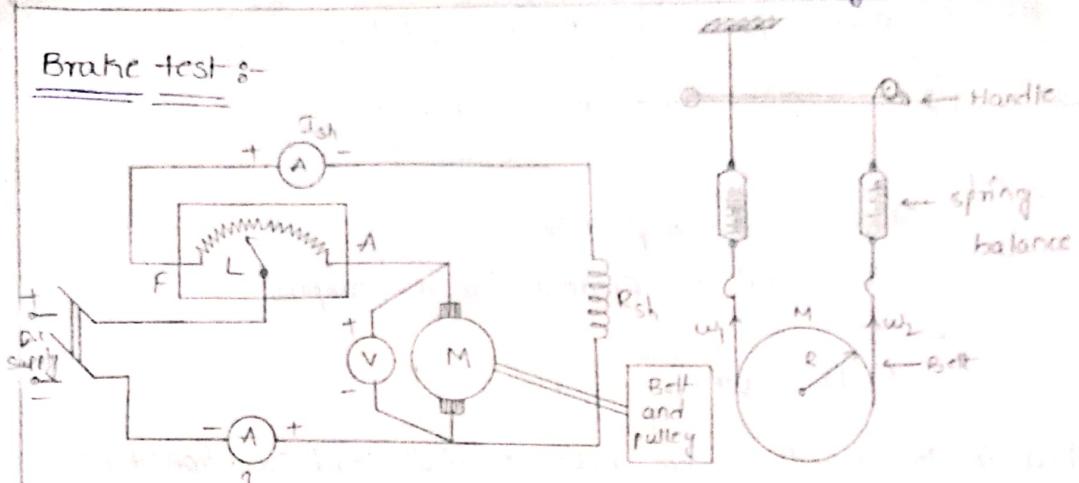


Methods of Testing [D.C. Machine]Brake test :-

Another method of testing the d.c motor is brake test method. This is a direct method of testing the motor. In this method, the motor is put on the direct load by means of a belt and pulley arrangement. By adjusting the tension of belt, the load is adjusted to give the various values of currents. The load is finally adjusted to get full load current. The power developed gets wasted against the friction between belt and shaft. Due to the braking action of belt the test is called brake test.

The fig shows the experimental setup for performing brake test on a d.c shunt motor while the fig shows the belt and pulley arrangement mounted on the shaft of the motor.

The tension in the belt can be adjusted using the handle. The tension in kg can be obtained from the spring balance readings.

Let

R = Radius of pulley in metre.

N = Speed in r.p.m

w_1 = Spring balance reading on tight side in kg.

w_2 = Spring balance reading on slack side in kg.

So net pull on the belt due to friction at the pulley is the difference between the two spring balance readings.

$$\text{Net pull} = w_1 - w_2 \text{ kg} = 9.81(w_1 - w_2) \text{ N}$$

As radius R and speed N are known, the shaft torque developed can be obtained as,

$$T_{sh} = \text{net pull} \times R = 9.81(w_1 - w_2)R \text{ N-m}$$

Unit III, page:

Hence the output power can be obtained as,

$$P_{out} = \eta_{sh} \times w = 9.81 (w_1 - w_2) R \times \frac{2\pi N}{60} W$$

Now let,

V = Voltage applied in volts

I = Total line current drawn in ampere

then

$$P_{in} = VI \text{ W}$$

thus if the readings are taken on full load condition then the efficiency can be obtained as,

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100$$

Adjusting the load step by step still full load, number of readings can be obtained. The speed can be measured by tachometer. Thus all the motor characteristics can be plotted.

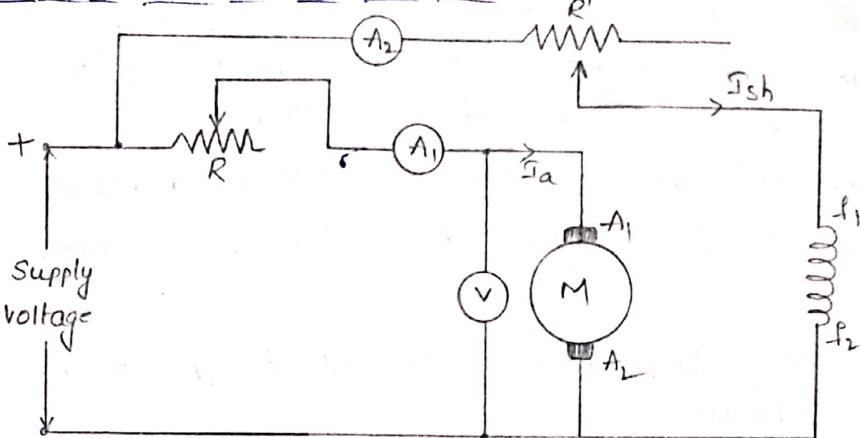
Advantages:-

1. Actual efficiency of the motor under working conditions can be found out.
2. The method is simple and easy to perform.
3. Can be performed on any type of d.c motor.

Disadvantages:-

1. Due to friction, heat is generated and hence there is large dissipation of energy.
2. Some type of cooling arrangement is necessary.
3. Convenient only for small machines due to limitations regarding heat dissipation arrangements.
4. The power developed gets wasted hence method is expensive.
5. The efficiency observed is on lower side.

* Swinburne's Test or No-load Test



Swinburne's Test

This is indirect method of testing d.c. motors in which flux remains practically constant i.e. specially in case of shunt and compound motors. without actually loading the motor the losses and hence efficiency at different loads can be found out.

The motor is run on no load at its rated voltage. At the starting some resistance is connected in series with the armature which is cut when motor attains sufficient speed. Now the speed of the motor is adjusted to the rated speed with the help of shunt field rheostat as shown in fig.

The no load armature current I_a is measured by ammeter A_1 whereas the shunt current is measured by Ammeter A_2 .

If V is the supply voltage then motor input at no load will be,

$$\text{power input at no-load} = V(I_a + I_{sh}) \text{ watts.}$$

There will be cu loss in the field winding which will be given as,

$$\text{field copper loss} = V \times I_{sh}$$

let R_a be the resistance of armature

$$\text{Armature copper loss} = I_a^2 \cdot R_a$$

thus the stray losses which includes iron, friction and windage losses can be obtained as,

$$\begin{aligned} \text{stray losses} &= \text{Input at no-load} - \text{field copper losses.} \\ &\quad - \text{No load armature copper losses} \end{aligned}$$

$$\text{stray losses} = V(I_a + I_{sh}) - (V \times I_{sh}) - (I_a^2 \cdot R_a) = W_b$$

In the field and armature windings there will be copper loss due to flow of current which will increase the temperature of the field and armature winding when the motor is loaded. This increase in temperature will affect their resistances.

thus the new value of field resistance R'_{sh} and that of armature R'_a can be found by considering that rise in temperature as about $40^\circ C$.

if α_1 = Resistance temperature co-efficient of copper at room temperature

$$R'_a = R_a [1 + \alpha_1 \times 40]$$

At room temperature the shunt field winding resistance will be,

$$R_{sh} = \frac{V}{I_{sh}}$$

$$\therefore R'_sh = R_{sh} (1 + \alpha_1 \times 40)$$

$$\text{Now shunt winding current, } I'_{sh} = \frac{V}{R'_sh}$$

$$\text{New field copper loss} = I'^2_{sh} \times R_{sh}$$

Now if we want to find the efficiency of the motor at say $\frac{1}{4}$ th full load. It can be calculated as follows,

let

$I_{F.L}$ = full load current of motor.

