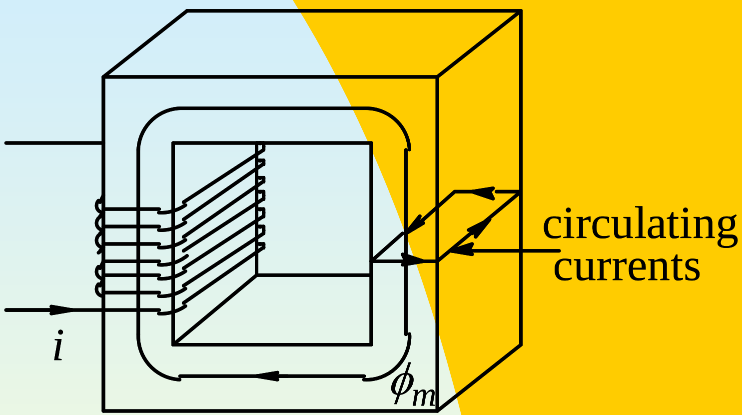
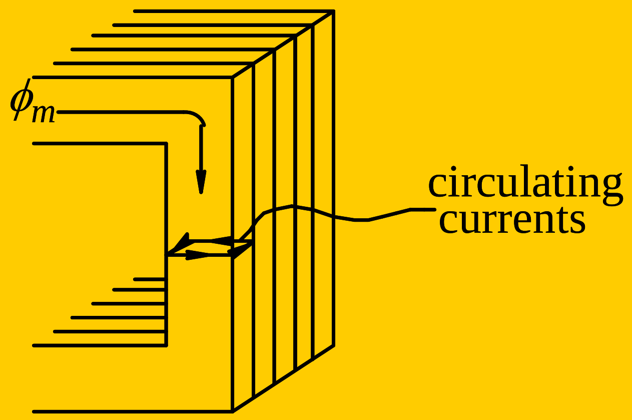
Eddy Current and Hysteresis Losses



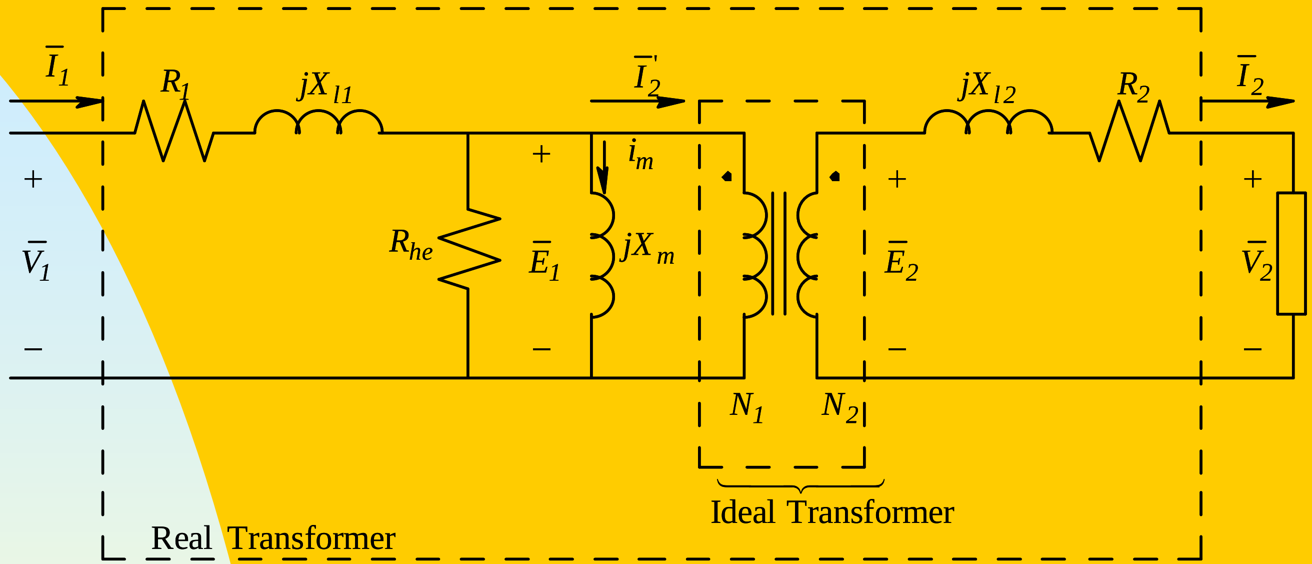
(a)



(b)

- Laminating the core reduces Eddy-Current Losses
- Laminations 0.2 to 1 mm thick at 50/60 Hz
- Losses represented by a parallel Resistor

Obtaining Equivalent Circuit parameters



- Open-Circuit Test
  - Magnetizing Reactance and Core-Loss Equivalent Resistance
- Short-Circuit Test
  - Leakage Impedances

