Ajay Kumar Garg Engineering College, Ghaziabad

CLASS NOTES

Subject Name: ELECTROMECHANICAL ENERGY CONVERSION-I

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Unit 1

Electromechanical Energy Conversion Principles

Introduction:

Electrical energy is seldom available naturally and is rarely directly utilized. There are two conversion takes place-------

a. One form to electrical form
b. Electrical form to original form or any other desired form

The device through which we convert one form to electrical form & back to original form or any other desired form is studied in EMEC.

Like—Transformers, D.C. Machines, A. C. Machines (Induction and Synchronous)

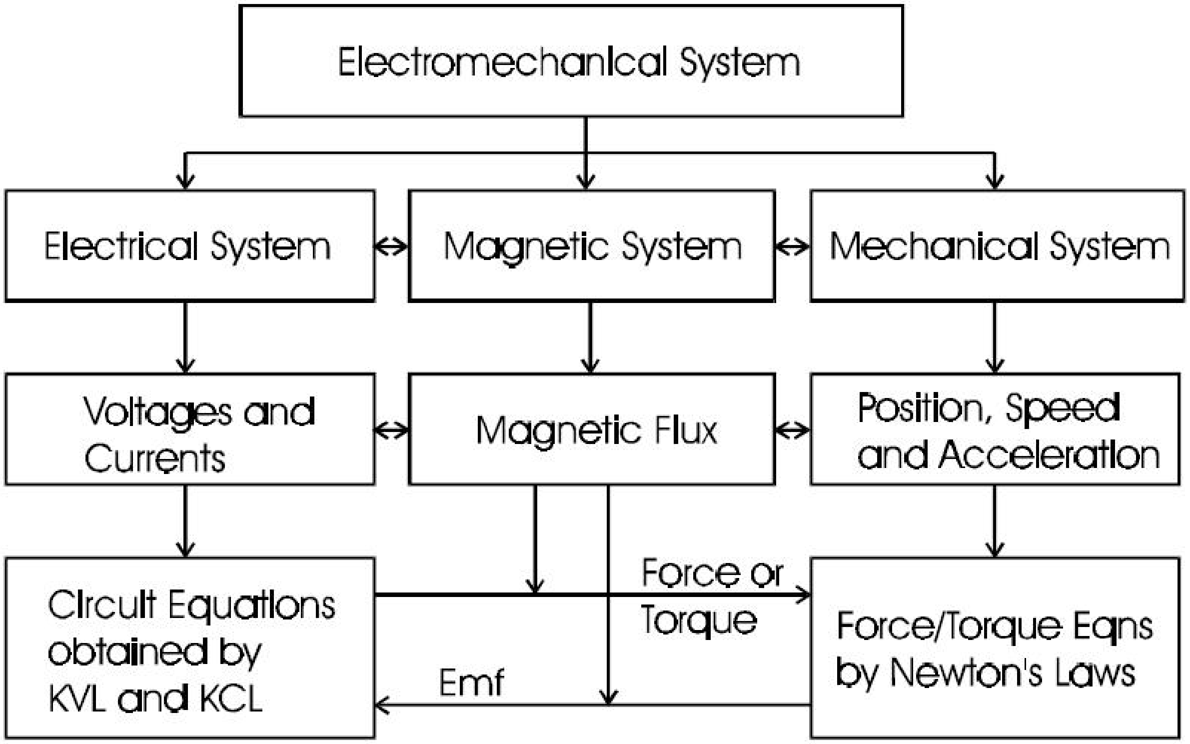
These devices can be transducers for low energy conversion processing and transporting. A second category of such devices is meant for production of force or torque with limited mechanical motion like electromagnets, relays, actuators etc.

A third category is the continuous energy conversion devices like motors or generators which are used for bulk energy conversion and utilization.

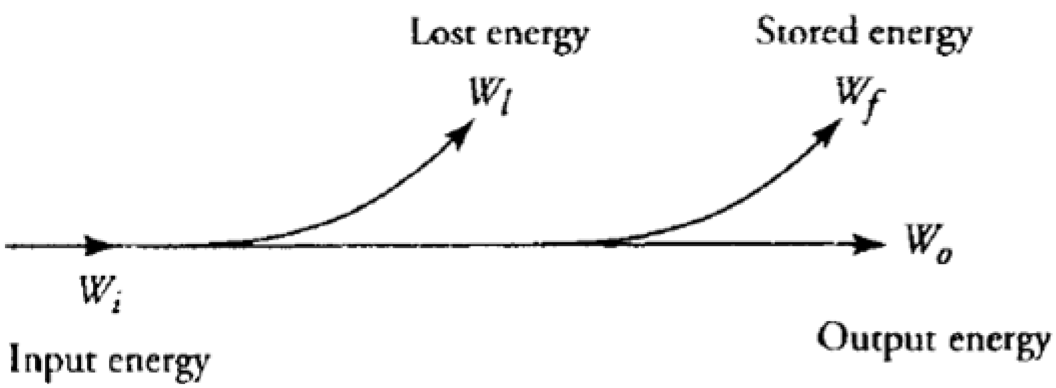
EMEC-----------via----------Medium of magnetic or electric field. For practical devices magnetic medium is most suitable.

When we speak of electromechanical energy conversion, however, we mean either the conversion of electric energy into mechanical energy or vice versa.

Electromechanical energy conversion is a reversible process except for the losses in the system. The term "reversible" implies that the energy can be transferred back and forth between the electrical and the mechanical systems.



Concept map of electromechanical system modeling



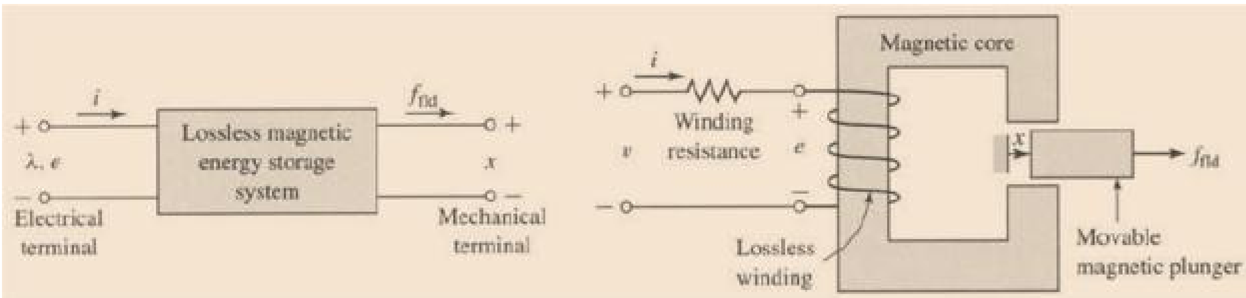
Energy Flow Diagram

From energy diagram we can see that principle of energy conservation is accurately followed.
i.e Input Energy=Losses + Stored Energy + Output Energy.

Singly Excited System:

Consider a singly excited linear actuator as shown below. The winding resistance is R. At a certain time instant *t*, we record that the terminal voltage applied to the excitation winding is *v*, the excitation winding current i, the position of the movable plunger x, and the force acting on the plunger **F** with the reference direction chosen in the positive direction of the x axis, as shown in the diagram. After a time interval dt, we notice that the plunger has moved for a distance dx under the action of the force **F**. The mechanical done by the force acting on the plunger during this time interval is thus

$$dw_m = Fdx$$



Singly Excited system energy conversion

The amount of electrical energy that has been transferred into the magnetic field and converted into the mechanical work during this time interval can be calculated by subtracting the power loss dissipated in the winding resistance from the total power fed into the excitation winding as

$$dw_e = dw_f + dw_m = vidt - Ri^2 dt$$

Since,

$$e = \frac{d\lambda}{dt} = v - Ri$$

So,

$$dw_f = dw_e - dw_m = eidt - Fdx = id\lambda - Fdx$$

we can also write,

$$e = \frac{d\lambda}{dt} = v - Ri$$

$$dw_f(\lambda, x) = \frac{dw_f(\lambda, x)}{d\lambda} d\lambda + \frac{dw_f(\lambda, x)}{dx} dx$$

the energy stored in a magnetic field can be expressed as

$$w_f(\lambda, x) = \int_0^\lambda i((\lambda, x) d\lambda$$

For a magnetically linear (with a constant permeability or a straight line magnetization curve such that the inductance of the coil is independent of the excitation current) system, the above expression becomes

$$W_f(\lambda, x) = \frac{1}{2}\frac{\lambda^2}{L(x)}$$

and the force acting on the plunger is then

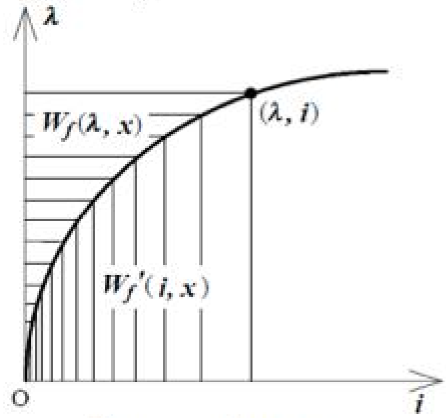
$$F = -\frac{\partial W_f(\lambda, x)}{\partial x} = \frac{1}{2}\left[\frac{\lambda}{L(x)}\right]^2 \frac{dL(x)}{dx} = \frac{1}{2}i^2\frac{dL(x)}{dx}$$

