Energy conversion I

Lecture 9:

Topic 2: Transformers & its performance (S. Chapman, ch. 2)

- Introduction
- Types and Construction of Transformers.
- Ideal Transformer.
- Theory of operation of real single-phase transformers.
- The Equivalent Circuit of a Transformer.
- The Per-Unit System of Measurement
- Transformer voltage regulation and efficiency
- **Autotransformers**
- **Three phase transformers**

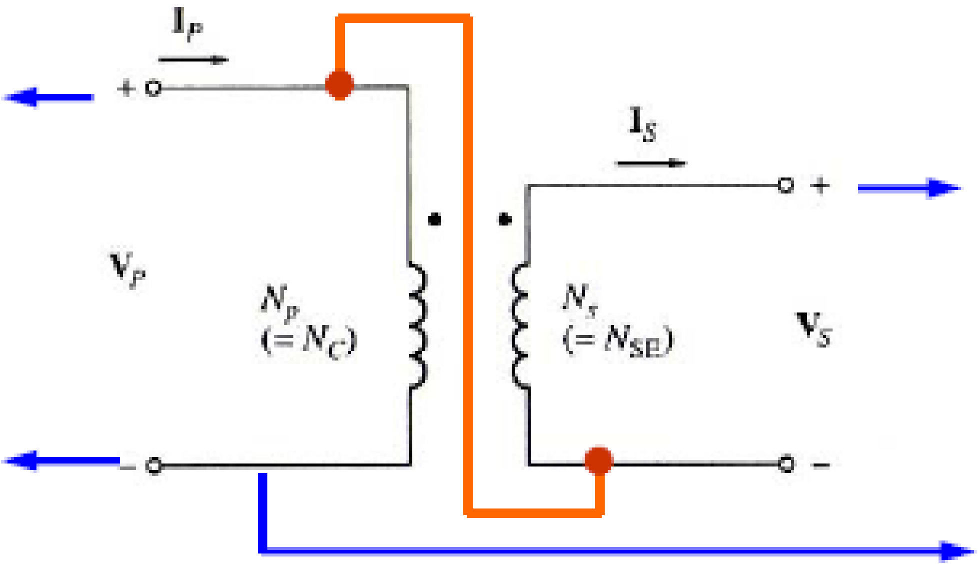
Autotransformers

For voltage ratios close to 1 it is usual to use autotransformer instead of Transformer.

For voltage ratios close to one, autotransformer is much smaller in weight and volume compared to transformer.

For voltage ratios close to one, kVA rating of autotransformer is much higher than transformer used to make it.

Problem: no electrical isolation!

