Different kinds of Transformers

Outcome of this lecture

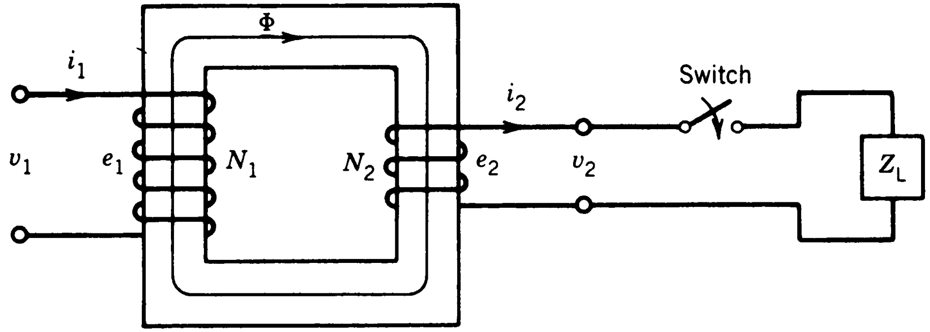
At the end of this lecture you will be able to:

- Explain the operation principle of a transformer
- Model a transformer with a lamped-parameters equivalent circuit
- Calculate the parameters of the equivalent circuit from measurements
- Use the equivalent circuit to calculate
  - The power balance
  - The efficiency
- Understand what the harmonics in three phases transformers mean and how they are produced

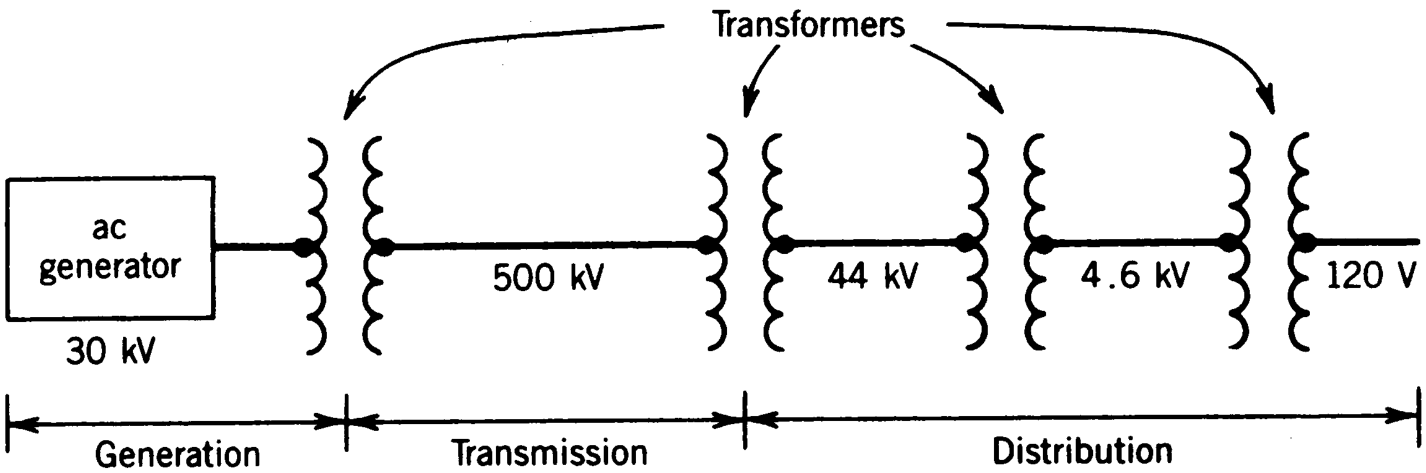
- You will also learn about different possible connections of three phase transformers.

Transformers applications

- Change voltage level
- Isolation of circuits
- Match the impedance

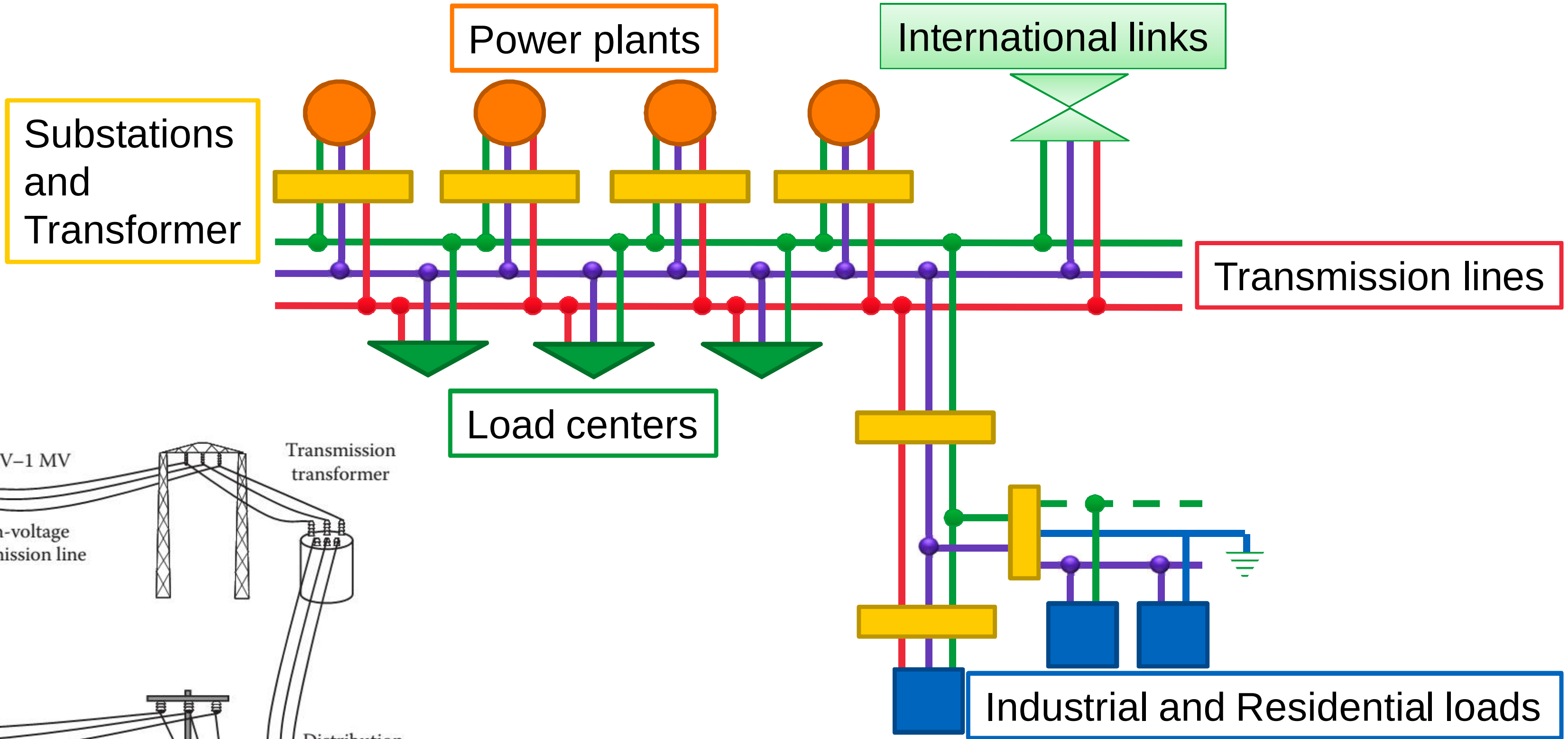


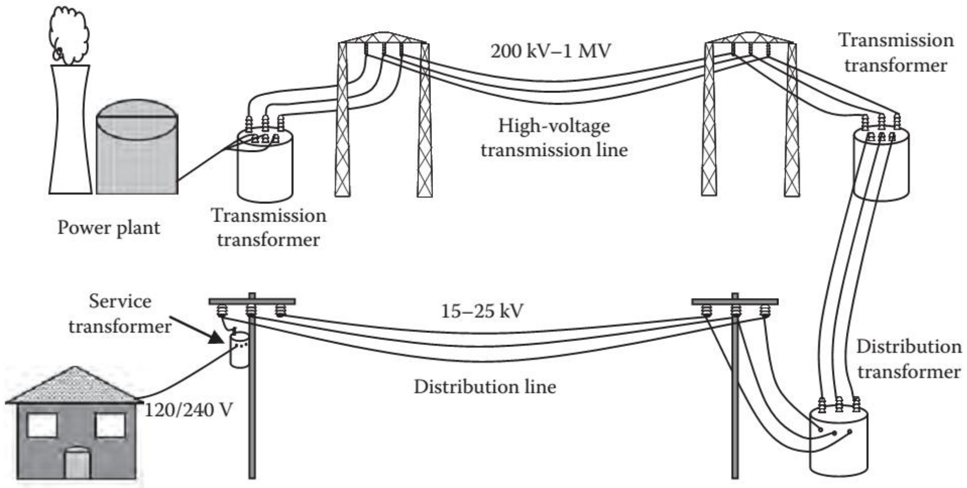
Power transmission



General power system configuration

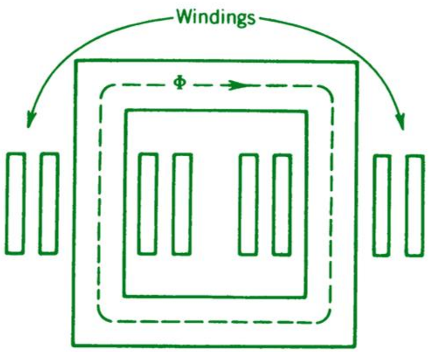
- The quasi totality of the electric power generated worldwide is three-phase.





