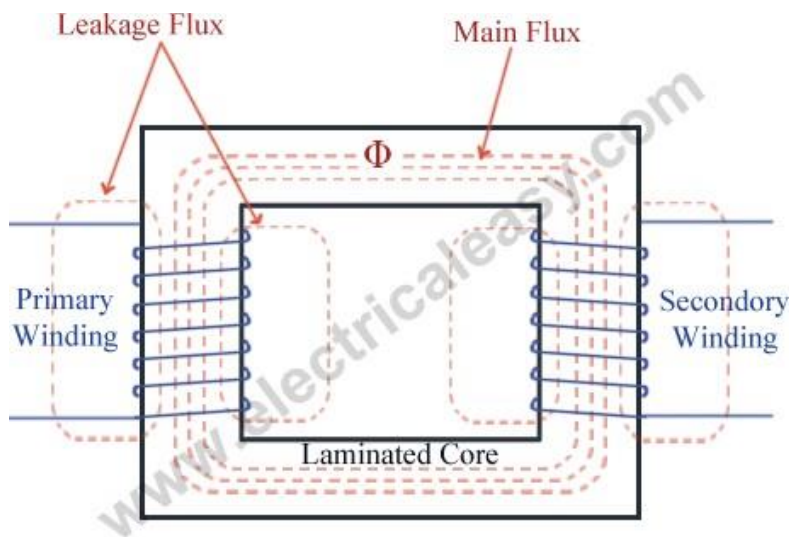
Transformer

electrical transformer is a static electrical machine which transforms electrical power from one circuit to another circuit, without changing the frequency. Transformer can increase or decrease the voltage with corresponding decrease or increase in current.

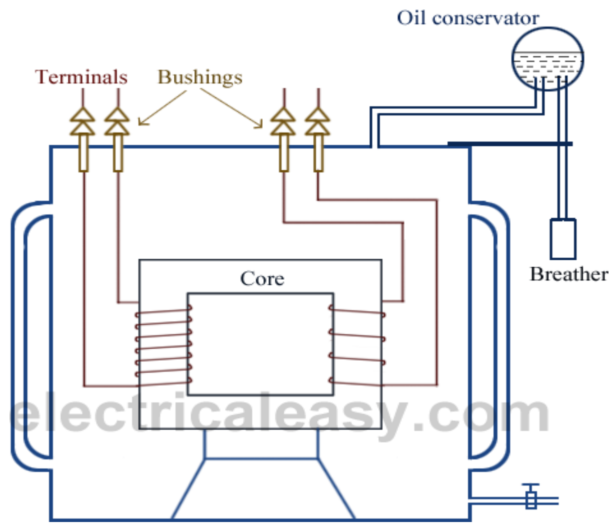
Working principle of transformer



The **basic principle behind working of a transformer** is the phenomenon of mutual induction between two windings linked by common magnetic flux. The figure at right shows the simplest form of a transformer. Basically a transformer consists of two inductive coils; primary winding and secondary winding. The coils are electrically separated but magnetically linked to each other. When, primary winding is connected to a source of alternating voltage, alternating magnetic flux is produced around the winding. The core provides magnetic path for the flux, to get linked with the secondary winding. Most of the flux gets linked with the secondary winding which is called as 'useful flux' or main 'flux', and the flux which does not get linked with secondary winding is called as 'leakage flux'. As the flux produced is alternating (the direction of it is continuously changing), EMF gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This emf is called 'mutually induced emf', and the frequency of mutually induced emf is same as that of supplied emf. If the secondary winding is closed circuit, then mutually induced current flows through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit (secondary).

