Lecture 17:
Three-Phase Systems

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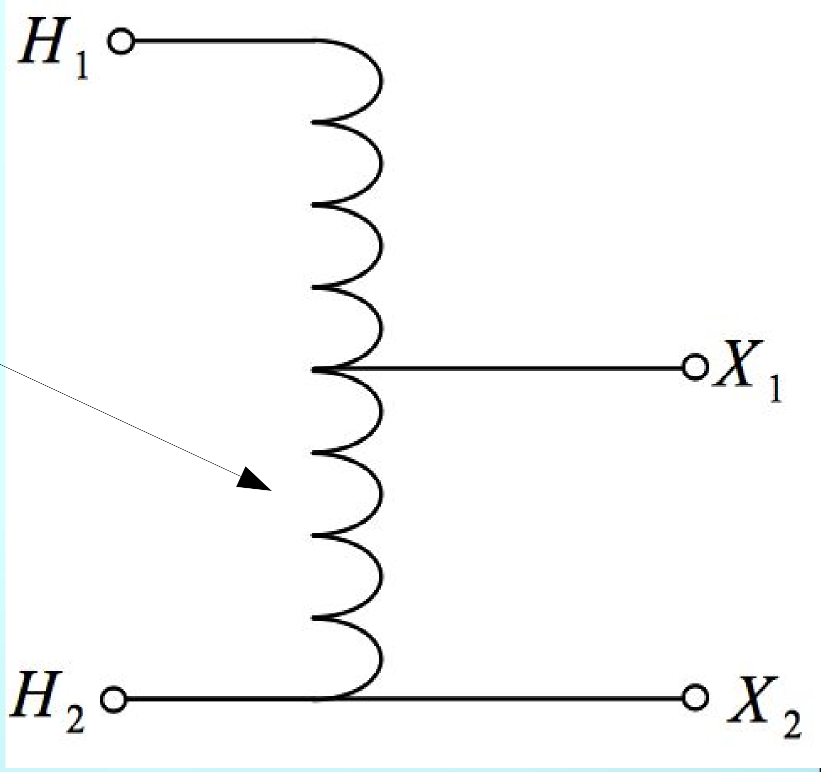
Autotransformers

<u>Autotransformers</u>

- Only has one winding
  - One portion of winding for both primary and secondary
- Standard equations still apply
- Require less copper
  - Cheaper
  - Smaller
- Disadvantage is more hazardous



Three-Phase Systems

- Why generate in three-phase?
  - More efficient generation/transmission/use
  - Three-phase equipment smaller per unit power
  - Easy to create rotating magnetic fields (motors)
  - Smoother power transfer
    - Smoother torque in motors
    - Smoother conversion to DC (e.g. for battery storage)
  - Cost effective transmission
    - Less conductors required
- If we generate/transmit in three-phase, how do we get single-phase?
  - Tap into single leg of three-phase using transformer

Three-Phase Systems

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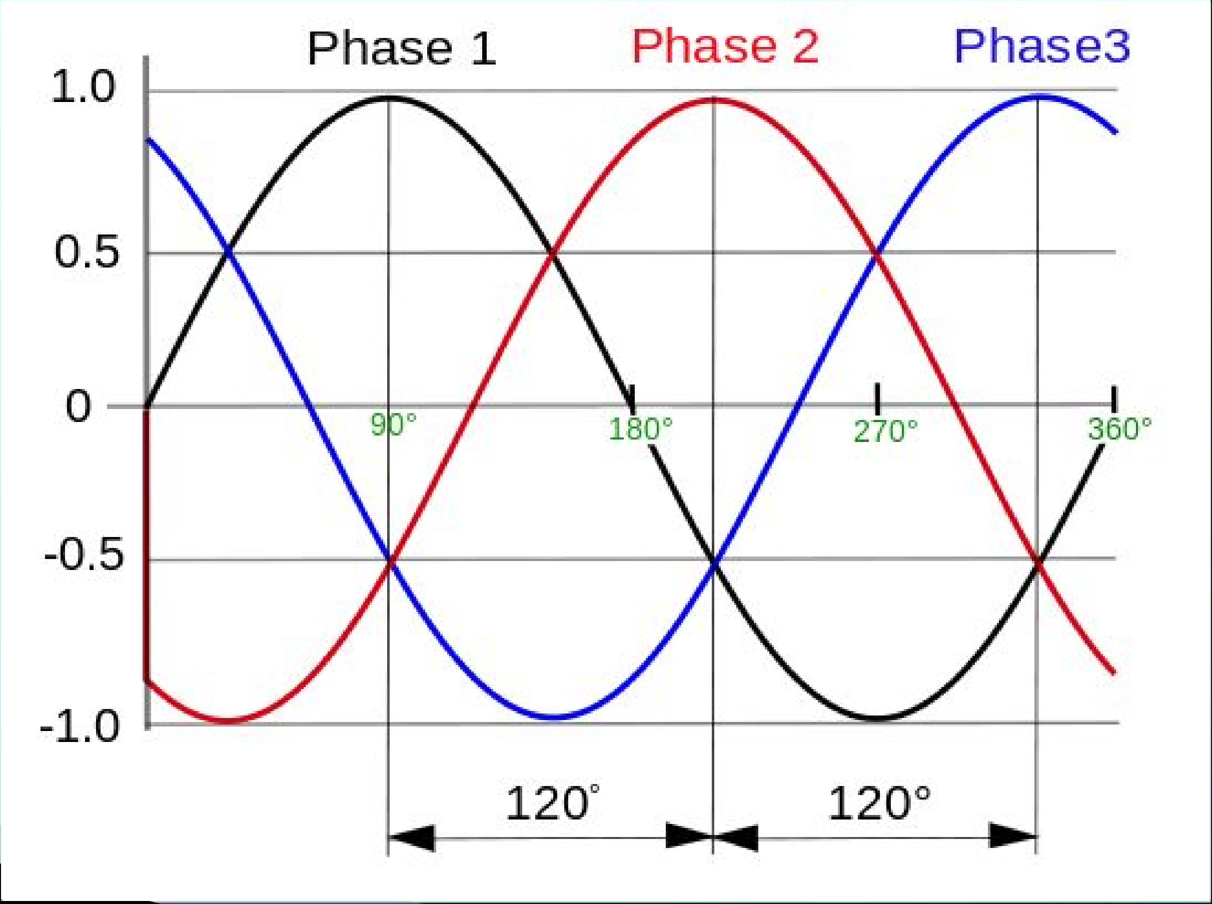
- AC electricity primarily generated and transmitted in the form of three-phase
  - Each phase voltage 120° apart