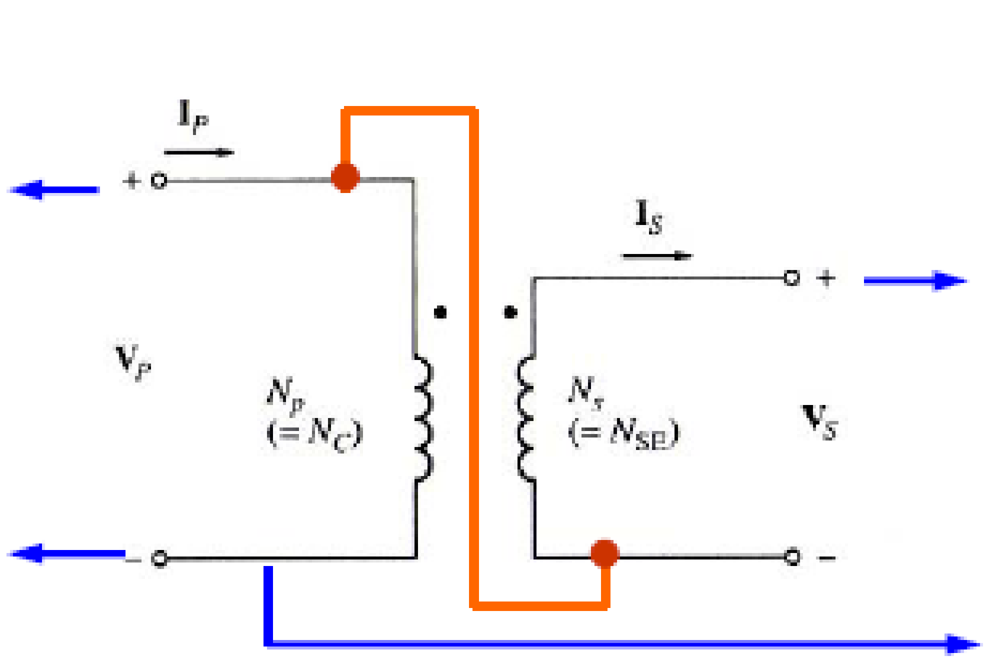


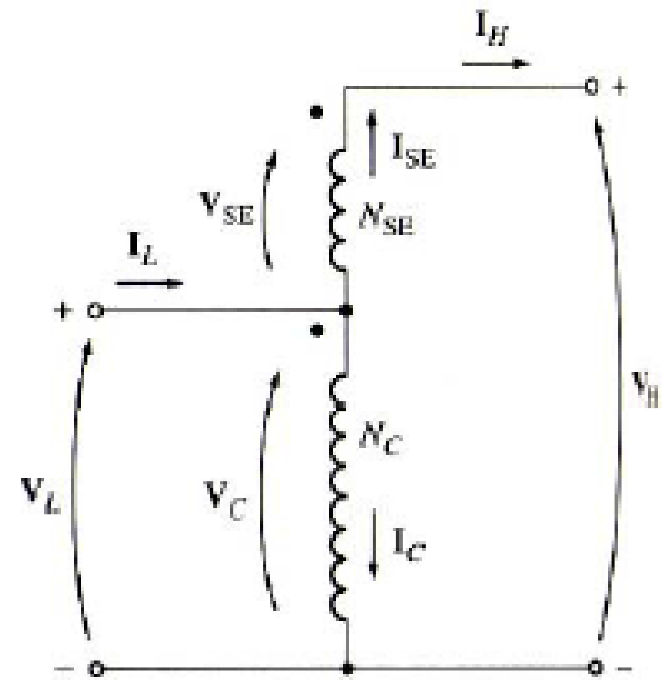
$$\frac{V_c}{V_{SE}} = \frac{N_c}{N_{SE}}$$

$$\frac{I_C}{I_{SE}} = \frac{N_{SE}}{N_c}$$

C: Common coil
SE: Series coil

Step-up Autotransformers





$V_L = V_C$

$V_H = V_C + V_{SE}$

$I_L = I_C + I_{SE}$

$I_H = I_{SE}$

$$\frac{V_L}{V_H} = \frac{V_C}{V_C + V_{SE}} = \frac{N_C}{N_C + N_{SE}} = \frac{I_H}{I_V}$$