Basic construction of transformer

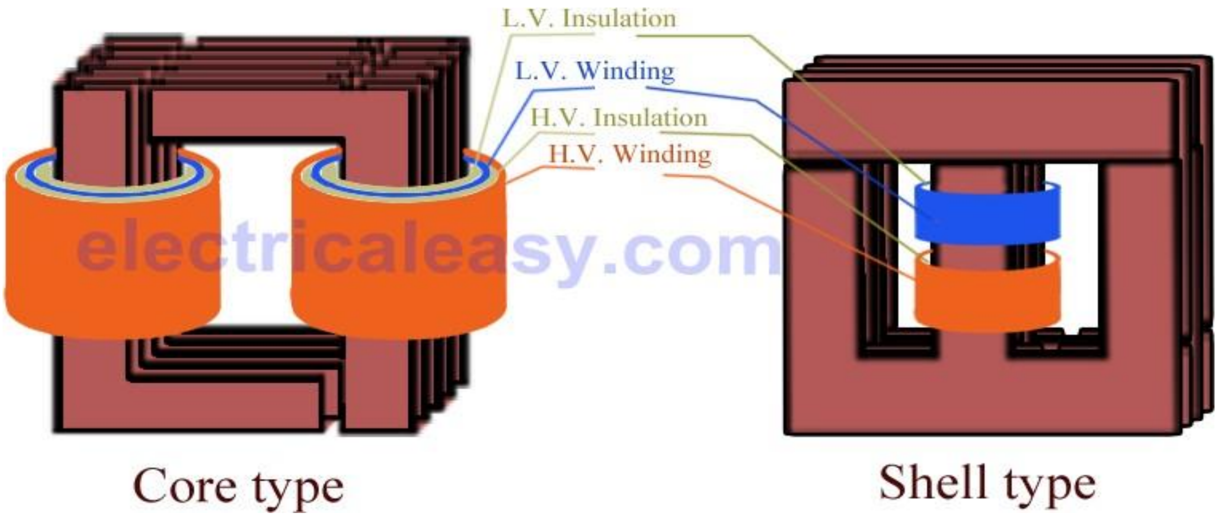
Basically a transformer consists of two inductive windings and a laminated steel core. The coils are insulated from each other as well as from the steel core. A transformer may also consist of a container for winding and core assembly (called as tank), suitable bushings to take our the terminals, oil conservator to provide oil in the transformer tank for cooling purposes etc. The figure at left illustrates the basic construction of a transformer. In all types of transformers, core is constructed by assembling (stacking) laminated sheets of steel, with minimum air-gap between them (to achieve continuous magnetic path). The steel used is having high silicon content and sometimes heat treated, to provide high permeability and low hysteresis loss. Laminated sheets of steel are used to reduce eddy current loss. The sheets are cut in the shape as E,I and L. To avoid high reluctance at joints, laminations are stacked by alternating the sides of joint. That is, if joints of first sheet assembly are at front face, the joints of following assemble are kept at back face.



Types of transformers
Transformers can be classified on different basis, like types of construction, types of cooling etc.

(A) On the basis of construction, transformers can be classified into two types as;

(i) Core type transformer and (ii) Shell type transformer, which are described below.



(i) Core type transformer
In core type transformer, windings are cylindrical former wound, mounted on the core limbs as shown in the figure above. The cylindrical coils have different layers and each layer is insulated from each other. Materials like paper, cloth or mica can be used for insulation. Low voltage windings are placed nearer to the core, as they are easier to insulate.

(ii) Shell type transformer
The coils are former wound and mounted in layers stacked with insulation between them. A shell type transformer may have simple rectangular form (as shown in above fig), or it may have a distributed form.

(B) On the basis of their purpose

1. Step up transformer: Voltage increases (with subsequent decrease in current) at secondary.
2. Step down transformer: Voltage decreases (with subsequent increase in current) at secondary.

(C) On the basis of type of supply

1. Single phase transformer
2. Three phase transformer
3.

(D) On the basis of their use

1. Power transformer: Used in transmission network, high rating
2. Distribution transformer: Used in distribution network, comparatively lower rating than that of power transformers.
3. Instrument transformer: Used in relay and protection purpose in different instruments in industries
   - Current transformer (CT)
   - Potential transformer (PT)
   -

Why Transformers are rated in kVA?
Copper Cu loss of a transformer depends on current, and iron loss depends on voltage. Thus, total transformer loss depends on volt-ampere (VA). It does not depend on the phase angle between voltage and current, i.e. transformer loss is independent of load power factor. This is the reason that transformers are rated in kVA.

Losses in transformer

In any electrical machine, 'loss' can be defined as the difference between input power and output power. An electrical transformer is an 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.
Losses in transformer are explained below -

(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:
  $W_h = \eta B_{max}^{1.6} f V$ (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 = I12R1

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.