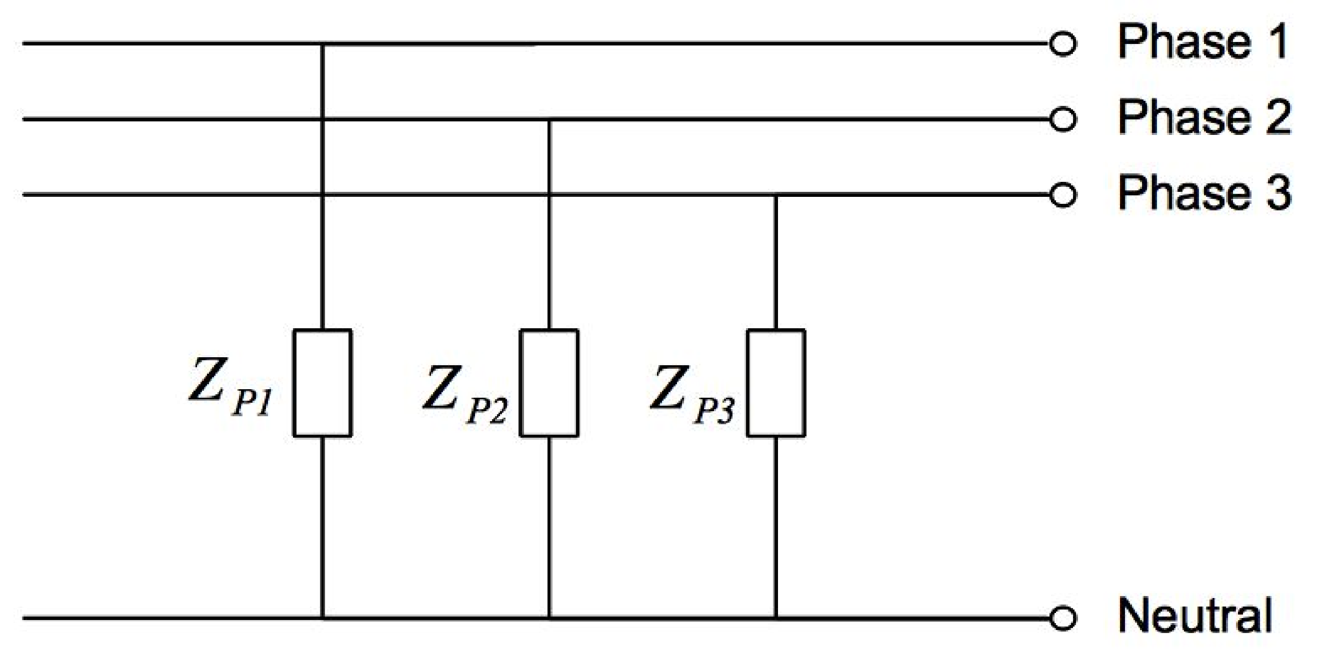
If load balanced, current 120° apart as well

