ATME College of Engineering

Department of EEE
Emitting Elite Energy

Module-2

Three-Phase Transformer, Parallel Operation of Transformer and Autotransformer

Module-2

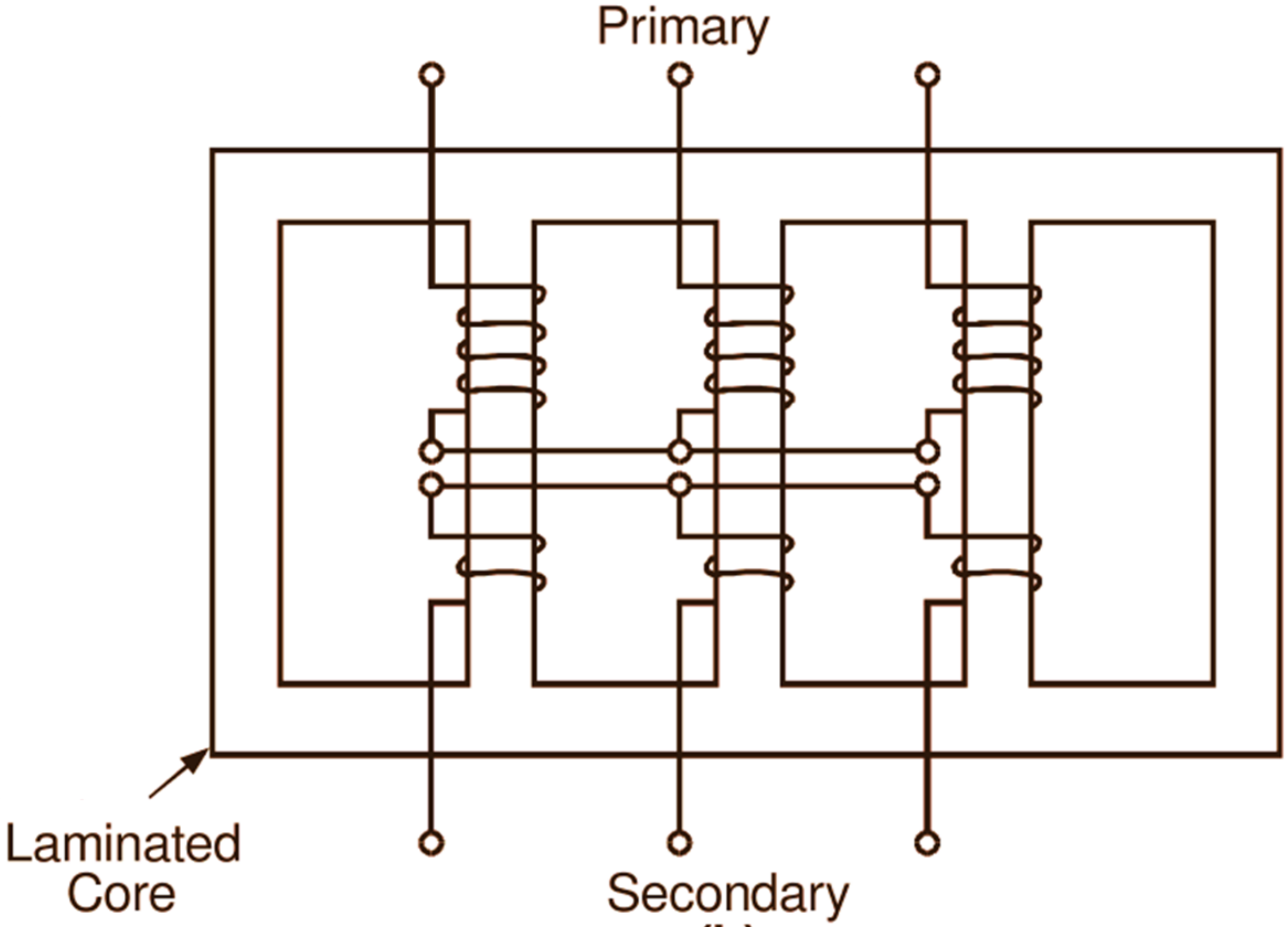
Three-phase Transformers: Introduction, Constructional features of three-phase transformers. Transformer connection for three-phase operation– star/star, delta/delta and star/delta, comparative features. Labeling of three-phase transformer terminals.

Parallel Operation of Transformers: Necessity of Parallel operation, conditions for parallel operation– Single phase and three phases. Load sharing in case of similar and dissimilar transformers. Numerical.

Autotransformers and Tap changing transformers: Introduction to autotransformer-copper economy, equivalent circuit, no load, and on-load tap changing transformers. Numerical.

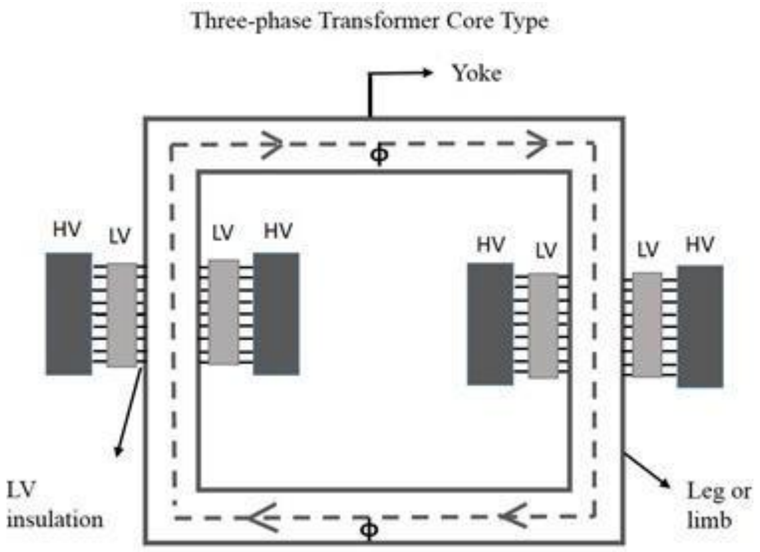
Constructional features of three-phase transformers:

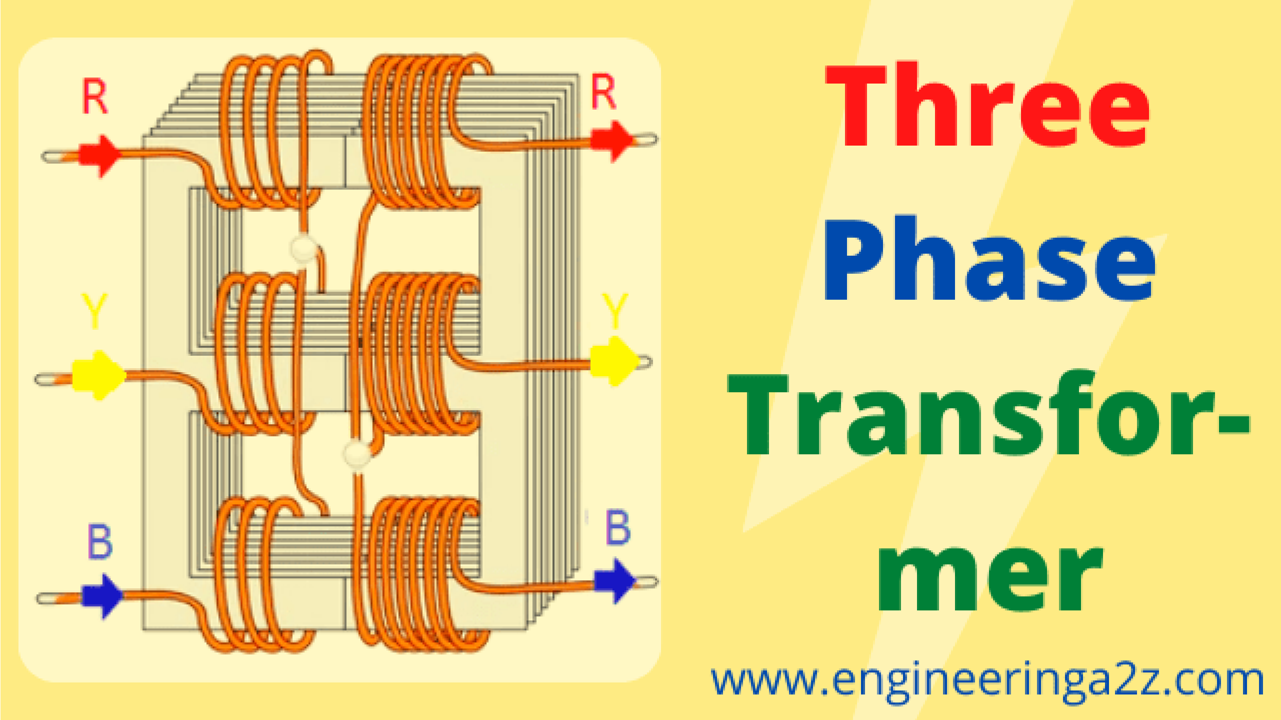
Core Type Construction:

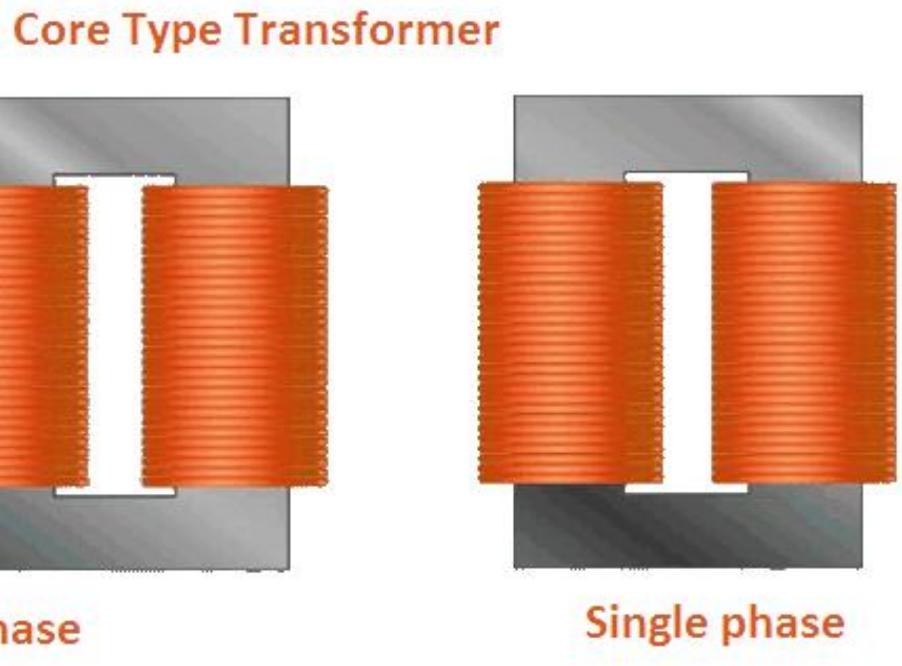


Constructional features of three-phase transformers:

Core Type Transformer:

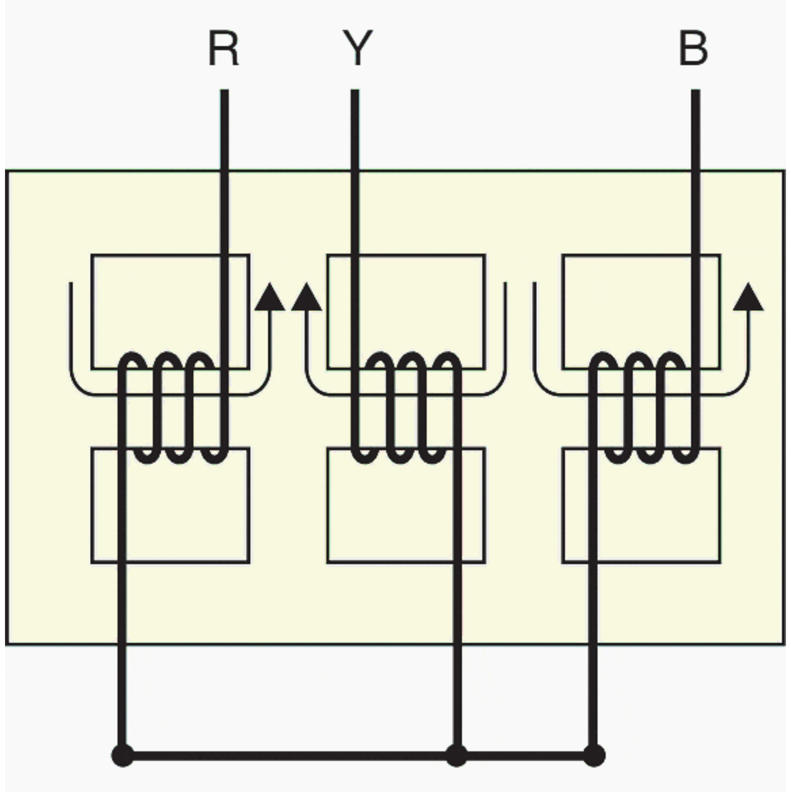


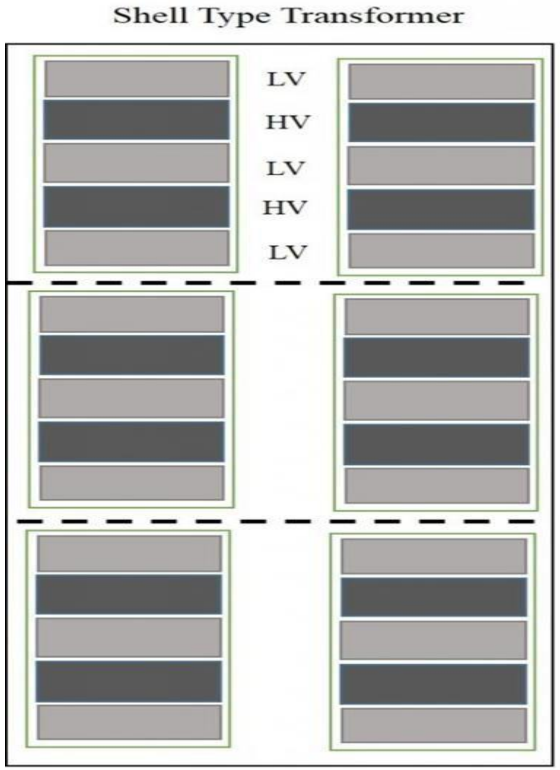



Core Type Transformer
Three phase
Single phase

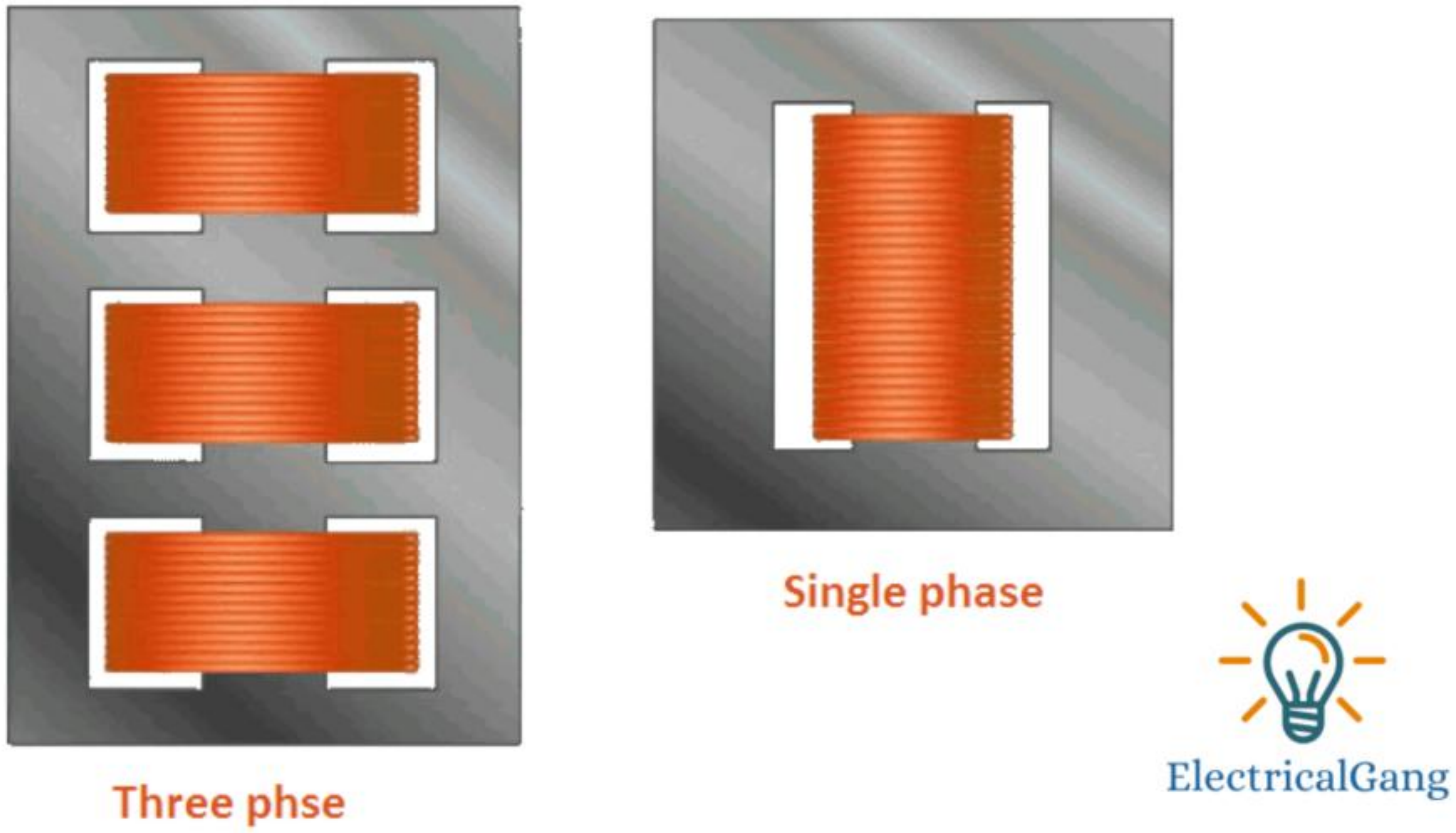
Constructional features of three-phase transformers:

Shell Type Transformer:

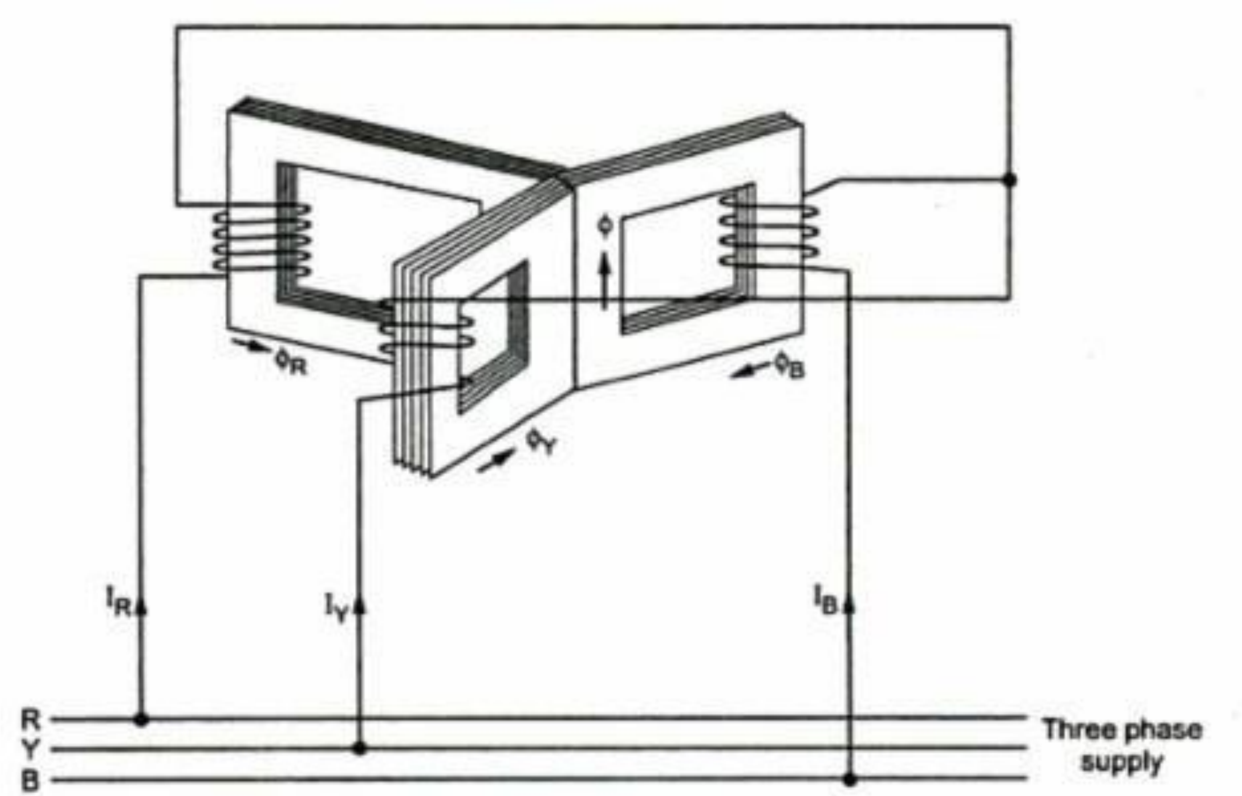




Single Phase & Three Phase Transformer



Working of Three-Phase Transformers:

