2\Omega$, $L = 1/377\text{H}$, $\omega = 377$ rad/s, and $I_m = 10\text{A}$,

$$v(t) = \sqrt{(2\times 10)^2 + \left(\frac{1}{377}\times 377\times 10\right)^2}\cos\left(377t - \tan^{-1}\left(\frac{2\times 10}{\frac{1}{377}\times 377\times 10}\right)\right)$$

$$v(t) = 22.36\cos(377t - 63.4^o)\ V$$

REVIEW OF PHASORS

- Frequency-domain approach (phasors)

Time-domain $\rightarrow$ Frequency-domain

$$v(t) \rightarrow \bar{V} \qquad R \rightarrow R$$

$$i(t) \rightarrow \bar{I} \qquad L \rightarrow j\omega L = jX_L \quad (X_L = \omega L)$$

$$C \rightarrow \frac{1}{j\omega C} = \frac{-j}{\omega C} = jX_C \quad (X_C = \frac{-1}{\omega C})$$

- In frequency-domain $\bar{V} = Z\ \bar{I}$ (Ohm's law) where Z can be a series-parallel combination of *R*, X_C, *and/or* X_L.

REVIEW OF PHASORS

- Frequency-domain approach:

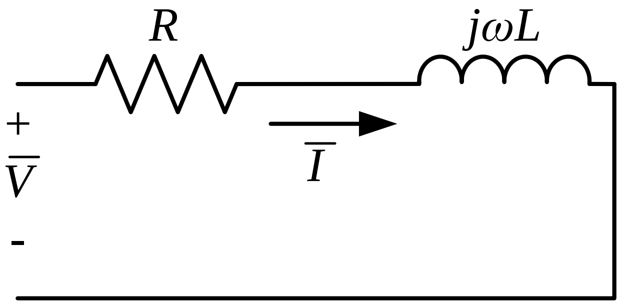
$$\bar{V} = (R + j\omega L)\bar{I} \text{ where } \bar{I} = \frac{10}{\sqrt{2}}\angle -90^o \text{ A (RMS)}$$

$$\bar{V} = \left(2 + j377\frac{1}{377}\right)\frac{10}{\sqrt{2}}\angle -90^o$$

$$\bar{V} = \left[\sqrt{2^2 + 1^2}\angle\left(\tan^{-1}\left(\frac{1}{2}\right)\right)\right]\frac{10}{\sqrt{2}}\angle -90^o$$

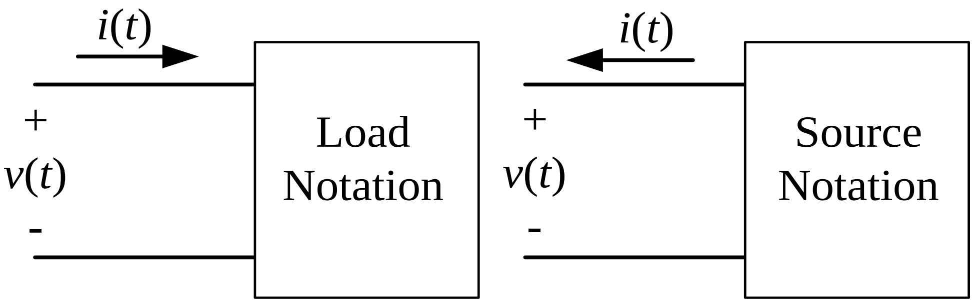
$$\bar{V} = \left(\frac{10\sqrt{5}}{\sqrt{2}}\right)\angle\left(26.56^o - 90^o\right)$$

$$\bar{V} = 15.81\angle\left(-63.4^o\right) \text{ V(RMS)}$$



TWO-TERMINAL NETWORK

- A two-terminal electrical network has voltage at its terminals and current flowing in and out of its terminals.