$\mathbf{S_{TR} = I_{SE} \times V_{SE}}$

$\mathbf{S_{ATR} = I_H \times V_H = I_{SE} \times V_H}$

$$\frac{S_{ATR}}{S_{TR}} = \frac{V_H}{V_{SE}} = \frac{N_C + N_{SE}}{N_{SE}}$$

>>1 If voltage ratio is close to 1

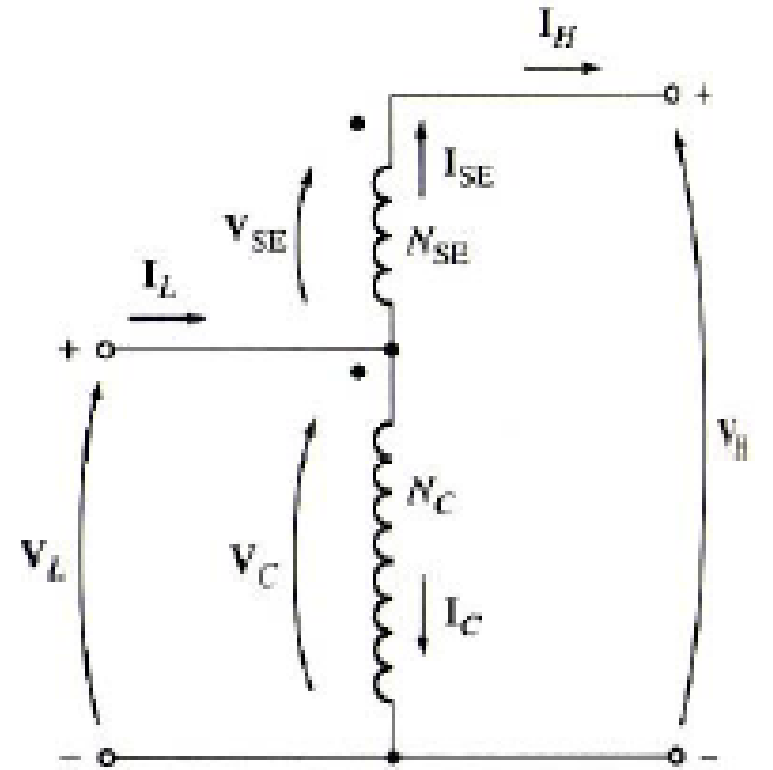
Autotransformer rating

$$\frac{S_{\mathrm{ATR}}}{S_{\mathrm{TR}}} = \frac{V_H}{V_{SE}} = \frac{N_C + N_{SE}}{N_{SE}}$$

$$\frac{V_H}{V_L} = \frac{N_C + N_{SE}}{N_C}$$

S_{TR} : Transformer or each winding kVA (S_W)

S_{ATR} : Autotransformer kVA (S_{IO})



Example: For a <u>5000 kVA</u>, 110 kV / 138 kV we can use a 110 / 28 transformer:

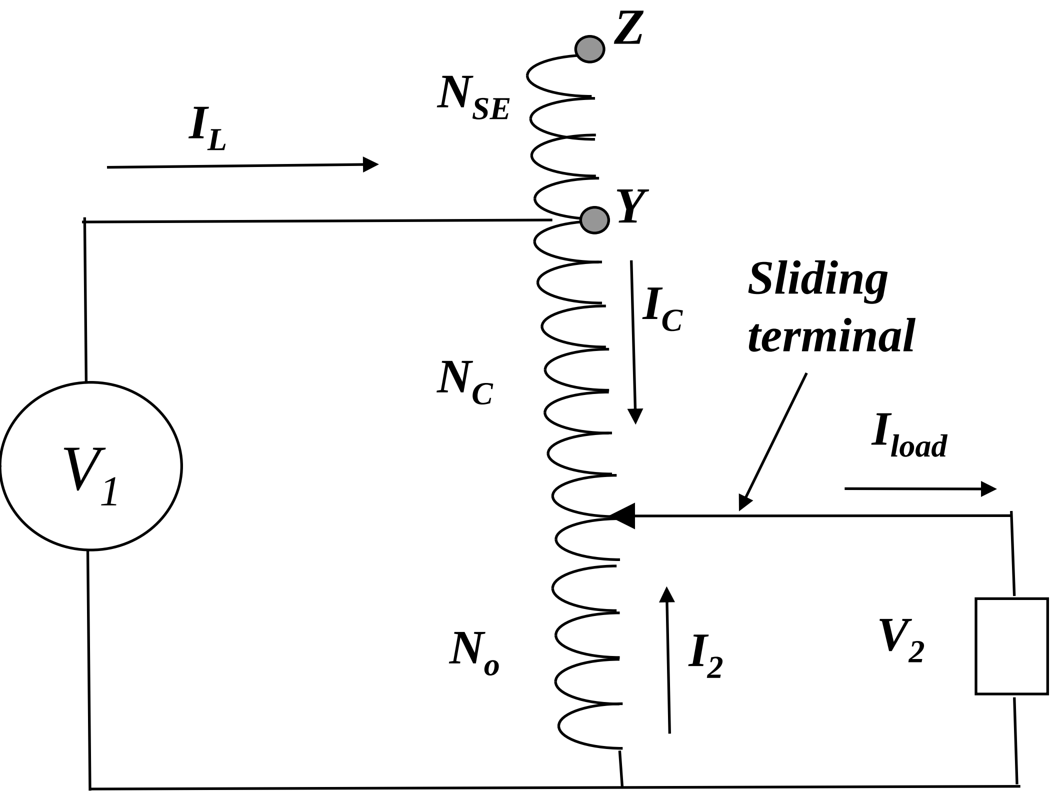
N_C: 110 , N_{SE} = 28

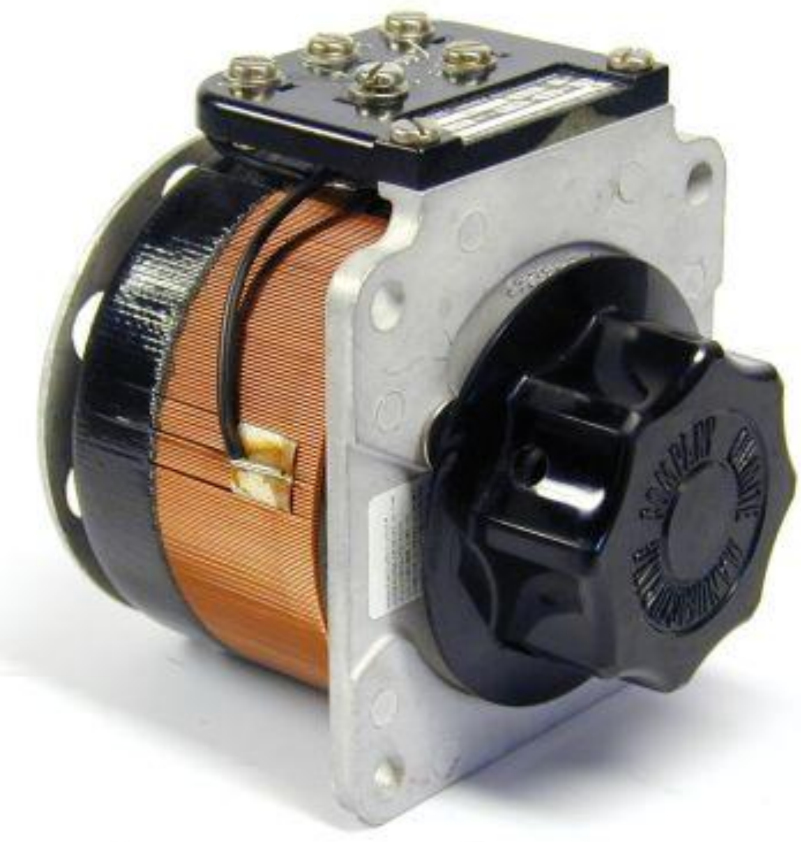
$S_{TR} = S_W$ = 28 / (28 + 110) * 5000 = <u>1015 kVA</u>

Think about Efficiency of Autotransformer compared to Transformer

Variable Autotransformer (VARIAC)

Used as Variable AC voltage Source





Output voltage varies between 0 to $(N_{SE}+N_C)/N_C \times V_1$

Inrush current of transformer

For a transformer connected to a sinusoidal voltage in the steady state:

$$\varphi(t) = \varphi_M \sin \omega t \quad \Rightarrow v(t) = N\varphi_M \omega \cos \omega t$$

$$V_M = N\varphi_M \omega$$

While for a demagnetized core connected to a sinusoidal voltage :

$$\varphi(t) = \frac{1}{N}\int_0^t V_M \sin \omega t dt = -\frac{V_M}{N\omega}\cos \omega t\Big|_0^t = \frac{V_M}{N\omega}(1-\cos \omega t)$$

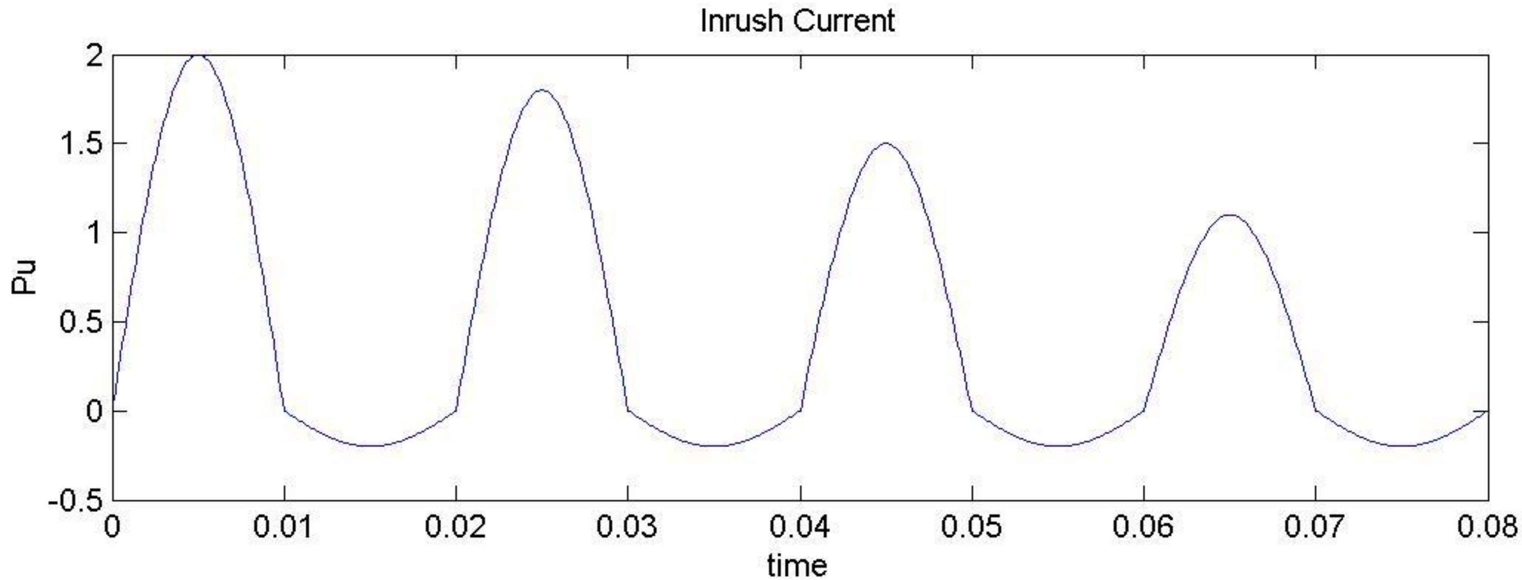
$$\varphi(\omega t = \pi) = 2 \times \frac{V_M}{N\omega} \quad !!$$