w_F = field copper loss

w = stray losses.

$$\text{Load current at } \frac{1}{4} \text{ th full load} = \frac{I_{F.L}}{4}$$

$$\therefore \text{Motor input at } \frac{1}{4} \text{ th full load} = V \times \frac{I_{F.L}}{4} \text{ watts.}$$

$$\text{Armature current at } \frac{1}{4} \text{ th full load, } I'_a = \frac{I_{F.L}}{4} - I'_{sh}$$

$$\text{Armature copper loss at } \frac{1}{4} \text{ th full load} = I'^2_a R_a = \left[\frac{I_{F.L}}{4} - I'_{sh} \right]^2 R_a$$

$$\therefore \text{Motor output at } \frac{1}{4} \text{ th full load} = \text{Motor input at } \frac{1}{4} \text{ th load} - \text{Losses}$$

$$= \left(V \times \frac{I_{F.L}}{4} \right) - \left(\frac{I_{F.L}}{4} - I'_{sh} \right)^2 R_a - w_F - w$$

$$= \left(V \times \frac{I_{F.L}}{4} \right) - I'^2_a R_a - w_F - w$$

$$\text{Efficiency at } \frac{1}{4} \text{ th full load, } \eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{losses}}{\text{Input}}$$

$$\therefore \frac{\left(V \times \frac{I_{F.L.}}{4} \right) - I_b^2 R_a - W_F - W}{V \times \frac{I_{F.L.}}{4}}$$

this is the efficiency of motor when the load on motor is $\frac{1}{4}$ of full load which can be found without loading the motor. The efficiencies at other loads can be calculated similarly.

Advantages:-

1. Since constant losses are known, the efficiency can be estimated at any load.
2. The motor is not required to be loaded i.e. only test to be carried out is the no load test.

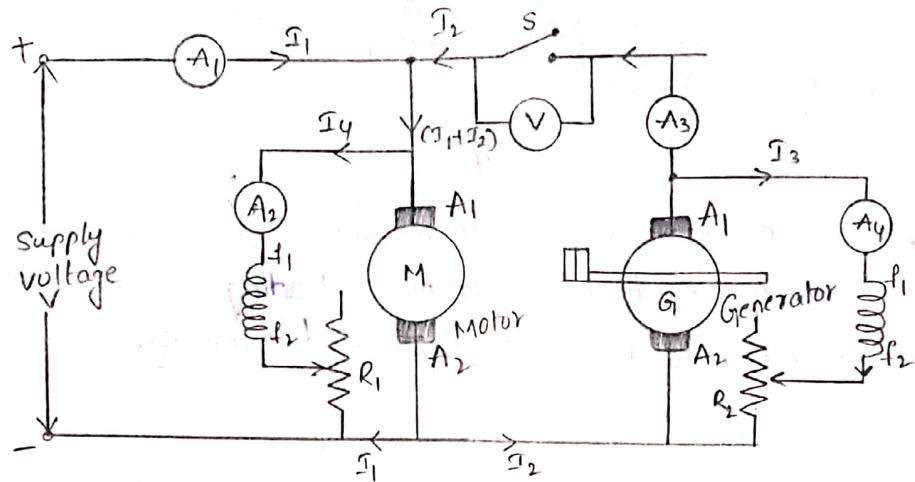
Disadvantages:-

1. The only test which is carried out is the no load test. Hence it is difficult to know whether there will be satisfactory commutation at full load.
2. As it is a no load test it cannot be performed on a series motor.

* Hopkinson's Test :-

This test is called regenerative test or back to back test which can be carried out on two identical d.c. machines mechanically coupled to each other and simultaneously tested. Thus the full load test can be carried out on two identical shunt machines without wasting their outputs. One of the machines is made to act as a motor while the other as a generator. The mechanical output obtained from the motor drives the generator whose electrical output supplies the greater part of input to the motor. The motor is connected to the supply mains only to compensate for losses since in absence of losses, the motor-generator set would have run without any external power supply. But due to losses, the generator output is not sufficient to drive the motor. Thus motor takes current from the supply to account for losses.

The fig shows the connection diagram for Hopkinson's test. The two shunt machines are connected in parallel. One of the machines is then started as a motor. Here the startor connections are not shown for simplicity.



The switch S is kept open. The other machine which is coupled to first will act as load on first which is acting as motor. Thus second machine will act as a generator. The speed of motor is adjusted to normal value with the help of the field rheostat. The voltmeter reading is observed. The voltage of the generator is adjusted by its field rheostat so that voltmeter reading is zero. This will indicate that the generator voltage is having same magnitude and polarity of that of supply voltage. This will prevent heavy circulating current flowing in the local loop of armatures on closing the switch. Now switch S is closed. The two machines can be put into any load by adjusting their field rheostats. The generator current I_2 can be adjusted to any value by increasing the excitation of generator or by reducing the excitation of motor. The various readings by different ammeters are noted for further calculations.

The input to the motor is nothing but the output of the generator and small power taken from supply. The mechanical output given by motor after supplying losses will in turn drive the generator.

Let

$$V = \text{Supply Voltage}$$

I_1 = Current taken from the Supply.

I_2 = current supplied by generator

I_3 = exciting current of generator

I_4 = exciting current of motor

R_a = resistance of armature of each machine.

η = efficiency of both generator and motor.

$$\text{Input to the motor} = V(I_4 + I_2)$$

$$\text{Output of motor} = \eta \times \text{Input} = \eta V(I_1 + I_2)$$

The output of motor will be given as input to the generator.

$$\text{Input to generator} = \eta V(I_1 + I_2)$$

$$\text{Output of generator} = \eta \times \text{Input} = \eta \cdot \eta V(I_1 + I_2) \quad \dots \textcircled{1}$$

The output of generator can also be given as,

$$\text{Output of generator} = V \cdot I_2 \quad \dots \textcircled{2}$$

From equations $\textcircled{1}$ and $\textcircled{2}$

$$\eta^2 V(I_1 + I_2) = V I_2$$

$$\eta^2 = \frac{I_2}{I_1 + I_2}$$

$$\eta = \sqrt{\frac{I_2}{I_1 + I_2}}$$

But the assumption of equal efficiencies of two machines is true in case of only large output machines where difference in armature currents of two machines is not large. Also the difference in excitation current required to circulate full load current in the armature will not affect the iron losses. But in case of small machines the difference between armature and field currents is large. So efficiencies cannot be assumed to be same. Here the stray losses are assumed to be equal whereas armature and field copper losses are separately determined for estimating the efficiencies separately.

$$\text{Armature copper loss in generator} = (I_2 + I_3)^2 R_a$$

$$\text{Armature copper loss in motor} = (I_1 + I_2 - I_4)^2 R_a$$

$$\text{Copper loss in field winding of generator} = V I_3$$

$$\text{Copper loss in field winding of motor} = V I_4$$

But total losses in generator and motor are equal to the power supplied by the mains.

$$\text{Power drawn from Supply} = V I_2$$

The stray losses of both machines can be calculated as,

$$\begin{aligned} \text{Total stray loss for both the machines} &= V I_2 - [(I_2 + I_3)^2 R_a + (I_1 + I_2 - I_4)^2 R_a \\ &\quad + V I_3 + V I_4] \\ &= W_s \text{ (say)} \end{aligned}$$

Assuming that stray losses are equally divided between the two machines.