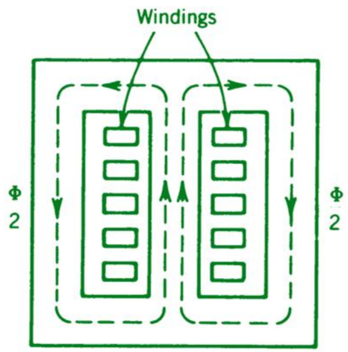
Transformer structure

Core-type

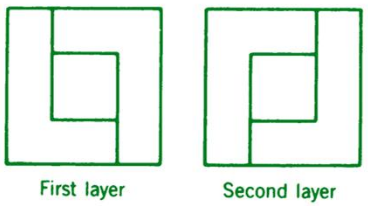


(a)

Shell-type

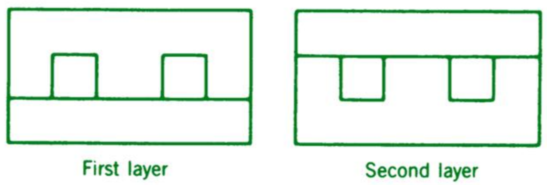


(b)



(c)

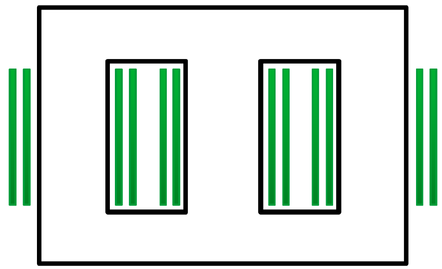
L-shaped lamination

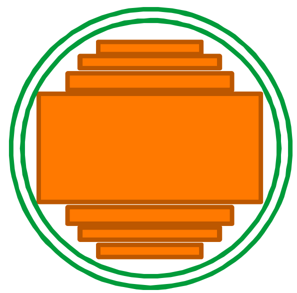


(d)

E-shaped lamination

Core-type 3 phases version

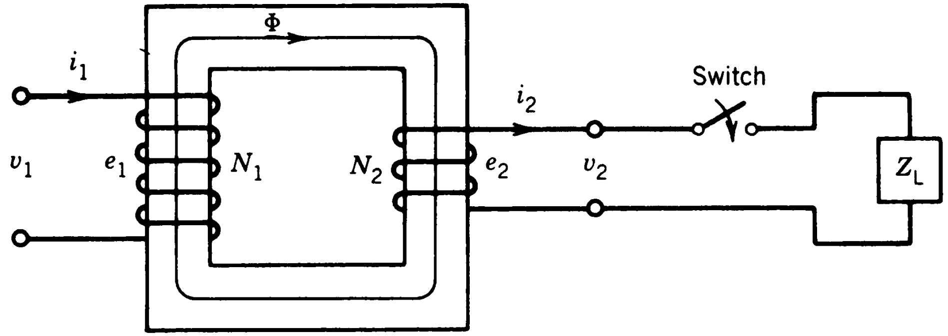




Cross section of the iron core and the windings

Ideal Transformer

- No losses
- No leakage
- No current needed for magnetizing



- Voltages

$$v_1 = e_1 = N_1 \frac{dF}{dt}$$
$$v_2 = e_2 = N_2 \frac{dF}{dt}$$
$$\Rightarrow \frac{v_1}{v_2} = \frac{N_1}{N_2} = a$$

turns ratio

- Power

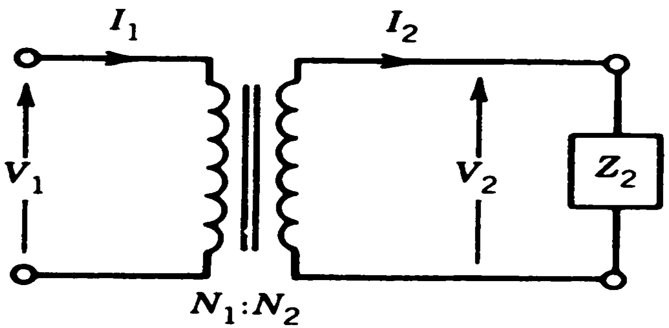
$$v_1 i_1 = v_2 i_2$$

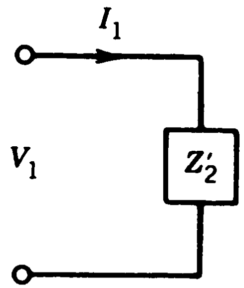
- Currents

$$N_1 i_1 - N_2 i_2 = 0 \Rightarrow \frac{i_1}{i_2} = \frac{N_2}{N_1} = \frac{1}{a}$$

Impedance transfer

How an impedance at the terminals of the secondary is seen from the primary side.





$$Z_2' = \frac{V_1}{I_1}$$

$$Z_2 = \frac{V_2}{I_2}$$

$$\frac{V_1}{V_2} = a$$

$$\frac{I_1}{I_2} = \frac{1}{a}$$

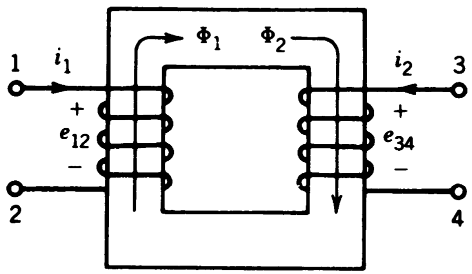
$$Z_2' = a^2 Z_2$$

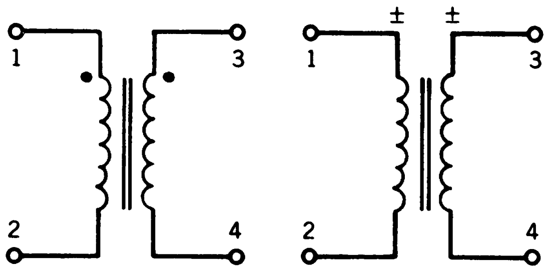
Polarity

- Current entering identical terminals produce fluxes in the same direction

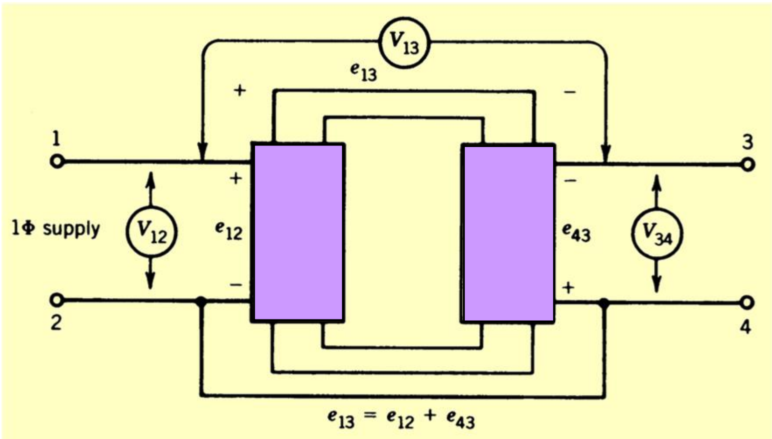
e_{12} and e_{34} are in phase.

??





Why this is important ?
Why we cannot measure
the voltages with a voltmeter ?

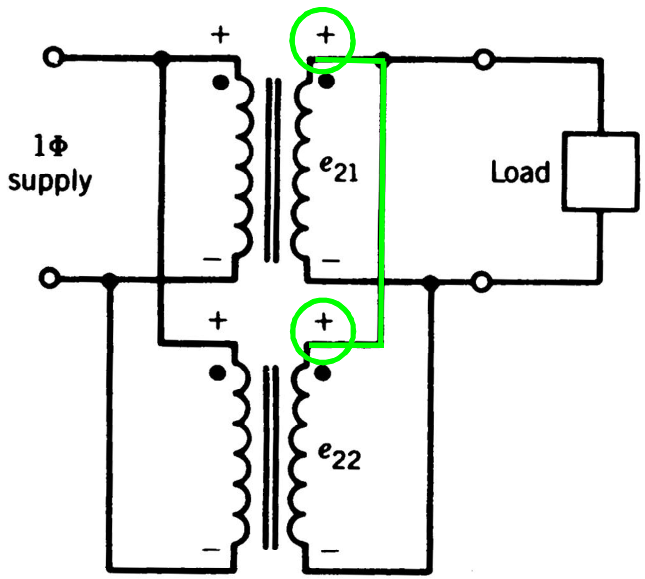


If V_{13}@$V_{12}+V_{34}$ then 1 and 4 identical

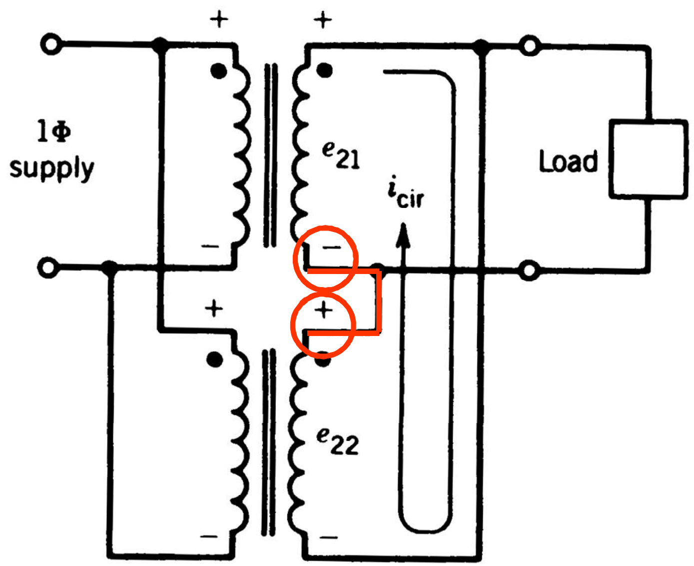
If V_{13} @ $V_{12}-V_{34}$ then 1 and 3 identical

Parallel operation

Polarity mismatch → Circulating current.