All day efficiency of transformer

As we have seen above, ordinary or commercial efficiency of a transformer can be given as

$$\text{ordinary efficiency} = \frac{\text{output (in watts)}}{\text{input (in watts)}}$$

But in some types of transformers, their performance can not be judged by this efficiency. For example, distribution transformers have their primaries energized all the time. But, their secondaries supply little load all no-load most of the time during day (as residential use of electricity is observed mostly during evening till midnight).
That is, when secondaries of transformer are not supplying any load (or supplying only little load), then only core losses of transformer are considerable and copper losses are absent (or very little). Copper losses are considerable only when transformers are loaded. Thus, for such transformers copper losses are relatively less important. The performance of such transformers is compared on the basis of energy consumed in one day.

$$\text{All day efficiency} = \frac{\text{output (in kWh)}}{\text{input (in kWh)}} \quad \text{(for 24 hours)}$$

All day efficiency of a transformer is always less than ordinary efficiency of it

Voltage Transformation Ratio

Voltage Transformation Ratio (K)
As derived above,

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = K$$

Where, K = constant
This constant K is known as **voltage transformation ratio**.

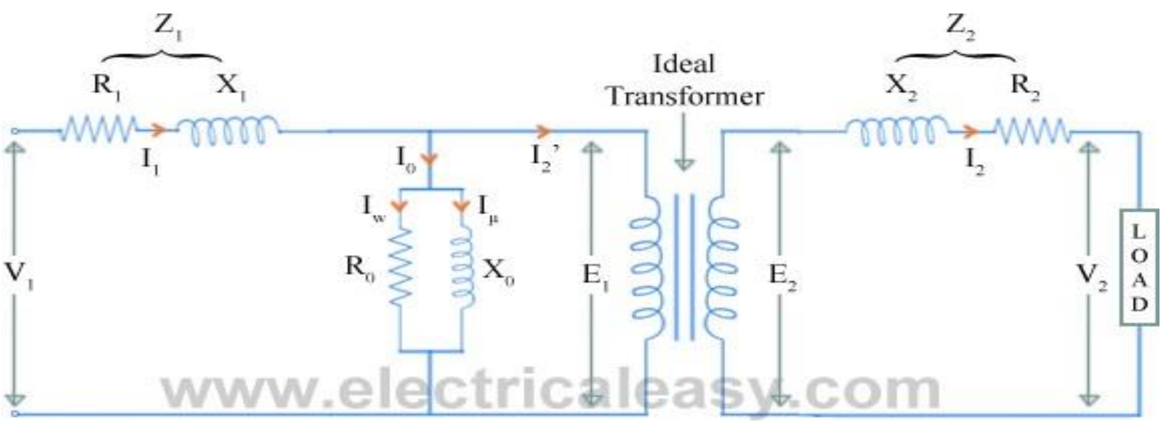
- If $N_2 > N_1$, i.e. $K > 1$, then the transformer is called step-up transformer.
- If $N_2 < N_1$, i.e. $K < 1$, then the transformer is called step-down transformer.

Equivalent circuit of Transformer

n 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.

Equivalent circuit of 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.



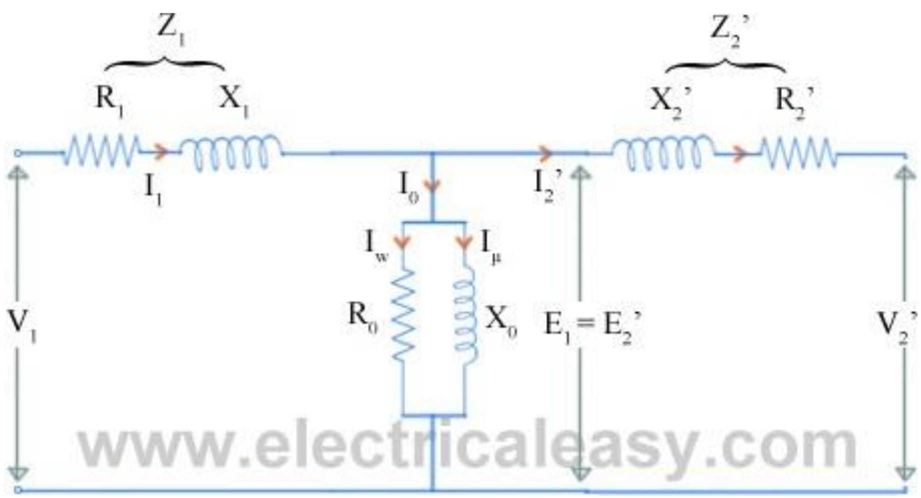
The no load current I_0 is divided into, pure inductance X_0 (taking magnetizing components I_μ) and non induction resistance R_0 (taking working component I_w) which are connected into parallel across the primary.

