Module - 3 : Transformers

Contents: Magnetic materials, BH characteristics, ideal and practical transformer, equivalent circuit, losses in transformers, regulation and efficiency. Auto-transformer and three-phase transformer connections.

Classification of Magnetic Materials:

All materials can be classified in terms of their magnetic behavior falling into one of five categories depending on their bulk magnetic susceptibility. The two most common types of magnetism are diamagnetism and paramagnetism, which account for the magnetic properties of most of the periodic table of elements at room temperature.

Diamagnetism: In a diamagnetic material the atoms have no net magnetic moment when there is no applied field. Under the influence of an applied field (H) the spinning electrons presses and this motion, which is a type of electric current, produces a magnetisation (M) in the opposite direction to that of the applied field. All materials have a diamagnetic effect, however, it is often the case that the diamagnetic effect is masked by the larger paramagnetic or ferromagnetic term. The value of susceptibility is independent of temperature.

Paramagnetism: There are several theories of paramagnetism, which are valid for specific types of material. The Langevin model, which is true for materials with non-interacting localised electrons, states that eachatom has a magnetic moment which is randomly oriented as a result of thermal agitation. The application of a magnetic field creates a slight alignment of these moments and hence a low magnetisation in the same direction as the applied field. As the temperature increases, then the thermal agitation will increase and it will become harder to align the atomic magnetic moments and hence the susceptibility will decrease. This behaviour is known as the Curie law.

Ferromagnetism: Ferromagnetism is only possible when atoms are arranged in a lattice and the atomic magnetic moments can interact to align parallel to each other. This effect is explained in classical theory by the presence of a molecular field within the ferromagnetic material, which was first postulated by Weiss in 1907. This field is sufficient to magnetise the material to saturation. In quantum mechanics, the Heisenberg model of ferromagnetism describes the parallel alignment of magnetic moments in terms of an exchange interaction between neighbouring moments. Weiss postulated the presence of magnetic domains within the material, which are regions where the atomic magnetic moments are aligned. The movement of these domains determines how the material responds to a magnetic field and as a consequence the susceptible is a function of applied magnetic field. Therefore, ferromagnetic materials are usually compared in terms of saturation magnetisation (magnetisation when all domains are aligned) rather than susceptibility. In the periodic table of elements only Fe, Co and Ni are ferromagnetic at and above room temperature. As ferromagnetic materials are heated then the thermal agitation of the atoms means that the degree of alignment of the atomic magnetic moments decreases and hence the saturation magnetisation also decreases.

Anti-ferromagnetism: In the periodic table the only element exhibiting antiferromagnetism at room temperature is chromium. Antiferromagnetic materials are very similar to ferromagnetic materials but the exchange interaction between neighbouring atoms leads to the anti-parallel alignment of the atomic magnetic moments. Therefore, the magnetic field cancels out and the material appears to behave in the same way as a paramagnetic material. Like ferromagnetic materials these materials become paramagnetic above a transition temperature, known as the Néel temperature, T_N. (Cr: T_N=37ºC).

Ferrimagnetism: Ferrimagnetism is only observed in compounds, which have more complex crystal structures than pure elements. Within these materials the exchange interactions lead to parallel alignment of atoms in some of the crystal sites and anti-parallel alignment of others. The material breaks down into magnetic domains, just like a ferromagnetic material and the magnetic behaviour is also very similar, although ferrimagnetic materials usually have lower saturation magnetisations. For example in Barium ferrite (BaO.6Fe2O3).

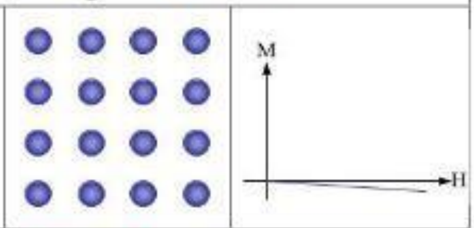
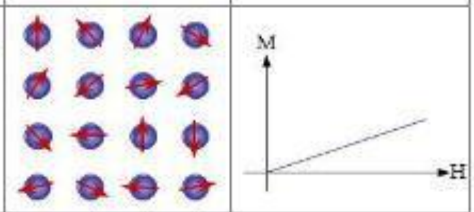
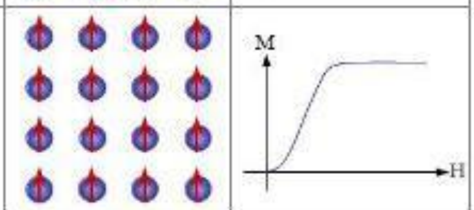
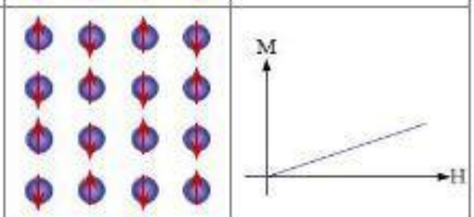
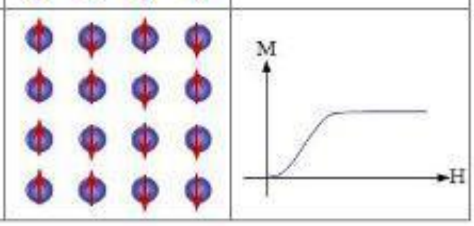
Type	Example	Atomic/Magnetic Behaviour	
Diamagnetism	Inert gases; many metals eg Au, Cu, Hg; non-metallic elements e.g. B, Si, P, S; many ions e.g. Na^+, Cl^- & their salts; diatomic molecules e.g. H_2, N_2; H_2O; most organic compounds	Atoms have no magnetic moment. Susceptibility is small & negative, -10^{-6} to -10^{-5}	
Paramagnetism	Some metals, e.g. Al; some diatomic gases, e.g. O_2, NO; ions of transition metals and rare earth metals, and their salts; rare earth oxides.	Atoms have randomly oriented magnetic moments. Susceptibility is small & positive, $+10^{-5}$ to $+10^{-3}$	
Ferromagnetism	Transition metals Fe, H, Co, Ni; rare earths with 64≤Z≤69; alloys of ferromagnetic elements; some alloys of Mn, e.g. MnBi, Cu_2MnAl.	Atoms have parallel aligned magnetic moments. Susceptibility is large (below T_C)	
Antiferromagnetism	Transition metals Mn, Cr & many of their compound, e.g. MnO, CoO, NiO, Cr_2O_3, MnS, MnSe, CuC_2.	Atoms have anti-parallel aligned magnetic moments. Susceptibility is small & positive, $+10^{-5}$ to $+10^{-3}$	
Ferrimagnetism	Fe_3O_4 (magnetite); γ-Fe_2O_3 (maghemite); mixed oxides of iron and other elements such as Sr ferrite.	Atoms have mixed parallel and anti-parallel aligned magnetic moments. Susceptibility is large (below T_C)	

