Voltage Regulation

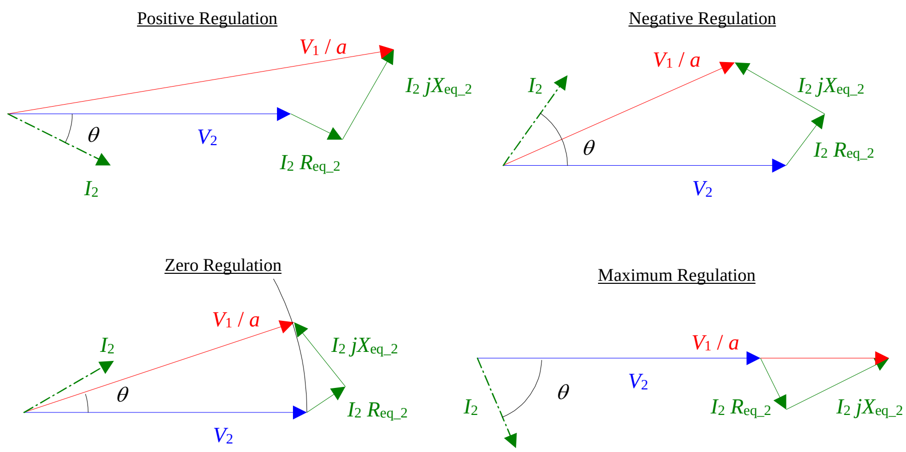
Definition:

$$percent \quad regulation = \frac{\left|V_{2,no-load}\right| - \left|V_{2,\,full-load}\right|}{\left|V_{2,\,full-load}\right|} \times 100$$

Practical Equation:

$$percent \quad regulation = \frac{\left|V_1/a\right| - \left|V_2\right|}{\left|V_2\right|} \times 100$$

Voltage Regulation



Transformer Efficiency

Definition:

$$\eta = \frac{output \quad power}{input \quad power} = \frac{P_2}{P_1}$$

Practical Equation:

$$\eta = \frac{P_1 - P_{losses}}{P_1} = \frac{P_2}{P_2 + P_{losses}} = \frac{P_2}{P_2 + P_{copper} + P_{core}}$$

Per Unit Equation:

$$\eta = \frac{\left|S_{2-pu}\right| \cos\phi}{\left|S_{2-pu}\right| \cos\phi + P_{core-pu} + \left|S_{2-pu}\right|^2 R_{eq-pu}}$$

Example: Voltage regulation

See Book, Example 3-5, p. 119

Per Unit System

- **From generation to the load centers, power systems have ratings and values that cover a large range**
  - e.g., 100 MVA of generation to 5 kVA loads; 765 kV transmission to 120 V utilization level
- **The per unit system of measurements simplifies the computation and analysis through a system**
- **Various electrical quantities are normalized with respect to a specific base value**
  - When working in a per unit system, it is important to specify the required base values
  - Electrical quantities such as voltage, current, power, and impedance are converted to per unit quantities

Per Unit (pu) System

$$pu \quad value = \frac{actual \quad value}{base \quad value \quad of \quad the \quad same \quad dimension}$$

$$base \quad current = \frac{base \quad apparent \quad power}{base \quad voltage}$$

$$base \quad impedance = \frac{base \quad voltage}{base \quad current}$$

$$per-unit \quad voltage \quad = \frac{actual \quad voltage}{base \quad voltage}$$

$$per-unit \quad current \quad = \frac{actual \quad current}{base \quad current}$$

$$per-unit \quad impedance \quad = \frac{actual \quad impedance}{base \quad impedance}$$

Per Unit System – Y connections, Transmission lines

$$base \quad voltage, \quad V_{Base} = V_{p-Base} = V_{LL-Base} \big/ \sqrt{3}$$

$$base \quad current, \quad I_{Base} = \frac{S_{1\phi-Base}}{V_{p-Base}} = \frac{S_{3\phi-Base}/3}{V_{LL-Base}/\sqrt{3}} = \frac{S_{3\phi-Base}}{\sqrt{3}\cdot V_{LL-Base}}$$

$$base \quad impedance, \quad Z_{Base} = \frac{V_{p-Base}}{I_{Base}} = \frac{V_{LL-Base}/\sqrt{3}}{I_{Base}}$$

$$Z_{Base} = \frac{(V_{p-Base})^2}{S_{1\phi-Base}} = \frac{(V_{LL-Base}/\sqrt{3})^2}{S_{3\phi-Base}/3} = \frac{(V_{LL-Base})^2}{S_{3\phi-Base}}$$