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 $X_0 = E_1 / I_\mu$.

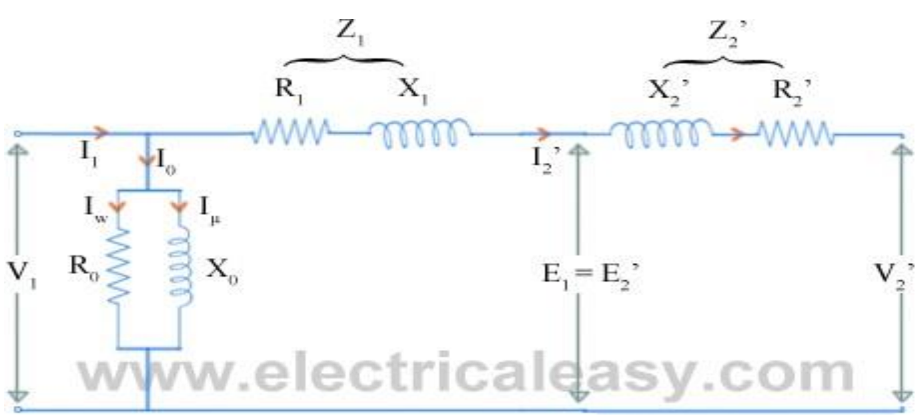
But, using this equivalent circuit does not simplifies the calculations. To make calculations simpler, it is preferable to transfer current, voltage and impedance either to primary side or to the secondary side. In that case, we would have to work with only one winding which is more convenient.

From the voltage transformation ratio, it is clear that,
$E_1 / E_2 = N_1 / N_2 = K$

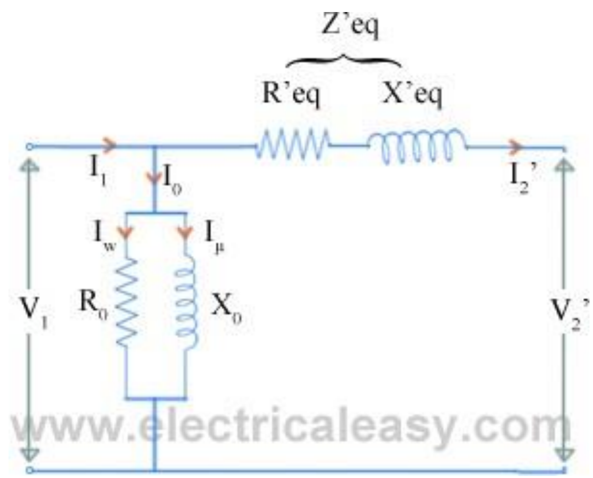
Now, lets refer the parameters of secondary side to primary.
Z_2 can be referred to primary as Z_2'
where, $Z_2' = (N_1/N_2)^2 Z_2 = K^2 Z_2$ .... where $K= N_1/N_2$.
that is, $R_2'+jX_2' = K^2(R_2+jX_2)$
equating real and imaginary parts,
$R_2' = K^2R_2$ and $X_2' = K^2X_2$.
And $V_2' = KV_2$
The following figure shows the **equivalent circuit of transformer with secondary parameters referred to the primary**.



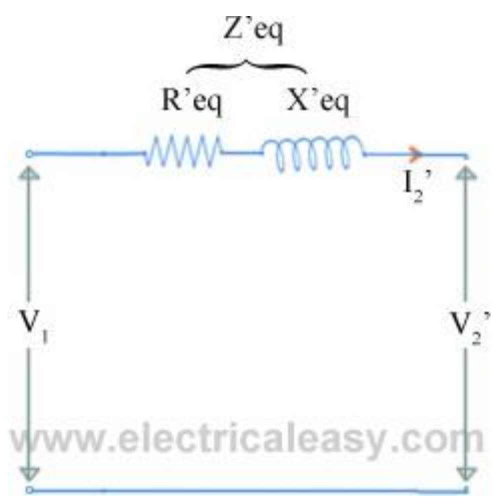
Now, as the values of winding resistance and leakage reactance are so small that, V_1 and E_1 can be assumed to be equal. Therefore, the exciting current drawn by the parallel combination of R_0 and X_0 would not affect significantly, if we move it to the input terminals as shown in the figure below.



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



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AUTO-TRANSFORMER

What is an Auto Transformer?