In the diagram below, it is shown that the magnetic energy is equivalent to the area above the magnetization or λ-i curve. Mathematically, if we define the area underneath the magnetization curve as the ***coenergy*** (which does not exist physically), i.e.

$$W_f'(i, x) = i\lambda - W_f(\lambda, x)$$

we can obtain

$$dW_f'(i,x) = \lambda di + id\lambda - dW_f(\lambda, x)$$
$$= \lambda di + Fdx$$
$$= \frac{\partial W_f'(i,x)}{\partial i}di + \frac{\partial W_f'(i,x)}{\partial x}dx$$



Energy and coenergy

Therefore,

$$\lambda = \frac{\partial W_f'(i,x)}{\partial i}$$

and $$F = \frac{\partial W_f'(i,x)}{\partial x}$$

From the above diagram, the coenergy or the area underneath the magnetization curve can be calculated by

$$W_f'(i,x) = \int_0^i \lambda(i,x)di$$

For a magnetically linear system, the above expression becomes

$$W_f'(i,x) = \frac{1}{2}i^2 L(x)$$

and the force acting on the plunger is then

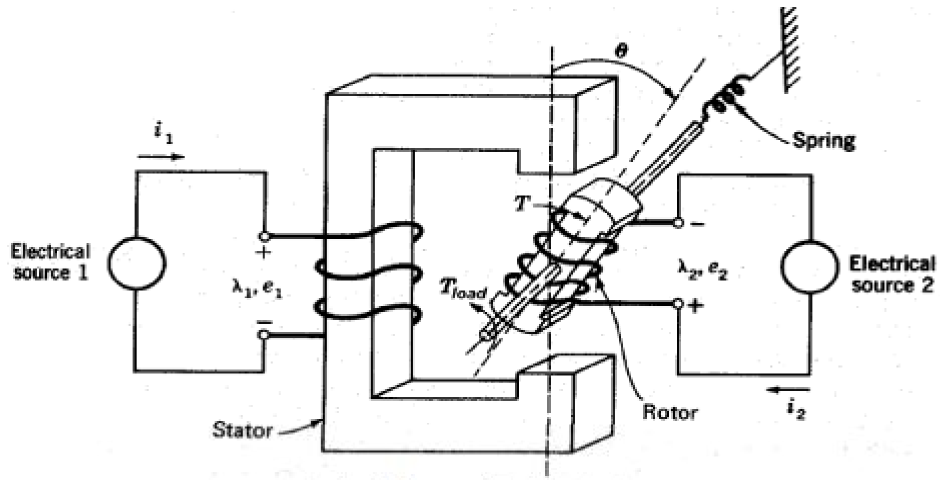
$$F = \frac{\partial W_f'(i,x)}{\partial x} = \frac{1}{2}i^2\frac{dL(x)}{dx}$$

Doubly Excited Rotating Actuator

The general principle for force and torque calculation discussed above is equally applicable to multi-excited systems. Consider a doubly excited rotating actuator shown schematically in the diagram below as an example. The differential energy and coenergy functions can be derived as following:

$$dW_f = dW_e - dW_m$$

where $$dW_e = e_1 i_1 dt + e_2 i_2 dt$$



A doubly excited actuator

$$e_1 = \frac{d\lambda_1}{dt}, \qquad e_2 = \frac{d\lambda_2}{dt}$$

and $$dW_m = Td\theta$$

Hence,

$$dW_f(\lambda_1, \lambda_2, \theta) = i_1 d\lambda_1 + i_2 d\lambda_2 - Td\theta$$

$$= \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \lambda_1} d\lambda_1 + \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \lambda_2} d\lambda_2$$

$$+ \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \theta} d\theta$$

and

$$dW_f{}'(i_1, i_2, \theta) = d\left[i_1\lambda_1 + i_2\lambda_2 - W_f(\lambda_1, \lambda_2, \theta)\right]$$

$$= \lambda_1 di_1 + \lambda_2 di_2 + Td\theta$$

$$= \frac{\partial W_f{}'(i_1, i_2, \theta)}{\partial i_1} di_1 + \frac{\partial W_f{}'(i_1, i_2, \theta)}{\partial i_2} di_2$$

$$+ \frac{\partial W_f{}'(i_1, i_2, \theta)}{\partial \theta} d\theta$$

Therefore, comparing the corresponding differential terms, we obtain

$$T = -\frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \theta}$$

$$T = \frac{\partial W_f{}'(i_1, i_2, \theta)}{\partial \theta}$$

For magnetically linear systems, currents and flux linkages can be related by constant inductances as following

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$$

or

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix}$$

where $L_{12}=L_{21}$, $\Gamma_{11}=L_{22}/\Delta$, $\Gamma_{12}=\Gamma_{21}=-L_{12}/\Delta$, $\Gamma_{22}=L_{11}/\Delta$, *and* $\Delta=L_{11}L_{22}-L_{12}^{2}$. The magnetic energy and coenergy can then be expressed as

$$W_f(\lambda_1, \lambda_2, \theta) = \frac{1}{2}\Gamma_{11}\lambda_1^2 + \frac{1}{2}\Gamma_{22}\lambda_2^2 + \Gamma_{12}\lambda_1\lambda_2$$

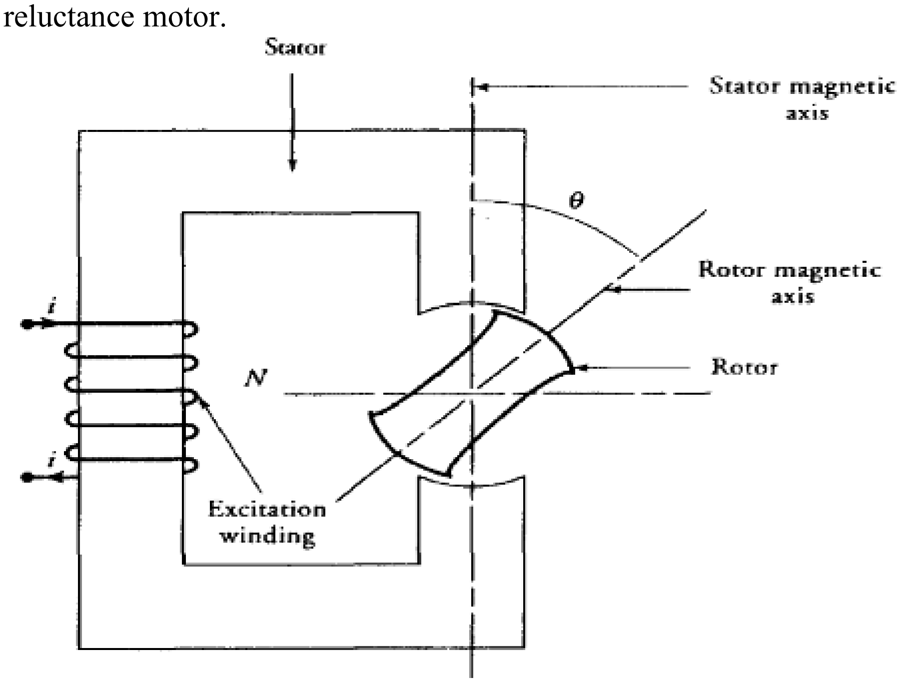
and

$$W_f'(i_1, i_2, \theta) = \frac{1}{2}L_{11}i_1^2 + \frac{1}{2}L_{22}i_2^2 + L_{12}i_1i_2$$

respectively, and it can be shown that they are equal.

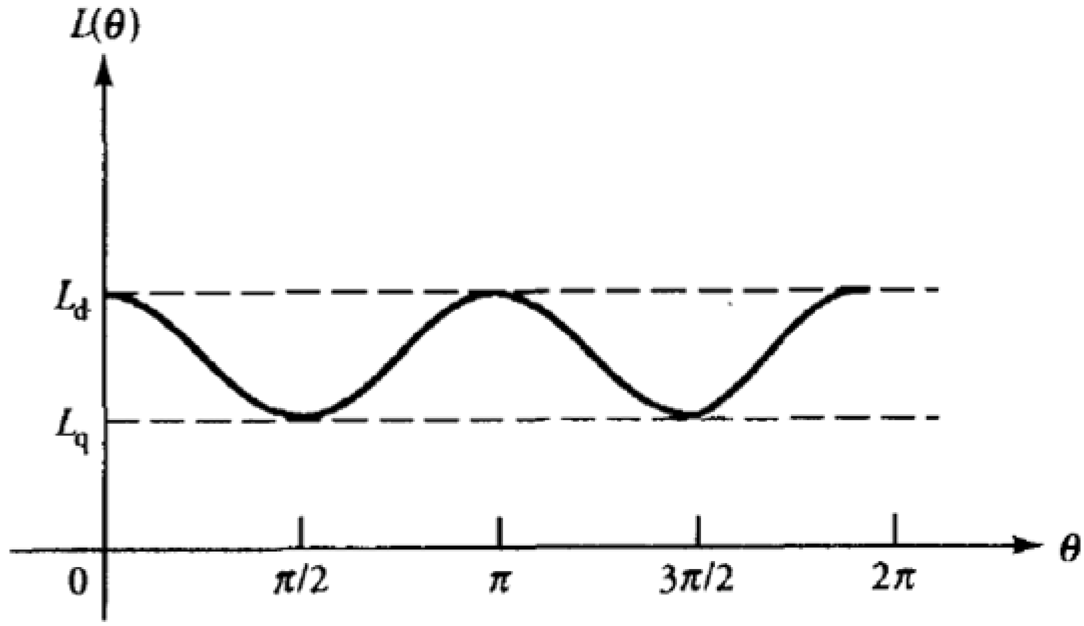
Reluctance Motor:

The reluctance motor is essentially a synchronous motor whose reluctance changes as a function of angular displacement θ. Owing to its constant speed operation, it is commonly used in electric clocks, record players, and other precise timing devices. Figure below shows elementary, single-phase, 2-pole reluctance motor.