$$\text{Stray losses for each machine} = W_s / 2$$

The machine which is acting as a motor,

$$\text{Total losses} = (I_1 + I_2 - I_4)^2 R_a + V I_4 + \frac{w_s}{2}$$

$$\text{Input to motor} = V(I_1 + I_2)$$

Efficiency of motor,

$$\eta_m = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{losses}}{\text{Input}}$$

$$\eta_m = \frac{V(I_1 + I_2) - [(I_1 + I_2 - I_4)^2 R_a + V I_4 + \frac{w_s}{2}]}{V(I_1 + I_2)}$$

The machine which is acting as a generator.

$$\text{Total losses} = (I_2 + I_3)^2 R_a + V I_3 + \frac{w_s}{2}$$

$$\text{Output of generator} = V I_2$$

Efficiency of generator

$$\eta_g = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{losses}}$$

$$\eta_g = \frac{V I_2}{V I_2 + [(I_2 + I_3)^2 R_a + V I_3 + \frac{w_s}{2}]}$$

Advantages:-

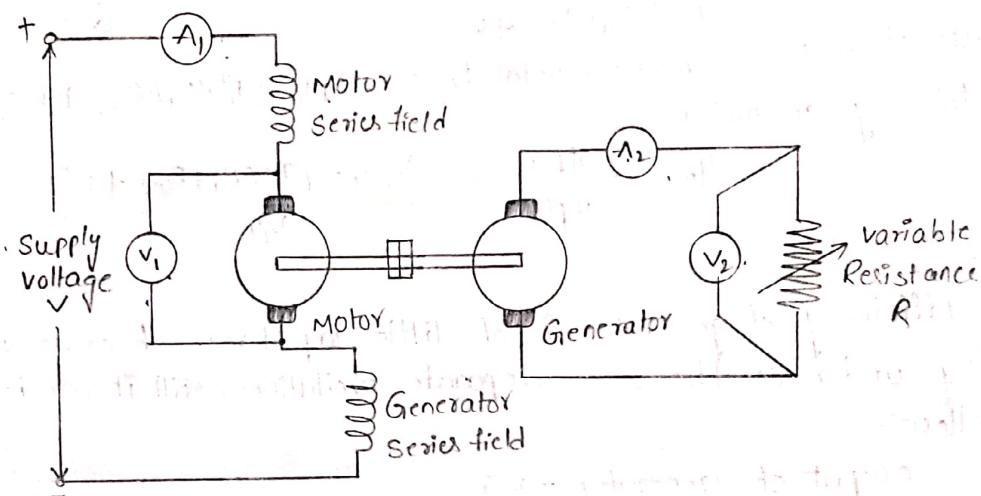
1. The power required for conducting the test is small compared to full load powers of the two machines.
2. Since the machines are operated at full load conditions, change in iron loss due to distortion in flux at full load will be included in the calculations.
3. As the machines are tested under full load conditions, the temperature rise and quality of commutation of the two machines can be observed.

Disadvantages:-

1. There is difficulty in availability of two identical machines.
2. The iron losses in the two machines cannot be separated. The iron losses are different in both the machines because of different excitations.

* field test:

This is one of the methods of testing the d.c. series motors. Unlike shunt motors, the series motor cannot be tested by the methods which are available for shunt motors as it is impossible to run the motor no load. It may run at dangerously high speed on no load. In case of small series motors, brake test may be employed. The series motors are usually tested in pairs. The field test is applied to two similar series motors which are coupled mechanically. The connection diagram for the test is shown in fig.



As shown in the fig. one machine is made to run as a motor while the other as a generator which is separately excited. The fields of the two machines are connected in series so that both the machines are equally excited. This will make iron losses same for the two machines. The two machines are running at the same speed. The generator output is given to the variable resistance R .

The resistance R is changed until the current taken by motor reaches full load value. This will be indicated by ammeter A_1 . The other readings of different meters are then recorded.

Let

$$V = \text{Supply Voltage.}$$

$$I_1 = \text{current taken by motor.}$$

$$I_2 = \text{load current.}$$

$$V_2 = \text{terminal p.d. of generator.}$$

$$R_a, R_{sc} = \text{armature and series field resistance of each machine.}$$

$$\text{power taken from Supply} = VI_1$$

$$\text{output obtained from generator} = V_2 I_2$$

$$\therefore \text{Total losses in both the machines, } W_T = VI_1 - V_2 I_2$$

Armature copper and field losses, $W_{Cu} = (R_a + 2R_{Se}) I_1^2 + I_2^2 R_a$

Total stray losses = $W_T - W_{Cu}$

Stray losses per machine, $W_s = \frac{W_T - W_{Cu}}{2}$

Since the two machines are equally excited and are running at same speed the stray losses are equally divided.

For Motors:

Input to motor = $V_1 I_1$

Total losses = Armature cu loss + Field cu loss + Stray loss.
= $I_1^2 C (R_a + R_{Se}) + W_s$

Output of motor = Input - Total losses = $V_1 I_1 - [I_1^2 C (R_a + R_{Se}) + W_s]$

Efficiency of motor,

$$\eta_m = \frac{\text{Output}}{\text{Input}} = \frac{V_1 I_1 - [I_1^2 C (R_a + R_{Se}) + W_s]}{V_1 I_1}$$

For Generators:

Efficiency of generator is of little importance because it is running under conditions of separate excitation. Still it can be found as follows.

Output of generator = $V_2 I_2$

Field cu loss = $I_1^2 R_{Se}$

Armature cu loss = $I_2^2 R_a$

Total losses = Armature cu loss + Field cu loss + Stray loss

= $I_2^2 R_a + I_1^2 R_{Se} + W_s$

Input to generator = Output + Total losses = $V_2 I_2 + [I_2^2 R_a + I_1^2 R_{Se} + W_s]$

Efficiency of generator,

$$\eta_g = \frac{\text{Output}}{\text{Input}}$$

$$\eta_g = \frac{V_2 I_2}{V_2 I_2 + [I_2^2 R_a + I_1^2 R_{Se} + W_s]}$$

The important point to be noted is that this is not regenerative method through the two machines are mechanically coupled because the generator output is not fed back to the motor as in case of Hopkinson's test but it is wasted in load resistance.

SINGLE PHASE TRANSFORMERS

Classification of Transformers:

There are many ways in which transformers can be classified.

The transformers can be classified as follows.

1. Based on number of phases:

- (a) Single phase transformer.
- (b) Three phase transformer.

2. Based on Construction or design:

- (a) Core type transformer.
- (b) Shell type transformer.
- (c) Belly type transformer.

3. Based on function:

- (a) Power transformer.
 - (i) Step-up transformer.
 - (ii) Step-down transformer.
- (b) Distribution transformer.
 - (i) pole-mounted transformer.
 - (ii) plinth-mounted transformer.

4) Instrument transformers:

- (i) Current transformer (C.T).
- (ii) Potential transformer (P.T.).

5) Based on Cooling:

- (a) oil-filled self-Cooled transformer.
- (b) oil-filled water-Cooled transformer.
- (c) Air-blast type transformer.