Typical Color Scheme:
Phase 1
Phase 2
Phase 3



Balanced Loads

- What is a balanced load?
  - All branches of load have equivalent impedance

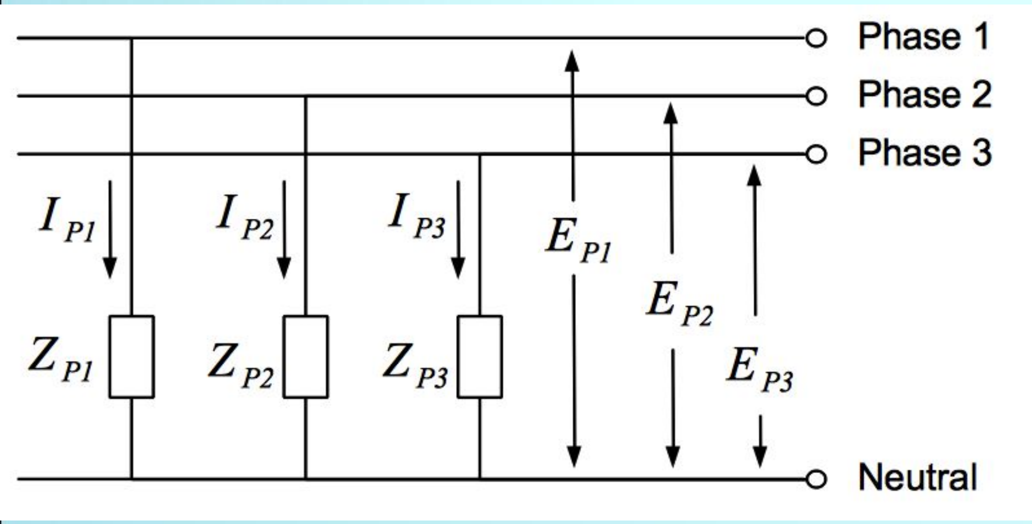


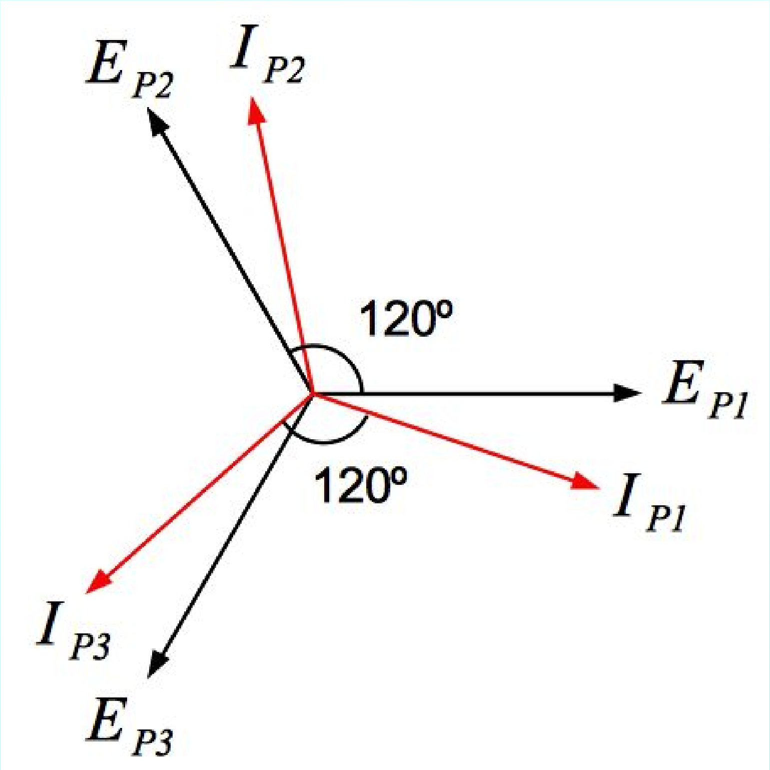
All phase impedances equivalent:

$$Z = Z_{P1} = Z_{P2} = Z_{P3}$$

Balanced Loads

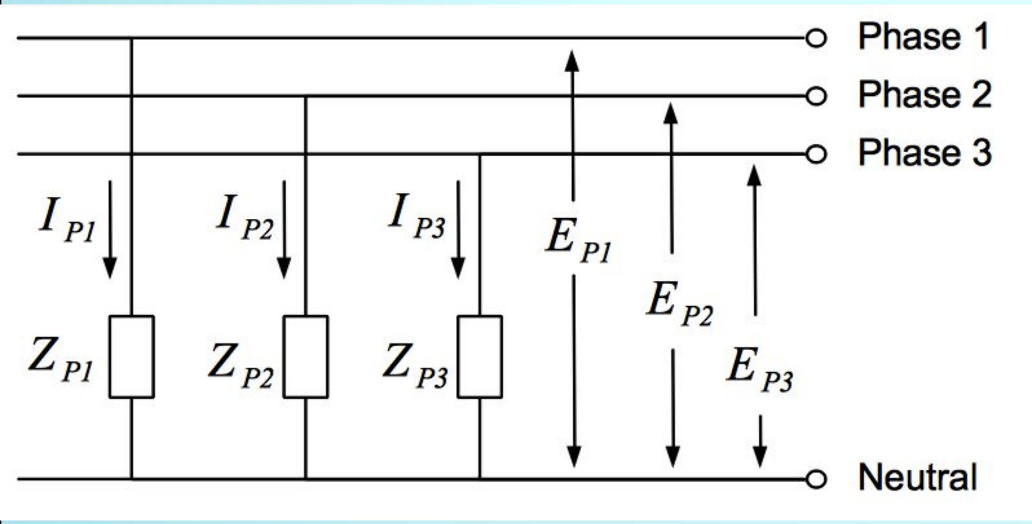
- Balanced generation with balanced load