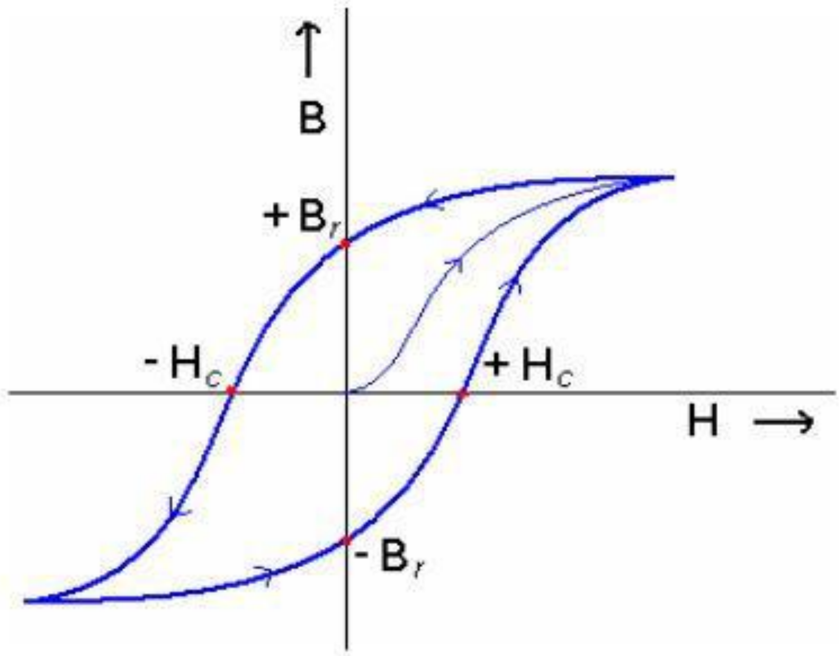
Table 2: A summary of the different types of magnetic behaviour.

Magnetic hysteresis:

1. Once magnetic saturation has been achieved, a decrease in the applied field back to zero results in a macroscopically permanent or residual magnetization, known as remanance, Mr. The corresponding induction, Br, is called retentivity or remanent induction of the magnetic material. This effect of retardation by material is called hysteresis.

2. The magnetic field strength needed to bring the induced magnetization to zero is termed as coercivity, Hc. This must be applied anti-parallel to the original field.

3. A further increase in the field in the opposite direction results in a maximum induction in the opposite direction. The field can once again be reversed, and the field-magnetization loop can be closed, this loop is known as hysteresis loop or B-H plot or M- H plot.



Semi-hard magnets:

•The area within the hysteresis loop represents the energy loss per unit volume of material for one cycle.

•The coercivity of the material is a micro-structure sensitive property. This dependence is known as magnetic shape anisotropy.

•The coercivity of recording materials needs to be smaller than that for others since data written onto a data storage medium should be erasable. On the other hand, the coercivity values should be higher since the data need to be retained. Thus such materials are called magnetically semi-hard.

•Ex.: Hard ferrites based on Ba, CrO_2, γ-Fe_2O_3; alloys based on Co-Pt-Ta-Cr, Fe-Pt and Fe-Pd, etc.

Soft magnets:

1.Soft magnets are characterized by low coercive forces and high magnetic permeabilities; and are easily magnetized and de-magnetized.

2.They generally exhibit small hysteresis losses.

3.Application of soft magnets include: cores for electro-magnets, electric motors, transformers, generators, and other electrical equipment.

4.Ex.: ingot iron, low-carbon steel, Silicon iron, superalloy (80% Ni-5% Mo-Fe), 45 Permalloy (55%Fe-45%Ni), 2-79 Permalloy (79% Ni-4% Mo-Fe), MnZn ferrite / Ferroxcube A (48% $MnFe_2O_4$-52%$ZnFe_2O_4$), NiZn ferrite / Ferroxcube B (36% $NiFe_2O_4$-64% $ZnFe_2O_4$), etc.

Hard magnets:

1. Hard magnets are characterized by high remanent inductions and high coercivities. •These are also called permanent magnets or hard magnets.

2. These are found useful in many applications including fractional horse-power motors, automobiles, audio- and video- recorders, earphones, computer peripherals, and clocks.

3. They generally exhibit large hysteresis losses.

4. Ex.: Co-steel, Tungsten steel, $SmCo_5$, $Nd_2Fe_{14}B$, ferrite $BaO.6Fe_2O_3$, Cunife (60% Cu 20% Ni-20% Fe), Alnico (alloy of Al, Ni, Co and Fe), etc

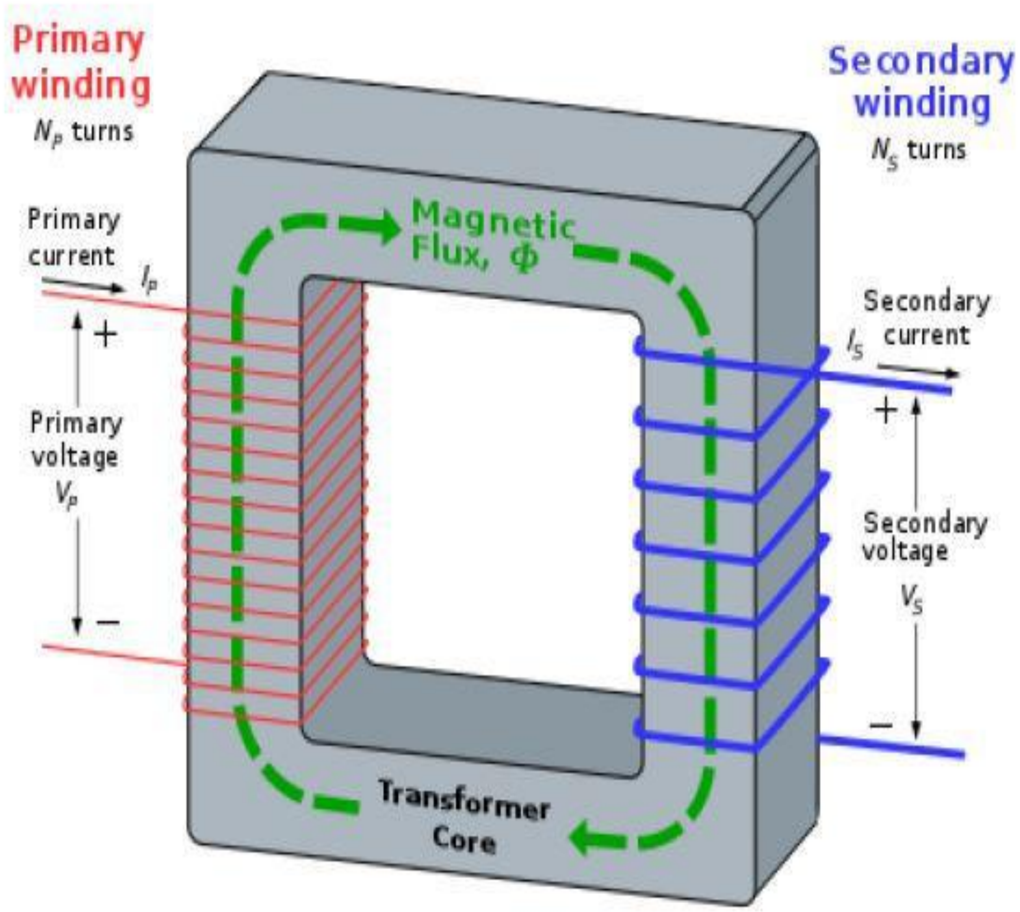
TRANSFORMER:

Working principle of transformer:

A Transformer is a static electrical device that transfers electrical energy between two or more circuits through electromagnetic induction. A varying current in one coil of the transformer produces a varying magnetic field, which in turn induces a varying electromotive force (e.m.f) or "voltage" in a second coil. Power can be transferred between the two coils through the magnetic field, without a metallic connection between the two circuits. Faraday's law of induction discovered in 1831 described this effect. Transformers are used to increase or decrease the alternating voltages in electric power applications.

Since the invention of the first constant-potential transformer in 1885, transformers have become essential for the transmission, distribution, and utilization of alternating current electrical energy. A wide range of transformer design is encountered in electronic and electric power applications.

E.M.F Equation of Transformer:



The primary winding draws a current when it is connected to an alternating voltage source this sinusoidal current produces a sinusoidal flux Φ that can be expressed as:

$$\phi = \phi_m sinwt \qquad ....(1)$$

Instantaneous emf induced in the primary winding is:

$$e_1 = -N_1 \frac{d\phi}{dt} \qquad ....(2)$$

Similarly, instantaneous emf induced in the secondary winding is:

$$e_2 = -N_2 \frac{d\phi}{dt} \qquad ....(3)$$

Substituting eq.(1) in (2) yields ,

$$e_1 = -N_1 \frac{d}{dt}(\phi_m sinwt) \qquad ....(4)$$

$$e_1 = -N_1 w \phi_m \, coswt \qquad ....(5)$$

$$e_1 = -N_1 w \phi_m \sin(wt - 90) \qquad ....(6)$$

The maximum value of e_1 is:

$$E_{m1} = N_1 w \phi_m \qquad ....(7)$$

The rms value of the primary emf is:

$$E_1 = \frac{E_{m1}}{\sqrt{2}} \qquad ....(8)$$

Substituting eq.(7) into eq.(8) yields,

$$E_1 = \frac{N_1 \, 2\pi f \phi_m}{\sqrt{2}} \qquad ....(9)$$

$$E_1 = 4.44 \phi_m N_1 \qquad ....(10)$$

Similarly the expression of the secondary emf is:

$$E_2 = 4.44\phi_m N_2 \qquad \text{........(11)}$$

The primary and secondary voltage can be determined from eq. (10) and (11) if other parameters are known.

Turns ratio of transformer:

Turns ratio is an important parameters for drawing an equivalent circuit of a transformer. The turn ratio is used to identify the step-up and step-down transformers. According to Faraday's law, the induced emf in the primary (e1) and the secondary (e2) winding are:

$$e_1 = -N_1 \frac{d\phi}{dt} \qquad \text{........(12)}$$

$$e_2 = -N_2 \frac{d\phi}{dt} \qquad \text{........(13)}$$

Dividing eq.(12) by eq.(11)

$$\frac{e_1}{e_2} = \frac{N_1}{N_2} \qquad \text{........(14)}$$

$$\frac{e_1}{e_2} = \frac{N_1}{N_2} = a \qquad \text{........(15)}$$

Similarly, dividing eq.(10) by eq.(11) yields,

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = a \qquad \text{........(16)}$$

Where a is the turns ratio of a transformer.

In case of $N_2 > N_1$, The transformer is called a step-up transformer, whereas for $N_1 > N_2$, the transformer is called a step-down transformer. The losses are zero in an ideal transformer. In this case, the input power of the transformer is equal to output power and this yields,

$$V_1 I_1 = V_2 I_2 \qquad \text{........(17)}$$

Eq.(17) can be rearranged as :

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = a \qquad \text{........(18)}$$

The ratio of primary current to the secondary current is:

$$\frac{I_1}{I_2} = \frac{1}{a} \qquad \text{........(19)}$$

Again , the magneto motive force produced by the primary current will be equal to the magneto motive force produced by the secondary current and it can be expressed as:

$$N_1 I_1 = N_2 I_2 \qquad \text{........(21)}$$

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{1}{a} \qquad \text{........(22)}$$

From eq.(22) it is concluded that the ratio of primary to secondary current is inversely proportional to the turns ratio of the transformer.

The input and output power of an ideal transformer is:

$$P_{in} = V_1 I_1 cos\, \phi_1 \qquad \text{........(23)}$$

$$P_{out} = V_2 I_2 cos\, \phi_2 \qquad \text{........(24)}$$

For an ideal condition, the angle ϕ_1 is equal to the angle ϕ_2 and output power can be re-arranged as,

$$P_{out} = \frac{V_1}{a} a\, I_1 cos\, \phi_1 \qquad \text{........(25)}$$

$$P_{out} = V_1 I_1 cos\, \phi_1 = P_{in} \qquad \text{........(26)}$$

From eq.(26), it is seen that the input and output power are the same in case of an ideal transformer , similarly the input and the output reactive power are:

$$Q_{out} = V_2 I_2 sin\, \phi_2 = V_1 I_1 sin\, \phi_1 = Q_{in} \qquad \text{........(27)}$$

From eq.(26) and eq.(27), the input and output power and reactive power can be calculated if other parameter are known .