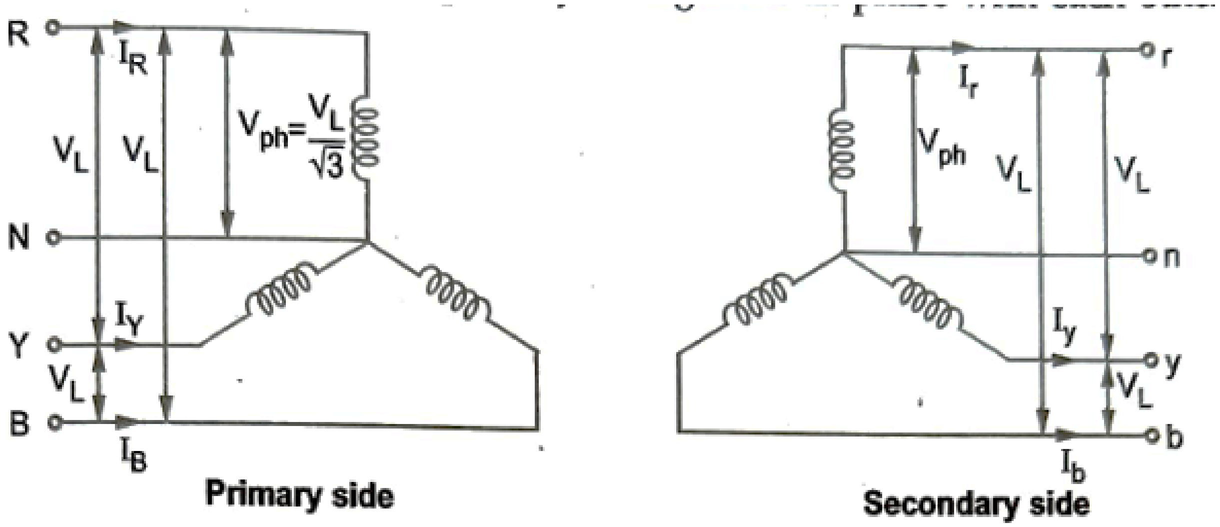


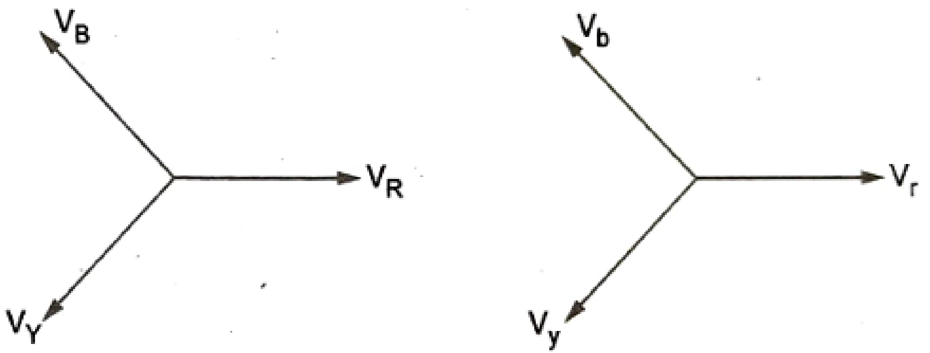
Three-Phase Transformer Connection:

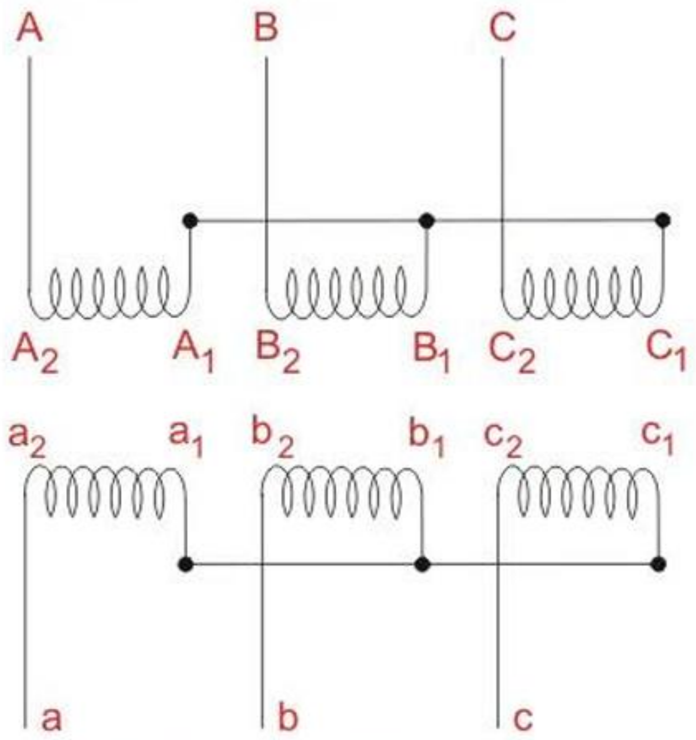
Primary and secondary windings of three phase transformers as three phase windings can be connected in different ways such as in star or delta.

1. Star-Star (Y-Y) connection
2. Delta – Delta (Δ - Δ) connection
3. Star-Delta (Y - Δ) connection
4. Delta-Star (Δ - Y) connection
5. Open Delta or V connection
6. Scott connection or T-T connection

Star-Star Connection:

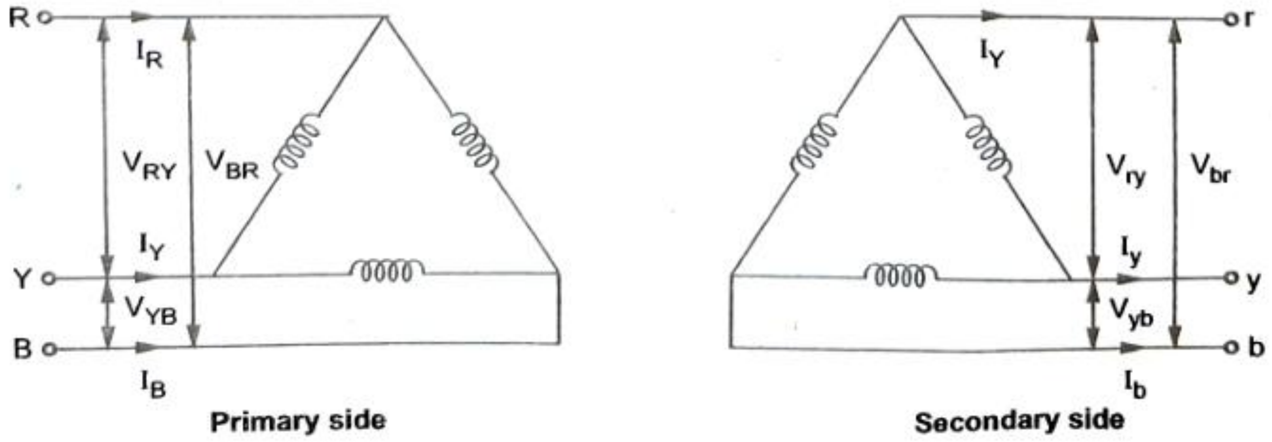


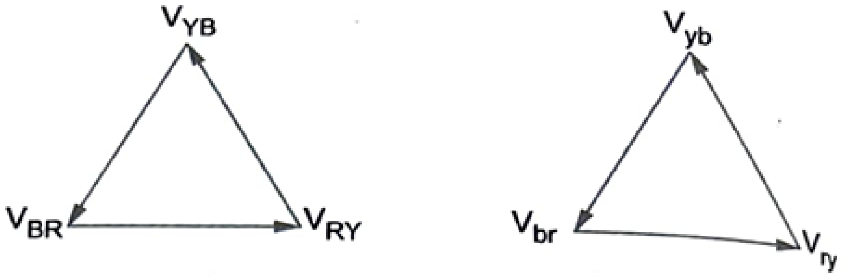


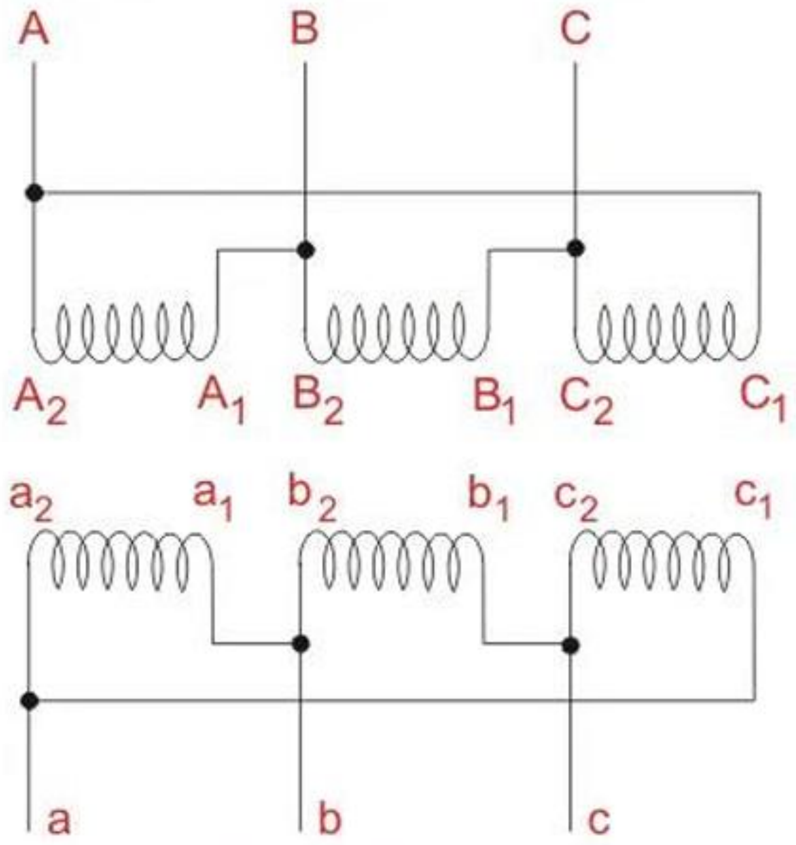


Star-Star Three Phase Transformer

Delta-Delta Connection:

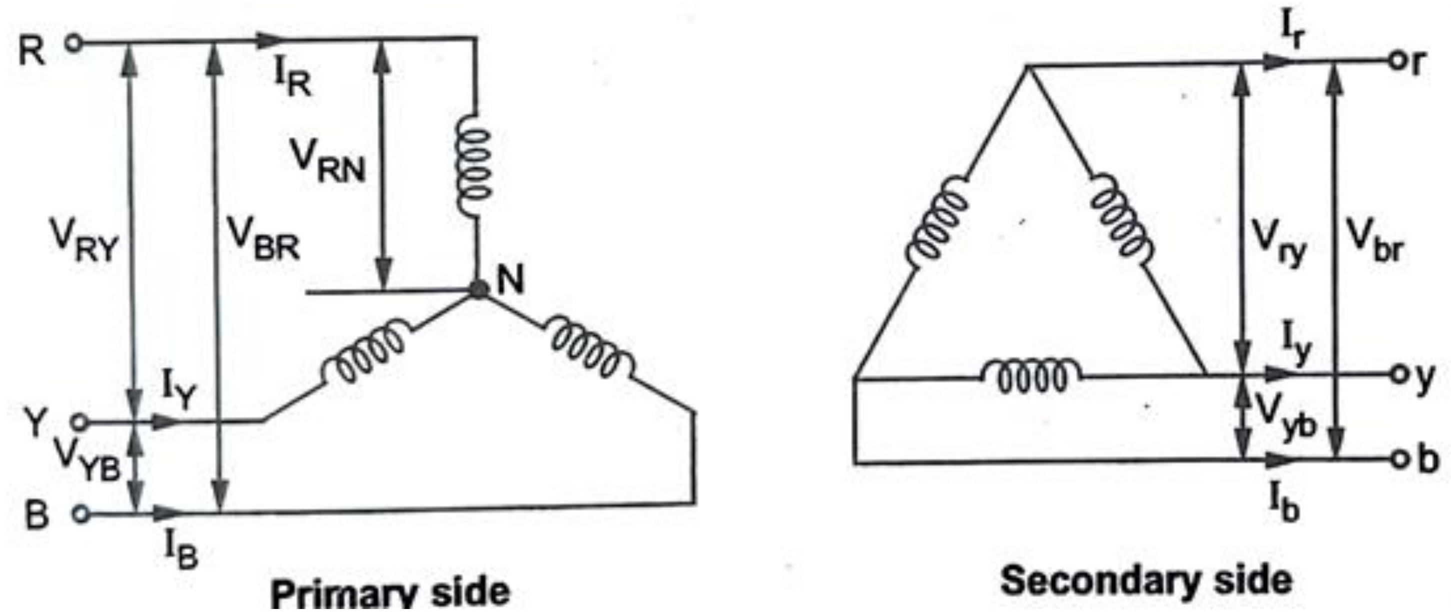


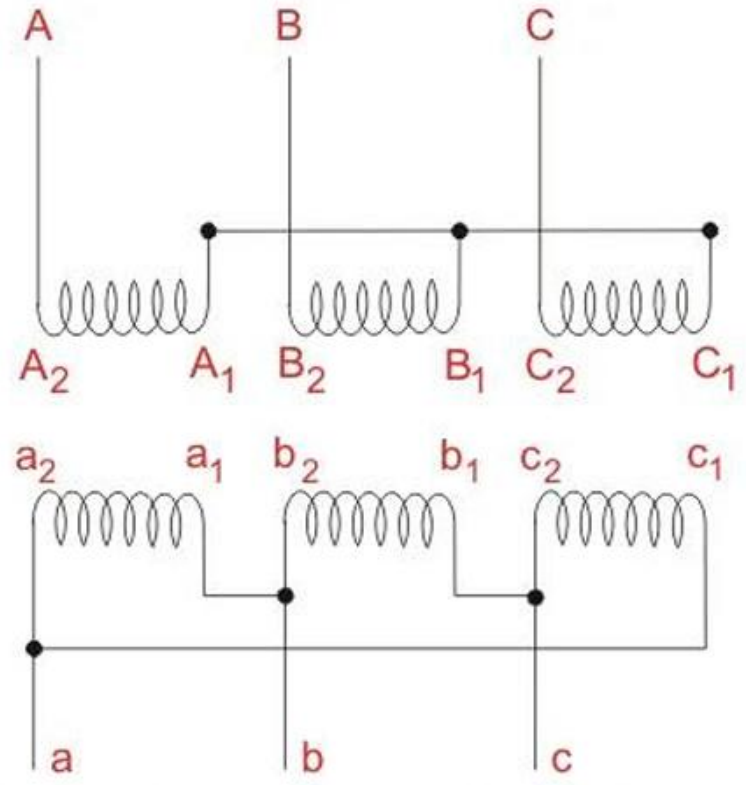




Delta-Delta Three Phase Transformer

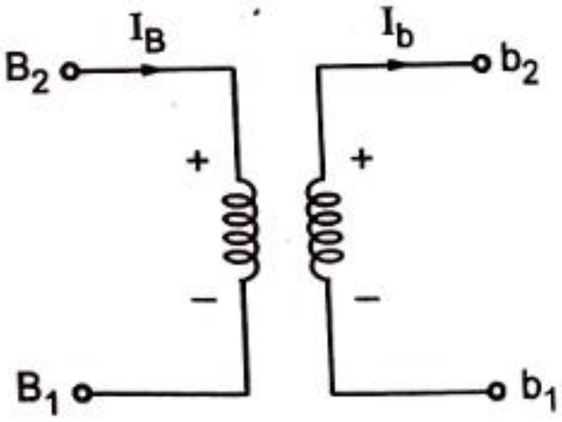
Star-delta transformer:



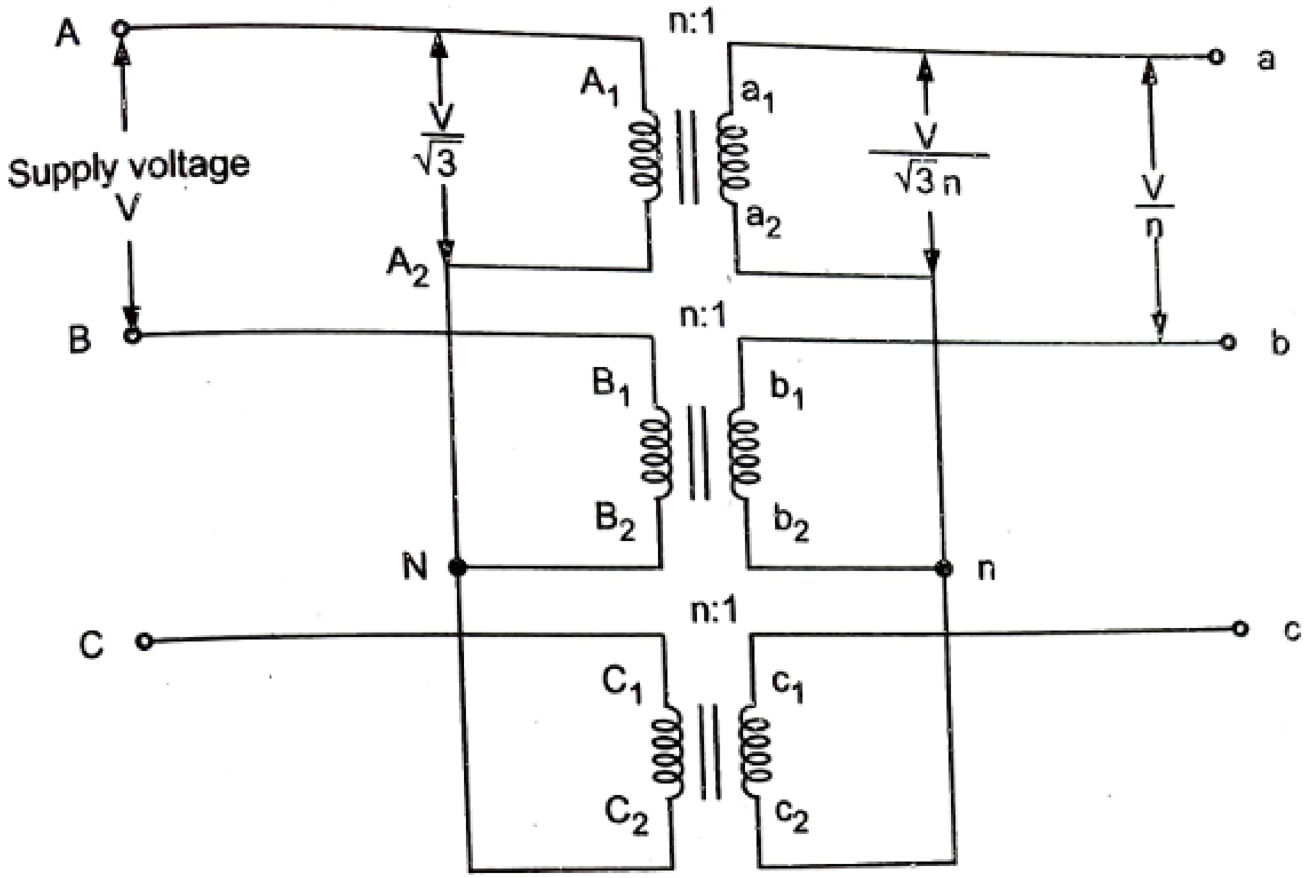


Star-Delta Three Phase Transformer

Labelling of Transformer:



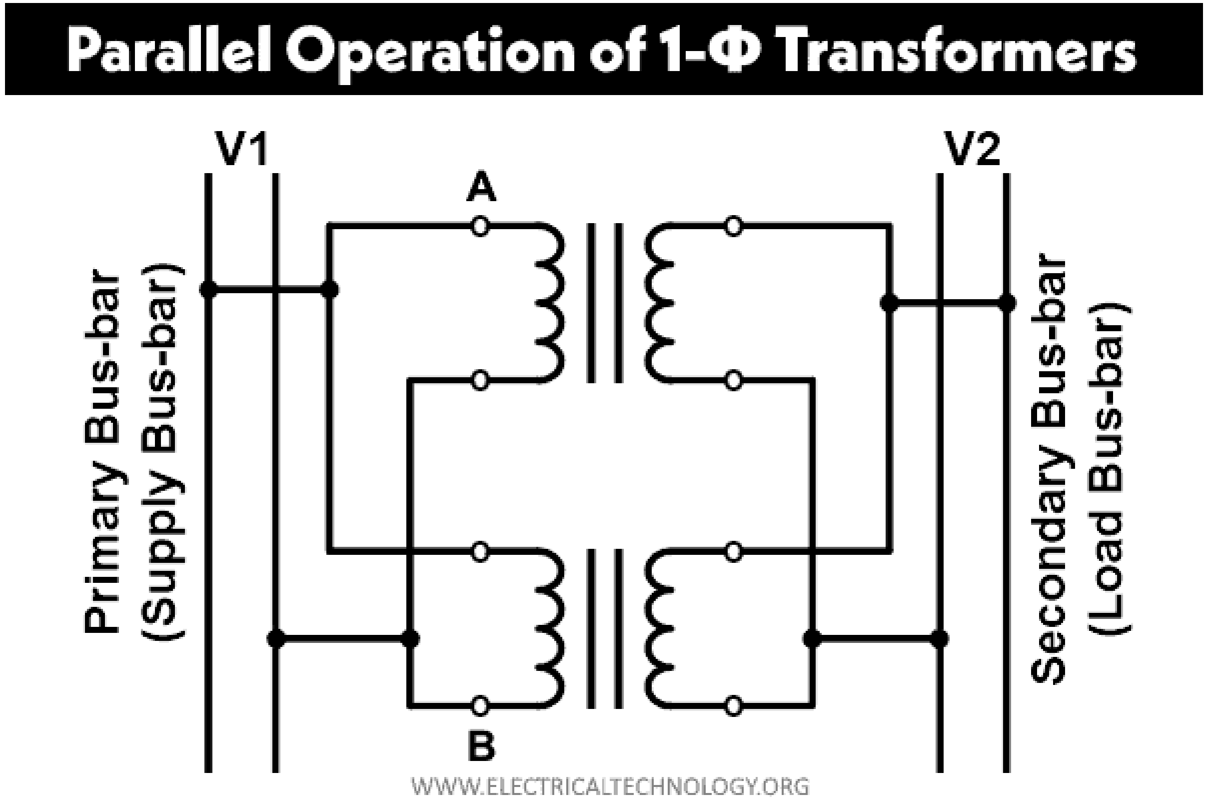
Labelling of transformer terminals



Comparative statement of star/star, delta/delta, and star/delta:

Type of connection	Primary Side			Secondary Side			
	Line voltage	Phase voltage	Phase Current	Phase Voltage	Phase Current	Line voltage	Line Current
Star-Star	V_L	$\frac{V_L}{\sqrt{3}}$	I_L	$\frac{KV_L}{\sqrt{3}}$	$\frac{I_L}{K}$	KV_L	$\frac{I_L}{K}$
Delta-Delta	V_L	V_L	$\frac{I_L}{\sqrt{3}}$	KV_L	$\frac{I_L}{K\sqrt{3}}$	KV_L	$\frac{I_L}{\sqrt{3}}$
Star-Delta	V_L	$\frac{V_L}{\sqrt{3}}$	I_L	$\frac{KV_L}{\sqrt{3}}$	$\frac{I_L}{K}$	$\frac{KV_L}{\sqrt{3}}$	$\frac{I_L}{\sqrt{3}}$
Delta-Star	V_L	V_L	$\frac{I_L}{\sqrt{3}}$	KV_L	$\frac{I_L}{K\sqrt{3}}$	$\sqrt{3}kv_L$	$\frac{I_L}{K\sqrt{3}}$

Parallel Operation of Transformers:



Necessity of parallel operation:

1. When the load is higher than the ratings of the individual transformers parallel operation of smaller units shares a high-capacity load.
2. To make the power system more reliable, parallel operation is needed. If any one unit develops a fault, it can be removed and other units in parallel can maintain the supply.
3. According to the demand for power, the transformers in parallel can be switched ON or OFF. This reduces the transformer losses and makes the overall system more efficient and economical.
4. When the number Of transformers are connected in parallel, then the cost of a standby unit is much less.

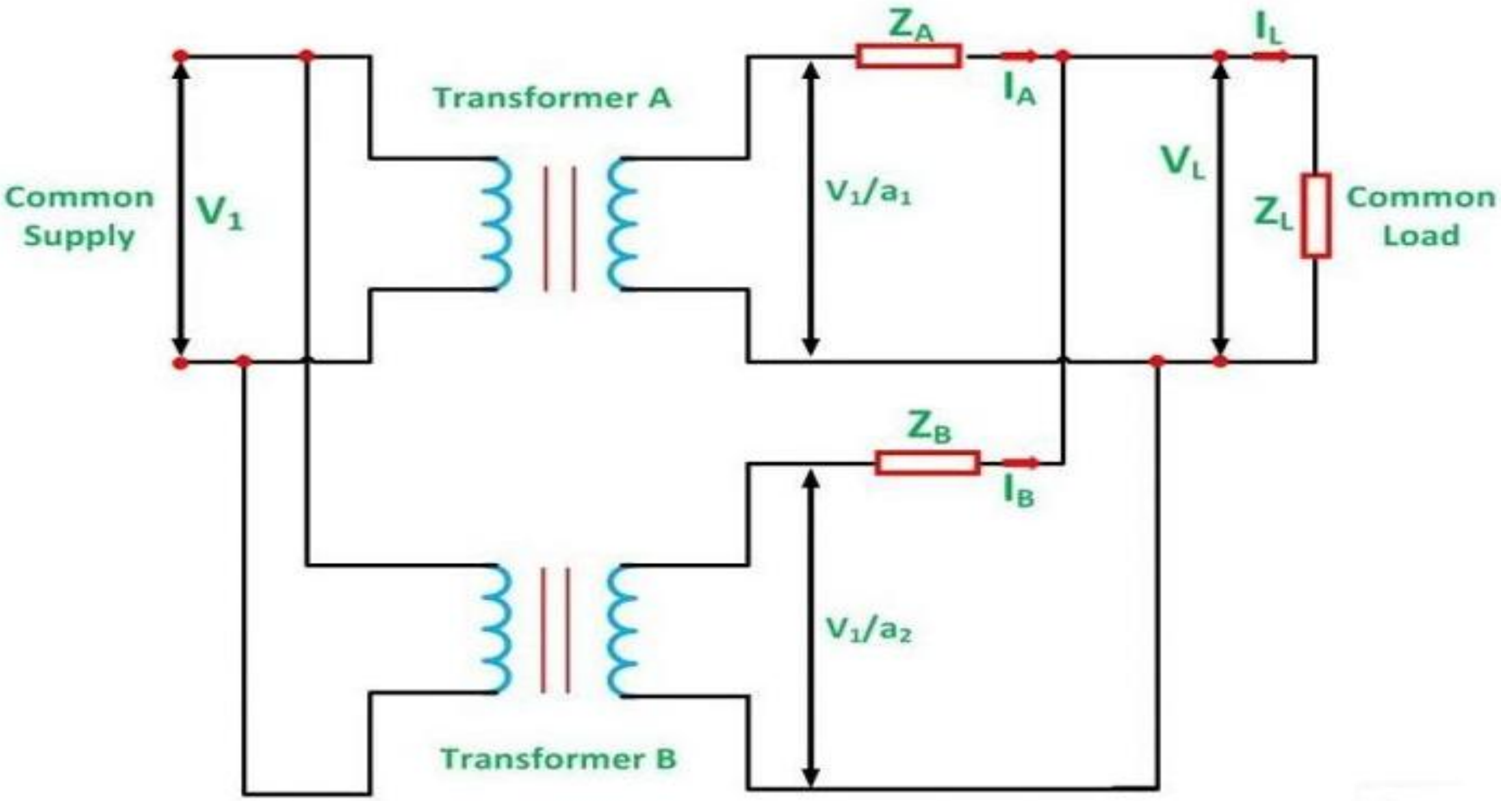
Advantages of using transformers in parallel:

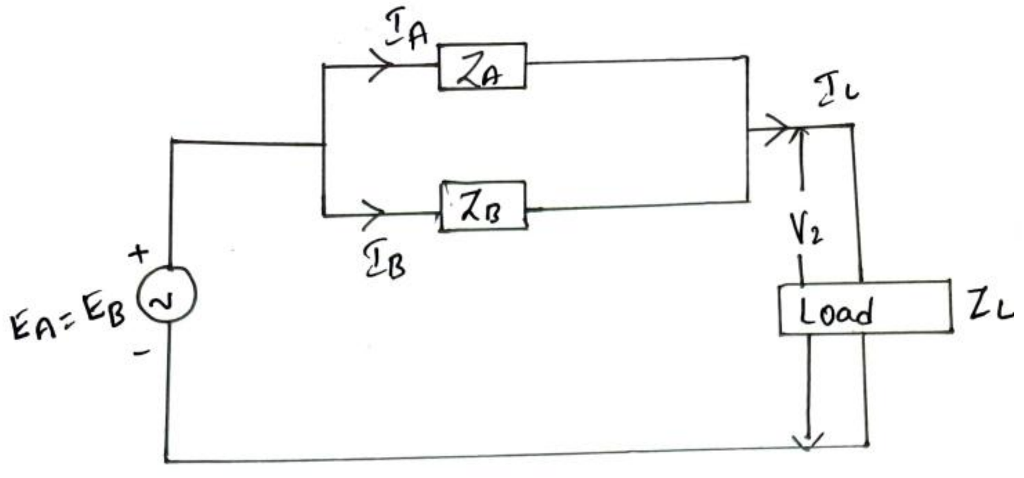
- To maximize electrical power system efficiency.
- To maximize electrical power system availability.
- To maximize power system reliability.
- To maximize electrical power system flexibility.