Per Unit System – Δ connection (less commonly used)

$$base \quad voltage, \quad V_{Base} = V_{LL-Base} = \sqrt{3}\cdot V_{p-Base}$$

$$base \quad current, \quad I_{Base} = \frac{S_{1\phi-Base}}{V_{LL-Base}} = \frac{S_{3\phi-Base}}{3\cdot V_{LL-Base}} = \frac{1}{\sqrt{3}} I_{Base-Y}$$

$$base \quad impedance, \quad Z_{Base} = \frac{V_{LL-Base}}{I_{Base}} = \frac{\sqrt{3}V_{p-Base}}{I_{Base-Y}/\sqrt{3}} = 3Z_{Base-Y}$$

$$Z_{Base} = \frac{(V_{LL-Base})^2}{S_{1\phi-Base}} = \frac{(V_{LL-Base})^2}{3\cdot S_{3\phi-Base}} = 3\cdot Z_{Base-Y}$$

Example

Find the pu impedances for the Transformer of Example 3-5, p. 119

a) For 15 kVA power base
b) For 30 kVA power base

Example (primary side)

S_{base} = 15 kVA $V_{Base,P} = 2300V$ **S_{base} = 30 kVA**

$$Z_{Base,P} = \frac{V_{Base,P}^2}{S_{Base}} = \frac{2300^2}{15000} = 352.7\,\Omega \qquad Z_{Base,P} = \frac{V_{Base,P}^2}{S_{Base}} = \frac{2300^2}{30000} = 176.4\,\Omega$$

$$R_{C,P,pu} = \frac{105.8\,k\Omega}{Z_{Base,P}} = 300\ pu \qquad R_{C,P,pu} = 600\ pu$$

$$X_{m,P,pu} = j\frac{11\,k\Omega}{Z_{Base,P}} = j31\ pu \qquad X_{m,P,pu} = j62\ pu$$

S_{base} is independent of primary and secondary side

$$X_{eq,P,pu} = j\frac{6.45\,\Omega}{Z_{Base,P}} = j0.0183\ pu = j1.83\%\ pu \qquad X_{eq,P,pu} = j3.66\%\ pu$$

$$R_{eq,P,pu} = \frac{4.45\,\Omega}{Z_{Base,P}} = 0.0126\ pu = 1.26\%\ pu \qquad R_{eq,P,pu} = 3.52\%\ pu$$

Example (secondary side)

S_{base} = 15 kVA $V_{Base,S} = 230V$ **S_{base} = 30 kVA**

$$Z_{Base,S} = \frac{V_{Base,S}^2}{S_{Base}} = \frac{230^2}{15000} = 3.527\,\Omega \qquad Z_{Base,S} = \frac{V_{Base,S}^2}{S_{Base}} = \frac{230^2}{30000} = 1.763\,\Omega$$

$$R_{C,S,pu} = \frac{1058\,\Omega}{Z_{Base,S}} = 300\ pu \qquad R_{C,S,pu} = 600\ pu$$

$$X_{m,S,pu} = j\frac{110\,\Omega}{Z_{Base,S}} = j31\ pu \qquad X_{m,S,pu} = j62\ pu$$

S_{base} is independent of primary and secondary side

$$X_{eq,S,pu} = j\frac{64.5\,m\Omega}{Z_{Base,S}} = j0.0183\ pu = j1.83\%\,pu \qquad X_{eq,S,pu} = j3.66\%\,pu$$

$$R_{eq,S,pu} = \frac{44.5\,m\Omega}{Z_{Base,S}} = 0.0126\ pu = 1.26\%\,pu \qquad R_{eq,S,pu} = 3.52\%\,pu$$

Homework 3

See web site
http://www.eng.fsu.edu/~steurer/eel3216.html

Problems 3-1 through 3-4 and 3-6 through 3-8 in book.