Ideal transformer and it's characteristics:

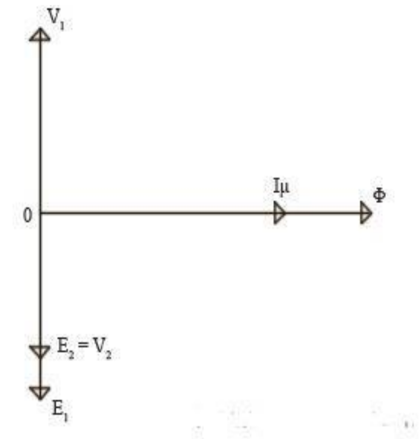
An ideal transformer is an imaginary transformer which has
- no copper losses (no winding resistance)
- no iron loss in core
- no leakage flux

In other words, an ideal transformer gives output power exactly equal to the input power. The efficiency of an idea transformer is 100%. Actually, it is impossible to have such a transformer in practice, but ideal transformer model makes problems easier.

Characteristics of ideal transformer:

- **Zero winding resistance**: It is assumed that, resistance of primary as well as secondary winding of an ideal transformer is zero. That is, both the coils are purely inductive in nature.
- **Infinite permeability of the core:** Higher the permeability, lesser the mmf required for flux establishment. That means, if permeability is high, less magnetizing current is required to magnetize the transformer core.

- **No leakage flux:** Leakage flux is a part of magnetic flux which does not get linked with secondary winding. In an ideal transformer, it is assumed that entire amount of flux get linked with secondary winding (that is, no leakage flux).
- **100% efficiency:** An ideal transformer does not have any losses like hysteresis loss, eddy current loss etc. So, the output power of an ideal transformer is exactly equal to the input power. Hence, 100% efficiency.



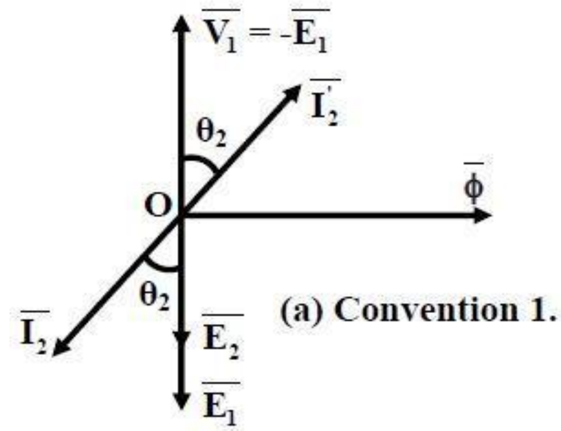


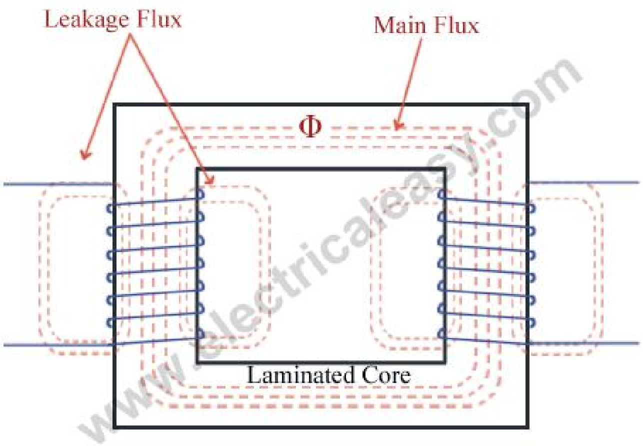
Fig. Transformer is unloaded. **Fig. Transformer is loaded.**

Now, if an alternating voltage V_1 is applied to the primary winding of an ideal transformer, counter emf E_1 will be induced in the primary winding. As windings are purely inductive, this induced emf E_1 will be exactly equal to the apply voltage but in 180 degree phase opposition. Current drawn from the source produces required magnetic flux. Due to primary winding being purely inductive, this current lags 90° behind induced emf E_1. This current is called magnetizing current of the transformer $I\mu$. This magnetizing current $I\mu$ produces alternating magnetic flux Φ. This flux Φ gets linked with the secondary winding and emf E_2 gets induced by mutual induction. This mutually induced emf E_2 is in phase with E_2. If closed circuit is provided at secondary winding, E_2 causes current I_2 to flow in the circuit.

For an ideal transformer, $E_1I_1 = E_2I_2$

Transformer with resistance and leakage reactance:

Magnetic leakage

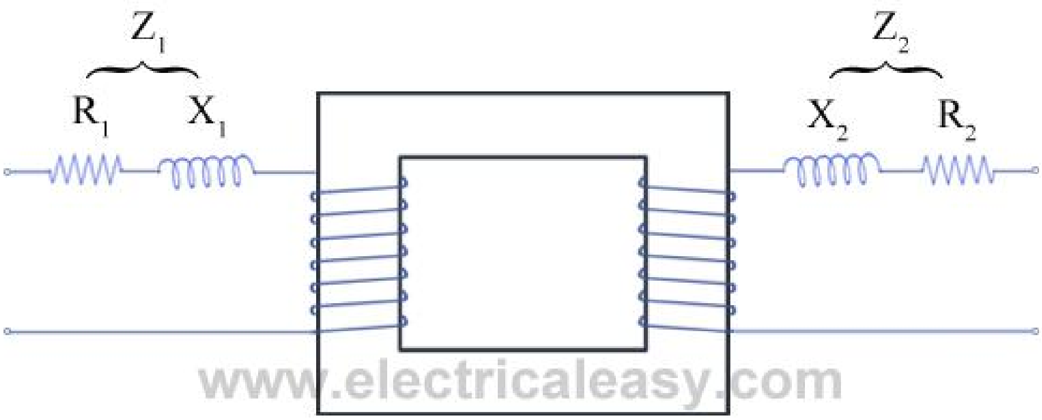


In a transformer it is observed that, all the flux linked with primary winding does not get linked with secondary winding. A small part of the flux completes its path through air rather than through the core (as shown in the fig at right), and this small part of flux is called as leakage flux or magnetic leakage in transformers. This leakage flux does not link with both the windings, and hence it does not contribute to transfer of energy from primary winding to secondary winding. But, it produces self induced emf in each winding. Hence, leakage flux produces an effect equivalent to an inductive coil in series with each winding. And due to this there will be leakage reactance.

(To minimize this leakage reactance, primary and secondary windings are not placed on separate legs, refer the diagram of core type and shell type transformer from construction of transformer.)

Practical Transformer with resistance and leakage reactance

In the following figure, leakage reactance and resitance of the primary winding as well as secondary winding are taken out, representing a practical transformer.



Where, R_1 and R_2 = resistance of primary and secondary winding respectively.