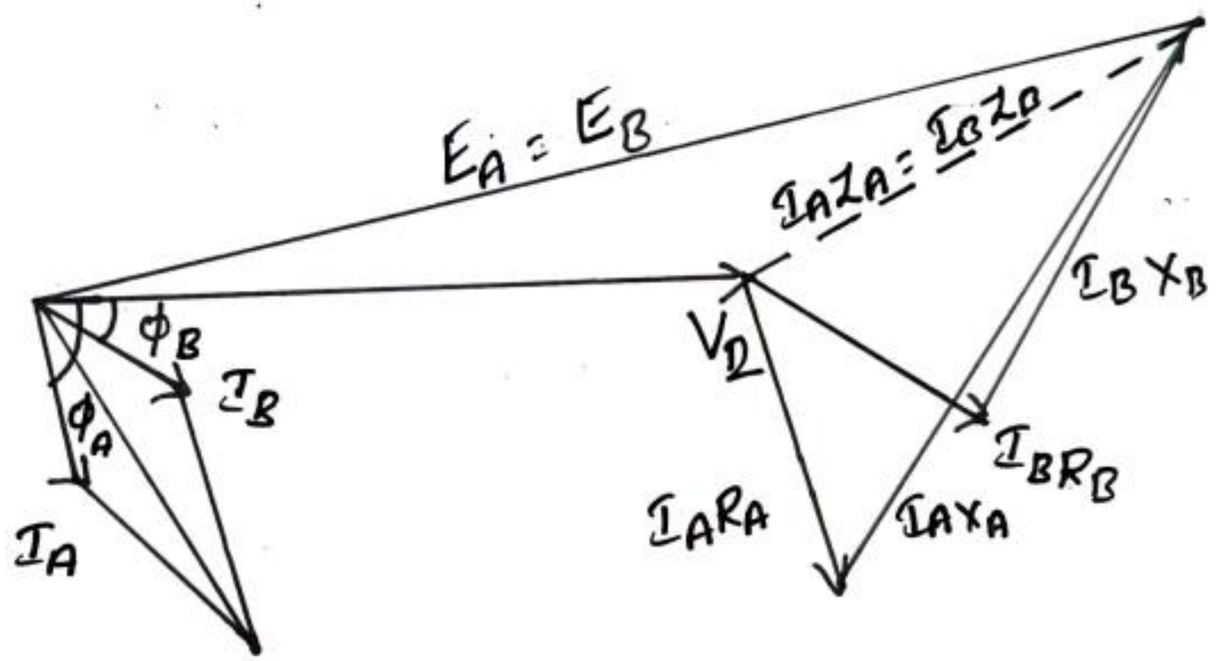
Conditions for parallel operation:

- The voltage ratio must be the same.
- The per unit impedance of each machine on its base must be the same.
- The polarity must be the same so that there is no circulating current between the transformers.
- The phase sequence must be the same and no phase difference must exist between the voltages of the two transformers.

Load sharing in case of similar transformers:




I_A
Z_A
I_L
Z_B
I_B
V_2
+
$E_A = E_B$
-
Load
Z_L


$E_A = E_B$
$I_A Z_A = I_B Z_B$
$I_B X_B$
V_2
ϕ_B
I_B
ϕ_A
I_A
$I_B R_B$
$I_A R_A$
$I_A X_A$

$$I_A + I_B = I_L \dots\dots\dots.(1)$$

$$V_L = \frac{V_1}{a_1} - I_A Z_A \dots\dots\dots.(2) \text{ and}$$

$$V_L = \frac{V_1}{a_2} - I_B Z_B \dots\dots\dots.(3)$$

Now putting the value of I_B from the equation (1) in equation (3) we will get,

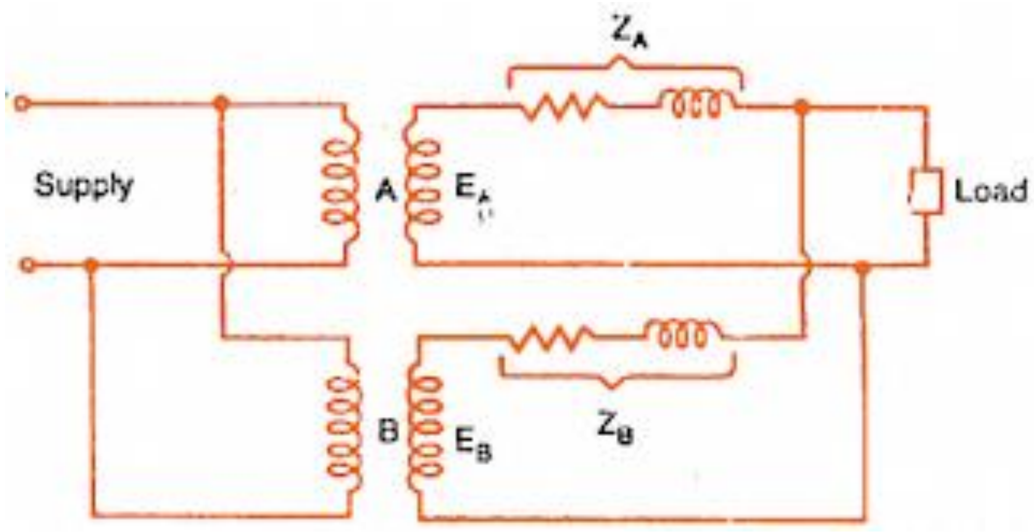
$$V_L = \frac{V_1}{a_2} - (I_L - I_A)\ Z_B \dots\dots\dots.(4)$$

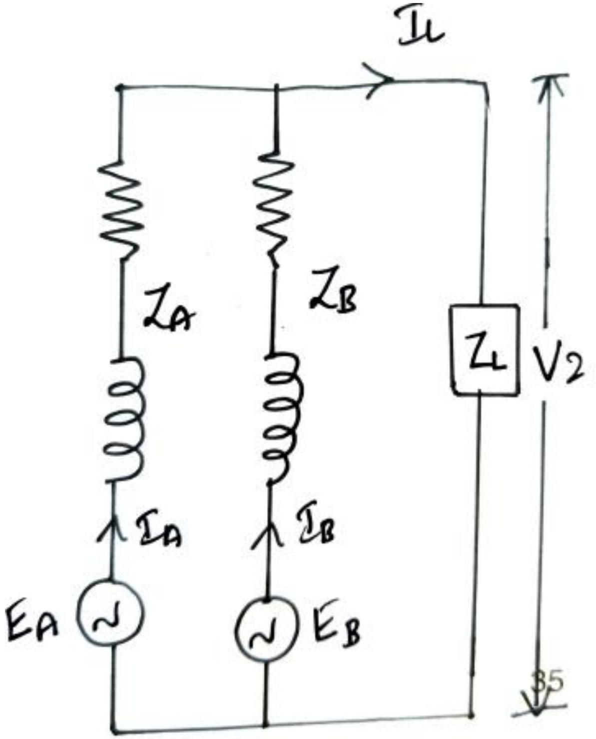
Solving equations (2) and (4) we will get,

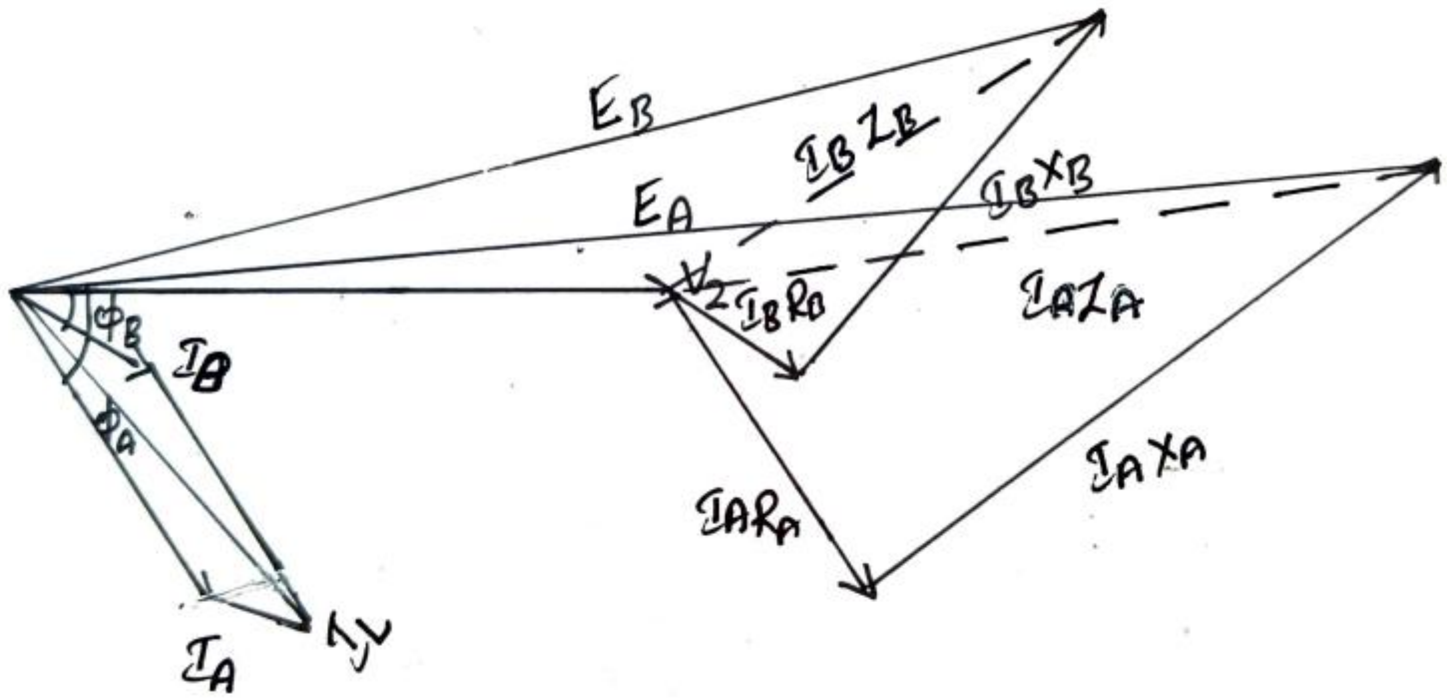
$$I_A = \frac{Z_B I_L}{Z_A + Z_B} + \frac{V_1\ (a_2 - a_1)}{a_1 a_2\ (Z_A + Z_B)} \dots\dots\dots(5)$$

$$I_B = \frac{Z_A I_L}{Z_A + Z_B} + \frac{V_1\ (a_2 - a_1)}{a_1 a_2\ (Z_A + Z_B)} \dots\dots\dots(6)$$

Load sharing in case of dissimilar transformers:




IL
ZA
ZB
ZL
V2
IA
IB
EA
EB


EB
IBZB
EA
IBXB
V2
IBRB
IAZA
ΦB
IB
ΦA
IAXA
IARA
IA
IL

$$I_C = \frac{E_A - E_B}{Z_A + Z_B}$$

$E_A = V_2 + I_A Z_A$; $E_B = V_2 + I_B Z_B$ …………(1)

$V_2 = I_L Z_L = (I_A + I_B) Z_L$…………..(2)

$E_A = (I_A + I_B) Z_L + I_A Z_A$ …….(3)

$E_B = (I_A + I_B) Z_L + I_B Z_B$ …….(4)

Subtract (4) from (3)