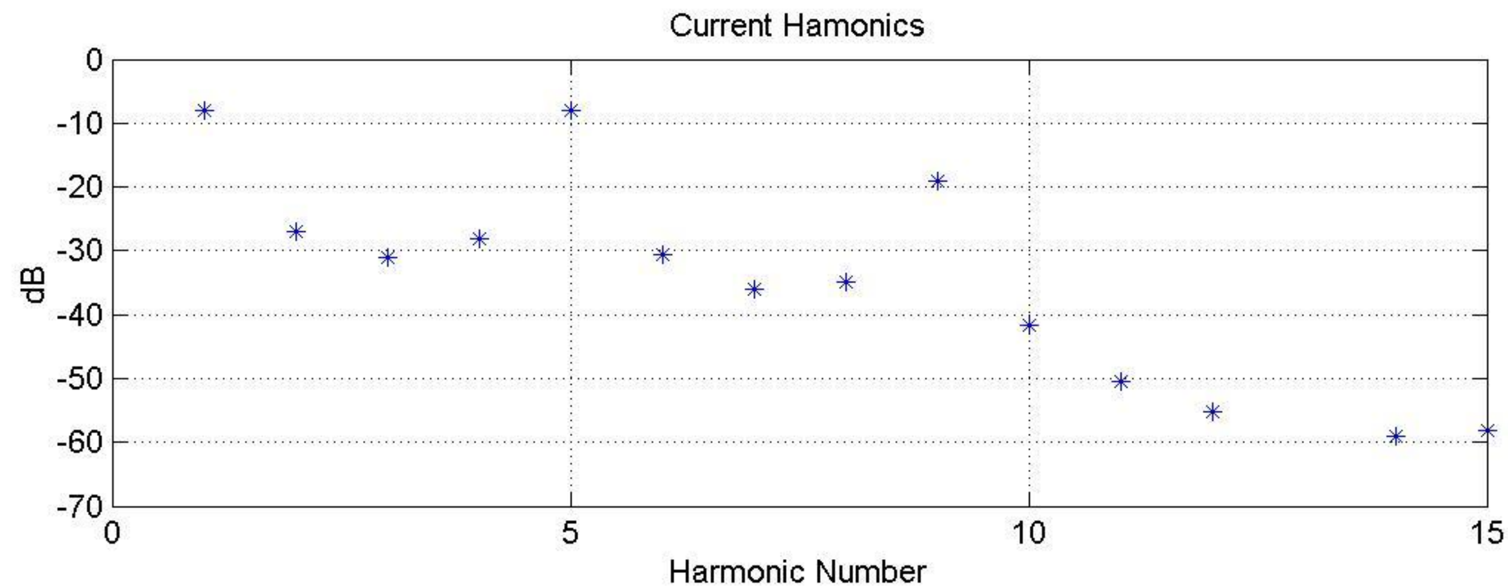
Huge magnetizing current to double the flux density.