X_1 and X_2 = leakage reactance of primary and secondary winding resp.
Z_1 and Z_2 = Primary impedance and secondary impedance resp.
$Z_1 = R_1 + jX_1$ ...and $Z_2 = R_2 + jX_2$.
The impedance in each winding lead to some voltage drop in each winding. Considering this voltage drop the **v**oltage equation of transformer can be given as -
$V_1 = E_1 + I_1(R_1 + jX_1)$ --------primary side
$V_2 = E_2 - I_2(R_2 + jX_2)$ --------secondary side

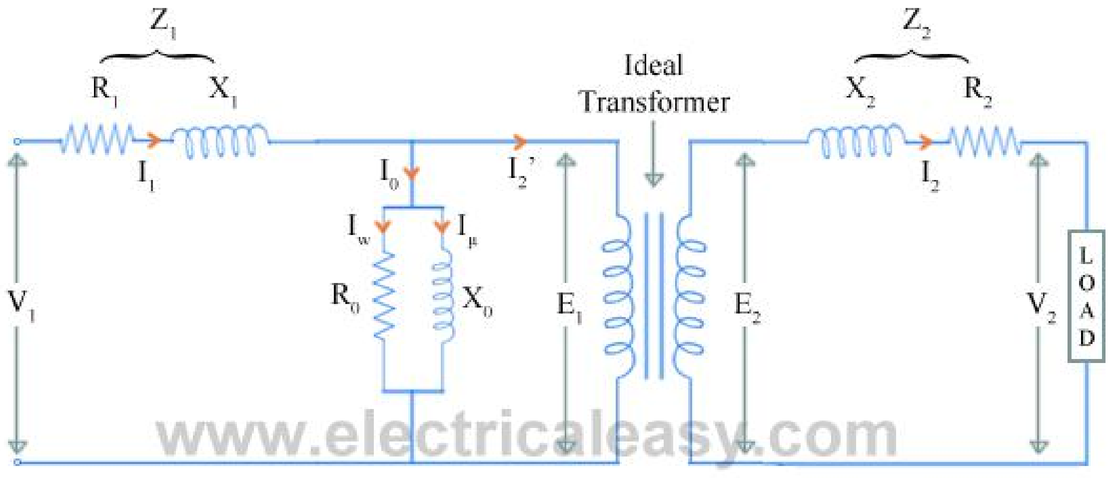
where, V_1 = supply voltage of primary winding
V_2 = terminal voltage of secondary winding
E_1 and E_2 = induced emf in primary and secondary winding respectively. (EMF equation of a transformer.)

Equivalent circuit of transformer:

In a practical transformer –

(a) Some leakage flux is present at both primary and secondary sides. This leakage gives rise to leakage reactances at both sides, which are denoted as X_1 and X_2 respectively.
(b) Both the primary and secondary winding possesses resistance, denoted as R_1 and R_2 respectively. These resistances causes voltage drop as, I_1R_1 and I_2R_2 and also copper loss $I_1^2R_1$ and $I_2^2R_2$.
(c) Permeability of the core can not be infinite, hence some magnetizing current is needed. Mutual flux also causes core loss in iron parts of the transformer.
We need to consider all the above things to derive equivalent circuit of a transformer.

Resistances and reactances of transformer, which are described above, can be imagined separately from the windings (as shown in the figure below). Hence, the function of windings, thereafter, will only be the transforming the voltage.



The no load current I_0 is divided into, pure inductance X_0 (taking magnetizing components I_μ) and non inductive resistance R_0 (taking working component I_w) which are connected into parallel across the primary. The value of E_1 can be obtained by subtracting I_1Z_1 from V_1. The value of R_0 and X_0 can be calculated as, $R_0 = E_1 / I_w$ and $X_0 = E_1 / I_\mu$.

But, using this equivalent circuit does not simplifies the calculations. To make calculations simpler, it is preferable to transfer current, voltage and impedance either to primary side or to the secondary side. In that case, we would have to work with only one winding which is more convenient.

From the voltage transformation ratio, it is clear that,

$E_1 / E_2 = N_1 / N_2 = K$

Now, lets refer the parameters of secondary side to primary.

Z_2 can be referred to primary as Z_2'

where, $Z_2' = (N_1/N_2)^2Z_2 = K^2Z_2$. ....where $K= N_1/N_2$.

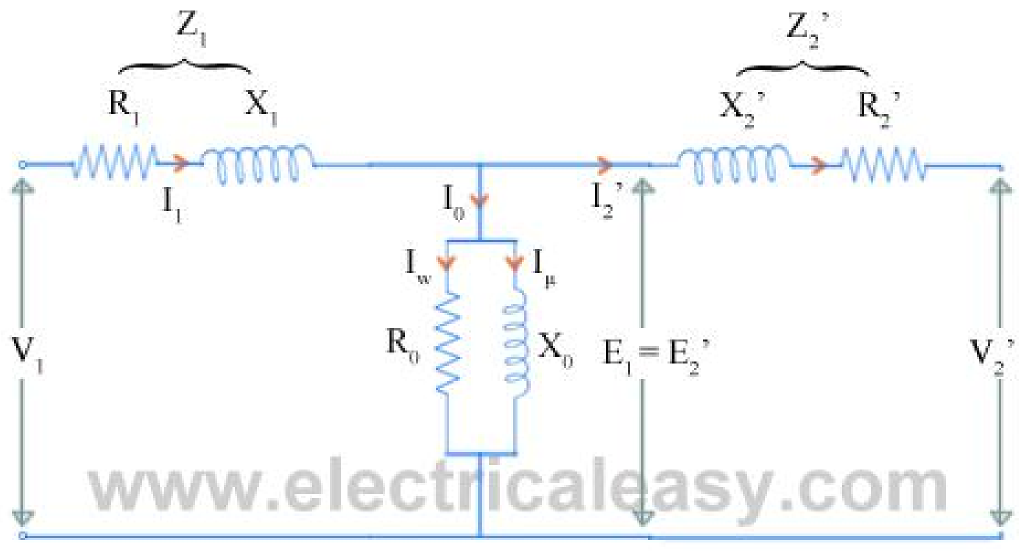
that is, $R_2'+jX_2' = K^2(R_2+jX_2)$

equating real and imaginary parts,

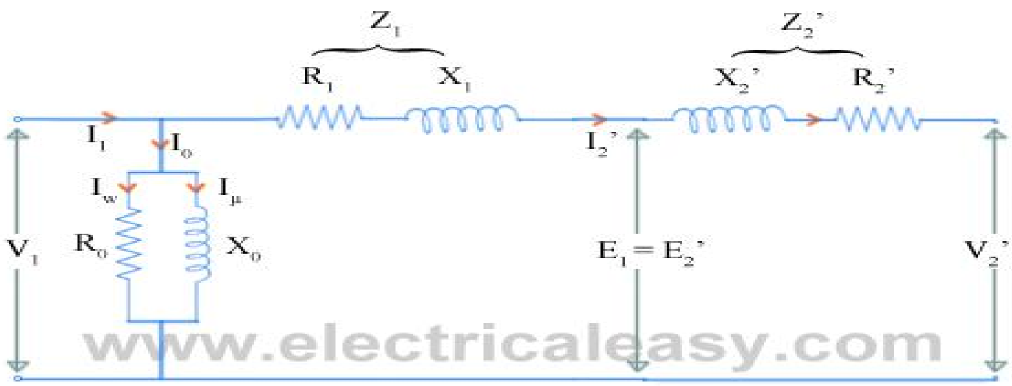
$R_2' = K^2R_2$ and $X_2' = K^2X_2$.