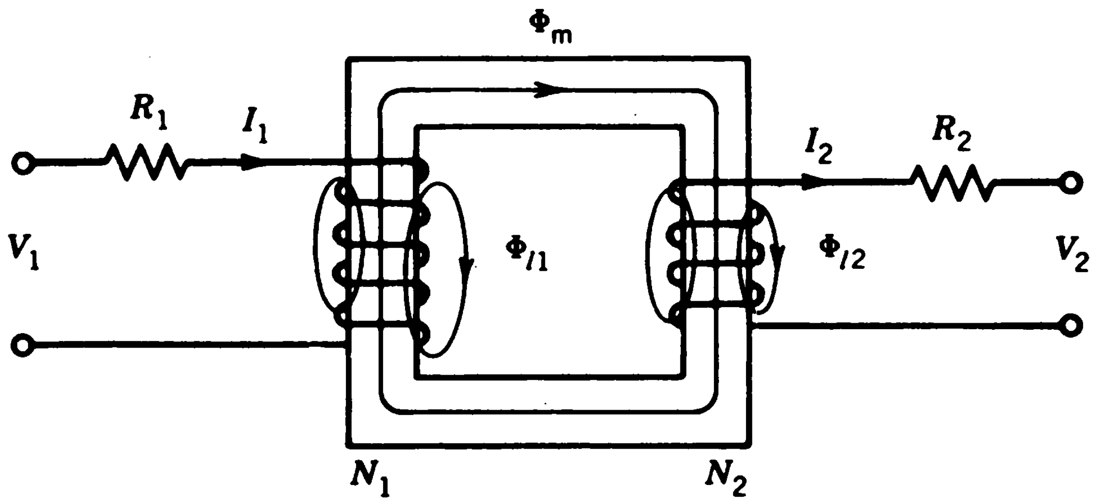
Correct connection



Wrong connection

Practical transformer

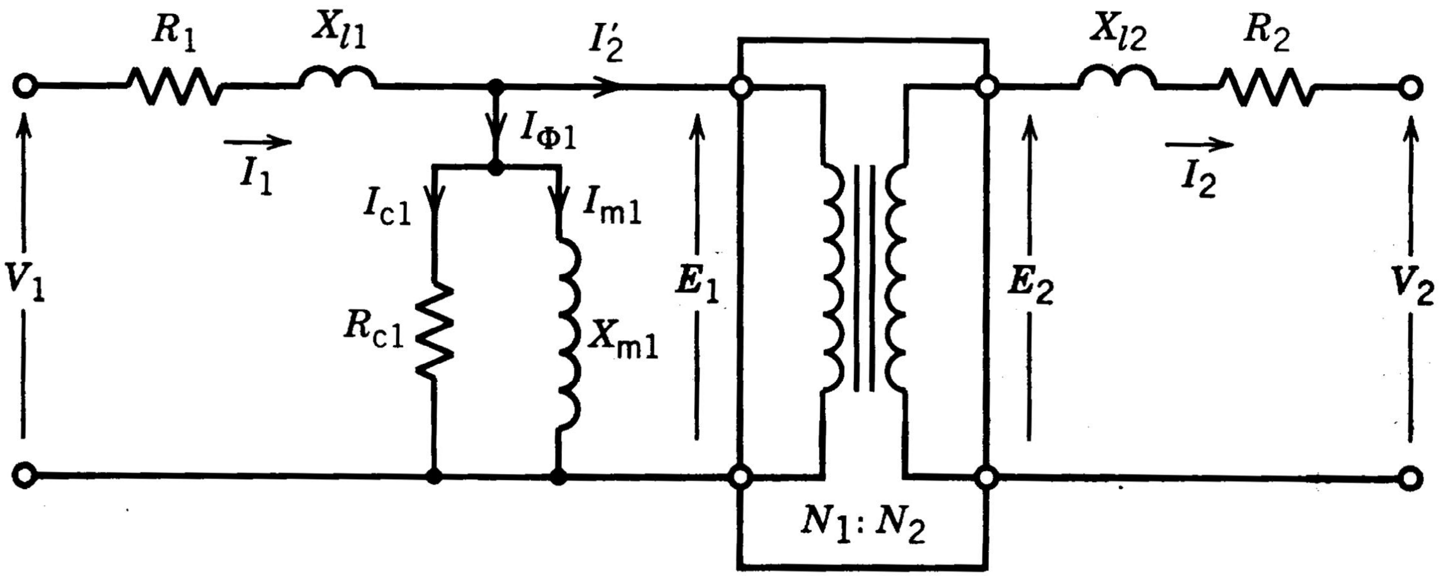
- Winding resistance
- Flux leakage
- Finite permeability
- Core losses



Transformer model is based on

- Physical reasoning
- Mathematic model of coupled circuits

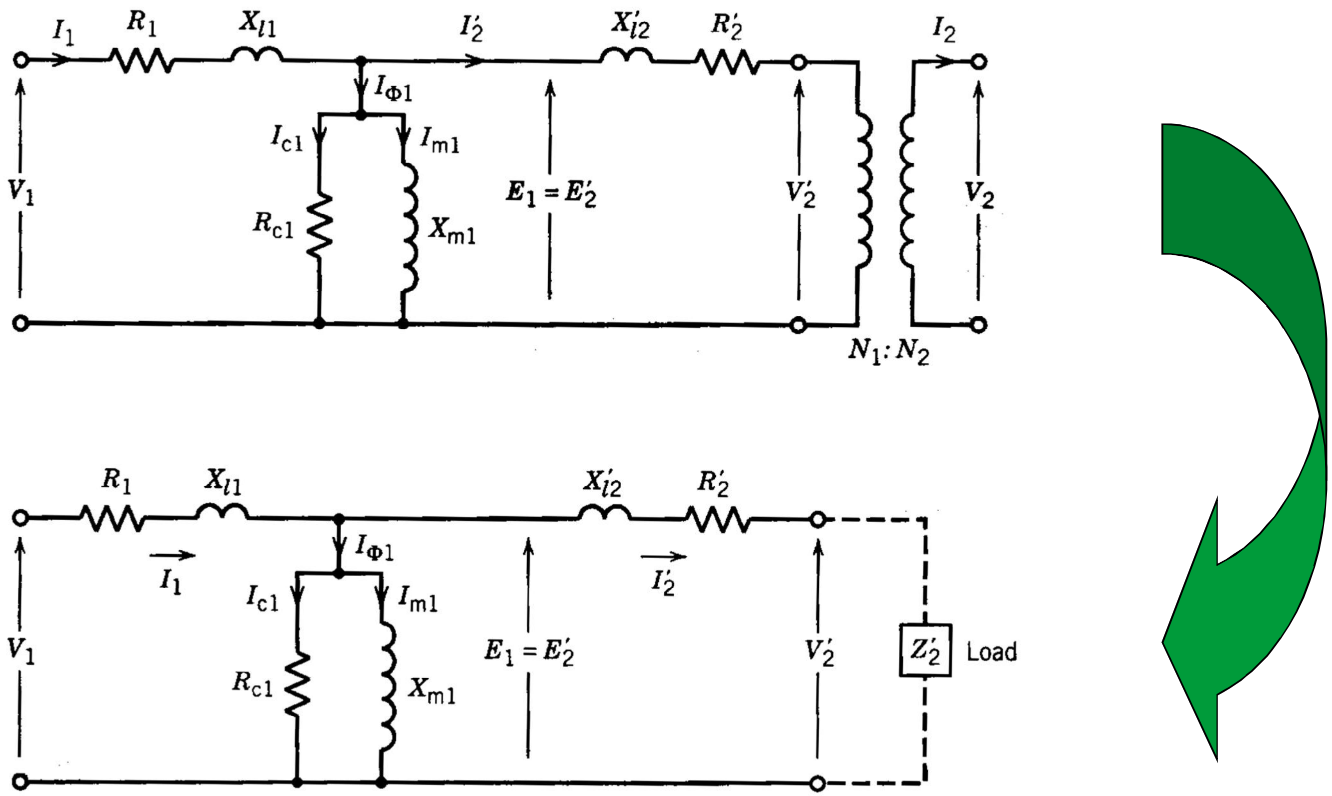
Lumped-parameters equivalent circuit



- Winding resistance in series with leakage inductance
- Magnetizing inductance in parallel with core resistance