Protection system should distinguish it (not a short circuit)

Practical Inrush current Waveform

Winding resistance and leakage inductance limits inrush current
Winding and core loss damps the initial condition effect





Three Phase transformers

Almost all power generated and distributed is three Phase.

Therefore Three phase transformers are required in power system.

They can be constructed three phase (three sets of winding wrapped on a common core)

- Lighter, Smaller, Cheaper, more efficient
- A very bulky device in high power

They can be build up using three single phase transformer

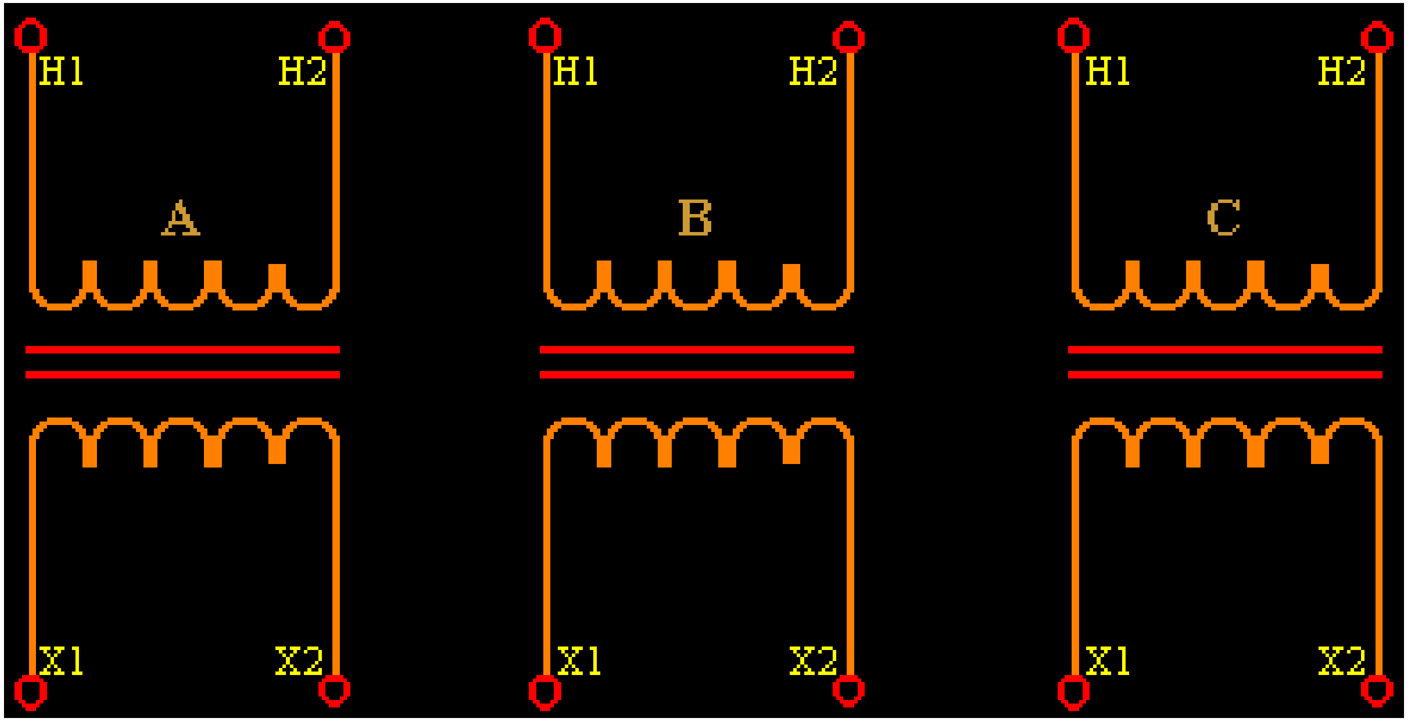
- Easier to transport
- Easier to replace and repair
- More expensive

For both cases per-phase analysis is used for steady state analysis (exactly the same techniques developed for single phase transformers)

Transformers Transport!