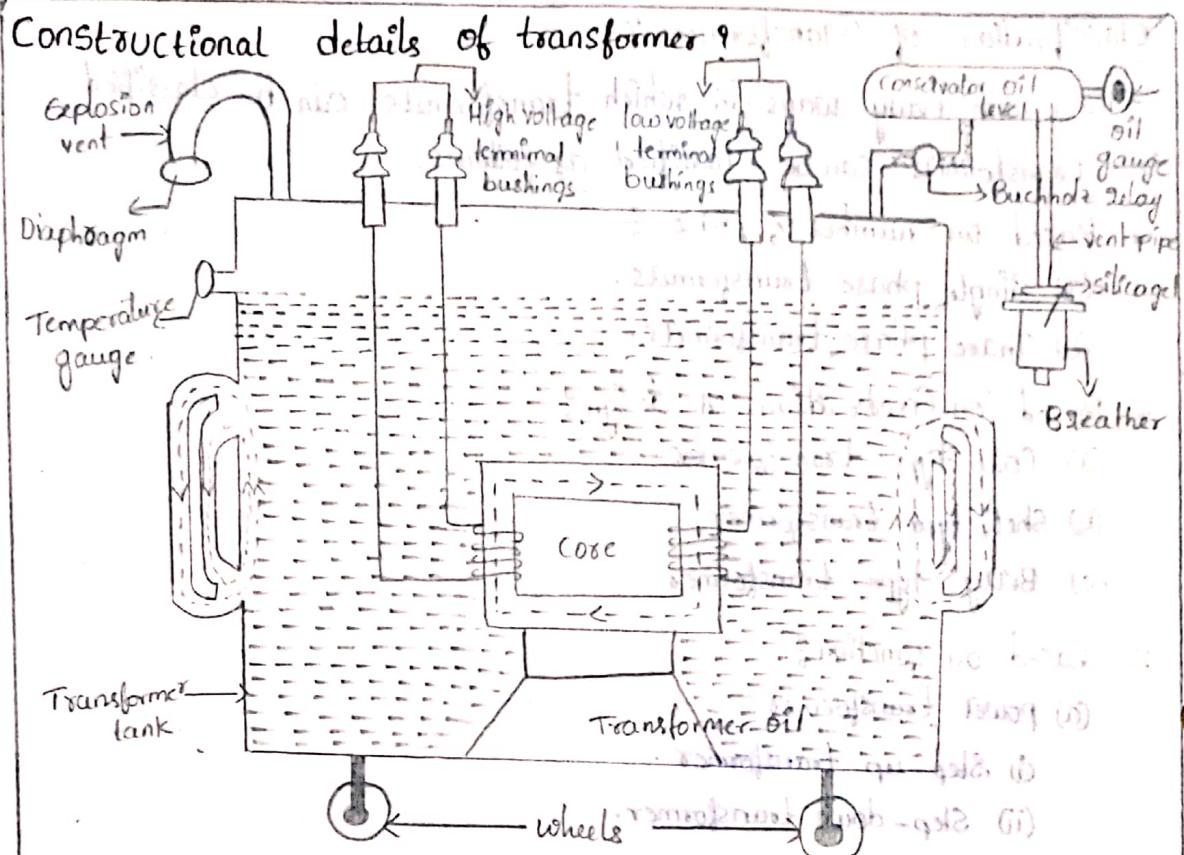
6) Based on type Core material:

- (a) Iron-Core transformer.

- (b) Air-Core transformer.

7) Special purpose transformer:

- (a) Auto-transformer.
- (b) welding transformer.
- (c) audio frequency transformer.
- (d) pulse transformer.
- (e) trigger transformer.



The transformer is simple in construction, since there are no rotating parts. The transformer has following parts:

- 1) Core
- 2) Windings
- 3) Tank
- 4) Transformer oil
- 5) Conservator
- 6) Breather.
- 7) Terminals and bushings.
- 8) Exhaust pipe, oil gauge.
- 9) Cooling System.

Core :

The purpose of core is to provide a path of low reluctance for the magnetic flux. It is made with silicon steel laminations. The purpose of laminating the core is to reduce eddy current loss. These laminations are made with silicon steel to reduce hysteresis loss, because silicon steel has low hysteresis Co-efficient. The thickness of lamination varies from 0.35 mm for 50 Hz frequency to 0.5 mm for 25 Hz frequency.

The core is divided into two parts namely Yoke and limb (or) leg. The vertical portion of the core on which winding is wound known as limb.

The top and bottom horizontal portions are called yoke of the core. Yoke and limb together provides a closed path for magnetic flux. The laminations are cut in the form of long strips of different shapes like L, E, I, U, C, etc.

Depending upon the type of construction of cores, the transformers are classified as,

- (i) Core type
- (ii) Shell type
- (iii) Belly type
- (iv) Core type transformer

In Core type transformer Core is surrounded by the winding. It has two limbs. In this type the magnetic flux has only one magnetic path. There may be some leakage flux that may links with one winding and not with the other. It is necessary to minimize the leakage of flux to improve the performance of transformer. In this type of transformer L.V is placed over the core and H.V winding is wound over L.V winding in order to minimize the amount of insulation required. Core type Construction is used for high voltage, high power transformer.

(ii) Shell-type transformer:

In Shell-type transformer the winding is surrounded by the core. It has three limbs, two side limbs and one central limb. In this type, the magnetic flux has two magnetic paths. The total flux passes through the central limb and half the flux is passing through the side limbs. The L.V and H.V windings are placed on the central limb, hence the winding is surrounding by the core. Shell type Construction is commonly used for low voltage, low power transformers. This type of construction is commonly used for small transformers.

(iii) Belly-type transformer:

In this case the distributed paths of the magnetic field are used. One limb of all the cores passes through the centre of the windings. The width of the core inside the coils is less than the width of the limb outside the winding. These are used to obtain the variable voltage.

Comparison between core-type and shell-type transformer:

Core-type T/F	Shell-type T/F.
i) In this type core is surrounded by the winding.	i) In this type winding is surrounded by the core.

- | | |
|--|--|
| 2) Cylindrical type winding is used | 3) The core has two limbs |
| 4) The magnetic flux has only one magnetic path. | 5) used for high voltage. |
| 6) The shape of core laminations are rectangular 'L' type. | 7) Cross-section area of core is less hence more turns required. |
| 8) Easy to insulate and repair. | 9) L.V and H.V windings are wound on both limbs. |
| | 2) Sandwiched type winding is used |
| | 3) The core has three limbs |
| | 4) Magnetic flux has two magnetic paths |
| | 5) used for low voltage. |
| | 6) The shape of core laminations are 'E' type. |
| | 7) Cross-section of core is more so less turns are required. |
| | 8) Difficult to insulate and repair. |
| | 9) The L.V and H.V windings are wound on central limb. |

② Windings :-

The windings are made with copper conductors and are placed on the cores. The winding which is connected to supply is known as primary and the winding which is connected to load is known as secondary winding. The winding which is connected to low voltage (L.V) is known as L.V winding and the winding which is connected to high voltage (H.V) is known as H.V winding.

According to the construction and arrangement, the windings are mainly classified into:-

- (i) Cylindrical type winding and
- (ii) sandwich type winding.

Cylindrical type winding :-

This winding is layered type and is made up of turns helically wound round with turns close to each other. This type of winding is most commonly used in core-type transformers.

Sandwich winding :-

In this type of winding the L.V and H.V windings are placed one over the other alternatively. This arrangement reduces the leakage reactance. This type of winding is mostly used in shell-type transformers.

③ Tank :-

Transformers are generally housed in a tightly-fitted sheet metal tanks filled with special insulating oil. The core and windings are completely

immersed in the oil inside the tank. In case of small transformers, the tanks are made with iron sheets whereas in case of large transformers, the tanks are made with cast-aluminium plates. Those sheets are water proof gaskets. When the transformer is working, heat is produced in the tank, hence needs cooling.