Definition: A transformer that has a single winding is known as an Auto Transformer. The term 'auto' is taken from a Greek word and the meaning of this is single coil works alone. The working principle of the autotransformer is similar to a 2-winding transformer but the only difference is, the portions of the single winding in this transformer will work at both sides of the windings like primary & secondary. In a normal transformer, it includes two separate windings that are not allied with each other. The autotransformer diagram is shown below.

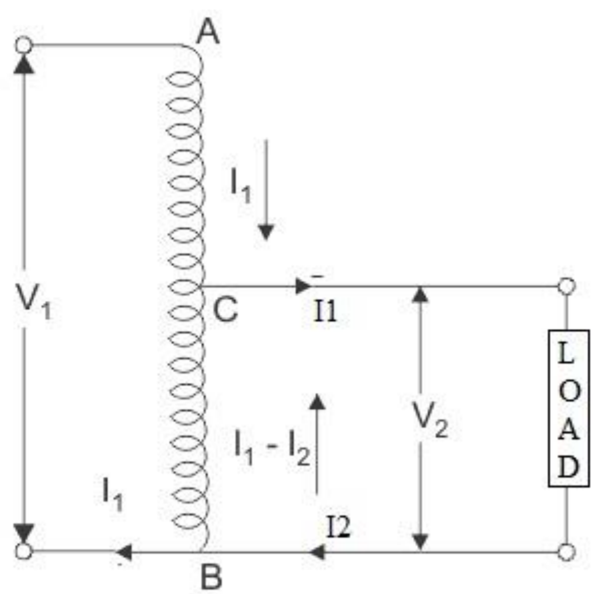
auto-transformer

Autotransformers are lighter, smaller, cheaper comparing with other transformers, but they will not provide electrical isolation between two windings.

Auto Transformer Construction

We know that the transformer includes two windings namely primary and secondary which are connected magnetically but insulated electrically. But in autotransformer, a single winding is used like both the windings

There are two types of autotransformer based on construction. In one type of transformer, there is continuous winding with the taps brought out at convenient points determined by the desired secondary voltage. However, in another type of autotransformer, there are two or more distinct coils that are electrically connected to form a continuous winding. The construction of Autotransformer is shown in the figure below.



auto-transformer-construction

The primary winding AB from which a tapping at 'C' is taken, such that CB acts as a secondary winding. The supply voltage is applied across AB, and the load is connected across CB. Here, the tapping may be fixed or variable. When an AC voltage V1 is applied across AB, an alternating flux is set up in the core, as a result, an emf E1 is induced in the winding AB. A part of this induced emf is taken in the secondary circuit.

Advantages of Auto Transformer

The advantages are

- It uses single winding, so these are smaller & cost-effective.
- These transformers are more efficient
- It needs lesser excitation currents to compare with the conventional type transformers.
- In these transformers, the voltage can be changed easily and smoothly
- Enhanced regulation
- Fewer losses
- It needs less copper
- Efficiency is high due to low losses in ohmic and core. These losses will be occurred because of the reduction in transformer material.

Disadvantages of Auto Transformer

The disadvantages are

- In this transformer, the secondary winding cannot be insulated from the primary.
- It is applicable in restricted areas where a small difference in the o/p voltage from i/p voltage is necessary.
- This transformer is not used for interconnecting systems like high voltage & low voltage.
- The leakage flux is small among the two windings so the impedance will below.
- If the winding in the transformer breaks, the transformer will not work then the full primary voltage comes into view across the o/p.
- It can be dangerous to the load while we are utilizing an autotransformer like a step-down transformer. So this transformer is used only to make small changes within the o/p voltage.

Applications of Auto Transformer

The applications are

- It increases the voltage drop for the distribution cable
- It is used as a voltage regulator
- It is used in audio, distribution, power transmission and railways
- Autotransformer with several tappings is used to start the motors like induction as well as synchronous.
- It is used in laboratories to obtain a varying voltage continuously.
- It is used like regulating transformers in voltage stabilizers.
- It increases the voltage in AC feeders
- It is applicable in electronics testing centers wherever frequently changing voltages are required.
- It is used where high voltages are necessary like boosters or amplifiers
- It is used in audio devices like speakers to match the impedance as well as to adjust the device for nonstop voltage supply.
- It is used in power stations where the voltage needs to step down and step up to equal the voltage at the receiving end which is necessary for the device.