A Single Phase Reluctance Motor

When the magnetic axes of the rotor and the stator are at right angles to each other (the quadrature or q-axis position), the reluctance is maximum, leading to a minimum inductance. As the rotor rotates with a uniform speed ω_m the inductance goes through maxima and minima as depicted in Figure below.



Variation of the reluctance of an induction motor as a function of the displacement angle θ

The inductance as a function of θ can be expressed as

$$L(\theta) = 0.5(L_d + L_q) + 0.5(L_d - L_q)\cos 2\theta$$

$$T_e = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta}$$

$$T_e = -\frac{1}{2} i^2 (L_d - L_q)\sin 2\theta$$

θ is expressed as $\theta = \omega_m t + \delta$

where θ is the initial position of the rotor's magnetic axis with respect to the stator's magnetic axis. The torque experienced by the rotor can now be rewritten as

$$T_e = -\frac{1}{2} i^2 (L_d - L_q)\sin 2(\omega_m t + \delta)$$

For a sinusoidal variation in the current,

$$i = I_m \cos \omega t$$

The torque developed is given by equation below

$$T_e = -\frac{1}{2} I_m{}^2 (L_d - L_q) \cos^2 \omega t \sin 2(\omega_m t + \delta)$$

Since $$2\cos^2 \alpha = 1 + \cos 2\alpha$$

$$2\sin\alpha \cos\beta = \sin(\alpha + \beta) + \sin(\alpha - \beta)$$

the torque expression becomes

$$T_e = -\frac{1}{4} I_m{}^2 (L_d - L_q)[\sin 2(\omega_m t + \delta) + 0.5\sin(2(\omega t + \omega_m t) + 2\delta) - 0.5\sin(2(\omega t - \omega_m t) - 2\delta)]$$

The average torque is developed at the synchronous speed is given by equation

$$T_{avg} = -\frac{1}{8} I_m{}^2 (L_d - L_q)\sin 2\delta$$

which is maximum when $\delta = 45^0$

Unit 2

D.C.Machine

D.C Machine Construction

A cross-section of a 4-pole dc machine is shown in. Only the main components of the machine have been identified and are discussed below.

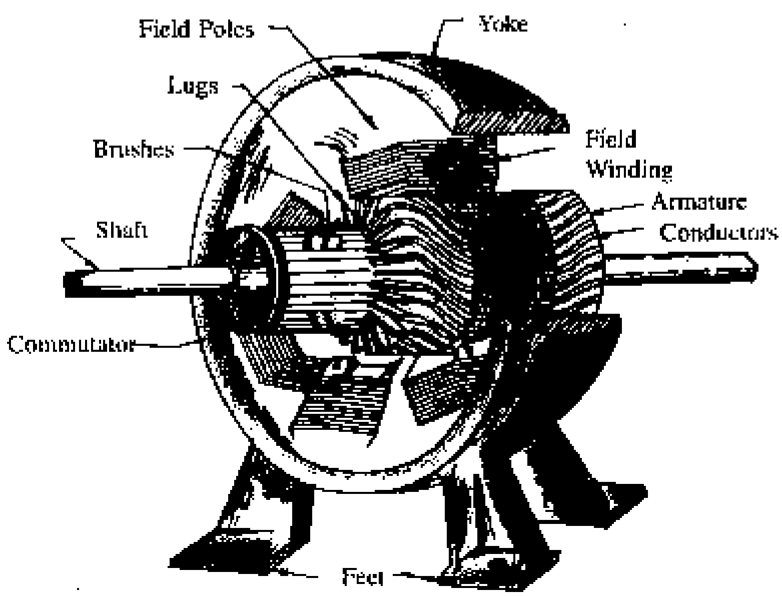
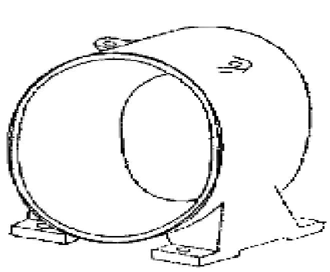


Fig 2.1

Stator

The stator of a dc machine provides the mechanical support for the machine and consists of the **yoke** and the **poles** (or field poles). The yoke serves the basic function of providing a highly permeable path for the magnetic flux. The poles are mounted inside the yoke and are properly designed to accommodate the field windings.



yoke.

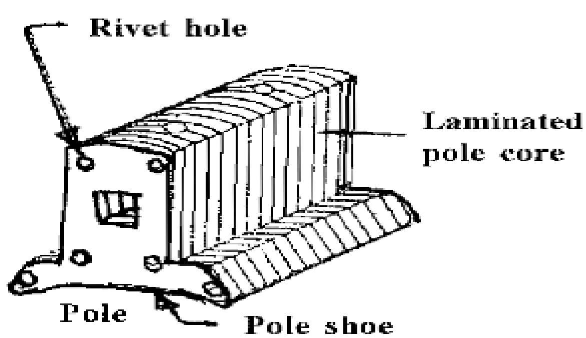


Fig 2.2

Field Winding

The field coils are wound on the poles in such a way that the poles alternate in their polarity. There are two types of field windings-a **shunt field winding** and a **series field winding.**

Armature

The rotating part of a dc machine, which is shrouded by the fixed poles on the stator, is called the armature. The effective length of the armature is usually the same as that of the pole. Circular in cross-section, it is made of thin, highly permeable, and electrically insulated steel laminations that are stacked together and rigidly mounted on the shaft.

Commutator

The commutator is made of wedge-shaped, hard-drawn copper segments as shown in Fig 2.3 It is also rigidly mounted on the shaft as depicted in Fig 2.3. The copper segments are insulated from one another by sheets of mica.

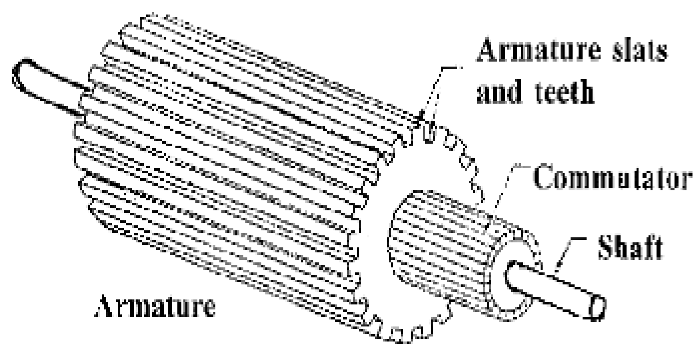


Fig 2.3

Brushes

Brushes are held in a fixed position on the commutator by means of brush holders. An adjustable spring inside the brush holder exerts a constant pressure on the brush.

Armature Windings

As mentioned in the previous section, the outer periphery of the armature has a plurality of slots into which the coils are either placed or wound. The armature slots are usually insulated. The maximum emf is induced in a full-pitch coil, that is, when the distance between the two sides of a coil is 180" electrical. A full-pitch coil, in other words, implies that when one side is under the center of a south pole, the other side must be under the center of the adjacent north pole.

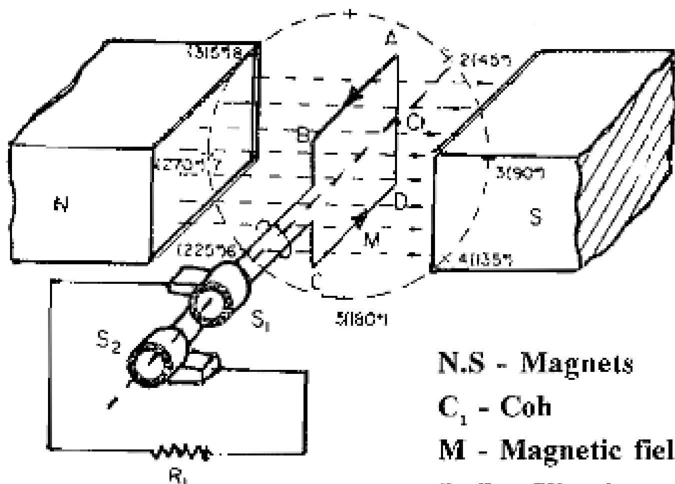
Lap Winding

In a lap-wound machine the two ends of a coil are connected to adjacent commutator segments. In the lap winding, the two ends of a coil are connected to adjacent commutator segments .

Wave Winding

The wave winding differs from the lap winding only in the way the coils are connected to the commutator segments. In the wave winding, the two ends of **a** coil are connected to those segments of the commutatorthat are **360"** electrical apart (2-pole pitches).This is done to ensure that the entire winding closes onto itself only once.

Induced Emf Equation



N.S - Magnets
C_1 - Coh
M - Magnetic field
S_1, S_2 - Slip rings
R_L - Load resistance

Fig 2.5

E.M.F. Equation of D.C. Generator:-

The e.m.f. generated in a direct current generator is proportional to the speed rotation of the armature, total number of armature conductors, total flux available in the field and the type of winding adopted in the armature.

Let, P = No. of poles.

Ø = flux per pole, in webers.

Z – total no. of conductors in the armature (number of slots in the armature x number of conductors per slot).