Referred equivalent circuits

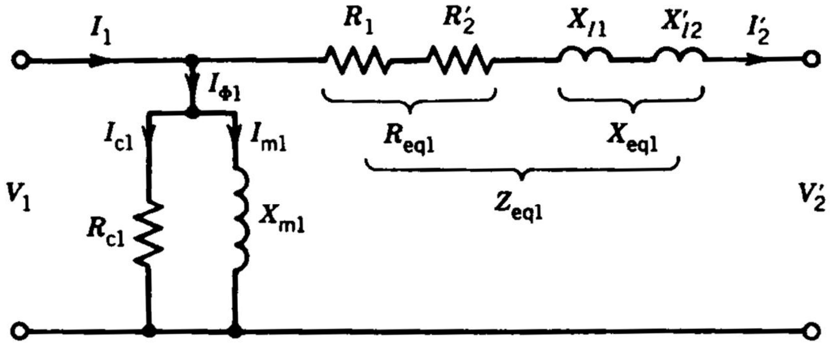
- Practical transformer = Lumped parameters circuit + Ideal transformer



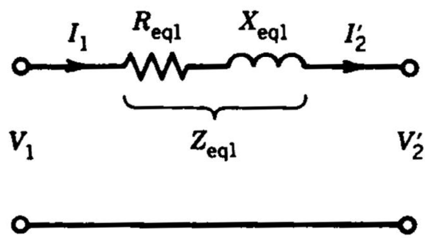
- Ideal transformer can be shifted to either side
- Circuit parameters are reduced to the appropriate values

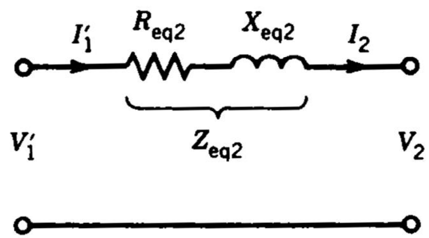
Approximate Equivalent Circuits

- I_1R_1 and I_1X_{l1} are small
- $|E_1| = |V_1|$
- Shunt branch can be moved to supply terminal



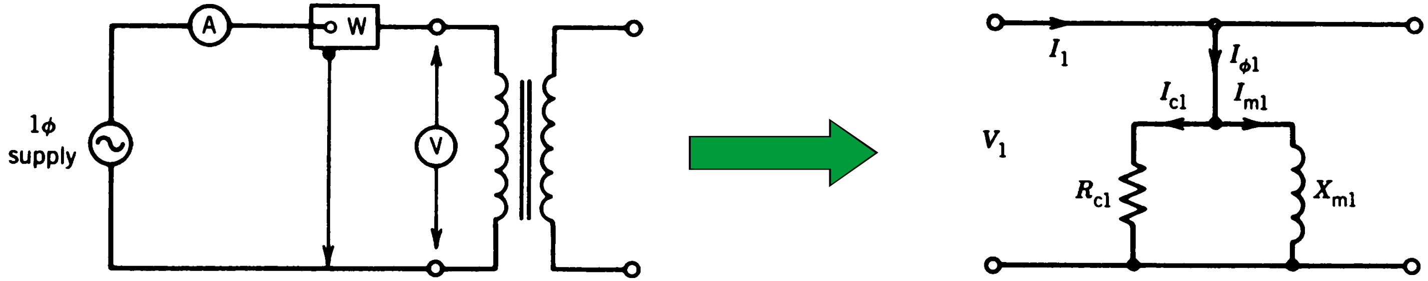
- I_F small (5% of rated current)
- Shunt branch removed



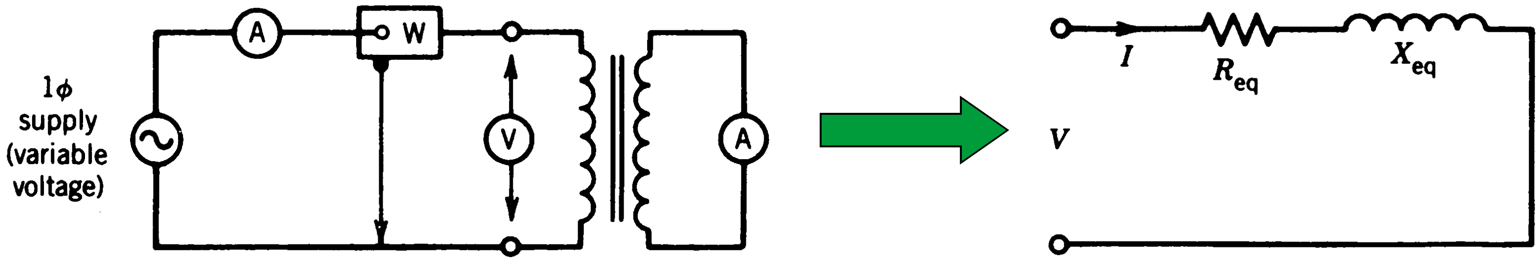


Equivalent Circuit Parameters

- No-load test (rated voltage on one side whereas the other side is open)



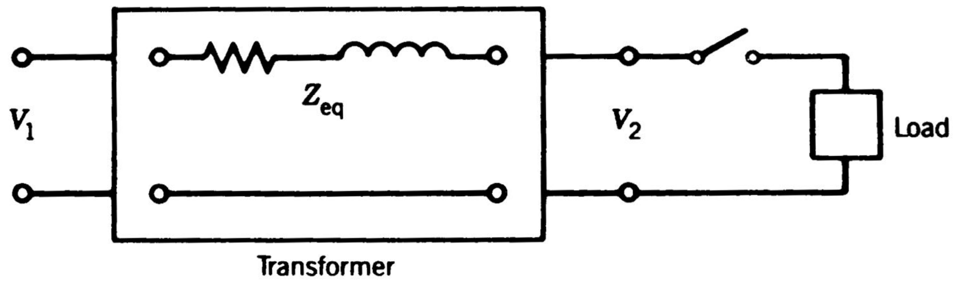
- Short-Circuit test (rated current on one side whereas the other side is short-circuited)



- Nameplate: S (kVA), V_1/V_2 (V)

Voltage regulation

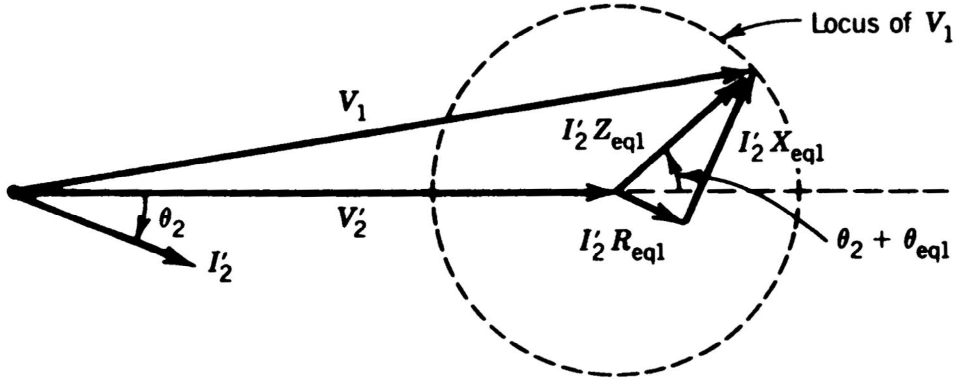
- At no load: $V_2 = V_1/a$
- Loaded: $V_2 = V_1/a \pm \Delta V_2$??



(a)

- Voltage regulation =

$$\frac{\left|V_2^{'}\right|_{NL} - \left|V_2^{'}\right|_L}{\left|V_2^{'}\right|_L}$$



(b) Phasor diagram

- Maximum voltage regulation occur if $\theta_L = -\theta_{eq1}$

Efficiency

- Efficiency

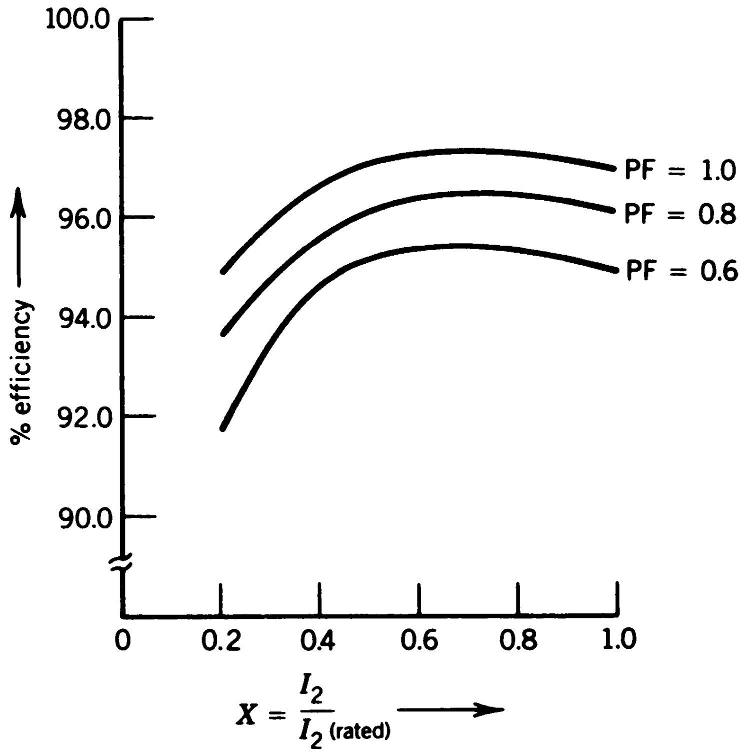
$$\eta = \frac{P_{out}}{P_{out} + P_c + P_{cu}}$$

$$\eta = \frac{V_2 I_2 \cos\theta_2}{V_2 I_2 \cos\theta_2 + P_c + I_2^2 R_{eq2}}$$