For cooling purpose, cooling tubes are welded around the tank.

An eye-bolt is welded to the tank at the top for lifting purpose and wheels are provided at the bottom for moving the T/F into position. A tank must be able to withstand all the stresses developed inside and has provision for connecting to the load and supply.

④ Transformer Oil :

The insulating oil which is used in the tank of a T/F is called T/F oil. It has three functions.

- 1) It acts as insulating medium between windings and tank.
- 2) It provides better cooling by circulating through the cooling tubes.
- 3) It carries away the heat generated in the core and windings and quench the arc if any.

The T/F oil is obtained by fractional distillation of crude petroleum. The mineral oil is most commonly used as T/F oil.

⑤ Conservator tank (Oil) Expansion tank :

It is a small tank mounted above the transformer and connected to the main tank by pipe. The oil level changes with change in temperature of oil which in turn depends upon the load on the T/F. The oil expands with the increase in load and contracts with decrease in load. Thus conservator is not completely filled with oil to facilitate the expansion. As it receives the oil during re-expansion, it is also called as expansion tank.

⑥ Breather :

The transformer oil expands when it is heated and contracts when cooled. When the oil expands, the air is expelled out and air is drawn inside under contraction of oil. This process is known as breathing. Thus the oil is in contact with air. The air entering the T/F through an apparatus called breather.

A breather consists of a silica gel crystals and is connected to the conservator through vent pipe. Silica gel absorbs the moisture. Silica gel is blue in colour when dry and becomes whitish pink when it absorbs moisture.

⑦ Terminals and Bushings:

The Connections to the windings are Copper rods. The windings are connected to H.v and L.v lines through insulator bushings, mounted over the T/F. The bushings consist of a current carrying element & a porcelain cylinder.

⑧ Exhaust pipe, oil gauge, Temperature gauge:

Many transformers are provided with exhaust pipe made of steel. It protects the tank from large expansion of the accidental gas formation.

Every T/F is provided with oil gauge and temperature gauge. Oil gauge indicates the level of oil in the tank. It provides an alarm which gives an alarm when the oil level has dropped. Temperature gauge indicates the temperature of the oil.

⑨ Cooling System:

Whenever current is flowing through the windings, heat is produced which should be dissipated, if it is not dissipated the windings may get damaged. Hence Cooling is necessary for a T/F which can be provided by different methods Such as natural air cooling, oil immersed forced air, water and oil coolings and air-blast cooling.

Minimization of hysteresis and eddy Current losses:

Tan² and Core losses (w_i) are caused by the alternating flux in the core and consists of hysteresis and eddy current losses.

$$\Rightarrow \text{Hysteresis loss, } w_h = k_h B_{\max}^{1.6} f_r (\text{watts})$$

$$\Rightarrow \text{Eddy current loss, } w_e = k_e B_{\max}^2 f^2 t^2 V (\text{watts})$$

where, k_h & k_e are proportional constants which depends on volume and material of core, frequency, V is the volume of the core, B_{\max} is the maximum value of flux density in the core. 't' is the thickness of core laminations.

\Rightarrow The hysteresis loss can be minimised by using Steel of high Silicon Content, whereas the Eddy Current loss can be minimised by making the core with thin laminations. Hence, iron losses can be minimised by making core with silicon steel laminations [lamination gauges between 0.3 to 0.5 mm].

EMF equation of a 1-φ transformer?

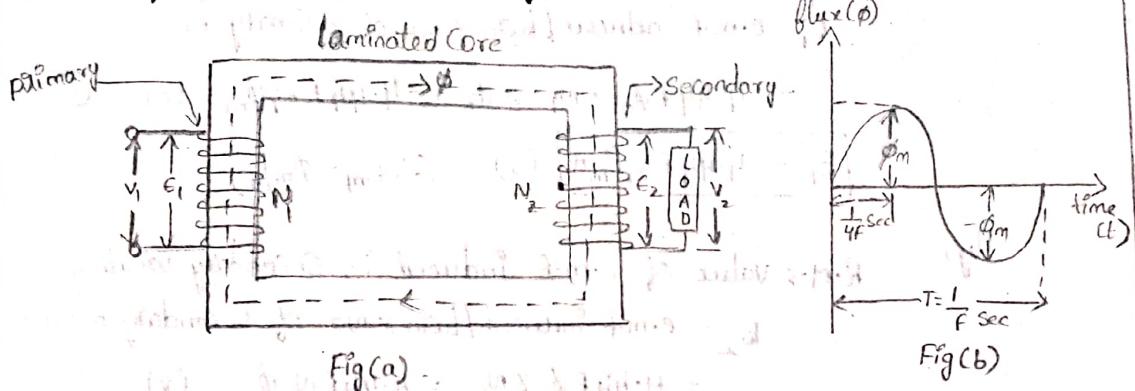


Fig (a)

Fig (b)

⇒ consider a 1-φ transformer as shown in fig (b).

Let,
 V_1 = Primary A.c Supply Voltage in volts (V)

I_1 = Primary Current in amperes (A)

E_1 = Induced EMF in primary in volts (V)

N_1 = no. of turns in primary winding.

N_2 = no. of turns in secondary winding.

E_2 = Induced emf in secondary in volts (V)

I_2 = Secondary Current in amperes (A)

V_2 = Secondary voltage in volts (V)

Φ_m = Maximum flux in Core in webers (wb)

$$\Phi_m = B_m \times A$$

f = Frequency of a.c Supply (Hz).

⇒ When a.c Voltage is applied to the primary winding, an alternating flux is produced in the core.

⇒ The magnetic flux increases from zero to maximum value ' Φ_m ' in 1/4 of cycle.

∴ Average rate of change of flux, $\frac{d\Phi}{dt} = \frac{\Phi_m}{1/4 f} = 4f\Phi_m$ (V)

⇒ Now, rate of change of flux is equal to the Average e.m.f induced per turn.

∴ Average e.m.f/turn = $4f\Phi_m$

We know,

Form factor = $\frac{R \cdot M.S \text{ Value}}{\text{Average Value}}$

R.M.S value of e.m.f/turn = $1.11 \times \text{Average e.m.f/turn}$.

$$= 1.11 \times 4f\Phi_m = 4.44f\Phi_m$$

Now, R.M.S value of e.m.f induced in primary winding,

$E_1 = \text{e.m.f induced / turn} \times \text{no. of primary turns}$.

$$= 4.44 F \phi_m \times N_1 \text{ Volts} = 4.44 F N_1 \phi_m \quad (\text{v}) - 1$$

$$\boxed{E_1 = 4.44 F N_1 B_m A} \quad (\text{v}) \quad (\because B_m = \phi_m/A)$$