Three phase transformer banks

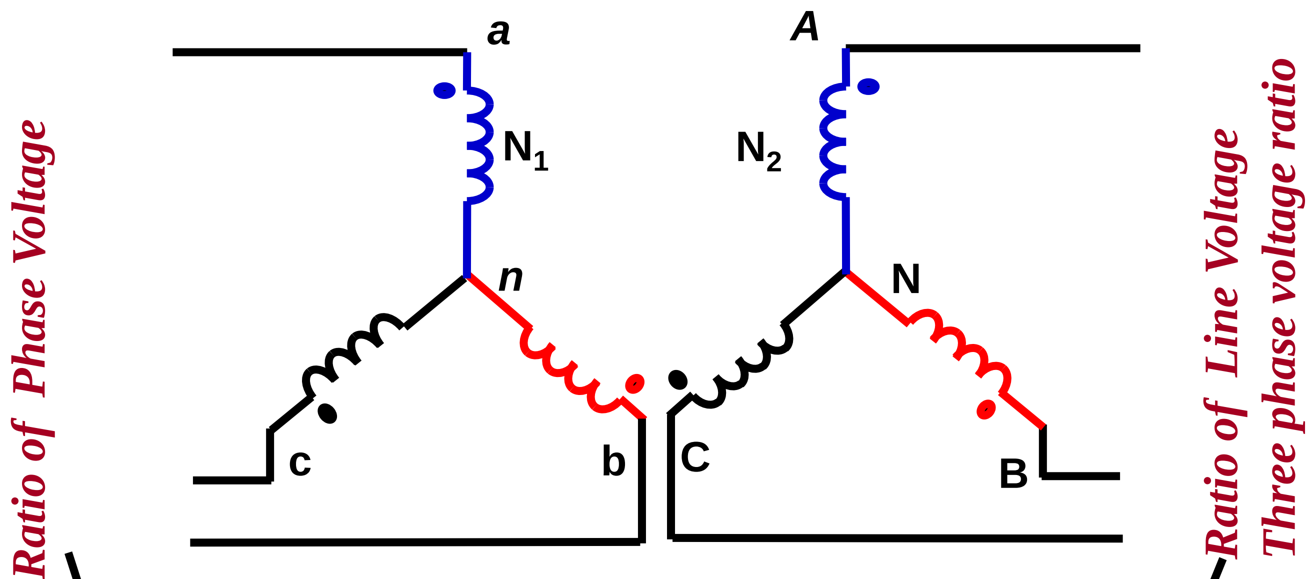
Three phase transformer Connections



Primaries and secondaries can be Y or Δ connected

Wye-wye (Y-y)
Wye-delta (Y-d)
Delta-wye (Δ-y)
Delta-delta (Δ-d)