And $V_2' = KV_2$

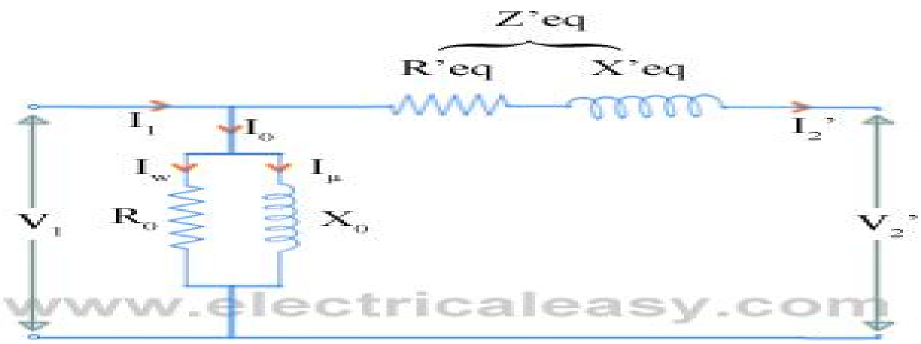
The following figure shows the **equivalent circuit of transformer with secondary parameters referred to the primary**.



Now, as the values of winding resistance and leakage reactance are so small that, V_1 and E_1 can be assumed to be equal. Therefore, the exciting current drawn by the parallel combination of R_0 and X_0 would not affect significantly, if we move it to the input terminals as shown in the figure below.

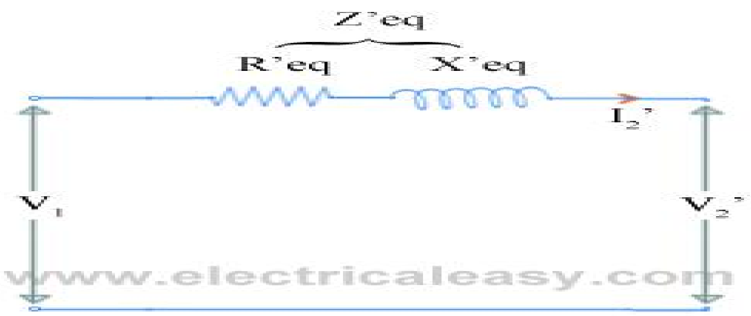


Now, let $R_1 + R_2' = R'_{eq}$ and $X_1 + X_2' = X'_{eq}$
Then the **equivalent circuit of transformer** becomes as shown in the figure below



Approximate equivalent circuit of transformer:

If only voltage regulation is to be calculated, then even the whole excitation branch (parallel combination of R0 and X0) can be neglected. Then the equivalent circuit becomes as shown in the figure below.



Transformer - Losses and Efficiency:

Losses in transformer:

In any electrical machine, 'loss' can be defined as the difference between input power and output power. An electrical transformer is a static device, hence mechanical losses (like windage or friction losses) are absent in it. A transformer only consists of electrical losses (iron losses and copper losses). Transformer losses are similar to losses in a DC machine, except that transformers do not have mechanical losses.

(i) Core losses or Iron losses:

Eddy current loss and hysteresis loss depend upon the magnetic properties of the material used for the construction of core. Hence these losses are also known as **core losses** or **iron losses**.

- **Hysteresis loss in transformer**: Hysteresis loss is due to reversal of magnetization in the transformer core. This loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. It can be given by, Steinmetz formula:
  $W_h = \eta B_{max}^{1.6} fV$ (watts)
  where, η = Steinmetz hysteresis constant
  V = volume of the core in m^3
- **Eddy current loss in transformer**: In transformer, AC current is supplied to the primary winding which sets up alternating magnetizing flux. When this flux links with secondary winding, it produces induced emf in it. But some part of this flux also gets linked with other conducting parts like steel core or iron body or the transformer, which will result in induced emf in those parts, causing small circulating current in them. This current is called as eddy current. Due to these eddy currents, some energy will be dissipated in the form of heat.

(ii) Copper loss in transformer

Copper loss is due to ohmic resistance of the transformer windings. Copper loss for the primary winding is $I_1^2R_1$ and for secondary winding is $I_2^2R_2$. Where, I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively. It is clear that Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load.

Efficiency of Transformer

Just like any other electrical machine, **efficiency of a transformer** can be defined as the output power divided by the input power. That is efficiency = output / input .

Transformers are the most highly efficient electrical devices. Most of the transformers have full load efficiency between 95% to 98.5% . As a transformer being highly efficient, output and input are having nearly same value, and hence it is impractical to measure the efficiency of transformer by using output / input. A better method to find efficiency of a transformer is using,

efficiency = (input - losses) / input = 1 - (losses / input).

Condition for maximum efficiency

Let,

Copper loss = $I_1^2R_1$

Iron loss = Wi

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2R_1 + W_i}{V_1I_1\cos\Phi_1}$$

$$\eta = 1 - \frac{I_1R_1}{V_1\cos\Phi_1} - \frac{W_i}{V_1I_1\cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1\cos\Phi_1} + \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\eta \text{ will be maximum at } \frac{d\eta}{dI_1} = 0$$

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\frac{I_1^2R_1}{V_1I_1^2\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$I_1^2R_1 = W_i$$

Hence, **efficiency of a transformer** will be maximum when copper loss and iron losses are equal.
That is Copper loss = Iron loss.

Voltage Regulation of Transformer:

Voltage regulation is a measure of change in the voltage magnitude between the sending and receiving end of a component. It is commonly used in power engineering to describe the percentage voltage difference between no load and full load voltages distribution lines, transmission lines, and transformers.