- The instantaneous power is $p(t) = v(t)\, i(t)$.
- For $i(t) = I_m \cos(\omega t + \theta_i)$ A and $v(t) = V_m \cos(\omega t + \theta_v)$ V we get

$$p(t) = V_m I_m \cos(\omega t + \theta_v) \cos(\omega t + \theta_i)$$

TWO-TERMINAL NETWORK

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

$$p(t) = \frac{V_m I_m}{2}\cos(\theta_v - \theta_i) + \frac{V_m I_m}{2}\cos(2\omega t + \theta_v + \theta_i) \quad \text{W}$$

The first term is time-independent, while the second term is a sinusoid at double frequency.

TWO-TERMINAL NETWORK

- The average power is thus

$$P = \frac{1}{T}\int_0^T P(t)\,d(t) \quad , \qquad T = \frac{2\pi}{\omega}$$

$$P_{in} = \frac{V_m I_m}{2}\cos(\theta_v - \theta_i).$$

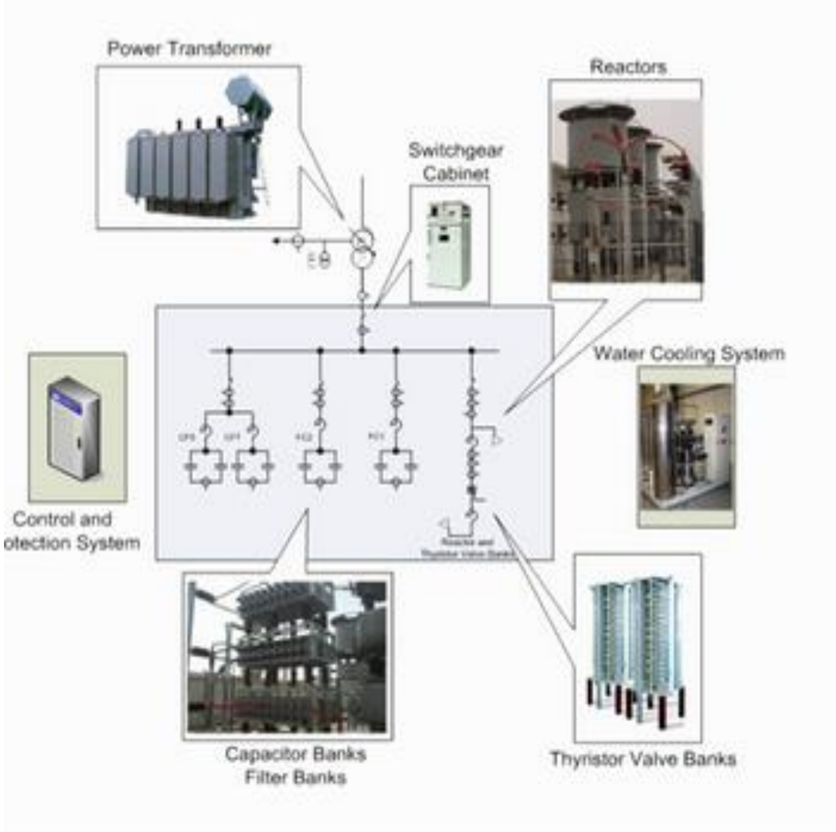
- This is called the active or real power and its unit is watts (W).
- The power factor is the cosine of the phase angle between $v(t)$ and i(t).

POWER FACTOR

- The power factor (*P.F.*) is thus $P.F. = \cos(\theta_v - \theta_i)$.
- The power factor can be:
  - Lagging: $0^o < \theta_v - \theta_i < 90^o$
  - Leading: $-90^o < \theta_v - \theta_i < 0^o$
  - Unity: $\theta_v - \theta_i = 0$

  Therefore, $0 \le P.F. \le 1$,

  and the highest real power exists when *P.F.*=1.



Source: grupovision.com

APPARENT POWER AND REACTIVE POWER

- The apparent power is $S = \frac{V_m I_m}{2}$
- The apparent power unit is volt-amps (VA).
- The reactive power is $Q_{in} = \frac{V_m I_m}{2}\sin(\theta_v - \theta_i)$.
- The reactive power unit is volt-amps-reactive

  (VARs).