3-phase transformer Y-Y (star-star)connection

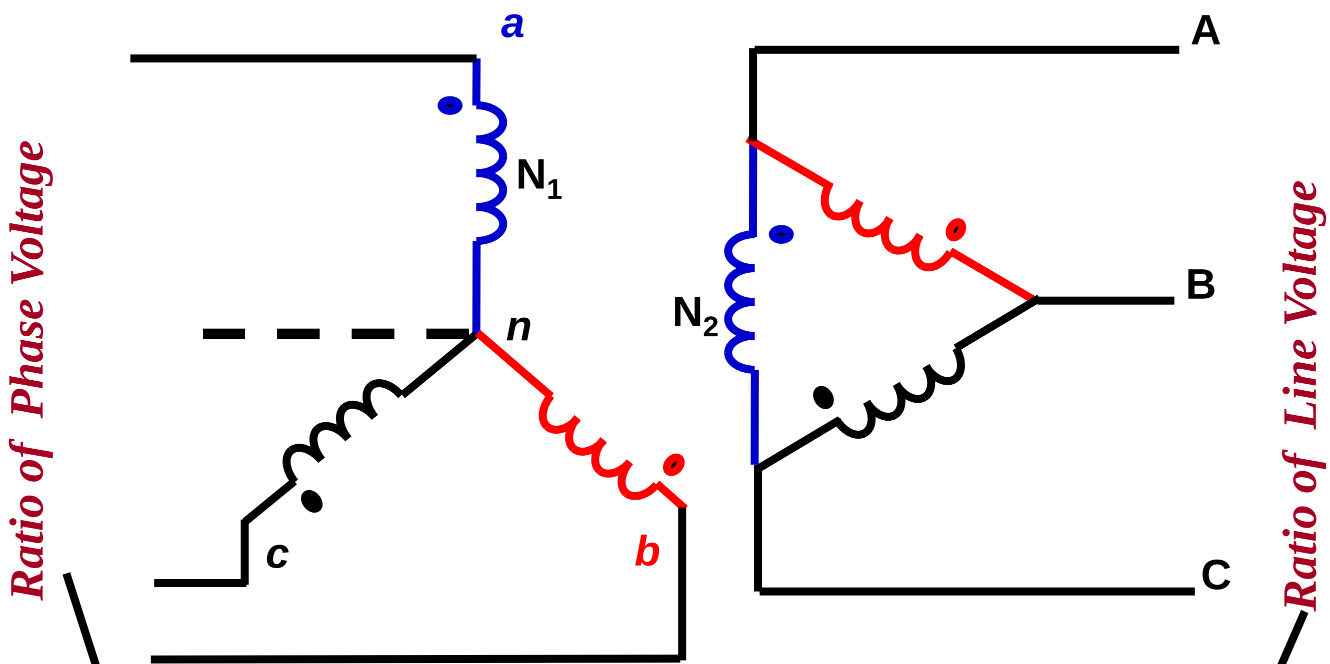


$$\frac{V_{an}}{V_{AN}} = \frac{N_1}{N_2} \qquad \frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}V_{an}}{\sqrt{3}V_{AN}} = \frac{N_1}{N_2} = a$$

One of the neutrals can be grounded

Not very common

3-phase transformer (Y-Δ) connection



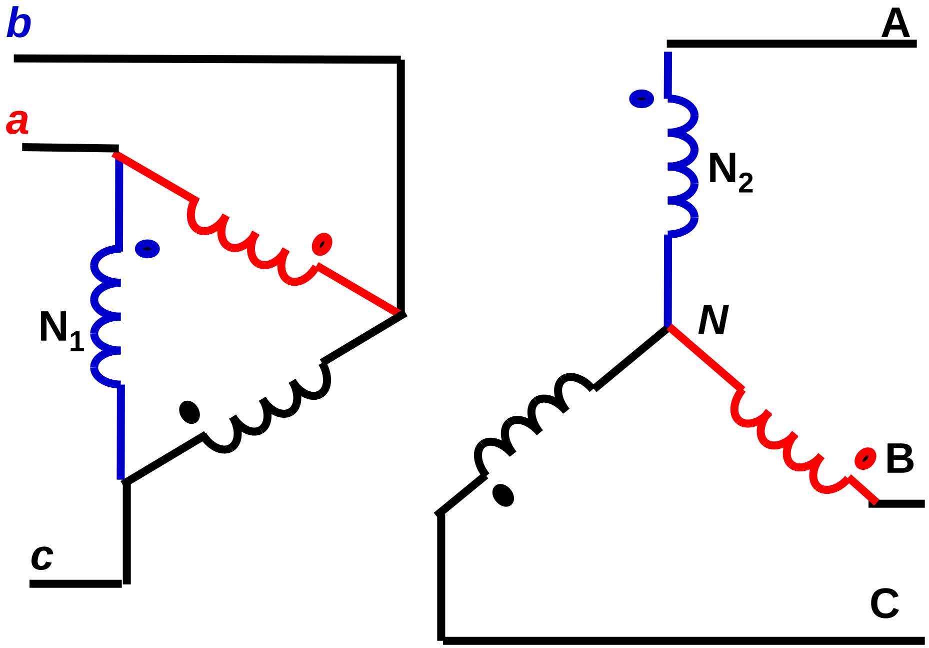
$$\frac{V_{an}}{V_{AC}} = \frac{N_1}{N_2} \qquad \frac{V_{Lp}}{V_{LS}} = \frac{\sqrt{3}\,V_{an}}{V_{AC}} = \frac{\sqrt{3}\,N_1}{N_2} = a$$

+ 30º phase shift!

Y: high voltage winding (power plant transformer)

y: low voltage winding to feed single phase and three phase loads

3-phase transformer (Δ -Y) connection



Ratio of Phase Voltage

$$\frac{V_{ac}}{V_{AN}} = \frac{N_1}{N_2}$$

Ratio of Line Voltage

$$\frac{V_{Lp}}{V_{LS}} = \frac{V_{ac}}{\sqrt{3}V_{AN}} = \frac{N_1}{\sqrt{3}N_2} = a$$

What about the phase shift?

Try to find *a* for a Δ – Δ transformer.