Transformer Simplified Model

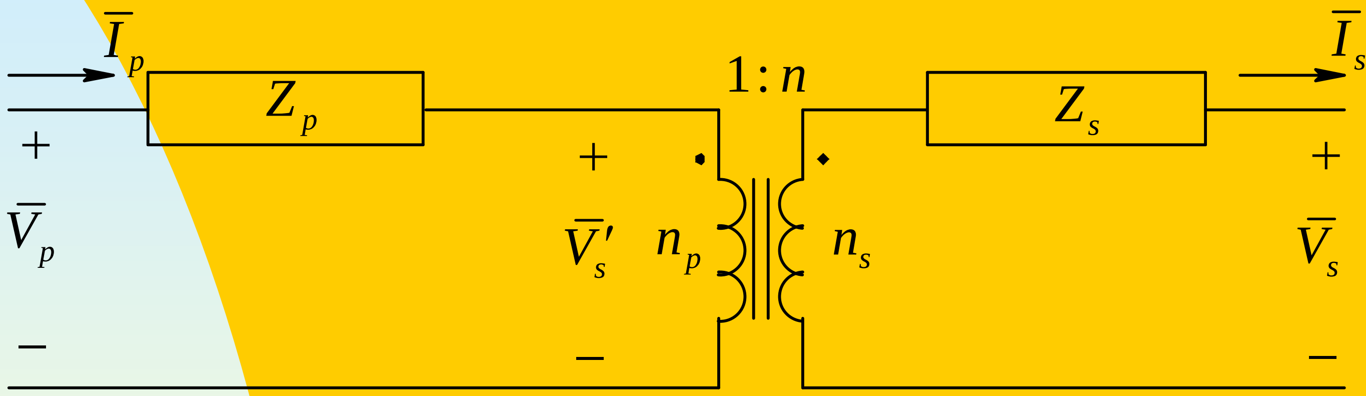
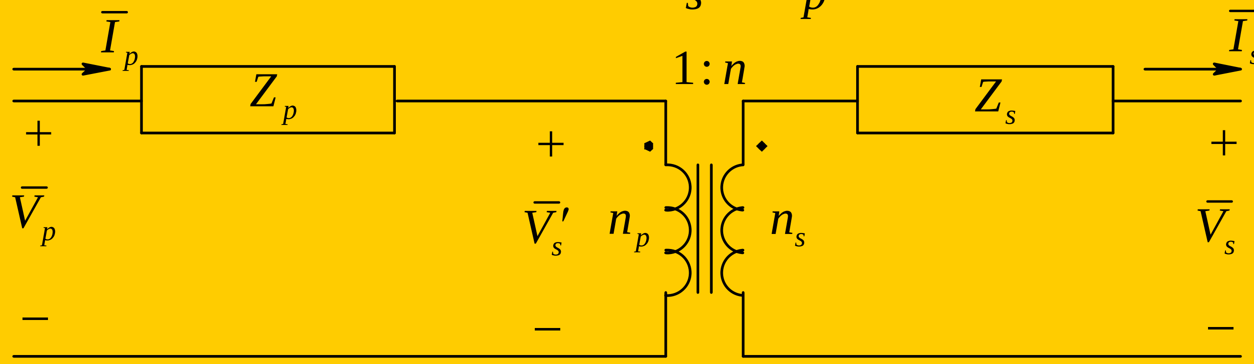


Fig. 6-7 Simplified transformer model.

$$n = n_s / n_p$$

Transferring Leakage Impedances from One Side to Another

$$n = n_s / n_p$$



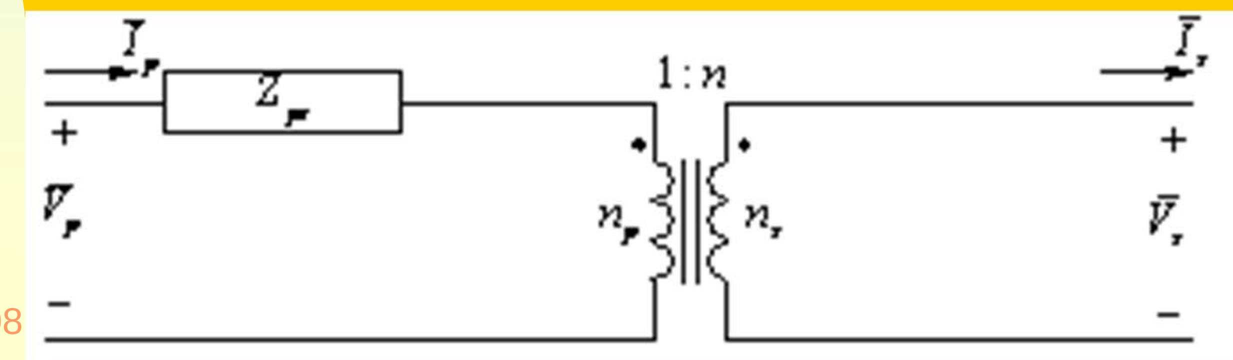
$$\bar{V}_s' = \frac{Z_s \bar{I}_s}{n}$$