My,

R.M.S value of e.m.f induced in secondary winding

$E_2 = \text{e.m.f induced / turn} \times \text{no. of secondary turns}$

$$= 4.44 F \phi_m \times N_2 = 4.44 F N_2 \phi_m \quad (\text{v}) - 2$$

$$\boxed{E_2 = 4.44 F N_2 B_m A} \quad (\text{v})$$

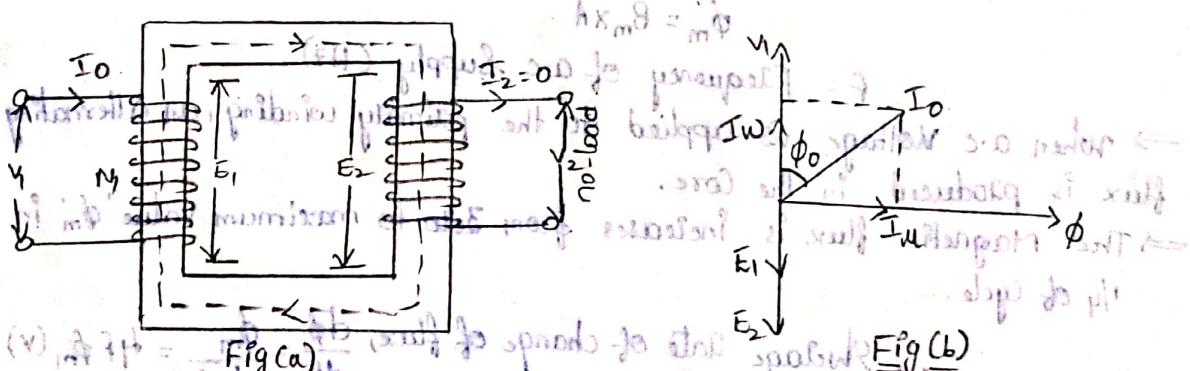
Equation 1 is known as e.m.f of primary winding of T/F.

Equation 2, is known as e.m.f equation of secondary wng of T/F.

Operation of Transformer on no-load and on load

No-load %

An ideal transformer is one that has no Core losses and Copper losses whenever load is not connected on the Secondary winding and primary winding is connected to a.c Supply, the condition is said to no-load condition of the transformer.



Consider a practical T/F whose secondary is open circuited ($I_2 = 0$) and the primary winding is connected a.c Supply as shown above.

The primary will draw a small no-load current I_0 which lags the applied voltage 'V' by an angle $\phi_0 < 90^\circ$ as shown in fig (b).

This primary no-load current I_0 has to supply

(i) Iron losses in the Core and

(ii) very small amount of Cu losses in primary wng.

$$\text{no-load loss power, } W_0 = V_1 I_0 \cos \phi_0$$

where ϕ_0 , power factor under no-load condition.

No-load current (I_0) can be resolved into two components. They are :-

① Active (or) Wattful (or) Working Component (I_w) :-

$$I_w = I_0 \cos \phi_0.$$

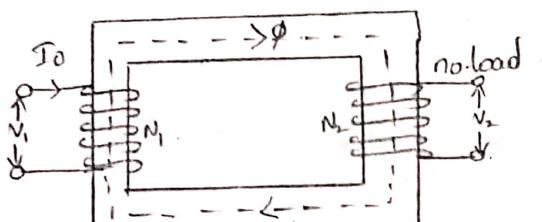
No-load power factor, $\cos \phi_0 = I_w / I_0$.

② Reactive (or) Magnetizing Component :-

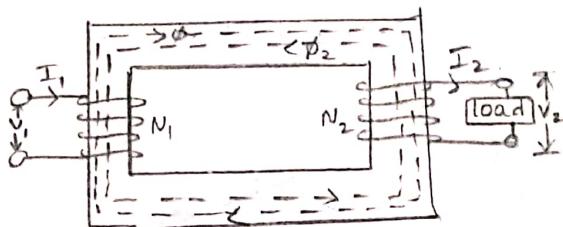
$$I_u = I_0 \sin \phi_0.$$

$$\sin \phi_0 = I_u / I_0.$$

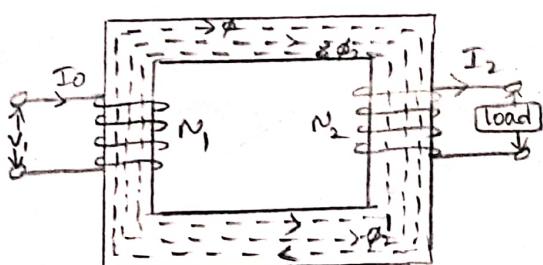
On load :-



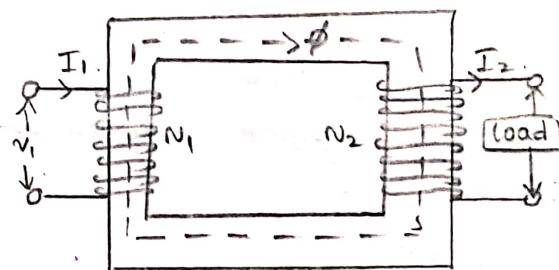
Fig(a)



Fig(b)



Fig(c)



Fig(d)

When the Secondary winding of a transformer is connected to a load, the transformer is said to be on load. When the T/F is loaded, a current I_2 will flow through the secondary winding. The current I_2 will be in phase with V_2 if the load is resistive, it lags behind V_2 if the load is inductive and it leads V_2 if the load is capacitive.

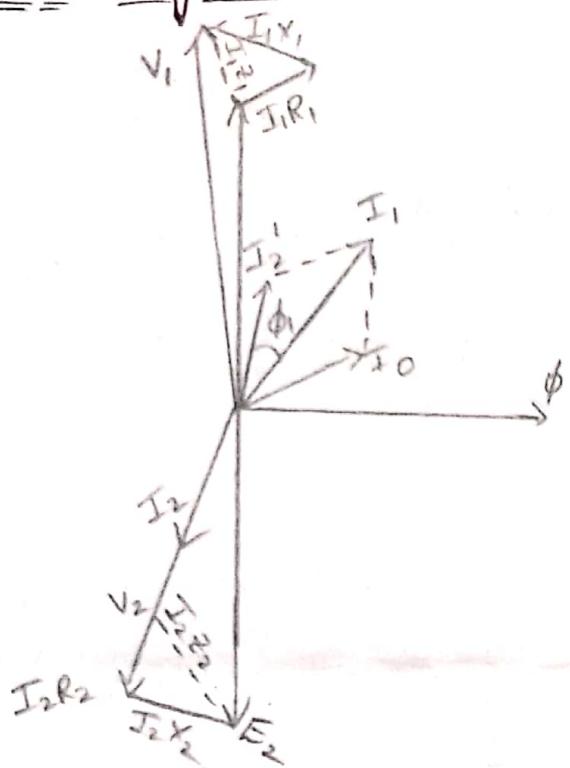
⇒ When the T/F is on no-load as shown in fig(a), it draws no-load current I_0 from the supply. The current I_0 sets up an m.m.f. ($N_1 I_0$) which produces flux ' ϕ ' in the core.

⇒ When load is connected as shown in fig(b) a current ' I_2 ' flows through the secondary long. This I_2 current set up its own m.m.f. ($N_2 I_2$) and hence produces flux ϕ_2 . This flux ' ϕ_2 ' produces the flux ' ϕ '. and also ϕ_2 flux weakens the flux ϕ and tends to reduce the primary back e.m.f. E_p . Hence, more current flows in primary.