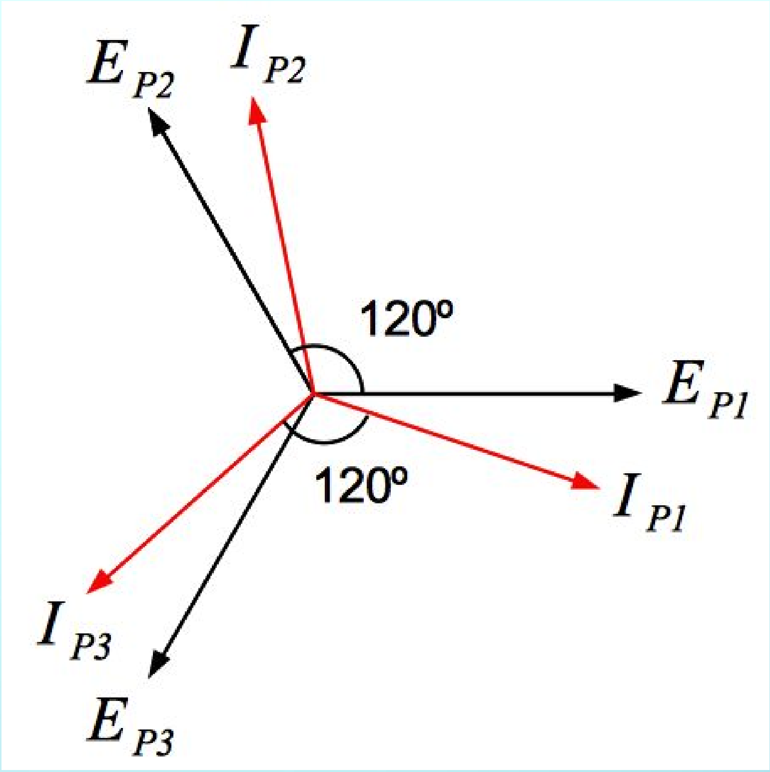




Balanced Loads

- Balanced generation with balanced load:
  - Combined phase currents sum to zero.





Perfect balance → no neutral current → decreased copper

Balanced Loads

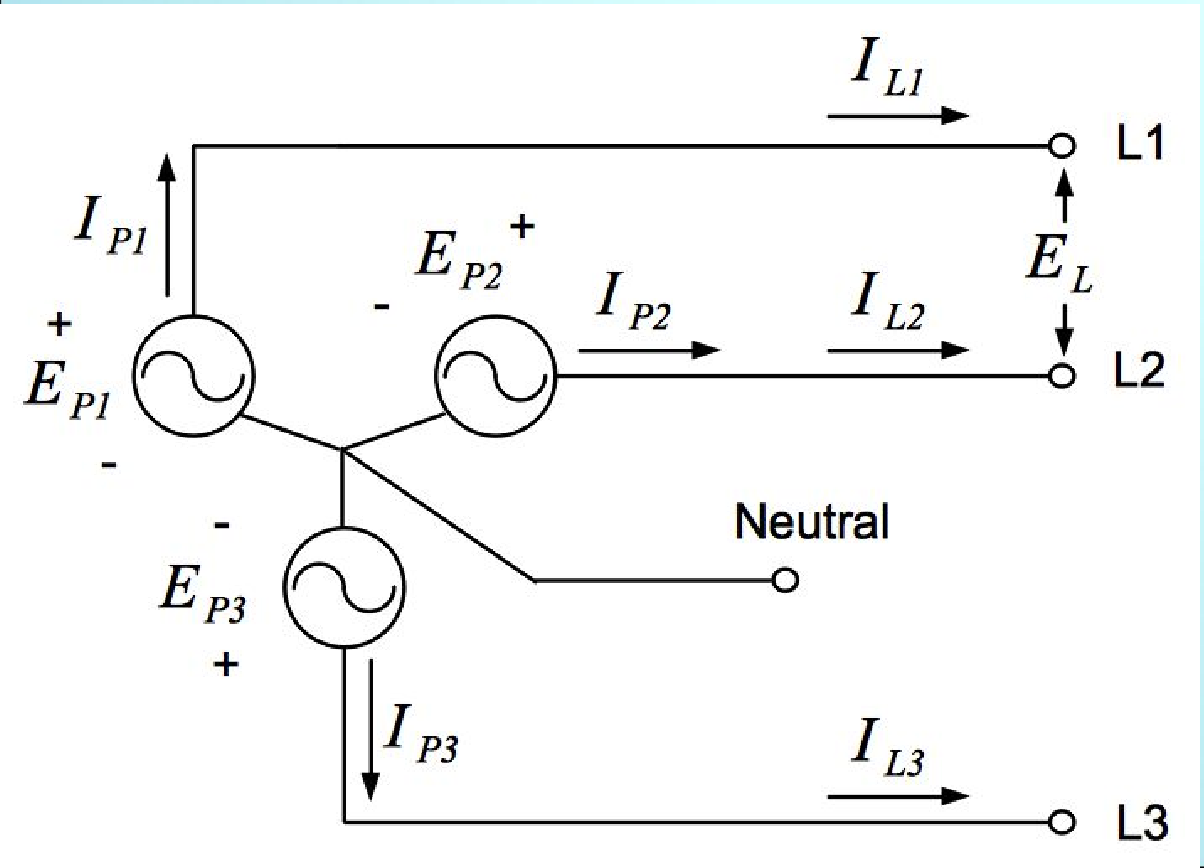
- Three-phase motors
  - Windings pretty well equivalent (if non-damaged)
  - Usually well balanced
- Power system distribution
  - Each house only has single-phase distribution
  - But on average (lots of houses), reasonably balanced
- Why balance loads?
  - More efficient
  - Cost effective
  - Better on equipment