N = Speed of rotation of armature in r.p.m.

A = No. of parallel paths in armature

Eg = e.m.f. induced in any parallel path is armature.

The EMF Equation of D.C. generator $(E_g) = \frac{\text{Ø}zn}{60} \times \frac{P}{A}$ volts

Where, A = P in case of lap wound generator,

A = 2 in case of wave wound generator.

Armature Reaction

When there is no current in the armature winding (a no-load condition), the flux produced by the field winding is uniformly distributed over the pole faces as shown in Figure 2.6 for a 2-pole dc machine. The induced emf in a coil that lies in the neutral plane, a plane perpendicular to the field-winding flux, is zero. This, therefore, is the neutral position under no load where the brushes must be positioned for proper commutation. The armature flux distribution due to the armature mmf is also shown in the figure below.

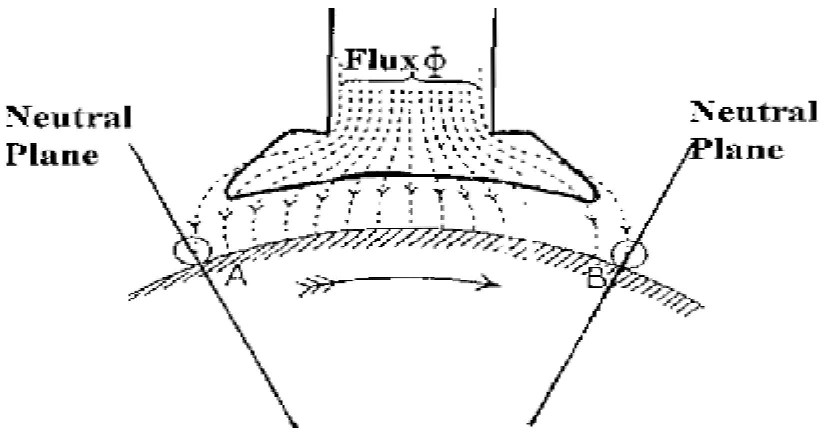


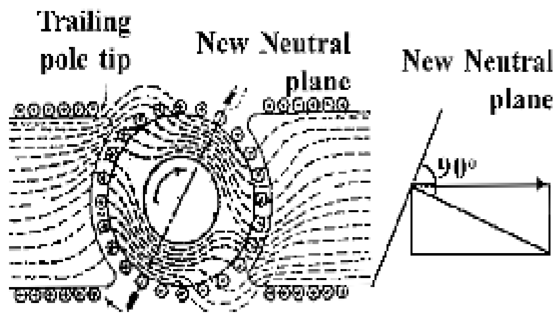
Fig 2.6

The flux distribution due to the field winding is suppressed in order to highlight the flux distribution due to the armature mmf. Note that the magnetic axis of the armature flux (the quadrature, or q-axis) is perpendicular to the magnetic axis of the field-winding flux (direct, or d-axis). Since both fluxes exist at the same time when the armature is loaded, the resultant flux is distorted . The armature flux has weakened the flux in one-half of the pole and has strengthened it in the other half. The armature current has, therefore, displaced the magnetic-field axis of the resultant flux in the direction of rotation of the generator. **As** the neutral plane is perpendicular to the resultant field, it has also advanced. The effect of the armature mmf upon the field distribution is called the **armature reaction.**The armature reaction has a demagnetizing effect on the machine. The reduction in the flux due to armature reaction suggests a substantial loss in the applied mmf per pole of the machine. In large machines, the armature reaction may have a devastating effect on the machine's performance under full load. Therefore, techniques must be developed to counteract its demagnetization effect. Some of the measures that are being used to combat armature reaction are summarized below:

The brushes may be advanced from their neutral position at no load (geometrical \neutral axis) to the new neutral plane under load. This measure is the least expensive. However, it is useful only for constant-load generators .Interpoles, or commutating poles as they are sometimes called, are narrow poles that may be located in the interpolar region centered along the mechanical neutral axis of the generator.

The interpole windings are permanently connected in series with the armature to make them effective for varying loads. The interpoles produce flux that opposes the flux due to the armature mmf. When the interpole is properly designed, the net flux along the geometric neutral axis can be brought to zero for any load. Because the interpole winding carries armature current, we need only a few turns of comparativelyheavy wire to provide the necessary interpole mmf.

Another method to nullify the effect of armature reaction is to make use of compensating windings. These windings, which also carry the armature current, are placed in the shallow slots cut in the pole faces



Commutation

For the successful operation of a dc machine, the induced emf in each conductor under a pole must have the same polarity. If the armature winding is carrying current, the current in each conductor under a pole must be directed in the same direction. It implies that as the conductor moves from one pole to the next, there must be a reversal of the current in that conductor. The conductor and thereby the coil in which the current reversal is taking place are said to be commutating. The process of reversal of current in a commutating coil is known as commutation.

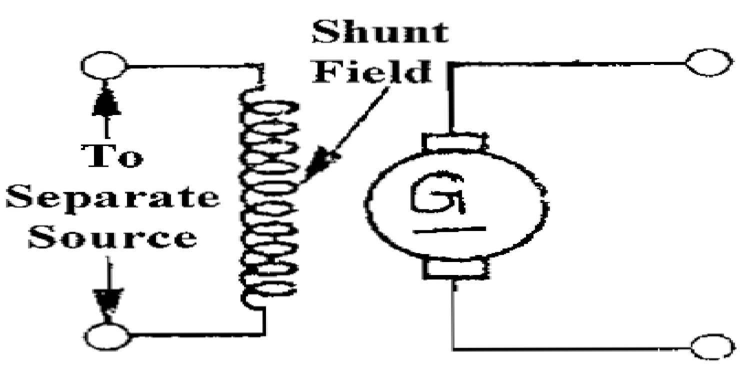
Types of D.C. Generators:

D.C. Generators are classified according to the manner in which their field windings are connected. The process of giving D.C. voltage to the field winding for producing magnetic field is called field excitation. The generators are classified as follows:

- D.C. generator
  - Seperately Excited D.C. generator
  - Self excited D.C. generator
    - Series Generator
    - Shunt generator
    - Compound generator
      - Long shunt Compound Generator
      - Short Shunt Compound generator

A Separately Excited DC Generator

As the name suggests, a separately excited dc generator requires an independent dc external source for the field winding and for this reason is used primarily in (a) laboratory and commercial testing and (b) special regulation sets. The externalsource can be another dc generator, a controlled or uncontrolled rectifier, or simply a battery.The equivalent circuit representation under steady-state condition of a separately excited dc generator is given in Figure 5.19. The steady-state condition implies that no appreciable change occurs in either the armature current or the armature speed for a given load. In other words, there is essentially no change in the mechanical energy or the magnetic energy of the system.



The Internal Characteristic

Under no load, the armature current is equal to the field current, which is usuallya small fraction of the load current. Therefore, the terminal voltage under no-load*V,,* is nearly equal to the induced emf E, owing to the negligible *l,R,* drop. As

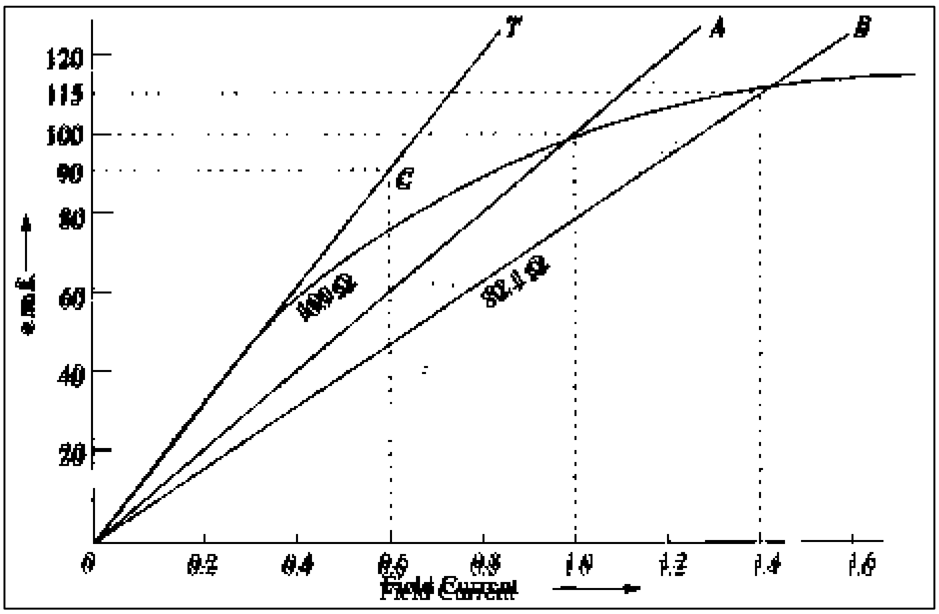
the load current increases, the terminal voltage decreases for the following

reasons:

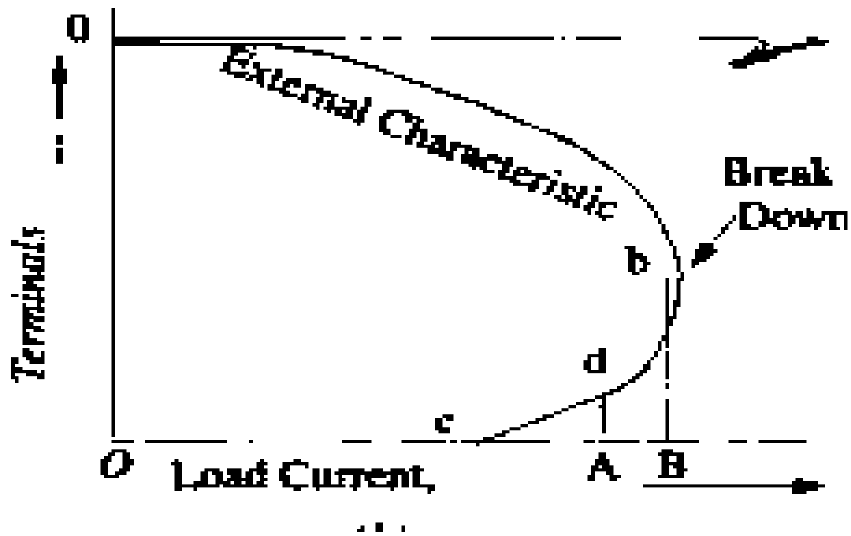
1.The increase in *l,R,* drop

2.The demagnetization effect of the armature reaction

3.The decrease in the field current due to the drop in the induced emf region.