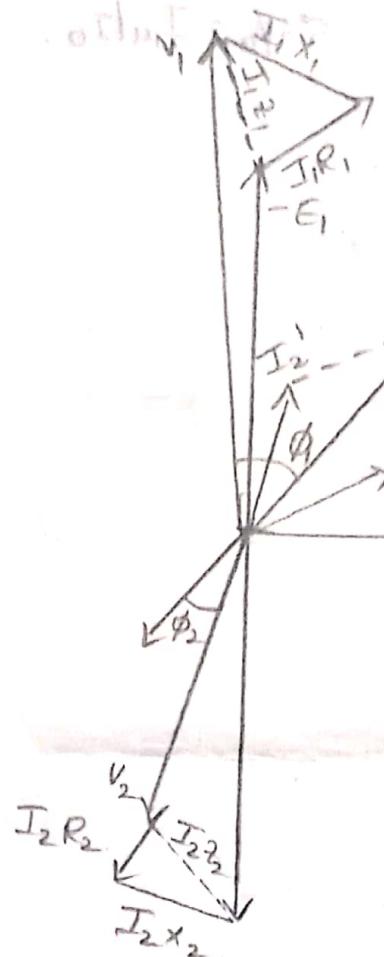
Let, the additional primary current be I_2' as shown in
as load component of primary current. This current
then the I_2' sets up an additional m.m.f $N_1 I_2'$, no
own flux ϕ_2' . $\Rightarrow \phi_2 = \phi_2' + \phi_1$, $N_2 I_2 = N_1 I_2'$.

\Rightarrow Hence, when the transformer is on load, the pair
has two currents I_2 and I_2' . I_2 is usually small a

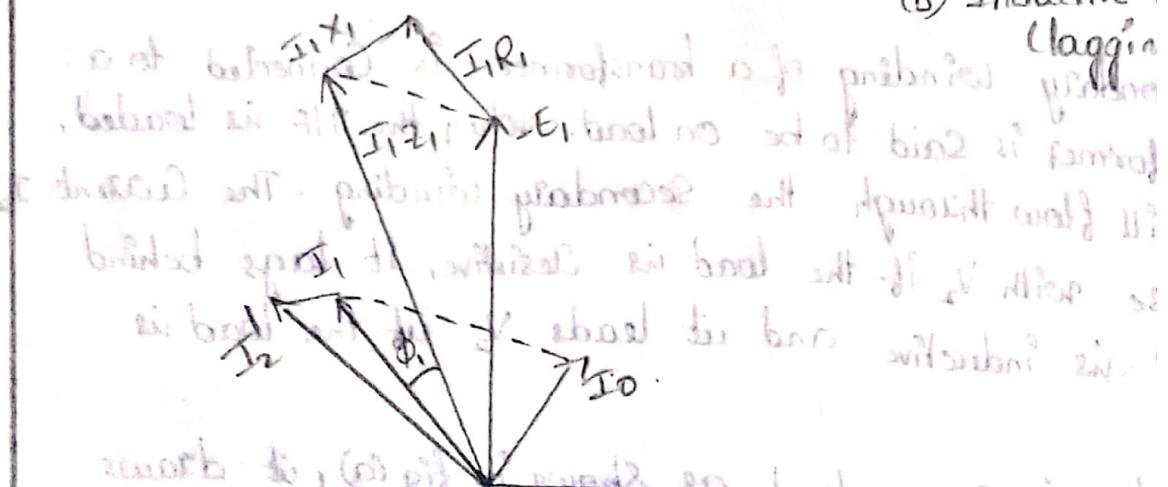
Phasor diagrams



(a) pure resistive load
(unity p.f.)

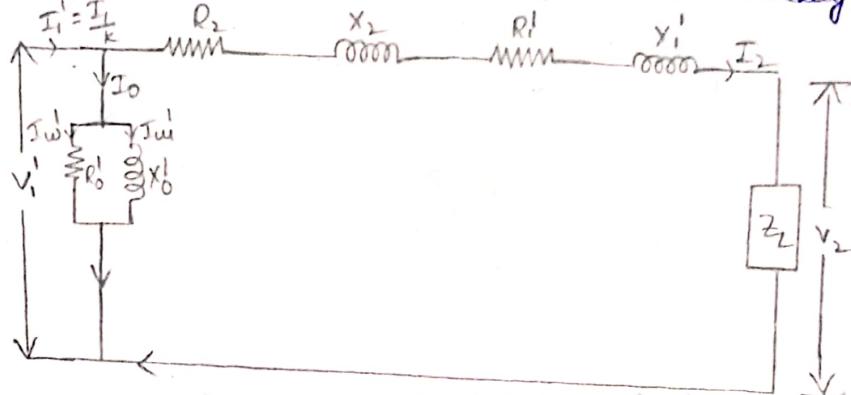


(b) Inductive load



referred to secondary:

If all the primary quantities are transferred to secondary side, we get equivalent circuit of a T/F referred to secondary.



$I_1' = \frac{I_2}{K}$; $X_1' = K^2 X_1$; $Z_1' = K^2 Z_1$; $V_1' = K V_1$
 All other values of resistance and reactance are evaluated with respect to I_1' .
 $I_1' = \frac{I_2}{K}$; $R_{02}' = R_2 + R_1'^2 / X_1'^2$; $Z_{02}' = X_2 + X_1'^2 / R_1'^2 = R_02 + j X_{02}$.
 Notice equivalent load Z_L is same as in primary side.
 Losses in a transformer.

Transformer is a static device, therefore there are no friction and windage losses. The various losses occur in a transformer are:

- Iron losses
- Total losses
- Copper losses
- Hysteresis loss
- Eddy Current loss.

Iron losses (w_i):

These losses are caused by the alternating flux in the core and consists of hysteresis and eddy current losses.

$$\text{Hysteresis losses } W_h = K_h B_{\max}^{1.6} F_v \text{ (Watts).}$$

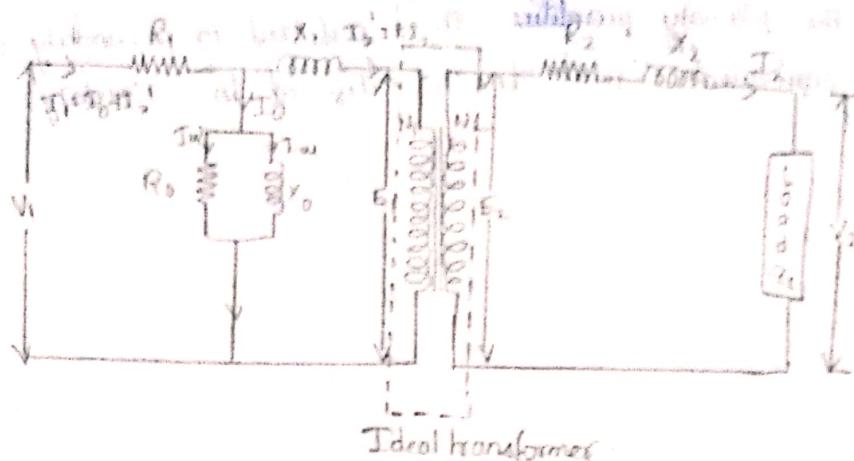
$$\text{Eddy current losses } W_e = K_e B_{\max}^2 F^2 t^2 v \text{ (Watts).}$$

$$\text{Total losses } (w_i) = W_h + W_e = \text{constant loss.}$$

Copper losses (w_{cu}):

These losses occur in both the primary and secondary windings due to their ohmic resistance.