Max efficiency

Fixed V_2 and θ_2 → $P_c = I_2^2 R_{eq2}$

Fixed V_2 and I_2 → $\cos\theta_2 = 1$



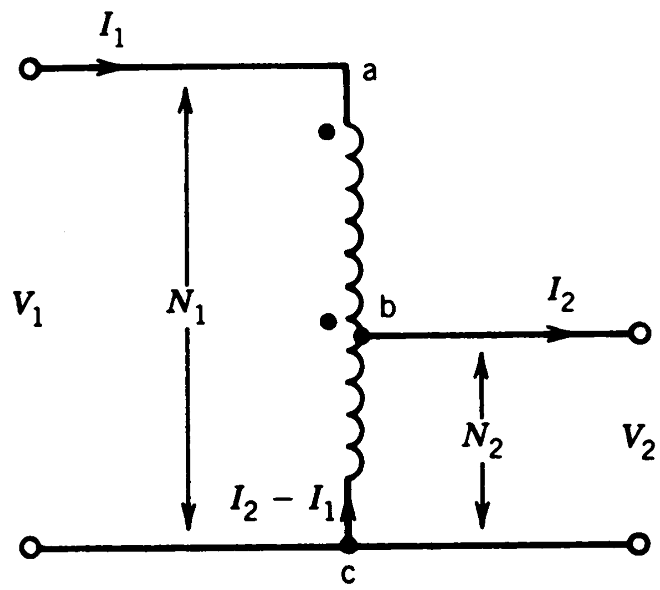
- All-day efficiency

$$\eta_{AD} = \frac{enrgy\ output\ over\ 24\ hours}{enrgy\ input\ over\ 24\ hours}$$

A figure of merit for distribution transformer

Autotransformer

- Same operation as two windings transformer
- Physical connection from primary to secondary
- Sliding connection allows for variable voltage
- Higher kVA delivery than two windings connection



- Autotransformer does not provide isolation between primary and secondary!
- Risk of hazard if not carefully connected and used

Three-phase transformer

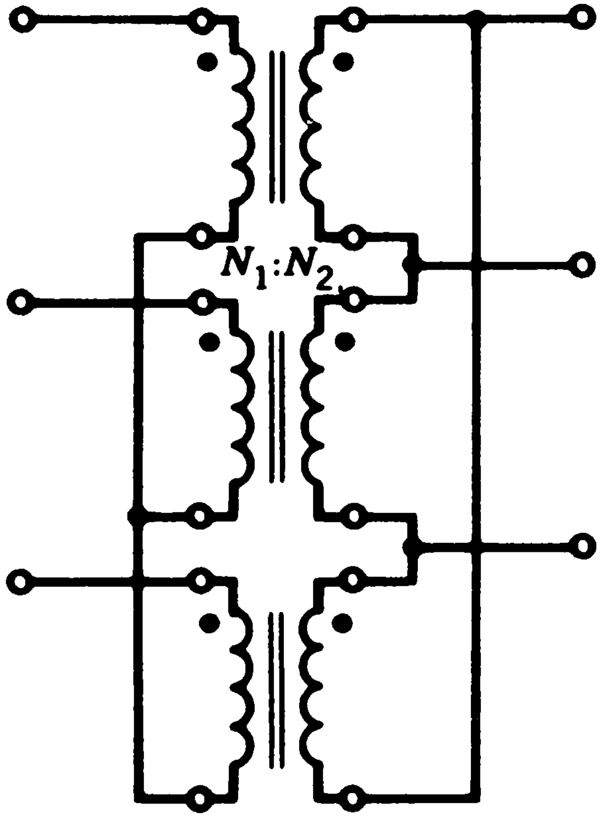
- Three similar single-phase transformers connected to form a three-phase transformer

- Four possible connection:

  Y-Δ Δ-Y Δ-Δ Y-Y

- Some connections result in phase shift

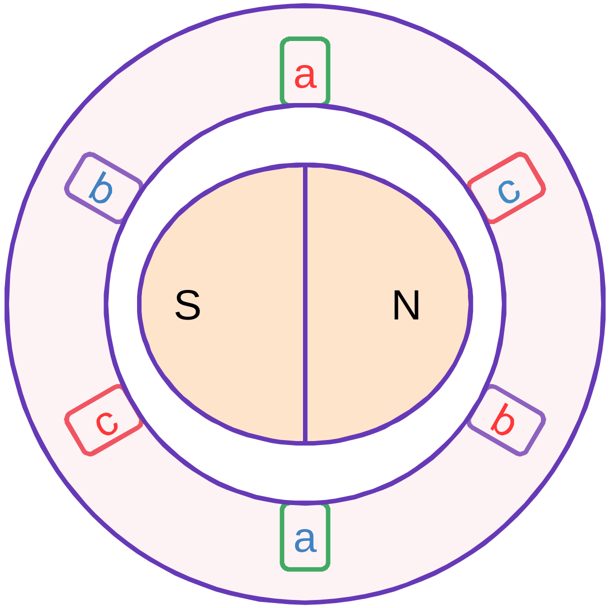
Can you make a sketch of the connections?