The External Characteristic



0
External Characteristic
Break
Down
b
d
c
Terminals
O
Load Current,
A
B

Unit 3

Motor

When a machine converts electric energy into mechanical energy, it is called a **motor.** There is no fundamental difference in either the construction or the operation of the two machines. In fact, the same machine may be used as a motor or a generator.

Operation of a DC Motor

Since there is no difference in construction between a dc generator and a dc motor, the three types of dc generators discussed in Chapter 5 can also be used as dc motors. Therefore, there are three general types of dc motors shunt, series,and compound. The permanent-magnet (I'M) motor is a special case of a shunt

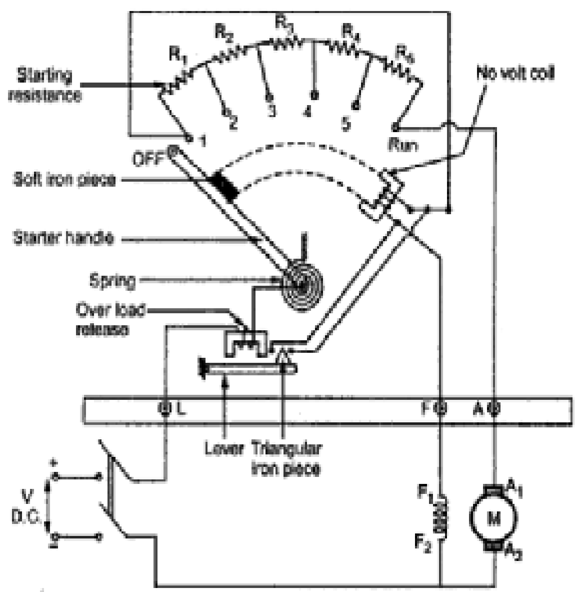
motor with uniform (constant) flux density. We can also have a separately excitedmotor if we use an auxiliary source for the field winding. Because it is notpractical to employ two power sources, one for the field winding and the other for the armature circuit, a separately excited motor is virtually nonexistent. However,a separately excited motor can also be treated as a special case of a shunt motor**..**A brief review is given here. In a dc motor, a uniform magnetic field is created by its poles. The armature conductors are forced to carry current by connecting them to a dc power source (supply) as shown in Figure 3.1. The current direction in the conductors under each pole is kept the same by the commutator. According to the Lorentz force equation, a current-carrying conductor when placed in a magnetic field experiences **a** force that tends to move it. This is essentially the principle ofoperation **of** a dc motor. **All** the conductors placed on the periphery **of** a dc motor are subjected to these forces, as shown in the figure. These forces cause the armature to rotate in the clockwise direction. Therefore, the armature **of *a*** dc motor rotates in the direction of the torque developed **by** the motor. For this reason, the torque developed by the motor is called the driving torque. Note that the torque developed by the conductors placed on the armature of a dc generator is in a direction opposite to its motion. Therefore, it can be labeled the retarding torque.

Starting a DC Motor

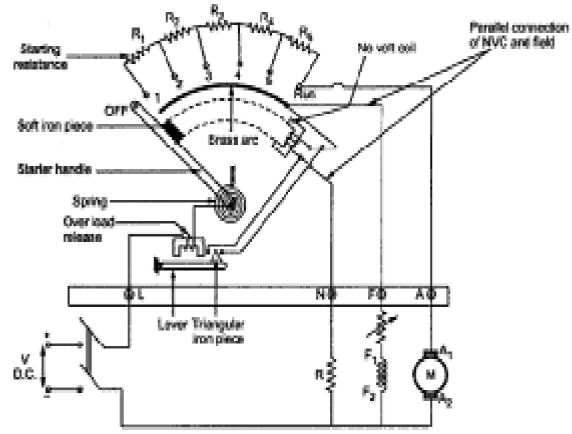
At the time of starting, the back emf in the motor is zero because the armature is not rotating. For a small value of the armature-circuit resistance R, the startingcurrent in the armature will be extremely high if the rated value of *V,* is impressed across the armature terminals. The excessive current can cause permanent damage to the armature windings. Thus, a dc motor should never be started at its rated voltage. In order to start a dc motor, an external resistance must be added in series with the armature circui .. The external resistance is gradually decreased as the armature comes up to speed. Finally, when the armature has attained its normal speed, the external resistance is "cut out" of the armature circuit..

It has been shown earlier that the speed of a motor is given by the relation

$$N = \frac{V - I_a R_a}{Z\Phi} \cdot \left(\frac{A}{P}\right) = K \frac{V - I_a R_a}{\Phi} \text{ r.p.s.}$$



3 point Starter



4 point Starter

Speed control of D.C. Motors:

Different ranges of speeds are required for different applications. A single motor can be used for different speeds for various works. Smooth speed control is possible in D.C. Shunt motor.

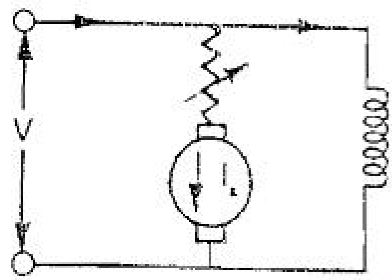
The speed of a D.C. motor can be expressed by the equation: Speed, $N \alpha (v - IaRa)/\phi$. Neglecting the small voltage drop IaRa, the speed is directly proportional to the voltage impressed across the armature and inversely proportional to the flux. Hence the speed of a D.C. motor can be controlled by varying the voltage or flux. The above two methods are known as.

1. Armature control and 2. Field control.

These methods are applied to shunt, series and compound motors.

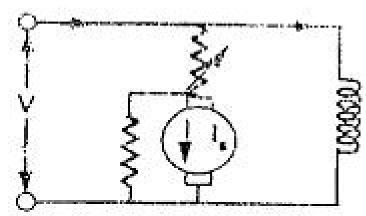
SPEED CONTROL OF D.C. SHUNT MOTOR

Armature Control Method:

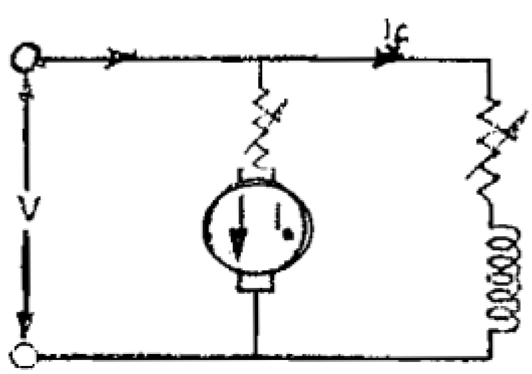


This method is used when spends below the no-load speed are required. As the supply voltage across the armature is varied by inserting a variable resistance in series with the armature. Circuit as shown in Fig.

As the controller resistance is increased, the Potential drop across the armature is decreased. So armature speed also decreases. In this method speed can be varied up to the rated speed.



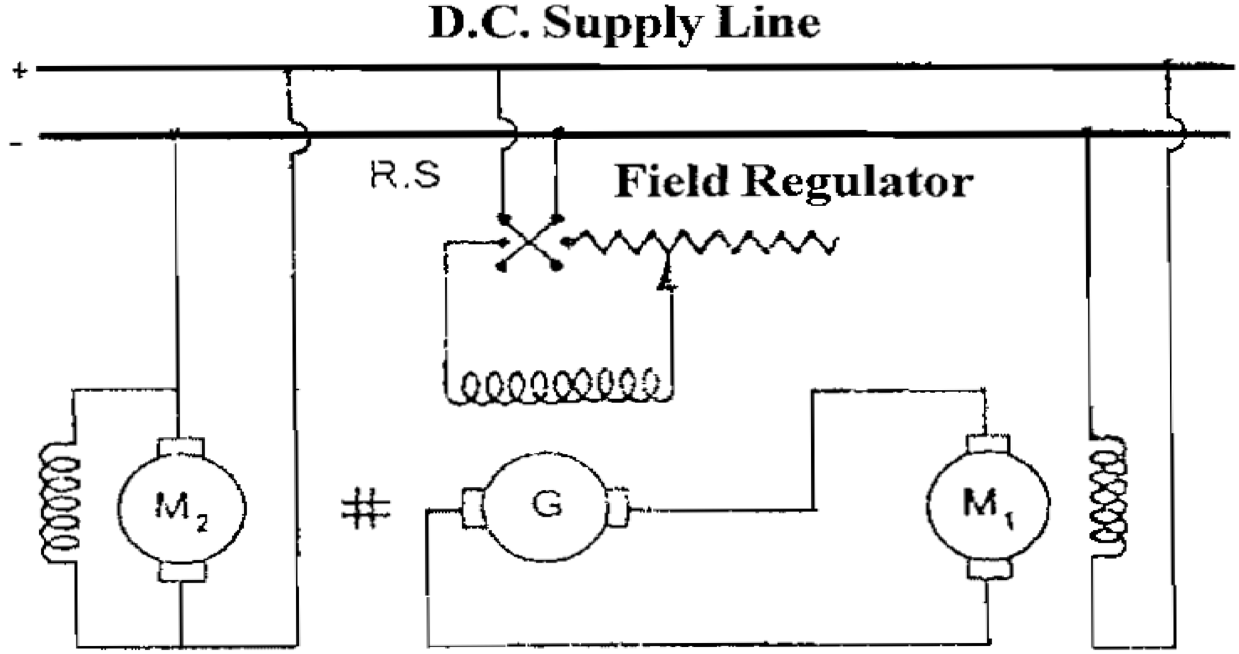
This method is very expensive because the power loss and not suitable for rapidly changing loads. A more suitable operation can be obtained by using a diverter across the armature in addition to armature control resistance as shown in Fig. . Now the changes in armature current (due to changes in load) will not be so effective in changing the P.D. across the armature.