$E_A – E_B = I_A Z_A – I_B Z_B$

$$I_A = \frac{(E_A - E_B) + I_B Z_B}{Z_A} \quad ………..(5)$$

$$E_B = I_B Z_B + I_B Z_L + \left(\frac{(E_A - E_B) + I_B Z_B}{Z_A}\right) Z_L$$

$$E_B = I_B Z_B + I_B Z_L + \frac{(E_A - E_B) Z_L}{Z_A} + \frac{I_B Z_B Z_L}{Z_A}$$

$$E_B - \frac{(E_A - E_B) Z_L}{Z_A} = I_B Z_B + I_B Z_L + \frac{I_B Z_B Z_L}{Z_A}$$

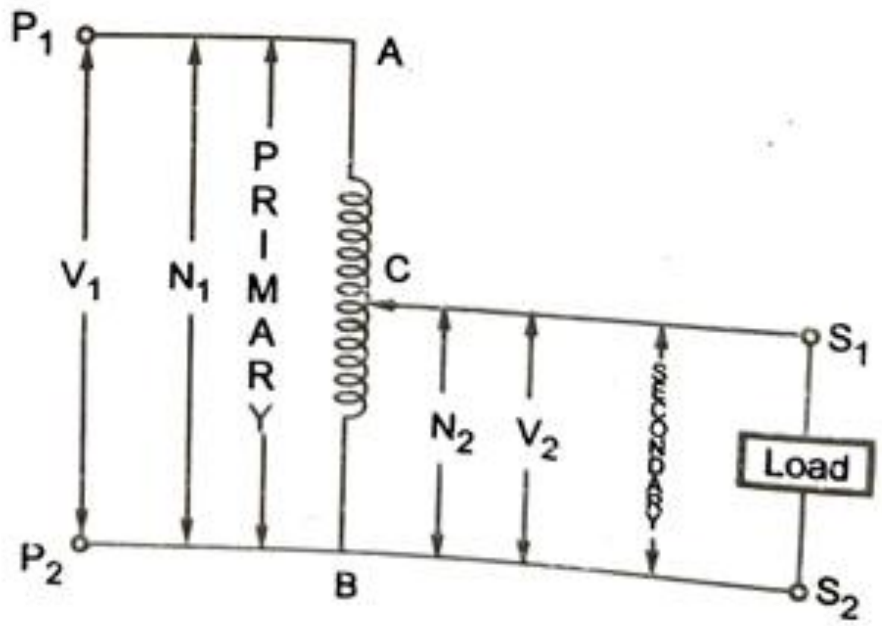
$$\frac{E_B Z_A - (E_A - E_B) Z_L}{Z_A} = I_B \left(\frac{Z_A Z_B + Z_A Z_L + Z_B Z_L}{Z_A}\right)$$

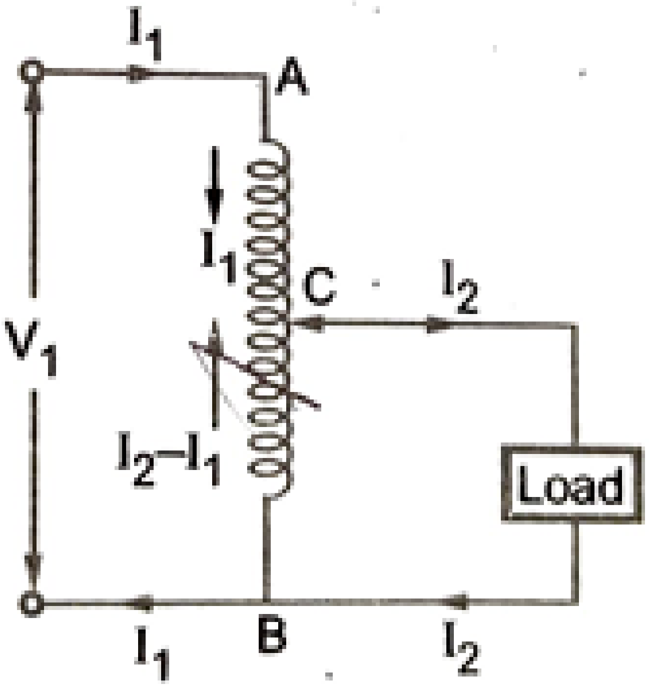
$$I_B = \frac{E_B Z_A - (E_A - E_B) Z_L}{Z_A Z_B + Z_A Z_L + Z_B Z_L} = \frac{E_B Z_A - (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$

$$I_B = \frac{E_B Z_A - (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$

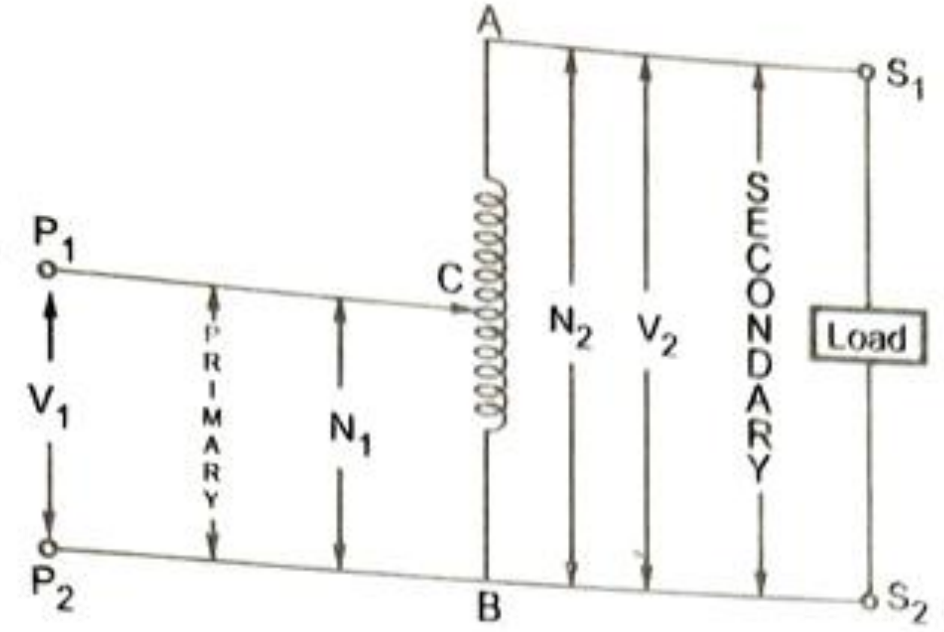
$$I_A = \frac{E_A Z_B - (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$

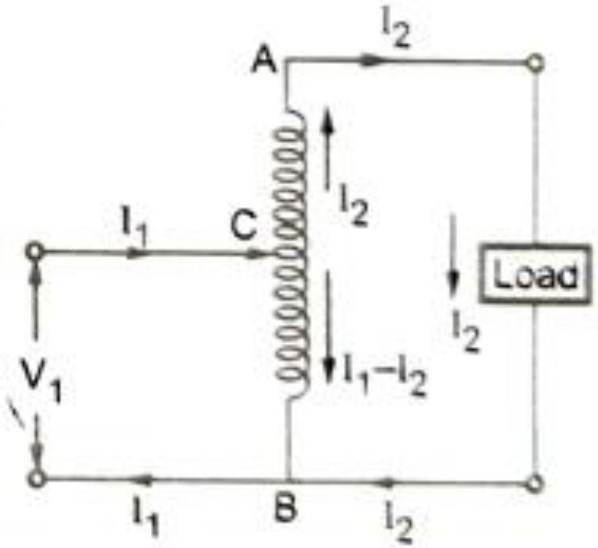
Construction of Autotransformers:





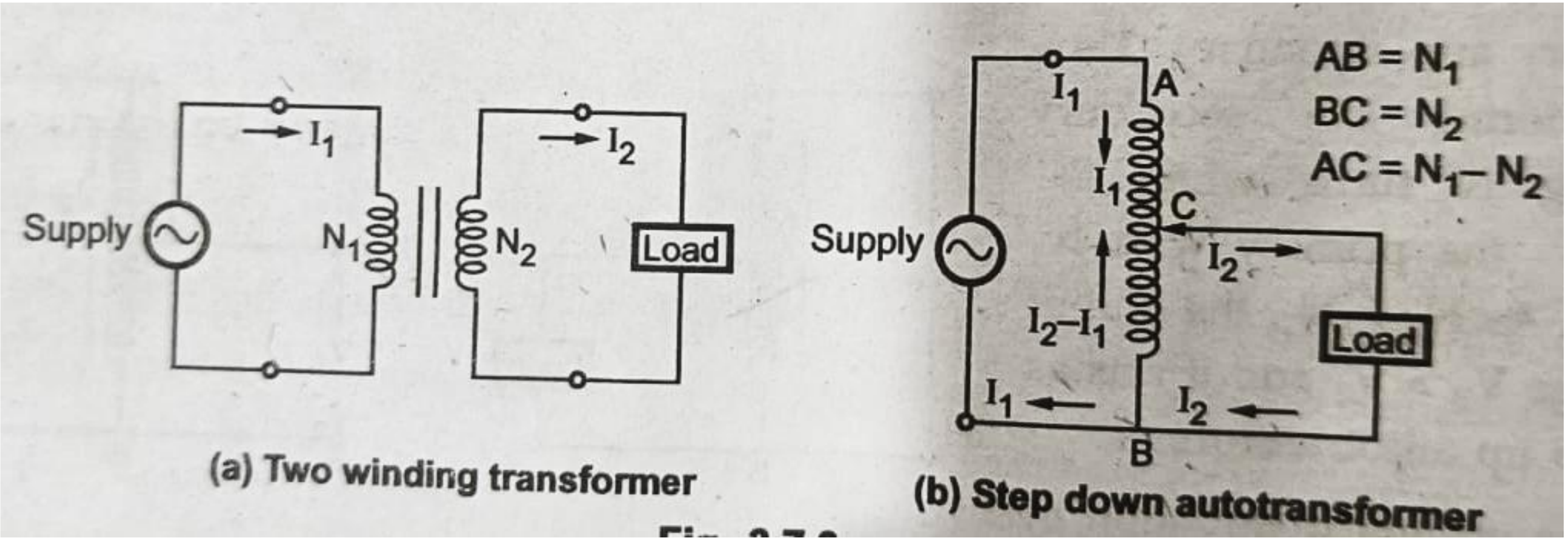
Step-down autotransformer





Step-up autotransformer

Saving of Copper in Auto Transformer as Compared to Ordinary Two-Winding Transformer:



Let W_{TW} = Total weight of copper in two winding transformers.

W_{AT} = Weight of copper in autotransformer

In two winding transformer,

Weight of copper of primary $\propto N_1 I_1$

Weight of copper of secondary $\propto N_2 I_2$

$$W_{TW} \propto N_1I_1 + N_2I_2 \quad \text{............Total weight of copper}$$

In case of step down autotransformer.