$$\bar{V}_p = \bar{V}_s' + Z_p \bar{I}_p$$

$$\bar{I}_s = \bar{I}_p / n$$

$$\frac{\bar{V}_p}{\bar{I}_p} = Z_{ps} = Z_p + \left(Z_s / n^2 \right)$$

$$\bar{V}_s' = \left(\frac{Z_s}{n^2} \right) \bar{I}_p$$



Transformer Equivalent Circuit in Per Unit

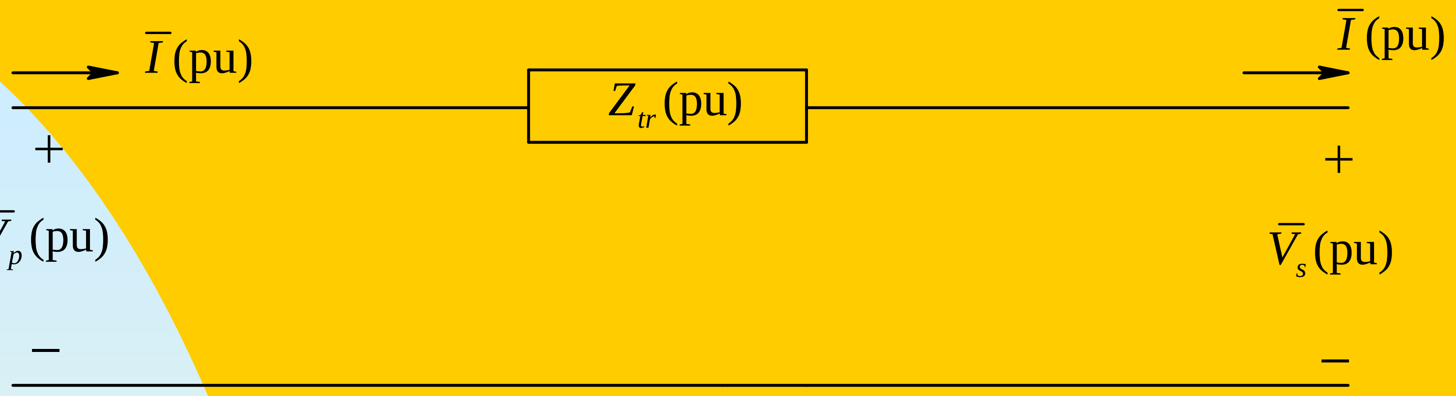


Fig. 6-9 Transformer equivalent circuit in per unit (pu).

$$\frac{V_{p,rated}}{V_{s,rated}} = \frac{1}{n}$$

$$Z_{p,base} = V_{p,rated} / I_{p,rated}$$

$$\frac{I_{p,rated}}{I_{s,rated}} = n$$

$$Z_{s,base} = V_{s,rated} / I_{s,rated}$$

$$\frac{Z_{p,base}}{Z_{s,base}} = \left(\frac{1}{n}\right)^2$$

$$Z_{tr}(\text{pu}) = \underbrace{Z_{ps}(\text{pu})}_{\left(=\frac{Z_{ps}}{Z_{p,base}}\right)} = \underbrace{Z_{sp}(\text{pu})}_{\left(=\frac{Z_{sp}}{Z_{s,base}}\right)}$$

Connection of Transformer Windings

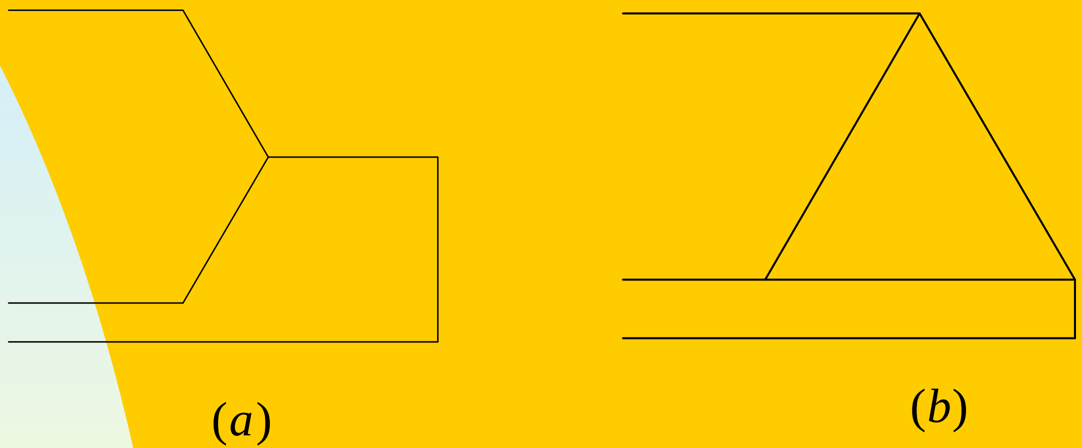


Fig. 6-10 Winding connections in a three-phase system.