And makes analysis a whole lot easier!

We will only consider balanced systems

Three-Phase Configurations

- Wye-Configuration (Star-Configuration)
  - 4-wire distribution
  - Neutral used for any return current due to imbalance



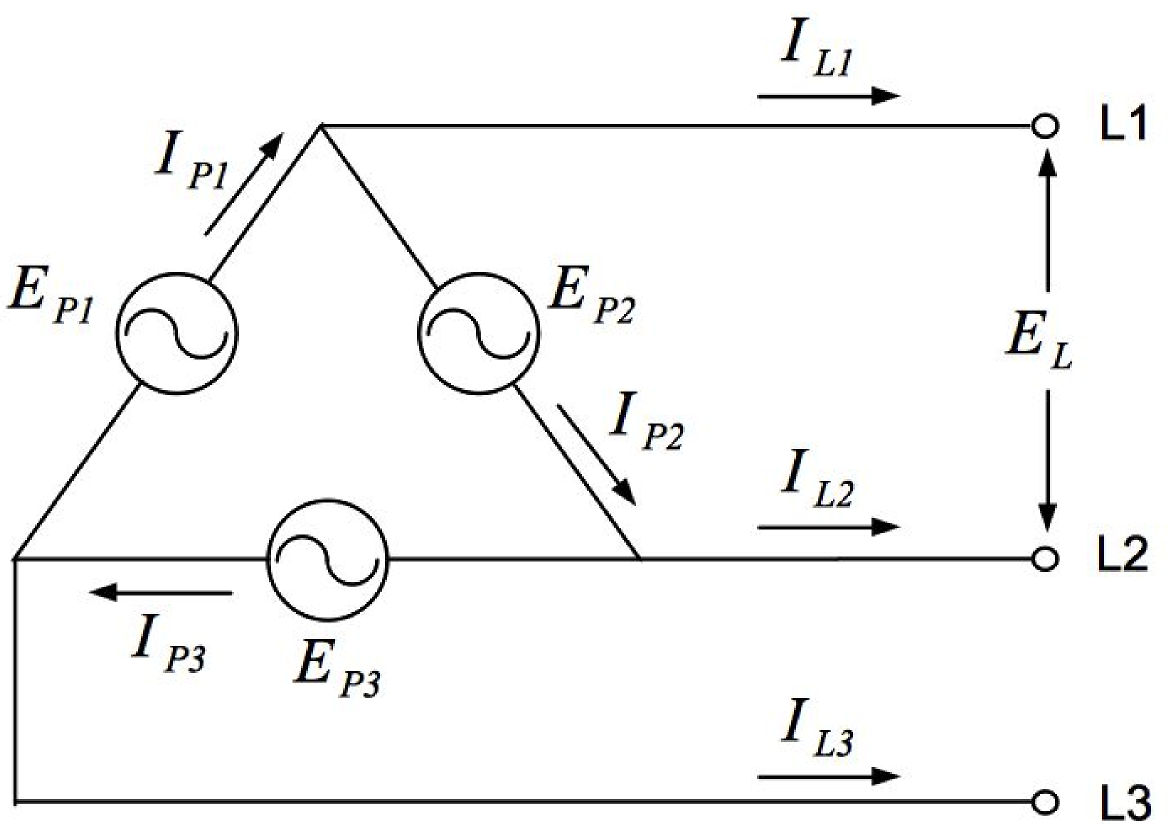
Phase/line relationships

$$E_L = \sqrt{3}\, E_P$$

$$I_L = I_P$$

Three-Phase Configurations

- Delta-Configuration
  - 3-wire distribution
  - No neutral (any required current return due to imbalance distributed on other legs)