By this method of speed control we can not have speeds below the rated speed. (Flux can not be increased). But the speed can be increased beyond the rated speed. By combining the field control and armature control methods, it is possible to get speed variations below or above normal speeds. The connection diagram for such a speed control is shown in fig. variable resistance are connected in the armature and field circuits.

Ward – Leonard System

This system is used where a very sensitive speed control is required.



M_1 is the main motor for which the speed control is required. The field of this motor is permanently connected across the D.C. supply lines. By applying a variable voltage across its armature, any desired speed can be obtained. This variable voltage is supplied by a motor-generator set which consists of either a D.C. or an A.C. motor M_2. The motor M_2 is directly coupled to the generator G.

The motor M_2 runs at an approximately constant speed. The output voltage of "G" is directly fed to the main motor M_1. The voltage of the generator can be varied from zero to its maximum value by means o its field regulator. The field current of the generator can be reversed by the reversing switch Rs. Therefore the generated voltage can be reversed and hence the direction of rotation of M_1 is also reversed.

It should be remembered that motor-generator set always runs in the same direction.

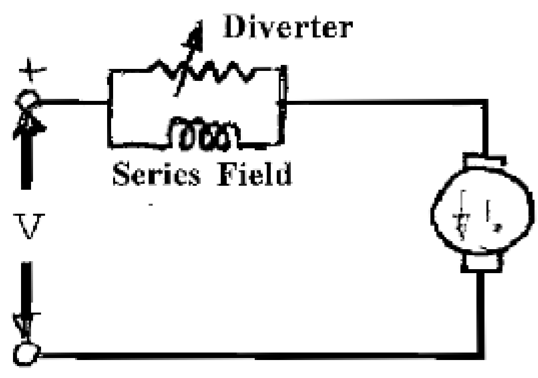
The capital cost of such a system is high, since three machines are employed. But this method is very effective and the speed control obtained is very smooth.

If a vasiable resisance is connected in series with the field circuit of motor M_1. The speed above the rated value can be obtained. The direction of rotation of a D.C. motor can be reversed either by

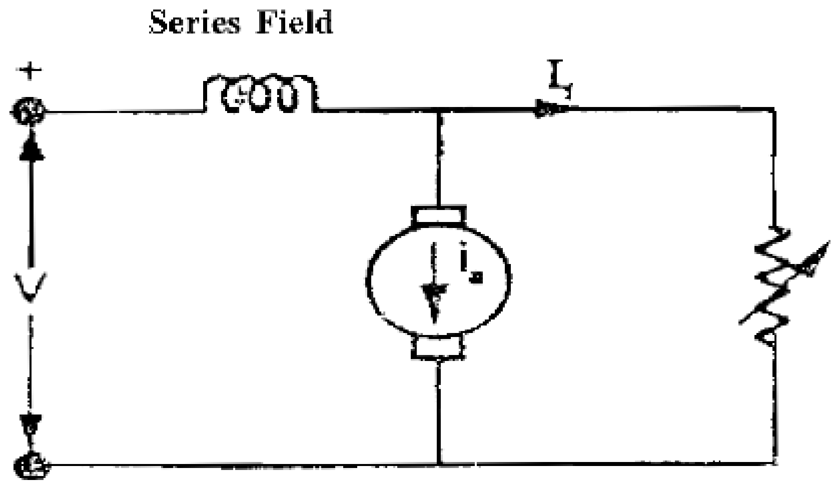
SPEED CONTROL OF D.C. SERIES MOTOR:-

Speed of a D.C. series motor can be controlled by the following methods

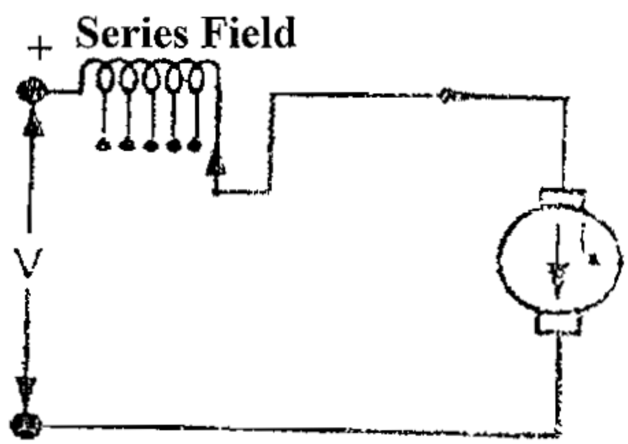
(1) Field Diverter Method:-



(2) **Armature Diverter Method:**



(3) Tapped Field Control



Losses and efficiency

The output of a generator or motor is always less than the input because some of the energy supplied is lost as heat. These losses raise the temperatures of the machine parts above that of surrounding air until such temperatures are reached that the heat losses are radiated as fast as they are generated. Certain of the losses depend upon the load. The temperature rise therefore depends upon the load also, and the maximum allowable temperature rise determines the maximum permissible load that the machine may carry. The limit of output occurs at the load for which the temperature rise becomes high enough to endanger the insulation of the windings.

Thus the consideration of machine losses is important for the following three reasons:

1. Losses appreciably influence the operating cost of the machine.
2. Losses determine the heating of the machine and hence the rating or power output that can be obtained without undue deterioration of the insulation.
3. The voltage drops or current components associated with supplying the losses must be properly accounted for in a machine representation.

Machine efficiency is given by

$$\text{Efficiency} = \frac{\text{output}}{\text{input}}$$

which can also be expressed as

$$\text{Efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} = 1 - \frac{\text{losses}}{\text{input}}$$

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}}$$

Testing of D.C machines

The following important performance tests are conducted on D.C. machines:

1. The magnetization or open circuit test.
2. The load characteristics
3. The determination of efficiency curve.
4. The temperature rise test.

The procedure to conduct the *magnetization* or *open circuit test* and *load characteristic* (external characteristic) *tests* has already been discussed.

The methods for determining efficiency can be divided into following three methods:

(i) Direct method (ii) Indirect method

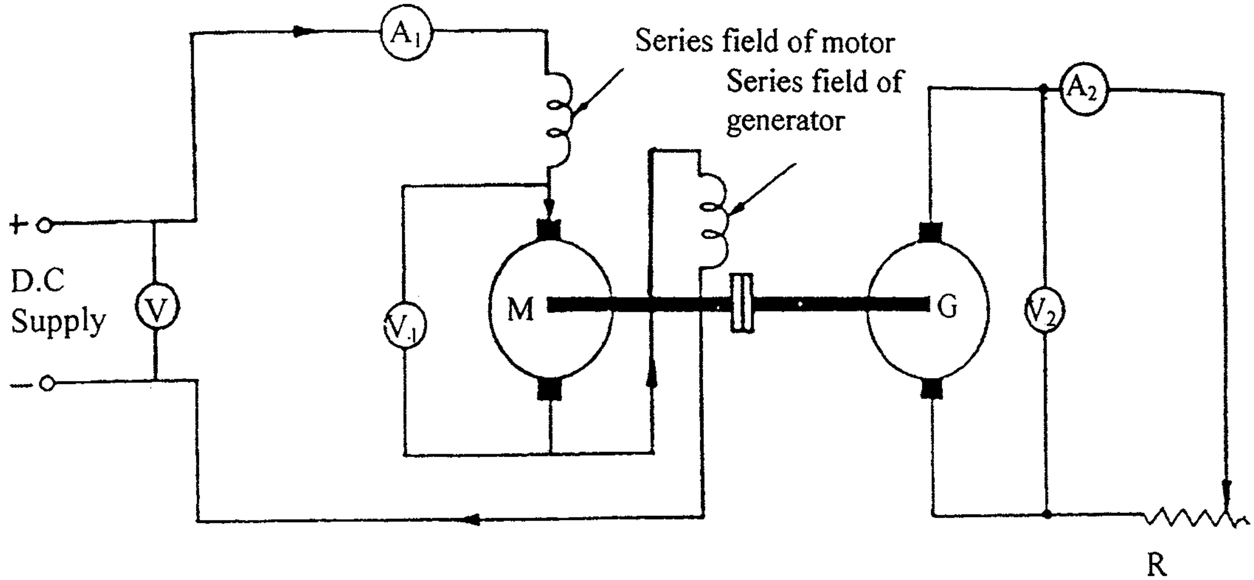
(iii) Regenerative method.