Including Nominal Turns-Ratio Transformer in Power Flow Studies

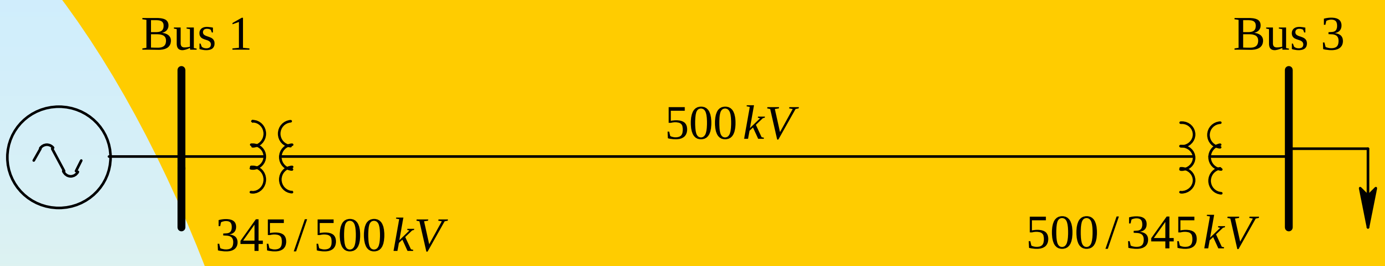


Fig. 6-11 Including nominal-voltage transformers in per-unit.

$$Z_{base}(\Omega) = \frac{kV_{base}^2 \text{(L-L)}}{MVA_{base} \text{(3-phase)}}$$

$$Z_{pu}(\text{new}) = Z_{pu}(\text{original}) \times \frac{MVA_{base}(\text{new})}{MVA_{base}(\text{original})}$$

Transformer Losses and Leakage Reactances

$$\%\text{Efficiency} = 100 \times \frac{P_{output}}{P_{input}} = 100 \times \left(1 - \frac{P_{losses}}{P_{input}}\right)$$

- Winding resistance well below 5%
- Efficiencies in excess of 99.5%

Leakage Reactances

- 7% to 20%

Regulation in Transformers

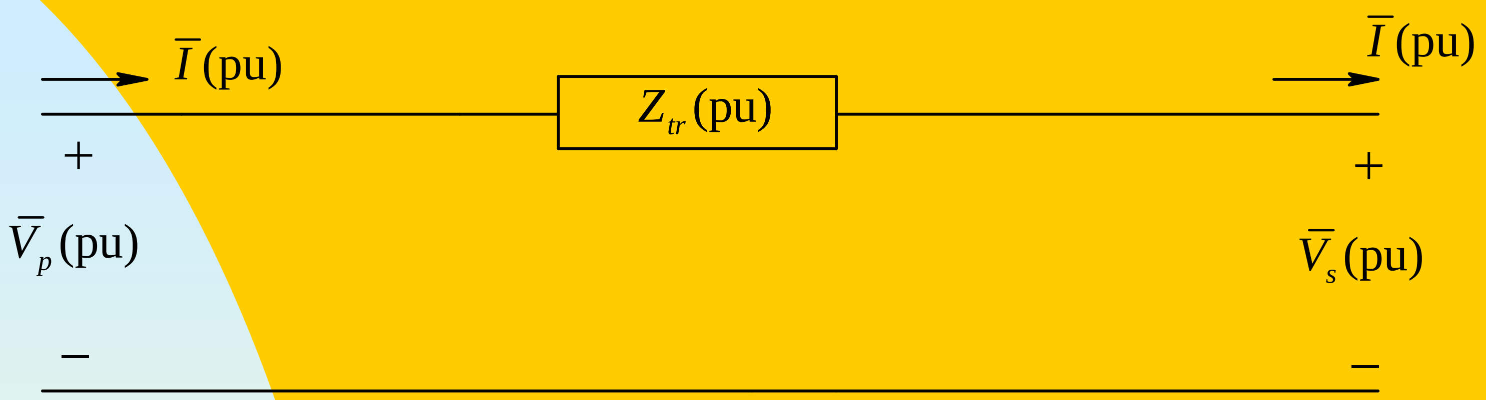


Fig. 6-9 Transformer equivalent circuit in per unit (pu).

$$\bar{V}_s(pu) = \bar{V}_P(pu) - jX_{tr}(pu)\bar{I}(pu)$$