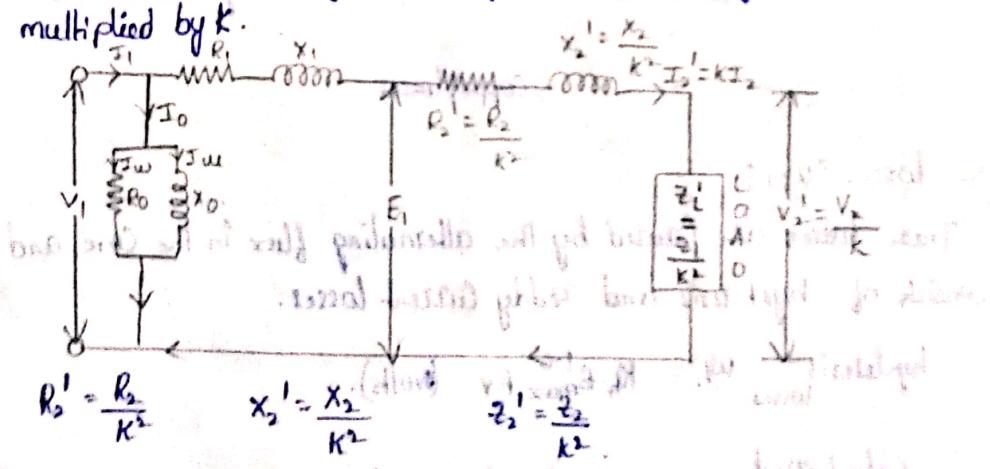
Equivalent circuit of a transformer



The equivalent circuit is useful to know the performance and behaviour of a transformer. The resistance R_0 represents the effect of core loss. The current I_w passing through R_0 and supplying the core losses. The reactance X_0 is a loss-free coil through which magnetizing Current I_m . The vector sum of I_w and I_m is the no-load primary current I_0 .

Equivalent Circuit referred to primary

If all the secondary quantities are transferred to primary side, we get equivalent circuit of a T/F referred to the primary. when the secondary quantities are referred to primary, resistance/reactances/ impedances are divided by k^2 , voltage are divided by k and currents are multiplied by k .



$$R_0' = \frac{R_2}{k^2}$$

$$X_2' = \frac{X_2}{k^2}$$

$$Z_L' = \frac{Z_L}{k^2}$$

$$V_1' = \frac{V_2}{k}$$

$$I_2' = kI_2$$

$$R_{01} = R_1 + R_0'$$

$$X_{01} = X_1 + X_0'$$

$$Z_{01} = R_{01} + jX_{01}$$

$$\text{Total Cu losses } W_{Cu} = I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{01} + I_2^2 R_{02} \text{ (W).}$$

\Rightarrow If Cu losses at full-load are W_{Cu} , then the Cu losses at one-half of full-load will be $\left(\frac{1}{2}\right)^2 W_{Cu}$.

\Rightarrow The Cu losses are the major losses and are may be 90% of the total losses.

$$\text{Total losses} = \text{Iron losses (W)} + \text{Copper losses (W}_{Cu}\text{).}$$

= Constant losses + Variable losses.

Efficiency of a transformer

The efficiency of a transformer is defined as the ratio of output power to the input power. It is expressed in percentage and is denoted by the letter 'η'.

$$\text{Efficiency, } \eta = \frac{\text{Output power}}{\text{Input power.}} = \frac{\text{O/p}}{\text{O/p + total losses.}}$$

$$= \frac{\text{I}_{lp} - \text{Total losses}}{\text{I}_{lp}.}$$

$$\% \eta = \frac{\text{Output power}}{\text{Input power}} \times 100.$$

A good transformer has a very high efficiency in the range of 95 to 99%. The O/p and I/p powers may be in watts (or) kilo-watts.

Voltage regulation of a transformer

The voltage regulation is defined as the change in secondary terminal voltage from no-load to full-load, expressed as a percentage of no-load secondary voltage.

$$\% \text{ voltage regulation} = \frac{\text{no-load voltage} - \text{full-load voltage}}{\text{no-load voltage.}} \times 100$$

$$\therefore \% \text{ voltage regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

i.e. E_2 = no-load voltage,

V_2 = full-load voltage.

(i) Regulation for lagging P.F.

The secondary voltage drop for lagging P.F is I_2 $(R_{02} \cos \phi_2 + X_{02} \sin \phi_2)$

$$(R_{02} \cos \phi_2 + X_{02} \sin \phi_2)$$

$$\% \text{ regulation} = \frac{\text{Voltage drop}}{\text{no-load voltage}} \times 100$$

$$= I_2 \left[R_{02} \cos \phi_2 + X_{02} \sin \phi_2 \right] / E_2 \times 100$$

(ii) Regulation for leading P.F

The secondary voltage drop for leading P.F is I_2 $(R_{02} \cos \phi_2 - X_{02} \sin \phi_2)$

$$(R_{02} \cos \phi_2 - X_{02} \sin \phi_2)$$

$$\% \text{ regulation} = \frac{\text{Voltage drop}}{\text{no-load voltage}} \times 100$$

$$= I_2 \left[R_{02} \cos \phi_2 - X_{02} \sin \phi_2 \right] / E_2 \times 100$$

(iii) Regulation for unity P.F

The secondary voltage drop for unity P.F is $I_2 R_{02}$ because

$$\phi_2 = 0, \sin \phi_2 = 0 \text{ and } \cos \phi_2 = 1$$

$$\% \text{ regulation} = \frac{I_2 R_{02}}{E_2} \times 100$$

Condition for maximum efficiency

$$\text{Full-load o/p power} = V_2 I_2 \cos \phi_2$$

$$\text{Iron losses} = W_i \text{ at load-on no-load condition}$$

$$\text{Full-load Cu losses} = W_{Cu} = I_2^2 R_{02} V \text{ (or) } I_2^2 R_{01}$$

$$\text{Efficiency, } (\eta) = \frac{\text{o/p}}{\text{IIP}} = \frac{\text{o/p}_{\text{load-on no-load}}}{{\text{o/p}_{\text{IIP}}} + \text{total losses}}$$

$$\eta = \frac{\text{o/p}}{\text{o/p} + W_i + W_{Cu}} = \frac{V_2 I_2 \cos \phi_2}{V_2 I_2 \cos \phi_2 + W_i + I_2^2 R_{02}} \quad \dots \text{①}$$

Dividing the required both numerator and denominator with I_2 , we get

$$\eta = \frac{V_2 \cos \phi_2}{V_2 \cos \phi_2 + \frac{W_i}{I_2} + I_2 R_{O2}}$$

For a T/F V_2 is approximately constant, hence efficiency is maximum when the denominator is minimum. Hence to get maximum efficiency, differentiate the denominator w.r.t I_2 and equate to zero.

$$= \frac{d}{dI_2} [V_2 \cos \phi_2 + \frac{W_i}{I_2} + I_2 R_{O2}] = 0.$$

$$= 0 - \frac{W_i}{I_2^2} + R_{O2} = 0$$

$$= I_2^2 R_{O2} = W_i \quad \rightarrow (2).$$

$$\text{Copper losses} = \text{Iron losses}$$

Hence, Efficiency of a transformer will be maximum when Copper losses are equal to iron losses.

From Eqn(2), the load current I_2 corresponding to maximum efficiency is given by

$$I_2 = \sqrt{\frac{W_i}{R_{O2}}}$$

All day efficiency (or) Energy definition

The All-day efficiency of a transformer is defined as the ratio of output in kWh to the input in kWh over a 24 hours period.

$$\therefore \text{All-day efficiency, } \eta_{\text{all-day}} = \frac{\text{kWh output in 24 hours}}{\text{kWh input in 24 hours}}$$

Since, the distribution transformer does not supply the rated load for the whole day hence the all-day efficiency of such transformer will be less than ordinary efficiency. The all-day efficiency can be calculated for any length of load cycle, knowing its load variations. As the efficiency is calculated for a day of 24 hours, hence it is called all-day efficiency.