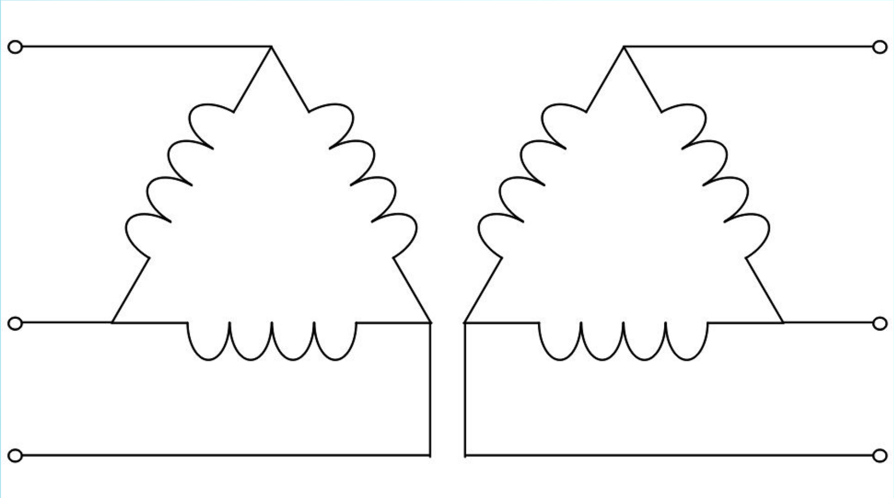


Phase/line relationships

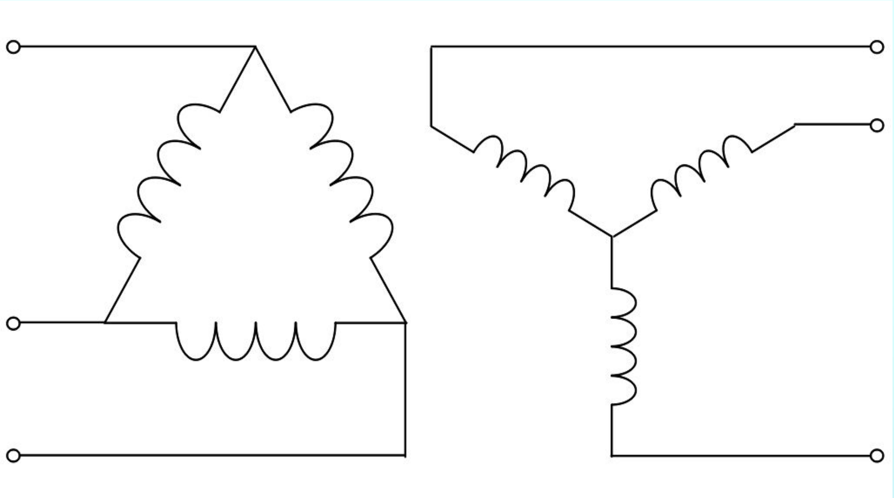
$$E_L = E_P$$
$$I_L = \sqrt{3}\, I_P$$

Three-Phase Transformers

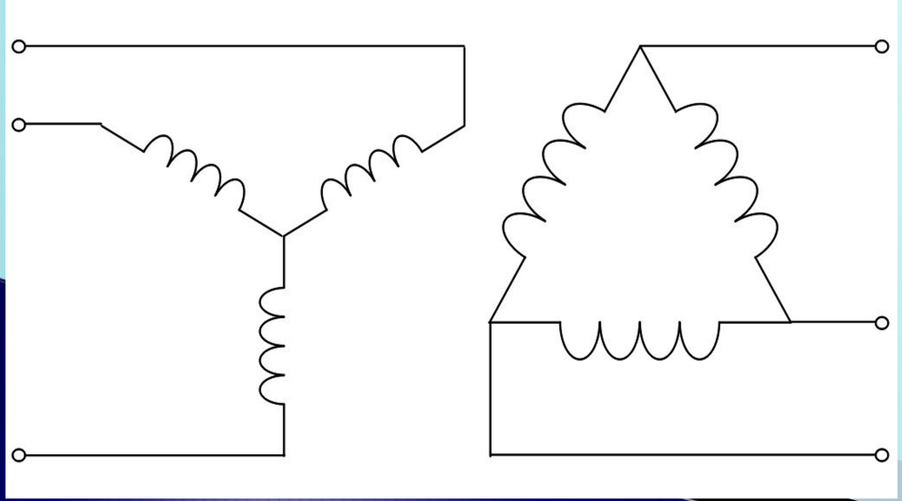
delta-delta



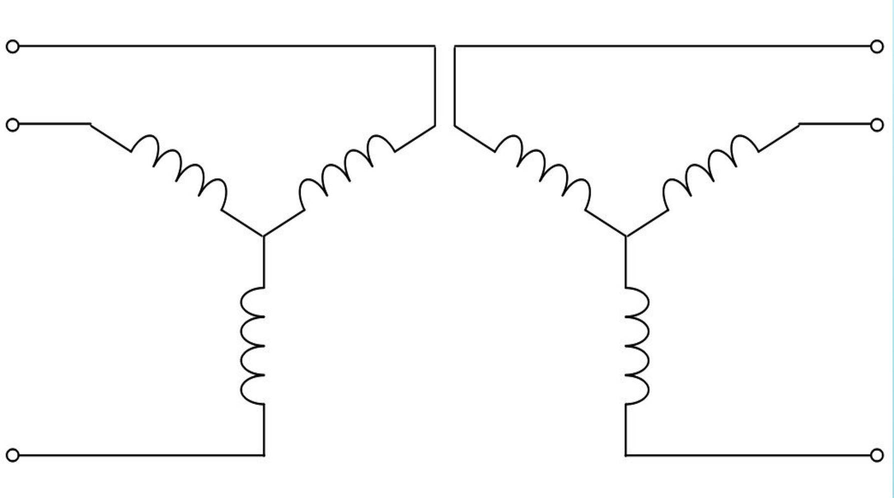
delta-wye



wye-delta



wye-wye



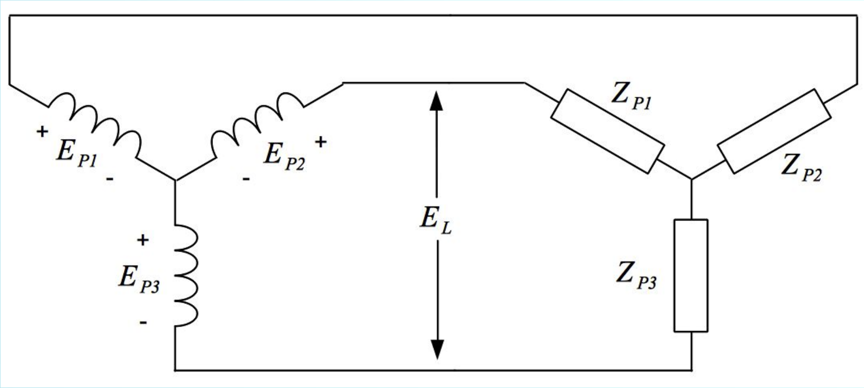
Three-Phase Circuits

- If balanced, can do analysis as single-phase.