Explanation of Voltage Regulation of Transformer: An electrical power transformer is open circuited, meaning that the load is not connected to the secondary terminals. In this situation, the secondary terminal voltage of the transformer will be its secondary induced emf E_2. Whenever a full load is connected to the secondary terminals of the transformer, rated current

I_2 flows through the secondary circuit and voltage drop comes into picture. At this situation, primary winding will also draw equivalent full load current from source. The voltage drop in the secondary is I_2Z_2 where Z_2 is the secondary impedance of transformer. Now if at this loading condition, any one measures the voltage between secondary terminals, he or she will get voltage V_2 across load terminals which is obviously less than no load secondary voltage E_2 and this is because of I_2Z_2 voltage drop in the transformer.

Expression of Voltage Regulation of Transformer

The equation for the **voltage regulation of transformer**, represented in percentage, is

$$Voltage\ regulation(\%) = \frac{E_2 - V_2}{V_2} \times 100\%$$

Voltage Regulation of Transformer for Lagging Power Factor

$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$$
$$= \frac{I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

Voltage Regulation of Transformer for Leading Power Factor

$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$$
$$= \frac{I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

Zero Voltage Regulation of a Transformer

'Zero voltage regulation' indicates that there is no difference between its 'no-load voltage' and its 'full-load voltage'. This means that in the voltage regulation equation above, voltage regulation is equal to zero. This is not practical – and is only theoretically possible in the case for an ideal transformer.

Auto transformer:

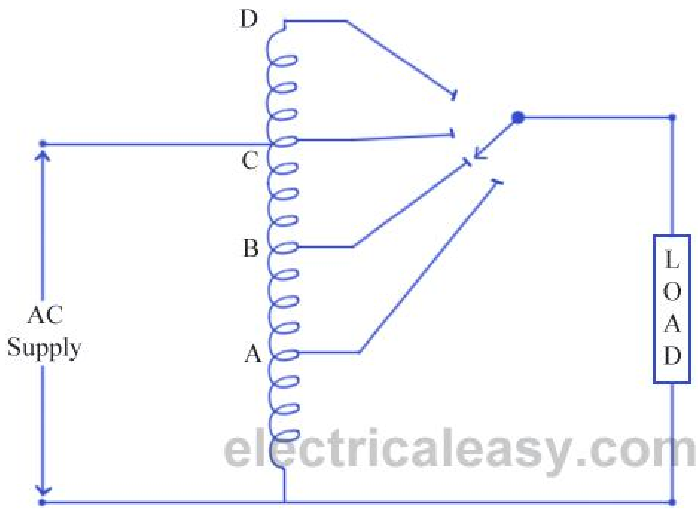
An **auto transformer** is an electrical transformer having only one winding. The winding has at least three terminals which is explained in the construction details below.

Some of the **advantages of auto-transformer** are that,

- they are smaller in size,
- cheap in cost,
- low leakage reactance,
- increased kVA rating,
- low exciting current etc.

An example of **application of auto transformer** is, using an US electrical equipment rated for 115 V supply (they use 115 V as standard) with higher Indian voltages. Another example could be in starting method of three phase induction motors.

Construction of auto transformer



Auto Transformer

An auto transformer consists of a single copper wire, which is common in both primary as well as secondary circuit. The copper wire is wound a laminated silicon steel core, with at least three tappings taken out. Secondary and primary circuit share the same neutral point of the winding. The construction is well explained in the diagram. Variable turns ratio at secondary can be obtained by the tappings of the winding (as shown in the figure), or by providing a smooth sliding brush over the winding. Primary terminals are fixed. Thus, in an auto transformer, you may say, primary and secondary windings are connected magnetically as well as electrically.

Working of auto transformer:

As I have described just above, an auto transformer has only one winding which is shared by both primary and secondary circuit, where number of turns shared by secondary are variable. EMF induced in the winding is proportional to the number of turns. Therefore, the secondary voltage can be varied by just varying secondary number of turns.

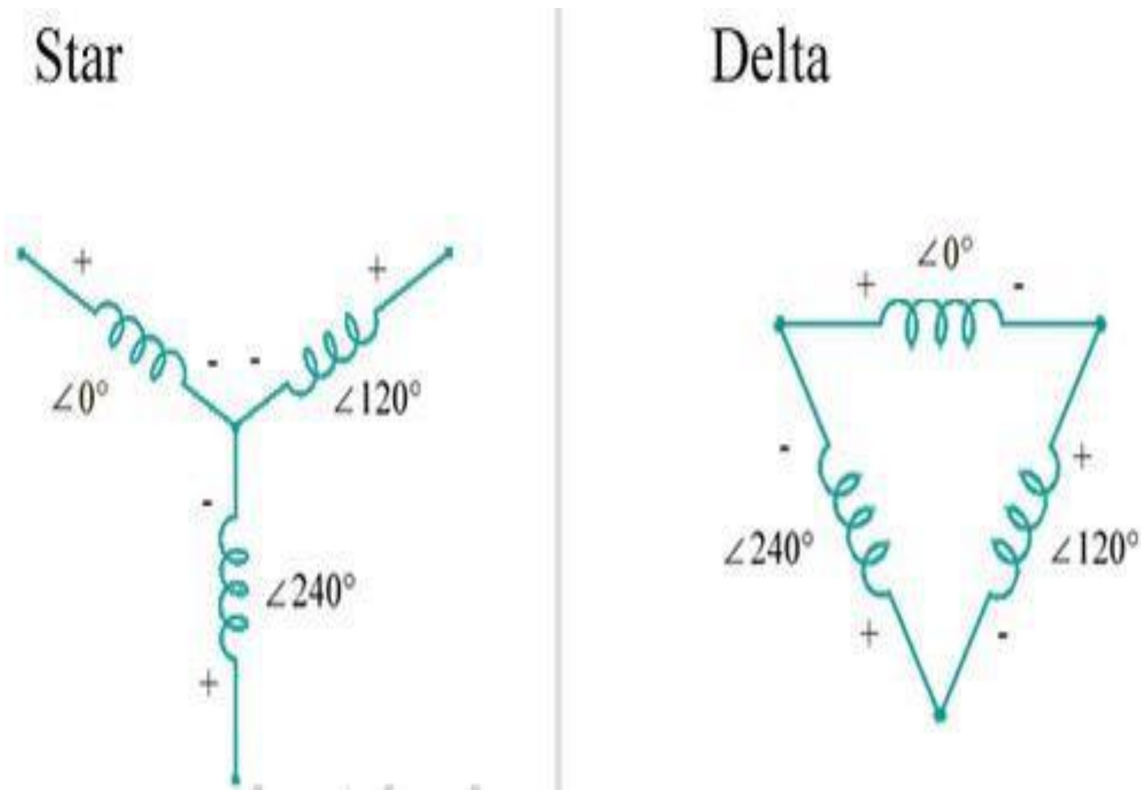
As winding is common in both circuits, most of the energy is transferred by means of electrical conduction and a small part is transferred through induction.