COMPLEX POWER

- The instantaneous power is

$$p(t) = \frac{V_m I_m}{2}\cos(\theta_v - \theta_i) + \frac{V_m I_m}{2}\cos(2\omega t + \theta_v + \theta_i) \quad \text{W}$$

- The time varying component

$$\frac{V_m I_m}{2}\cos(2\omega t + \theta_v + \theta_i) = \frac{V_m I_m}{2}\left\{\cos\left[(2\omega t + 2\theta_i) + (\theta_v - \theta_i)\right]\right\}$$

$$= \frac{V_m I_m}{2}\cos(2\omega t + 2\theta_i)\cos(\theta_v - \theta_i) - \frac{V_m I_m}{2}\sin(2\omega t + 2\theta_i)\sin(\theta_v - \theta_i)$$

COMPLEX POWER

- Define

$$Q_{in} = \frac{V_m I_m}{2}\sin(\theta_v - \theta_i), \qquad \text{(Reactive power)}$$

$$p(t) = P_{in} + P_{in}\cos(2\omega t + 2\theta_i) - Q_{in}\sin(2\omega t + \theta_i)$$

$$= P_{in}(1 + \cos(2\omega t + \theta_i)) - Q_{in}\sin(2\omega t + 2\theta_i)$$

- The real power can be written as

$$P_{in} = \frac{V_m I_m}{2}\cos(\theta_v - \theta_i) = \mathrm{V}_{rms} I_{rms}\cos(\theta_v - \theta_i)$$

PHASOR REPRESENTATION

$$P_{in} = \mathrm{Re}\{\frac{V_m I_m}{2} e^{j\theta_v} e^{-j\theta_i}\} = \mathrm{Re}\{V_{rms} e^{j\theta_v} I_{rms} e^{-j\theta_i}\}$$

- The reactive power can be written as

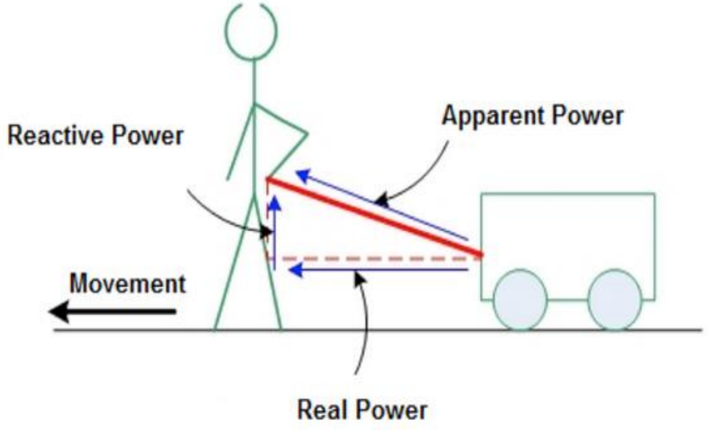
$$Q_{in} = \mathrm{Im}\{\frac{V_m I_m}{2} e^{j\theta_v} e^{-j\theta_i}\} = \mathrm{Im}\{V_{rms} e^{j\theta_v} I_{rms} e^{-j\theta_i}\}$$

- The voltages and currents can be written as phasors:

$V_{rms} e^{j\theta_v} = \bar{V}$ and $I_{rms} e^{j\theta_i} = \bar{I}$.

$$P_{in} = \mathrm{Re}(\bar{V}\ \bar{I}^*) = \mathrm{V}_{rms}\ I_{rms} \cos(\theta_v - \theta_i)$$

$$Q_{in} = \mathrm{Im}(\bar{V}\ \bar{I}^*) = \mathrm{V}_{rms}\ I_{rms} \sin(\theta_v - \theta_i)$$