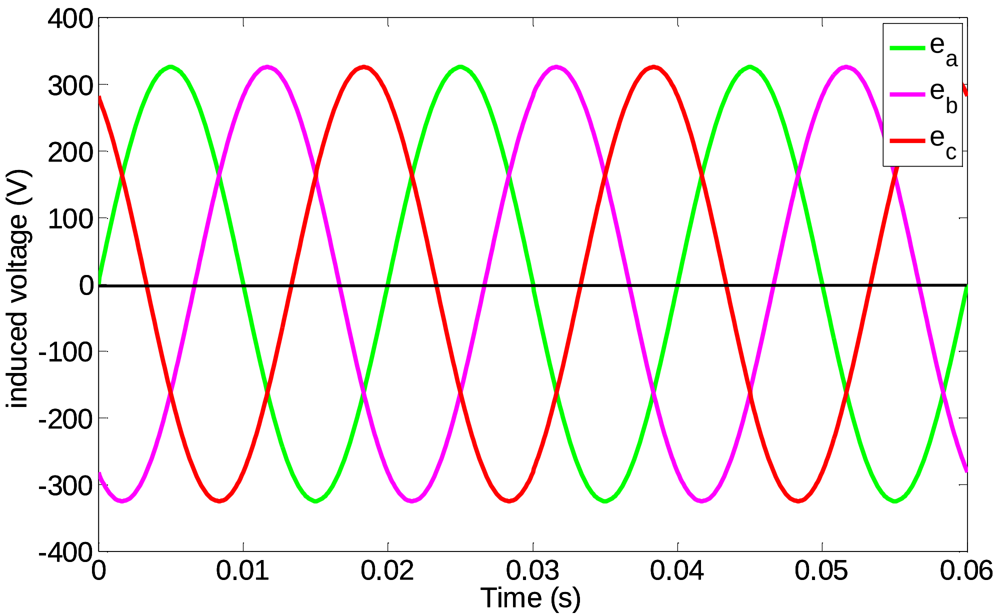


3-phase voltage generation

- Simple generator

$$e = N\frac{dF}{dt}$$

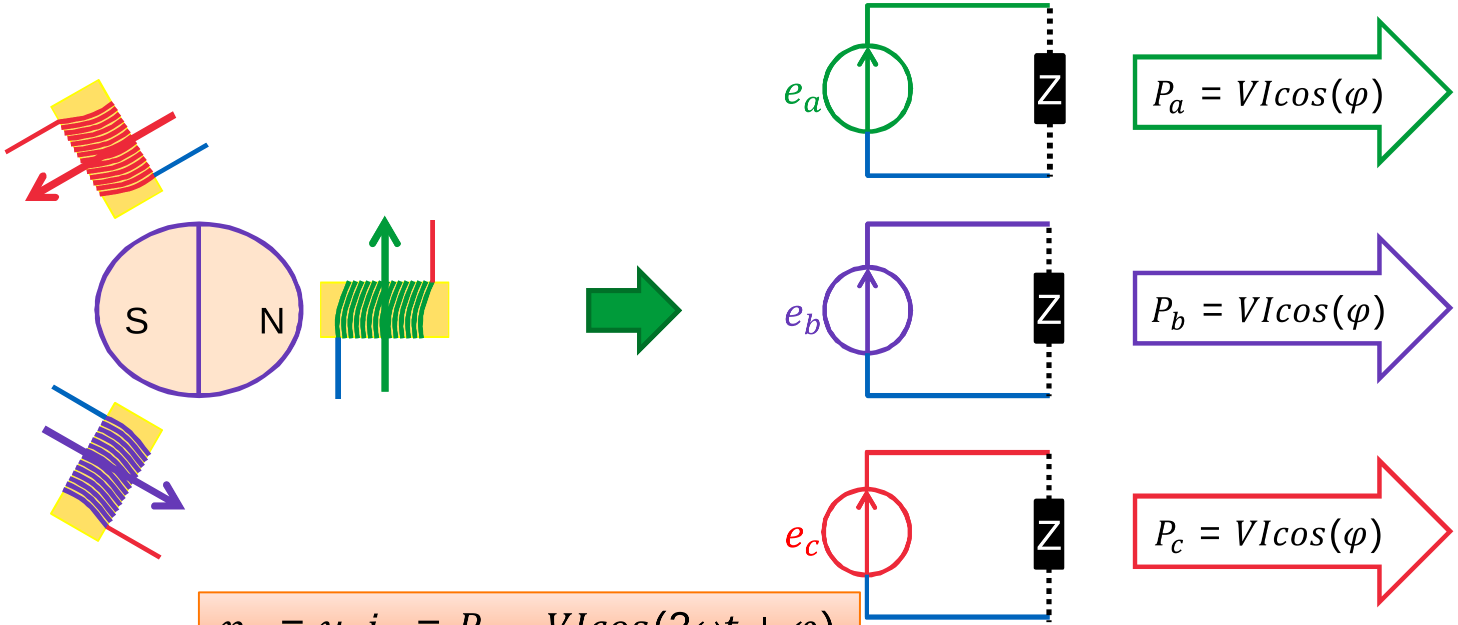




q Better utilization of iron and other materials

Connecting the 3-phase voltages

- 3 single-phase circuits at different phase angle!

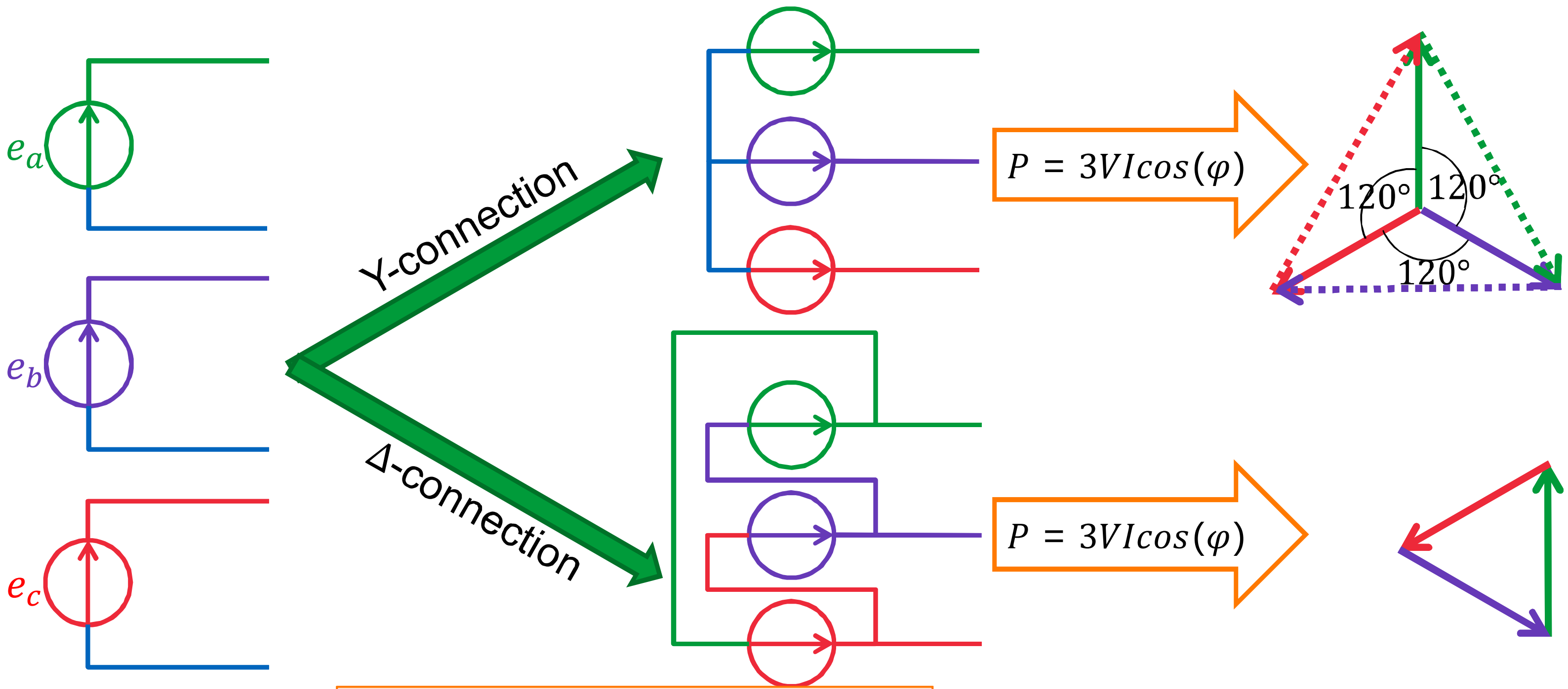


$$p_a = u_a i_a = P_a - VIcos(2\omega t + \varphi)$$

- The average power over one period is constant
- The instantaneous power is pulsating

Connecting the 3-phase voltages

- The potential difference is known but not the potentials !

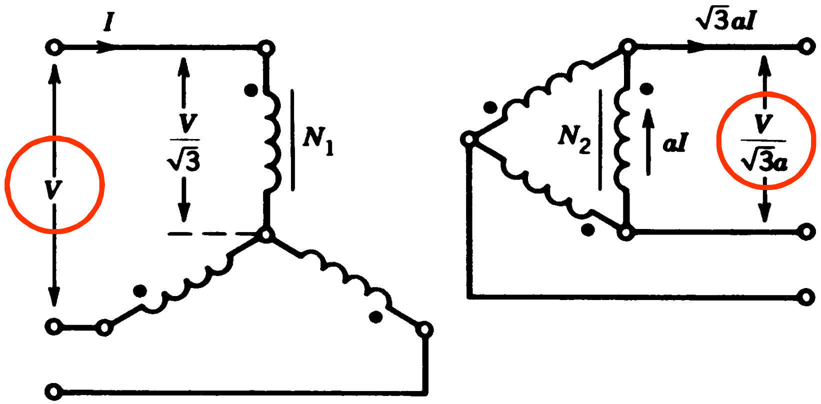


$$p = u_a i_a + u_b i_b + u_c i_c = 3P_a$$

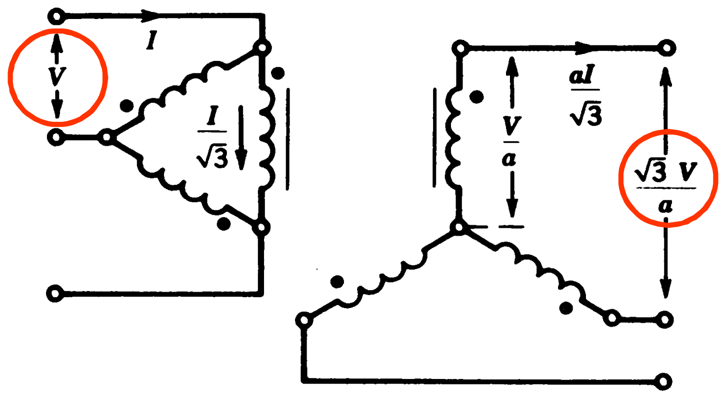
- The same power can be transferred with only 3 wires instead of 6
- The instantaneous power of 3 phase system is constant over time