The considerable **disadvantages of an auto transformer** are,

- any undesirable condition at primary will affect the equipment at secondary (as windings are not electrically isolated),
- due to low impedance of auto transformer, secondary short circuit currents are very high,
- harmonics generated in the connected equipment will be passed to the supply.

Three Phase Transformer Connections:

Three phase transformer connections In three phase system, the three phases can be connected in either star or delta configuration. In case you are not familiar with those configurations, study the following image which explains star and delta configuration. In any of these configurations, there will be a phase difference of 120° between any two phases.



Three phase transformer connections

Windings of a three phase transformer can be connected in various configurations as (i) star-star, (ii) delta-delta, (iii) star-delta, (iv)delta-star, These configurations are explained below.

Star-star (Y-Y)

- Star-star connection is generally used for small, high-voltage transformers. Because of star connection, number of required turns/phase is reduced (as phase voltage in star connection is $1/\sqrt{3}$ times of line voltage only). Thus, the amount of insulation required is also reduced.
- The ratio of line voltages on the primary side and the secondary side is equal to the transformation ratio of the transformers.
- Line voltages on both sides are in phase with each other.

- This connection can be used only if the connected load is balanced.

Delta-delta (Δ-Δ)

- This connection is generally used for large, low-voltage transformers. Number of required phase/turns is relatively greater than that for star-star connection.
- The ratio of line voltages on the primary and the secondary side is equal to the transformation ratio of the transformers.
- This connection can be used even for unbalanced loading.
- Another advantage of this type of connection is that even if one transformer is disabled, system can continue to operate in open delta connection but with reduced available capacity.

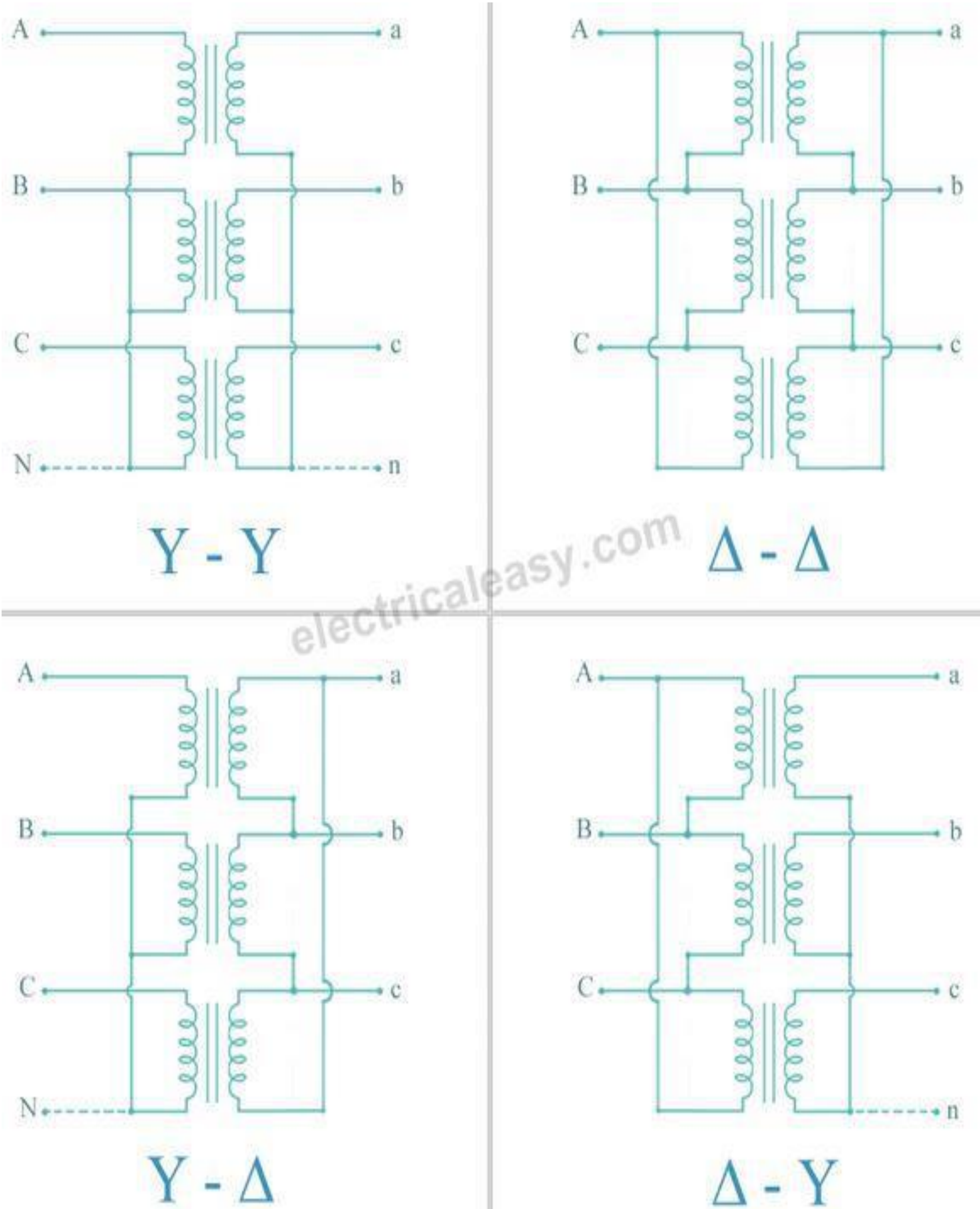
Star-delta OR wye-delta (Y-Δ)

- The primary winding is star star (Y) connected with grounded neutral and the secondary winding is delta connected.
- This connection is mainly used in step down transformer at the substation end of the transmission line.
- The ratio of secondary to primary line voltage is $1/\sqrt{3}$ times the transformation ratio.
- There is 30° shift between the primary and secondary line voltages.

Delta-star OR delta-wye (Δ-Y)

- The primary winding is connected in delta and the secondary winding is connected in star with neutral grounded. Thus it can be used to provide 3-phase 4-wire service.
- This type of connection is mainly used in step-up transformer at the beginning of transmission line.
- The ratio of secodary to primary line voltage is $\sqrt{3}$ times the transformation ratio.
- There is 30° shift between the primary and secondary line voltages.

Above transformer connection configurations are shown in the following figure.


A
B
C
N
a
b
c
n
Y - Y
Δ - Δ
Y - Δ
Δ - Y
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