Regenerative method. This method requires two identical machines, one of them works a motor and drives the other, which is mechanically coupled to it. The other machine works as a generator and feed back power into the supply. Thus the *total power drawn from the supply is only for supplying internal losses of the two machines*. Thus even *very large machines may be tested as the power required is small.*

Hopkinson test is a regenerative test for determining efficiency of D.C. machines.

For a d.c shunt motor change of speed from no load to full load is quite small. Therefore, mechanical loss can be assumed to remain same from no load to full load. Also if field current is held constant during loading, the core loss too can be assumed to remain same.

In this test, the motor is run at rated speed under no load condition at rated voltage. Since the motor is operating under no load condition, net mechanical output power is zero. Hence the gross power developed by the armature must supply the core loss and friction & windage losses of the motor.



Let V = supply voltage (reading of voltmeter V)

I_1 = motor input current (reading of ammeter A_1)

V_2 = terminal voltage of generator (reading of voltmeter V_2)

I_2 = load current of generator (reading of ammeter A_2)

R_a = armature resistance of each machine

R_{se} = series field resistance of each machine.

Input to the whole set $= VI_1$

Output $= V_2I_2$

Total losses of the set, $P_t = VI_1 - V_2I_2$

Armature and field copper loss of motor $= I_1^2(R_a + R_{se})$

Armature and field copper loss of generator $= I_2^2 R_a + I_1^2 R_{se}$

Total copper loss of the set, $P_c = I_1^2(R_a + R_{se}) + I_2^2 R_a + I_1^2 R$

$= I_1^2(R_a + 2R_{se}) + I_2^2 R_a$

Stray losses for the set $= P_t - P_c$

Stray losses per machine, $P_s = \dfrac{P_t - P_c}{2}$.

Motor Efficiency:

Motor input $= V_1 I_1$

Motor losses $= I_1^2(R_a + R_{se}) + P_s$

Motor output $= V_1 I_1 - [I_1^2(R_a + R_{se}) + P_s]$

∴ Motor efficiency, $\eta_m = \dfrac{V_1 I_1 - [I_1^2(R_a + R_{se}) + P_s}{V_1 I_1}$

Generator Efficiency:

Generator output $= V_2I_2$

Generator losses $= I_2^2 R_a + I_1^2 R_{se} + P_s$

Generator input $= V_2 I_2 + I_2^2 R_a + I_1^2 R_{se} + P_s$

∴ Generator efficiency, $\eta_e = \dfrac{V_2 I_2}{V_2 I_2 + I_2^2 R_a + I_1^2 R_{se} + P_s}$

Unit 4

Transformers

Introduction:

A transformer may be defined as a static device which converts electrical energy from one circuit to electrical energy into another circuit by principle of mutual induction through magnetic medium without change in frequency and both the circuits are electrically isolated.

Construction of a Transformer:

Basically two types of construction are in common use for the transformers: shell type and core type. In the construction of a shell-type transformer, the two windings are usually wound over the same leg of the magnetic core, as shown in Figure 4.1. In a core-type transformer, shown in Figure 3.2, each winding may be evenly split and wound on both legs of the rectangular core.

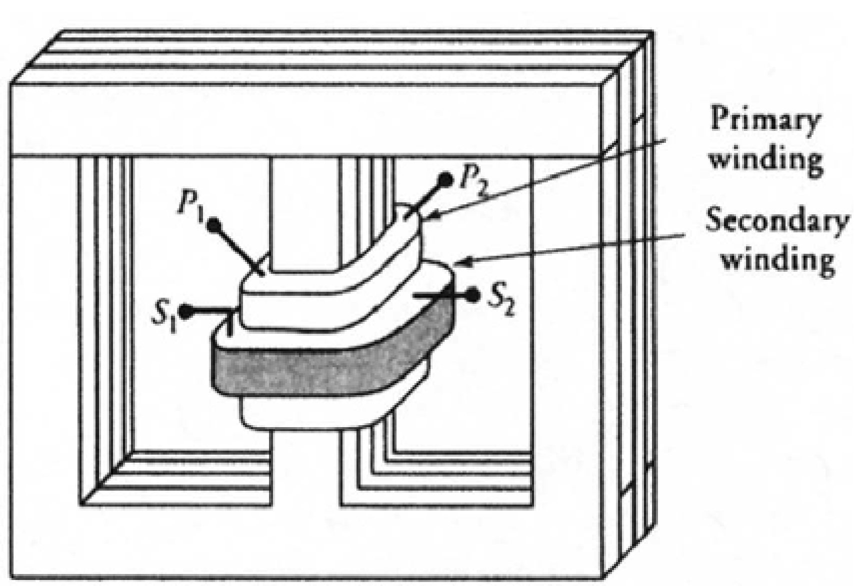


Figure 4.1 Shell-type transformer.

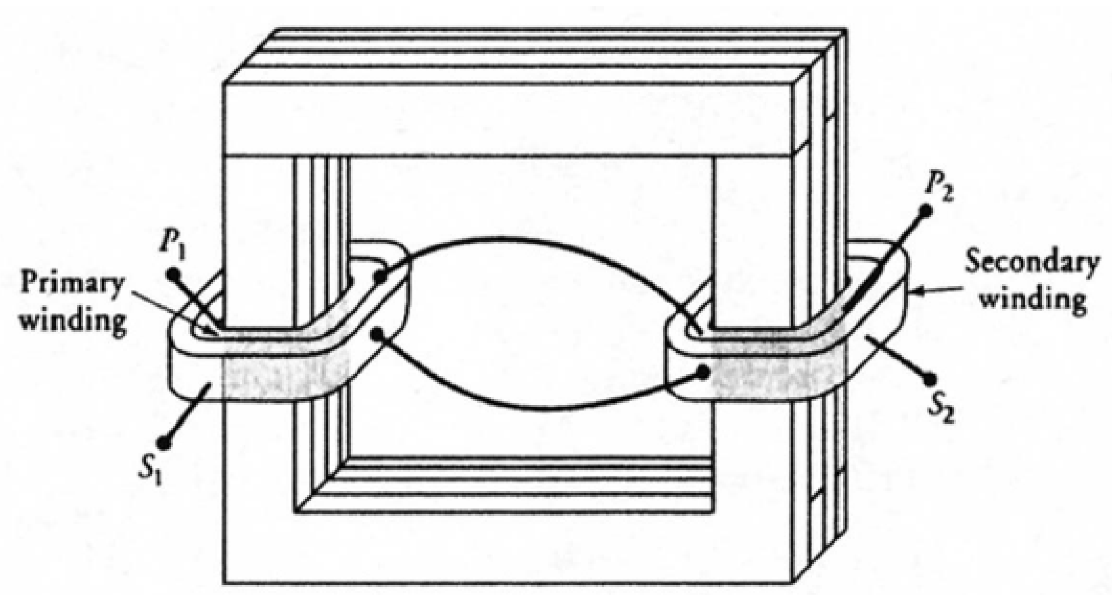


Figure 4.2 Core-type transformer.

For relatively low power applications with moderate voltage ratings, the windings may be wound directly on the core of the transformer. However, for high-voltage and/or high-power transformers, the coils are usually form-wound and then assembled over the core.

Ideal Transformer:

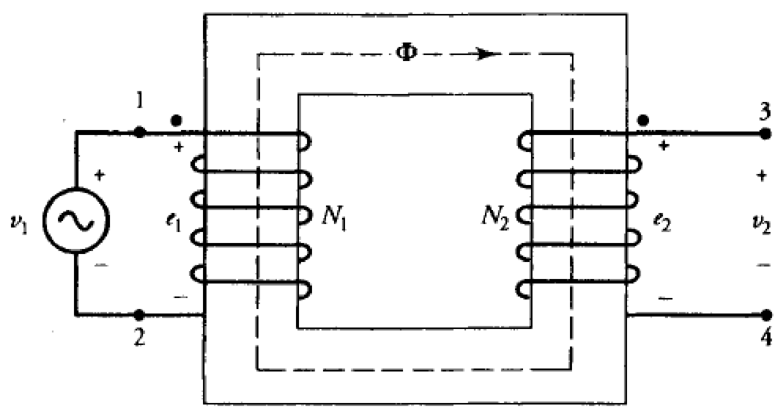


Figure 4.3 Ideal Transformer

Figure 4.3 shown above represents an ideal transformer and would be postulated as following:

a. The core of the transformer is highly permeable in a sense that it requires vanishingly small magneto-motive force (mmf) to set up the flux Φ, as shown in the figure.
b. The core does not exhibit any eddy-current or hysteresis loss.
c. All the flux is confined to circulate within the core.
d. The resistance of each winding is negligible.

Induced EMF

According to Faraday's law of induction:

$$e_1 = N_1 \frac{d\Phi}{dt} \;\&\; e_2 = N_2 \frac{d\Phi}{dt}$$

with its polarity as indicated in the figure.

In the idealized case assumed, the induced emf's e_1 and e_2 are equal to the corresponding terminal voltages v_1 and v_2 , respectively. Thus

$$\frac{v_1}{v_2} = \frac{e_1}{e_2} = \frac{N_1}{N_2}$$

In general we take transformation ratio as $\frac{N_1}{N_2} = a$.