Connections

- Y-Δ is used for voltage step-down

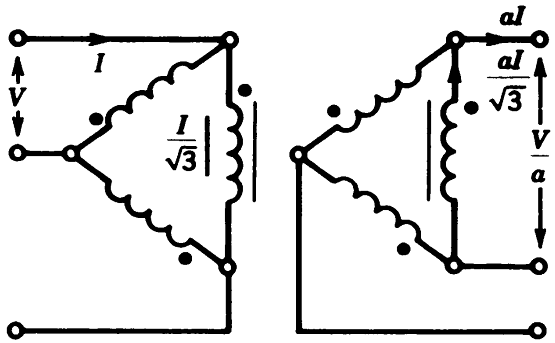


- Δ-Y is used for voltage step-up

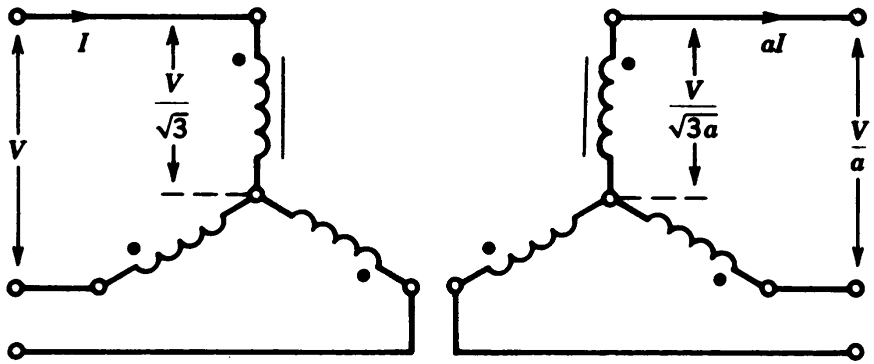


Connections - continue

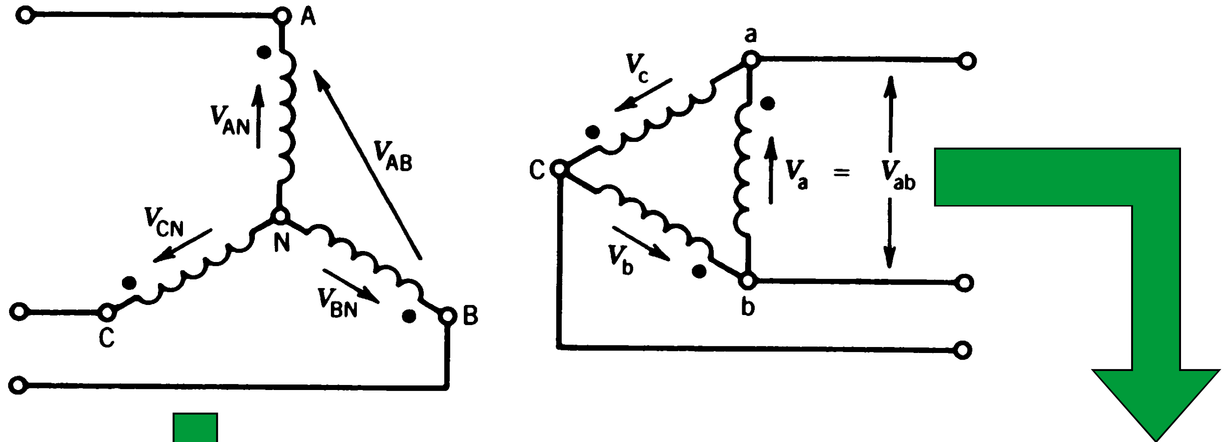
- Δ-Δ only possibility for open-delta connection

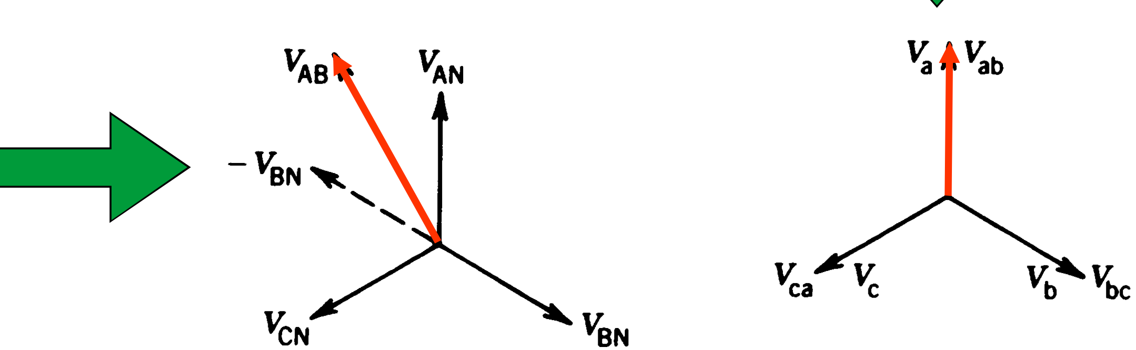


- Y-Y seldom used



Phase shift





- V_{AN} // V_a
- V_{AB} leads V_{ab} by 30^o

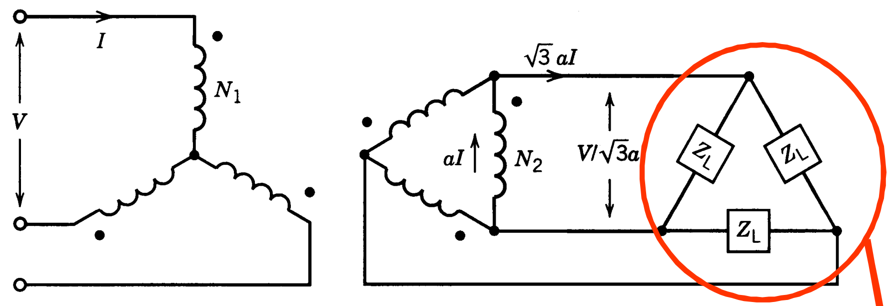
- Δ-Y also provides line-to-line phase shift
- Y-Y and Δ-Δ connections have no phase shift

Can you draw the phasor diagram for Δ-Y connection?

Single-phase equivalent circuit

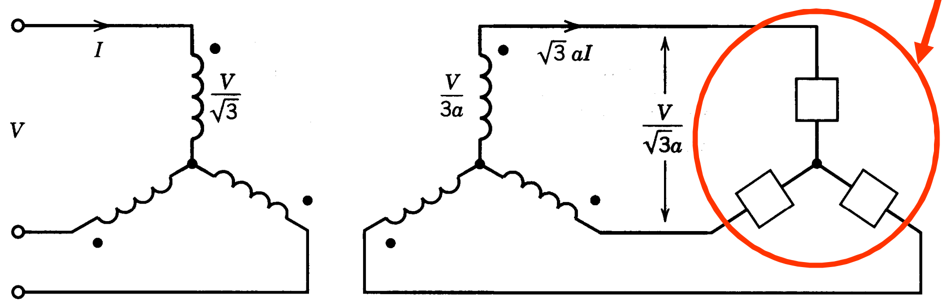
Validity conditions:

- Identical transformers
- Balanced source and load

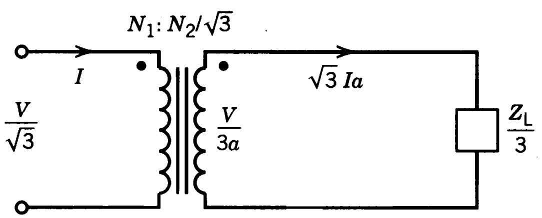


- Only one phase variables are used, the other phases are similar.

- Equivalent Y-representation

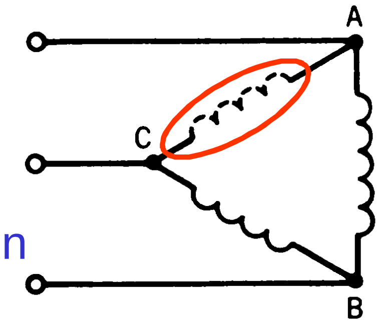


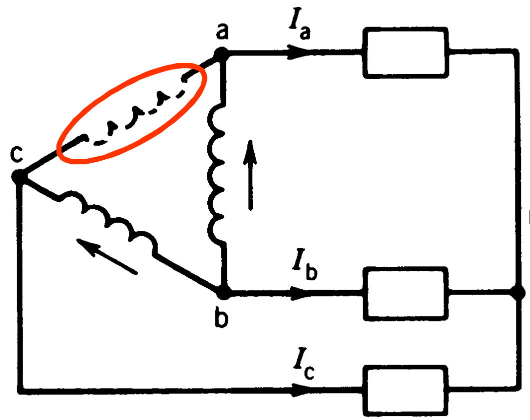
- Line-to-neutral = phase voltage



Three-phase transformer - open delta connection

- One phase can be removed
- Operation at reduced load
- Possible only in Δ- Δ connection





$$P_{bc} = V_{bc} I_c \cos(30 - f)$$

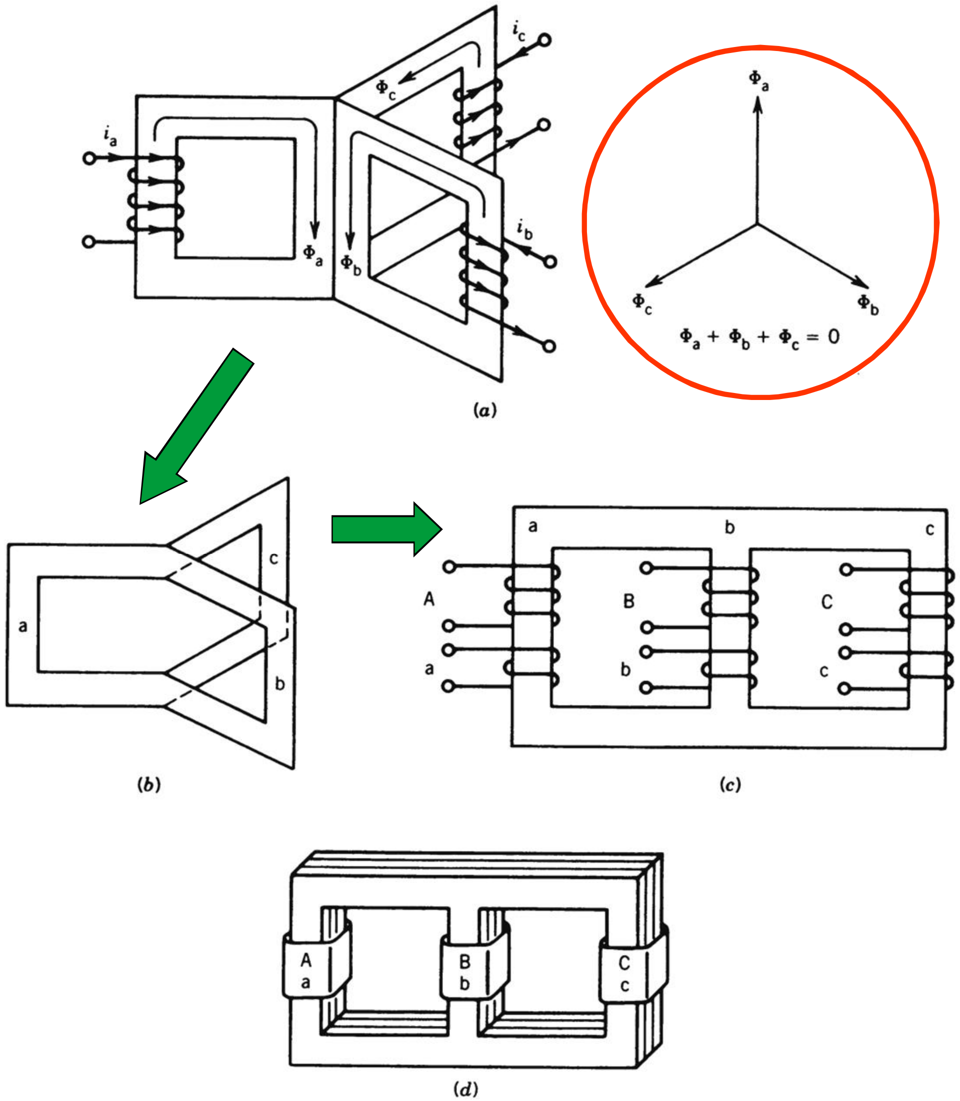
$$P_{V} = P_{ab} + P_{bc} = 2VI \cos 30^o$$