  - Use **phase** variables (voltage, current, impedance, etc)
  - Need to find line variables for some circuits
  - Can easily calculate total three-phase power.
- Can also include transformers
  - For this class we will not consider 3-phase transformers
  - See Ch. 12 if interested.

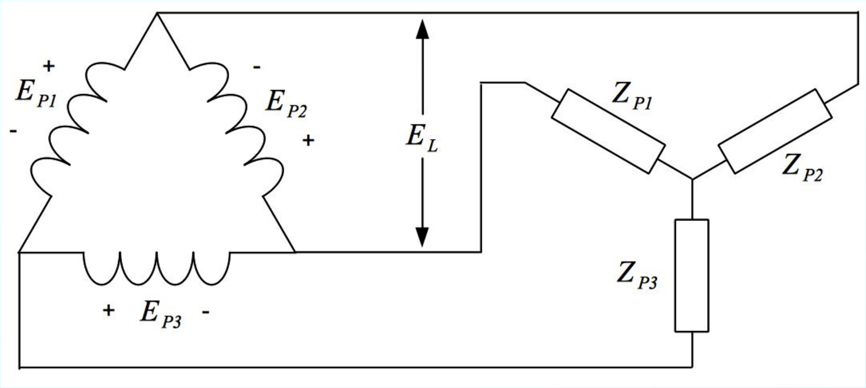
Three-Phase Circuits

- Can have wye or delta out of transformer secondary
- Can have wye or delta load

