Chapter 24

Three-Phase Systems

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Three-Phase Voltage Generation

- Three-phase generators
  - Three sets of windings and produce three ac voltages
- Windings are placed 120° apart
  - Voltages are three identical sinusoidal voltages 120° apart

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Three-Phase Voltage Generation

- Set of voltages such as these are balanced
- If you know one of the voltages
  - The other two are easily determined

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Four-Wire Systems

- Three loads have common return wire called neutral
- If load is balanced
  - Current in the neutral is zero
- Current is small
  - Wire can be smaller or removed
  - Current may not be zero, but it is very small

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Four-Wire Systems

- Outgoing lines are called line or phase conductors

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Three-Phase Relationships

- Line voltages
  - Voltages between lines either at the generator ($\mathbf{E}_{AB}$) or at the load ($\mathbf{V}_{AB}$)

Three-Phase Relationships

- **Phase voltages**
  - Voltages across phases
    - For a Y load, phases are from line to neutral
    - For Δ load, the phases are from line to line

Three-Phase Relationships

- Line currents
  - Currents in line conductors
- Phase currents
  - Currents through phases
  - For a Y load two currents are the same

Voltages in a Wye Circuit

- For a balanced Y system
  - Magnitude of line-to-line voltage is $\sqrt{3}$ times the magnitude of phase voltage
- Each line-to-line voltage
  - Leads corresponding phase voltage by 30°
- Line-to-line voltages form a balanced set

Voltages for a Wye Circuit

- Nominal voltages
  - 120/208-V
  - 277/480-V
  - 347/600-V systems

Voltages for a Wye Circuit

- Given any voltage at a point in a balanced, three-phase Y system
  - Determine remaining five voltages using the formulas

$$\mathbf{V}_{ab} = \sqrt{3}\mathbf{V}_{an}\angle 30^\circ$$

$$\mathbf{E}_{AB} = \sqrt{3}\mathbf{E}_{AN}\angle 30^\circ$$

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Currents for a Wye Circuit

- Line currents
  - Same as phase currents
  - $\mathbf{I}_a = \mathbf{V}_{an}/\mathbf{Z}_{an}$
- Line currents form a balanced set
  - If you know one current
    - Determine the other five currents by inspection

Currents for a Delta Load

- In a balanced delta
  - The magnitude of the line current is $\sqrt{3}$ times the magnitude of the phase current

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Currents for a Delta Load

- Each line current lags its corresponding phase current by 30°
- For any current in a balanced, three-phase delta load
  - Determine remaining currents by inspection

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Power in a Balanced System

- To find total power in a balanced system
  - Determine power in one phase
  - Multiply by three
- Use ac power formulas previously developed

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Power in a Balanced System

- Since magnitudes are the same for all three phases, simplified notation may be used

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Active Power to a Balanced Wye Load

- $P_\phi = V_\phi I_\phi \cos\,\theta_\phi$
- $P_T = 3P_\phi = 3V_\phi I_\phi \cos\,\theta_\phi$
- $P_T = \sqrt{3}V_L I_L \cos\,\theta_\phi$
- $P_\phi = I_\phi^2 R_\phi$
- $P_T = 3I_\phi^2 R_\phi$

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Reactive Power to a Balanced Wye Load

- $Q_\phi = V_\phi I_\phi \sin\,\theta_\phi$
- $Q_T = \sqrt{3}V_L I_L \sin\,\theta_\phi$
- $Q_\phi = I_\phi^2 X_\phi$
- Units are VARs

Apparent Power to a Balanced Wye Load

- $S_\phi = V_\phi I_\phi$
- $S_T = \sqrt{3}\, V_L I_L$
- $S_\phi = I_\phi^2 Z_\phi$

Apparent Power to a Balanced Wye Load

- Units are VAs
- Power factor is

$$F_p = \cos\theta_\phi = P_T/S_T = P_\phi/S_\phi$$

Power to a Balanced Delta Load

- Power formulas for Δ load are identical to those for Y load
- In all these formulas
  - Angle θ_ϕ is phase angle of the load impedance

Power to a Balanced Delta Load

- You can also use single-phase equivalent in power calculations
  - Power will be power for just one phase

Measuring Power in Three-Phase Circuits

- Measuring power to a 4-wire Y load requires three wattmeters (one meter per phase)
- Loads may be balanced or unbalanced
- Total power is sum of individual powers

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Measuring Power in Three-Phase Circuits

- If load could be guaranteed to be balanced
  - Only one meter would be required
  - Its value multiplied by 3

Measuring Power in Three-Phase Circuits

- For a three-wire system
  - Only two meters are needed
- Loads may be Y or Δ
- Loads may be balanced or unbalanced
- Total power is algebraic sum of meter readings

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Measuring Power in Three-Phase Circuits

- Power factor for a balanced load
  - Obtain from wattmeter readings using a watts ratio curve

$$tan\theta_{\phi} = \sqrt{3}\left(\frac{P_h - P_\ell}{P_h + P_\ell}\right)$$

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Measuring Power in Three-Phase Circuits

- From this, θ can be determined
- Power factor can then be determined from cos θ

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Unbalanced Loads

- Use Ohm's law
  - For unbalanced four-wire Y systems without line impedance
- Three-wire and four-wire systems with line and neutral impedance
  - Require use of mesh analysis

Unbalanced Loads

- One of the problems with unbalanced loads
  - Different voltages are obtained across each phase of the load and between neutral points

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Unbalanced Loads

- Unbalanced four-wire Δ systems without line impedance are easily handled
  - Source voltage is applied directly to load
- Three-wire and four-wire systems with line and neutral impedance
  - Require use of mesh analysis

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Power System Loads

- Single-phase power
  - Residential and business customers
- Single-phase and three-phase systems
  - Industrial customers
  - Therefore, there is a need to connect both single-phase and three-phase loads to three-phase systems

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Power System Loads

- Utility tries to connect one third of its single-phase loads to each phase
- Three-phase loads are generally balanced

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Power System Loads

- Real loads
  - Seldom expressed in terms of resistance, capacitance, and inductance
  - Rather, real loads are described in terms of power, power factors, etc.