Source: Tonex.com

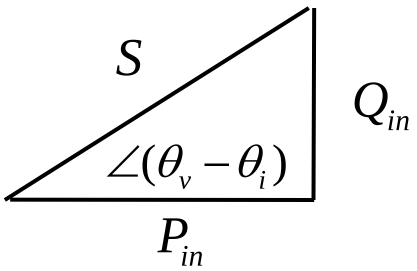
Complex Power

- Define the complex power as $\bar{S} = P_{in} + jQ_{in}$
- Then $\bar{S}$ can be written as $\bar{S} = \bar{V}\,\bar{I}^*$
- The quantity $\bar{I}^*$ is the complex conjugate of $\bar{I}$.
- $\bar{S}$ can also be written as

$$\bar{S} = S\angle(\theta_v - \theta_i)$$

- Note that

$$S = \frac{V_m I_m}{2} = \sqrt{P_{in}^2 + Q_{in}^2}$$



ALTERNATE FORMS OF COMPLEX POWER

- If the load is $\bar{Z} = R + jX$, connected across the source $\bar{V}$

By Ohm's law: $\bar{V} = \bar{Z}\ \bar{I}$, but $\bar{S} = \bar{V}\ \bar{I}^*$

Then $\bar{S}$ can be written as $\bar{S} = I^2 R + jI^2 X$ Also,

$P = I^2 R$ and $Q = I^2 X$, $\bar{Z}$and $P.F. = \cos(angle(\bar{Z}))$.

- Thus, $Q > 0$ when $\bar{Z}$ is inductive, $X = \omega L$

and $Q < 0$ when is capacitive, $X = -\dfrac{1}{\omega C}$

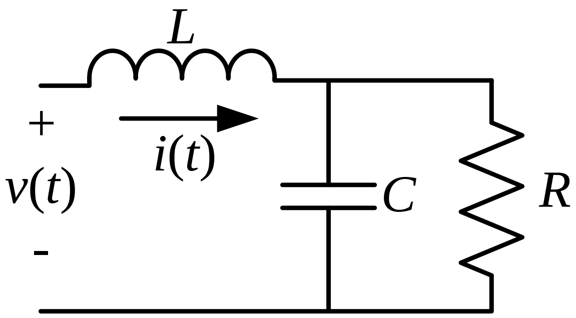
- $\bar{S}$ and $\bar{Z}$ are not phasors but complex quantities.

EXAMPLE: LC FILTER AND R LOAD

- The circuit shown is commonly used as an LC filter to supply a load, which is resistive in this case.
- Find the current, real, reactive, and complex powers, and the P.F. for $v(t) = \sqrt{2}V_{rms}\cos(377t)$

$$\bar{Z} = j\omega L + \left(R // \frac{-j}{\omega C} \right)$$

$$\bar{Z} = \frac{\omega L + j(\omega^2 RLC - R)}{\omega RC - j}$$



EXAMPLE: LC FILTER AND R LOAD

- Let

$$V_{rms} = 120\text{V}, L = 1\text{mH}, C = 6.8\text{mF}, \text{ and R} = 10\Omega.$$

$$\bar{Z} = 0.0197\angle -39.41^o = 0.0152 - j0.0125\Omega$$

$$\bar{I} = \frac{\bar{V}}{\bar{Z}} = \frac{120\angle 0^o}{0.0197\angle -39.41^o} = 6091.4\angle 39.41^o\,\text{A}$$

$$i(t) = 6091.4\sqrt{2}\cos(377t + 39.41^o)$$

$$\bar{S} = \bar{V}\ \bar{I}^* = 731\angle -39.41^o\,\text{kVA}$$

$$P_{in} = 731\cos(-39.41^o) = 564.8\text{kW}$$

$$Q_{in} = 731\sin(-39.41^o) = -464.1\text{kVAR}$$

$$\text{P.F.} = \cos(-39.41^o) = 0.773 \text{ leading } (\theta_v - \theta_i = -39.41^o)$$