$$P_{D} = 3VI$$

$$\frac{P_V}{P_D} = \frac{2\cos 30^o}{3} = 0.58$$

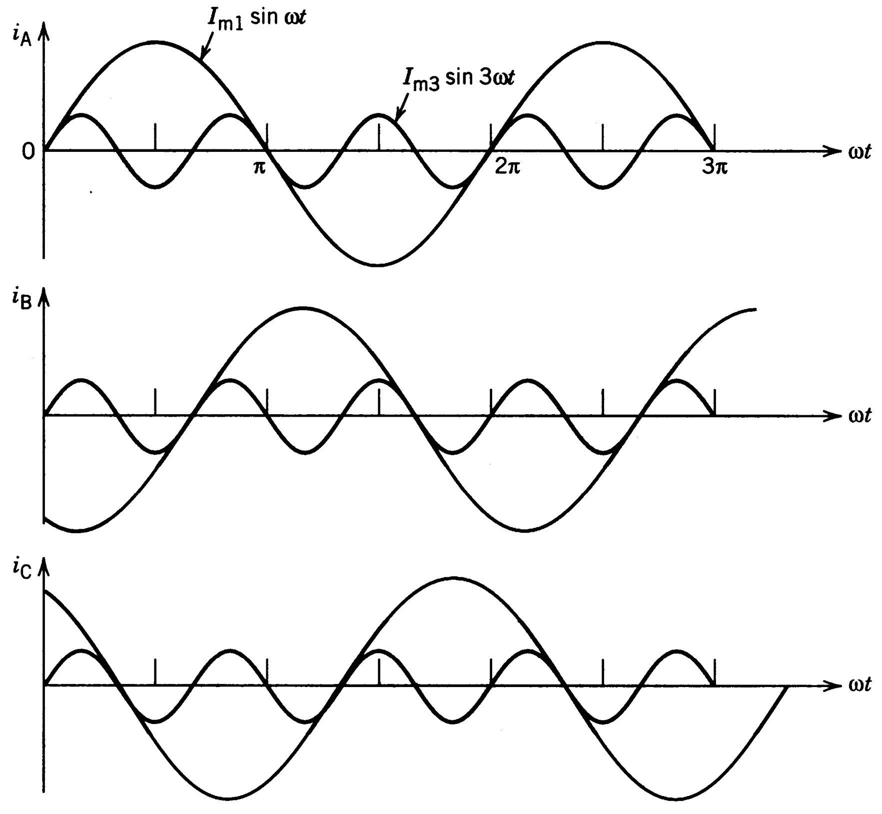
Three-phase transformer unit

- Balanced three-phase voltage
- Balanced three-phase flux
- Return leg can be removed
- In-plan construction easy to manufacture
- Same operation as transformer bank



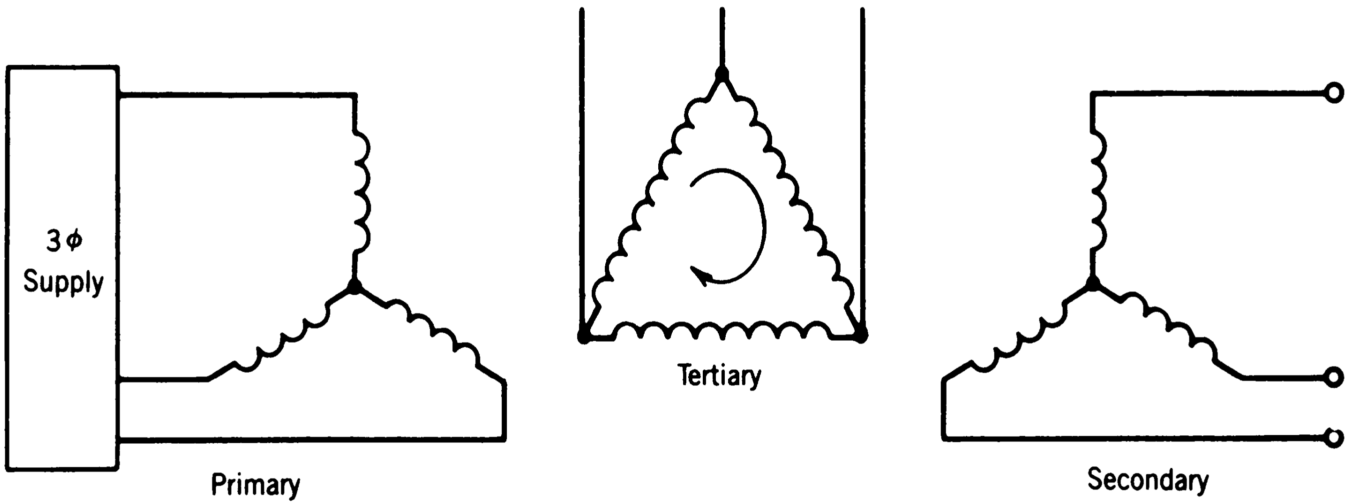
Harmonics in Three-Phase Transformer Banks

- Transformers are designed to operate at saturation
- Exciting current is non-sinusoidal with predominant third harmonic
- Third harmonics are in phase
- Third harmonic exists either in currents or in fluxes



Harmonics in Three-Phase Transformer Banks Yy+d

- Third harmonic current prohibited from both sides
- Tertiary provides the missing third harmonic current
- Voltages sinusoidal
- Tertiary can supply auxiliary load if needed

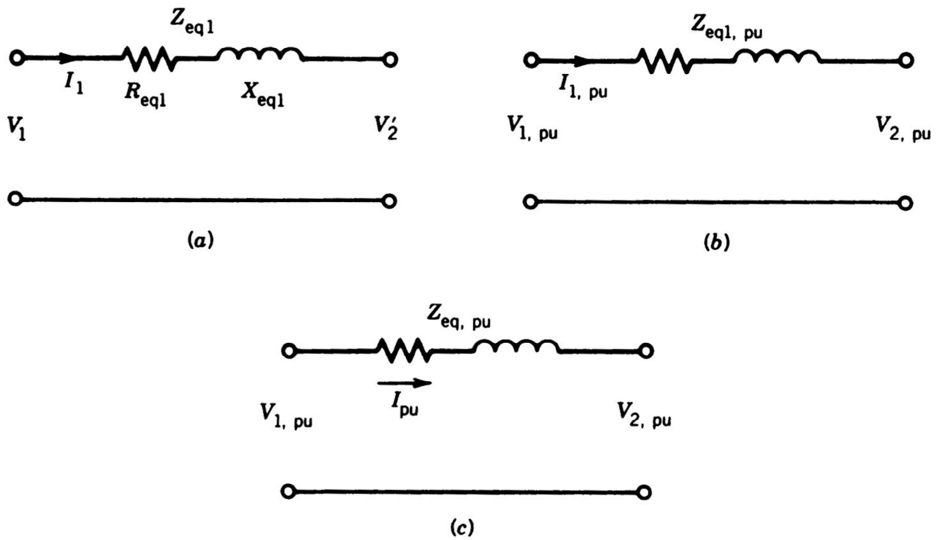


Per-unit system

- Base (reference) value of the quantity P_{base}, V_{base}

$$I_{base} = \frac{P_{base}}{V_{base}}$$

$$Z_{base} = \frac{V_{base}}{I_{base}}$$



$$\text{pu-quantity} = \frac{\text{actual q}}{\text{base q}}$$

- pu voltage equation and full load copper losses

$$V_{1,pu} = I_{1,pu} Z_{eq1,pu} + V_{2,pu}$$

Independent of the side

$$P_{Cu,FL} = R_{eq1,pu}$$