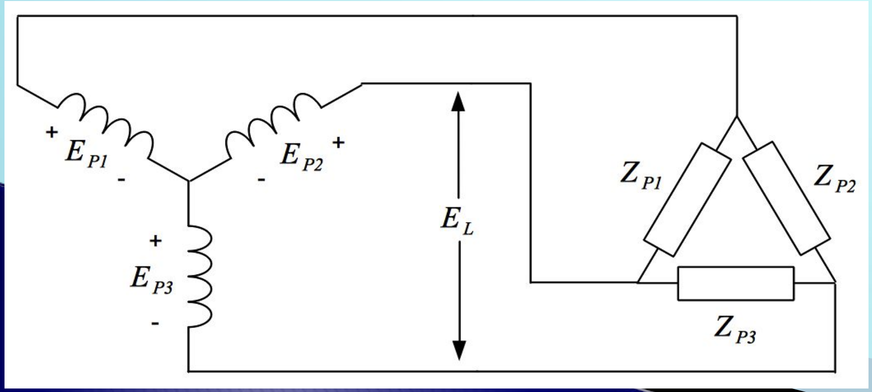
wye secondary – wye load



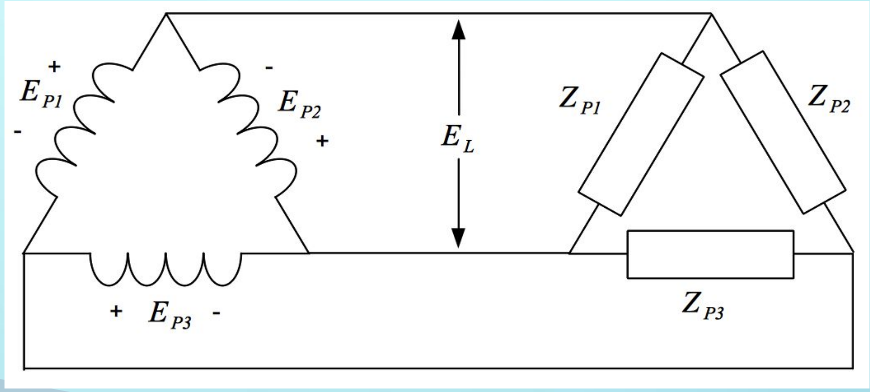
delta secondary – wye load



wye secondary – delta load



delta secondary – delta load



Three-Phase Circuits

- What to calculate?
  - Transformer secondary phase voltage, $E_{S,P}$
  - Transformer secondary line voltage, $E_{S,L}$
  - Transformer secondary phase current, $I_{S,P}$
  - Transformer secondary line current, $I_{S,L}$
  - Load phase voltage, $E_{L,P}$
  - Load line voltage, $E_{L,L}$
  - Load phase current, $I_{L,P}$
  - Load line current, $I_{L,L}$
  - Circuit real, reactive, apparent power, $P \; Q \; S$
  - Circuit power factor, PF

Three-Phase Circuits

- Relevant Equations (we'll consider magnitude only):
  - Ohm's Law: $E_P = I_P Z_P$
  - Real Power: $P = 3 E_P I_P PF$ $\quad P = \sqrt{3} E_L I_L PF$
  - Apparent Power: $S = \sqrt{P^2 + Q^2}$ $\quad S = 3 E_P I_P$ $\quad S = \sqrt{3} E_L I_L$
  - Reactive Power: $Q = \sqrt{S^2 - P^2}$
  - Power Factor: $PF = \frac{P}{S}$

Example: Wye-Wye Circuit

A wye-connected three-phase transformer supplies power to a wye-connected resistive load. The transformer secondary has a phase voltage of 277 V and the resistors of the load have a resistance of 8 Ω.

Step 1: Determine transformer phase voltage and line voltage:

Step 2: Determine load phase voltage and line voltage:

Step 3: Calculate load phase and line current:

Step 4: Determine transformer secondary phase and line current:

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Step 1: Determine transformer phase voltage and line voltage:

$$E_{S,P} = 277\text{V} \qquad E_{S,L} = \sqrt{3}\, E_{S,P} = 480\text{V}$$

Step 2: Determine load phase voltage and line voltage:

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$$E_{L,L} = E_{S,L} = 480\text{V} \qquad E_{L,P} = \frac{1}{\sqrt{3}} E_{S,L} = 277\text{V}$$

Step 3: Calculate load phase and line current:

Step 4: Determine transformer secondary phase and line current:

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Step 3: Calculate load phase and line current:

$$I_{L,P} = E_{L,P} / Z_{L,P} = 34.6\text{A} \qquad I_{L,L} = I_{L,P} = 34.6\text{A}$$

Step 4: Determine transformer secondary phase and line current:

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Example: Wye-Wye Circuit

For previous circuit example, determine real, reactive, and apparent power:

Example: Wye-Wye Circuit

For previous circuit example, determine real, reactive, and apparent power:

$$PF = 1$$

$$P = 3\,E_{L,P}\,I_{L,P}\,PF = 3 * 277\text{V} * 34.6\text{A} = 28.8\text{kW}$$

$$S = P = 28.8\text{kVA}$$

$$Q = 0\text{kVAR}$$

Resistive circuit so no reactive power!

Example: Wye-Delta Circuit

A wye-connected three-phase transformer supplies power to a delta-connected induction motor. The transformer secondary has a phase voltage of 277 V and motor windings have a total impedance of 8 Ω. The motor operates with a power factor of 0.8.

Step 1: Determine transformer phase voltage and line voltage:

Step 2: Determine load phase voltage and line voltage:

Step 3: Calculate load phase and line current:

Step 4: Determine transformer secondary phase and line current:

Example: Wye-Delta Circuit

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Step 3: Calculate load phase and line current:

$$I_{L,P} = E_{L,P} / Z_{L,P} = 60\text{A} \qquad I_{L,L} = \sqrt{3}\,I_{L,P} = 104\text{A}$$

Step 4: Determine transformer secondary phase and line current:

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Step 4: Determine transformer secondary phase and line current:

$$I_{S,L} = I_{L,L} = 104\text{A} \qquad I_{S,P} = I_{S,L} = 104\text{A}$$

Example: Wye-Wye Circuit

For previous circuit example, determine real, reactive, and apparent power:

Example: Wye-Wye Circuit

For previous circuit example, determine real, reactive, and apparent power:

$$PF = 0.8$$

$$P = 3\,E_{L,P}\,I_{L,P}\,PF = 3 * 480\text{V} * 60\text{A} * 0.8 = 69.1\text{kW}$$

$$S = \frac{P}{PF} = \frac{69{,}100}{0.8} = 86.4\text{kVA}$$

$$Q = \sqrt{S^2 - P^2} = 51.8\text{kVAR}$$

Upcoming in class

- More 3-phase circuits
  - Delta and Wye connections

- Electrical Distribution

- CHANGE TO SYLLABUS
  - There IS lab next week
  - We will do project later (probably week before Thanksgiving)