Weight of copper of section AC $\propto (N_1 – N_2)$

Weight of copper of section BC $\propto N_2 (I_2 – I_1)$

$W_{AT} \propto (N_1 – N_2) I_1 + N_2 (I_2 - I_1)$

Taking ratio of the weights,

$$\frac{W_{TW}}{W_{AT}} = \frac{N_1 I_1 + N_2 I_2}{(N_1 - N_2)I_1 + N_2(I_2 - I_1)} = \frac{N_1 I_1 + N_2 I_2}{N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1}$$

$$= \frac{N_1 I_1 + N_2 I_2}{N_1 I_1 + N_2 I_2 - 2N_2 I_1}$$

But $K = \frac{N_2}{N_1} = \frac{I_1}{I_2}$

$$\frac{W_{TW}}{W_{AT}} = \frac{N_1 I_1 + KN_1(I_1/K)}{N_1 I_1 + KN_1(I_1/K) - 2(KN_1)I_1} = \frac{2N_1 I_1}{2N_1 I_1 - 2KN_1 I_1}$$

$$\frac{W_{TW}}{W_{AT}} = \frac{1}{1-K}$$

$$W_{AT} = (1-K)\, W_{TW}$$

Saving of copper = $W_{TW} - W_{AT} = W_{TW} - (1-K)W_{TW}$

Saving of copper = $K\, W_{TW}$ …… For step down autotransformer

Thus saving in copper is K times the total weight of copper in two winding transformer.

Saving of copper = $\frac{1}{K} w_T$ …… For step up autotransformer

Advantages of Auto transformer:

- Copper required is very less.
- The efficiency is higher compared to two winding transformer.
- The size and hence cost is less compared to two winding transformer.
- The resistance and leakage reactance is less compared to two winding transformer
- The copper losses I^2R, are less.
- Due to less resistance and leakage reactance, the voltage regulation is superior than the two winding transformer.
- VA rating is more compared to two winding version.
- A smooth and continuous variation of voltage is possible.

Disadvantages of Auto transformer:

- Low impedance hence high short circuit currents for short circuits on secondary side.
- If a section of winding common to primary and secondary is opened, full primary voltage appears across the secondary resulting in higher voltages on secondary and danger of accidents.
- No electrical separation between primary and secondary which is risky in case of high voltage levels.
- Economical only where the voltage ratio is less than 2.

Applications of Auto transformer:

- It is used as a starter to give up to 50 to 60% of full voltage to the stator of a squirrel cage induction motor during starting.
- It is used to give a small boost to a distribution cable, to correct the voltage drop.
- It is also used as a voltage regulator
- Used in power transmission and distribution system and also in the audio system and railways.

Equivalent circuit of Autotransformer:

Consider an autotransformer as shown in the fig
R_1 and X_1 are the resistance and inductance of that part of the winding which carries only current I_1.
R_2 and X_2 are the resistance and inductance of that part of the winding which behaves as secondary.
Applying Kirchhoff's law,

Applying Kirchhoff's law,

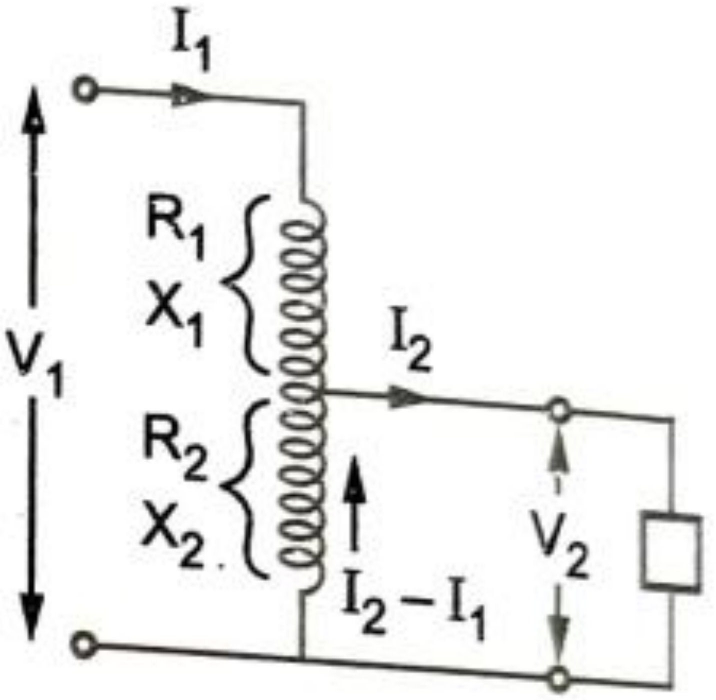
$V_1 = E_1 + I_1(R_1 + jX_1) - (I_2 - I_1)(R_2 + jX2)$ ……………..(1)

$E_2 = V_2 + (I_2 - I_1)(R_2 + jX_2)$ ……………..(2)

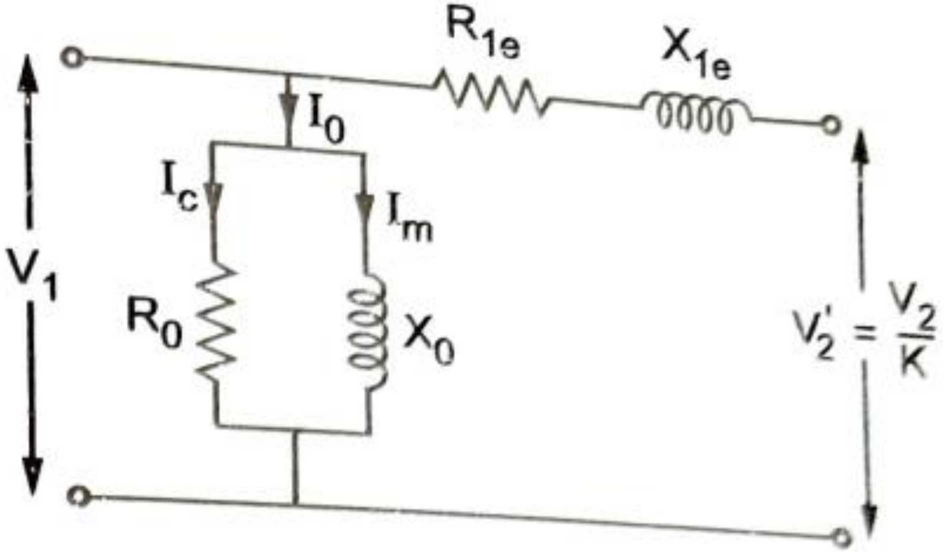
$$K = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{I_2}{I_1} = \text{Transformation ratio}$$

$$E_1 = \frac{E_2}{K}, \quad I_2 = \frac{I_2}{K}$$ and using in eqn(1)

$$V_1 = \frac{E_2}{K} + I_1(R_1 + jX_1) + I_1(R_2 + jX_2) - \frac{I_1}{K}(R_2 + jX_2)$$
…………..(3)



Using equation (2) and (3)



$$V_1 = \frac{V_2+(I_2-I_1)(R_2+jX_2)}{K} + I_1(R_1+jX_1) + I_1(R_2+jX_2) - \frac{I_1}{K}(R_2+jX_2)$$

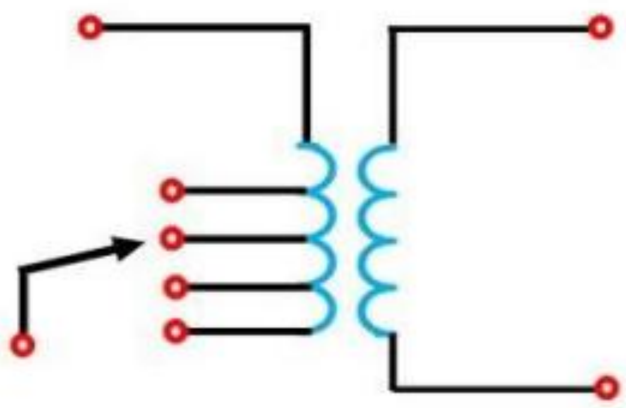
$$I_2 = \frac{I_1}{K} \text{ and combining the term of } I_1 \text{ we get}$$

$$V_1 = \frac{V_2}{K} + I_1\left\{R_1 + R_2\left(\frac{1}{K^2} - \frac{2}{K} + 1\right) + j\left[X_1 + X_2\left(\frac{1}{K^2} - \frac{2}{K} + 1\right)\right]\right\}$$

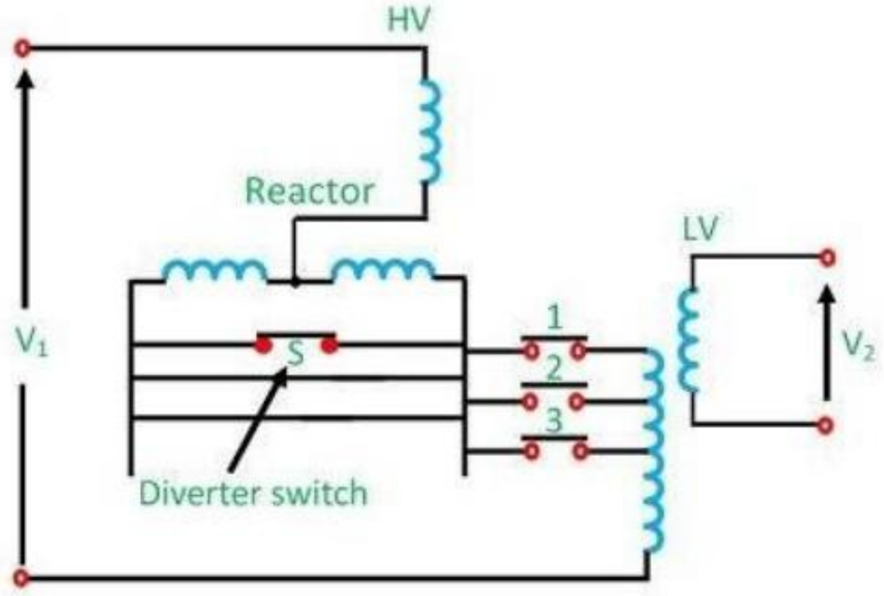
$$V_1 = \frac{V_2}{K} + I_1\left\{R_1 + R_2\left(\frac{1}{K} - 1\right)^2 + j\left[X_1 + X_2\left(\frac{1}{K} - 1\right)^2\right]\right\}$$

$V_1 = V_2' + I_1 R_{1e} + I_1 X_{1e}$ ………..(4)

Tap-changing Transformers:



Off-load tap-changing transformer



On-load tap changing using a reactor


thank
you