In accordance with our assumptions, the mmf of the primary current $N_1 i_1$, must be equal and opposite to the mmf of the secondary $N_2 i_2$ That is,

$$\text{Or, } \frac{i_1}{i_2} = \frac{N_2}{N_1}$$

It is evident that

$$v_1 i_1 = v_2 i_2$$

This equation simply confirms our assumption of no losses in an idealized transformer. It highlights the fact that, at any instant, the power output (delivered to the load) is equal to the power input (supplied by the source).

For sinusoidal variations in the applied voltage, the magnetic flux in the core also varies sinusoidally under ideal conditions. If the flux in the core at any instant t is given as

$$\Phi = \Phi_m \sin \omega t$$

Hence, $$e_1 = N_1 \omega \Phi_m \cos \omega t$$

Or, $$E_1 = \frac{1}{\sqrt{2}} N_1 \Phi_m \angle 0^0 = 4.44 f N_1 \Phi_m \angle 0^0$$

Similarly, $$E_2 = \frac{1}{\sqrt{2}} N_2 \Phi_m \angle 0^0 = 4.44 f N_2 \Phi_m \angle 0^0$$

Hence, $$\frac{V_1}{V_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2}$$

And $$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

The complex power supplied to the primary winding by the source is equal to the complex power delivered to the load by the secondary winding. i.e.

$$V_1 I_1^* = V_2 I_2^*$$

If Z_2, is the load impedance on the secondary side, then $Z_2 = \frac{V_2}{I_2} = \frac{1}{a^2}\frac{V_1}{I_1} = \frac{1}{a^2} Z_1$

Non-Ideal Transformer:

A non-ideal transformer has lump-sum winding resistances, leakage fluxes and finite permeability.

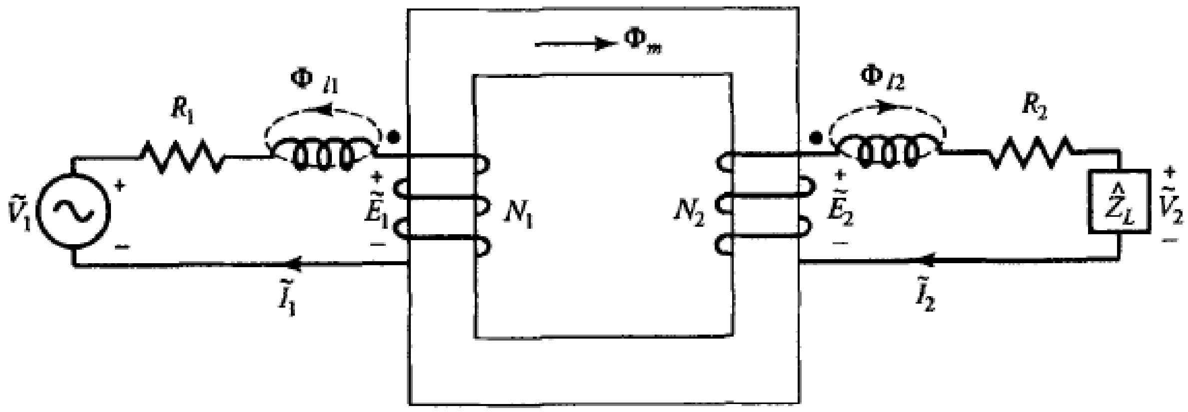


Figure 4.5 Hypothetical windings showing leakage and mutual flux linkages separately

The primary leakage flux set up by the primary does not link the secondary. Likewise, the secondary leakage flux restricts itself to the secondary and does not link the primary. The common flux that circulates in the core and links both windings is termed the mutual flux.
If X_1 & X_2, are the leakage reactances of the primary and secondary windings, a real transformer can then be represented in terms of an idealized transformer with winding resistances and leakage reactances

In the case of a non-ideal transformer,

$$\frac{V_1}{V_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2}$$

And
$$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

And
$$V_1 = E_1 + (R_1 + jX_1)I_1$$
$$V_2 = E_2 - (R_1 + jX_1)I_2$$

For a non-ideal transformer, $V_1 \neq E_1$ & $V_2 \neq E_2$.

The core of a nonideal transformer has finite permeability and core loss. Therefore, even when the secondary is left open (no-load condition) the primary wind**ing** draws some current, **known** as the excitation current, from the source.

$$I_\Phi = I_c + I_m$$

The core-loss component of the excitation current accounts for the magnetic loss (the hysteresis loss and the eddy-current loss) in the core of a transformer.

$$I_c = \frac{E_c}{R_c}$$

The magnetizing component of the excitation current is responsible to set up the mutual flux in the core.

$$jI_m = \frac{E_c}{X_m}$$

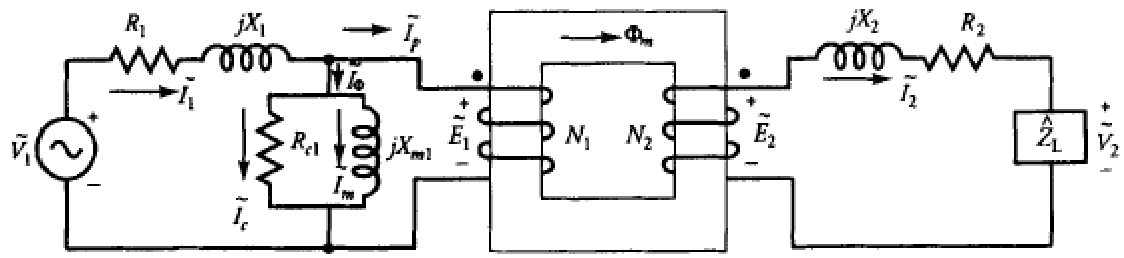


Figure 4.6 Equivalent circuit of a transformer including winding resistances, leakage reactance, core-loss resistance, magnetizing reactance, and an ideal transformer.

When we increase the load on the transformer, the following sequence of events takes place:

- The secondary winding current increases.
- The current supplied by the source increases.
- The voltage drop across the primary winding impedance Z_2, increases.
- The induced emf E_c drops.
- Finally, the mutual flux decreases owing to the decrease in the magnetizing current.

However, in a well-designed transformer, the decrease in the mutual flux from no load to full load is about 1% to 3%.

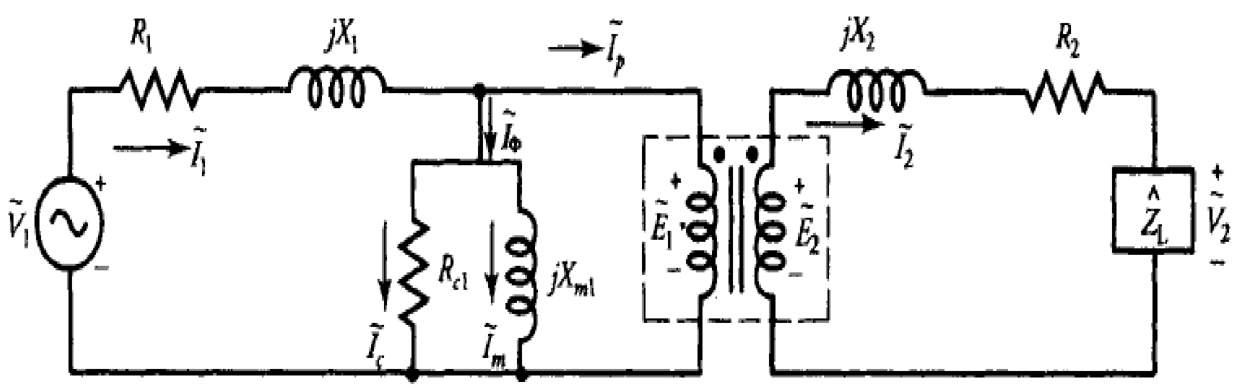


Figure 4.7 An exact equivalent circuit of a real transformer.

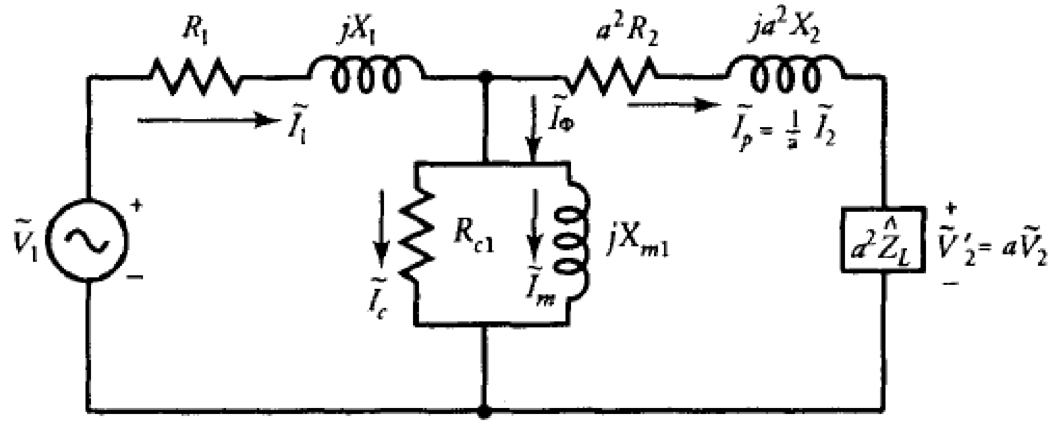


Figure 4.8 The exact equivalent circuit as viewed from the primary side of the transformer.

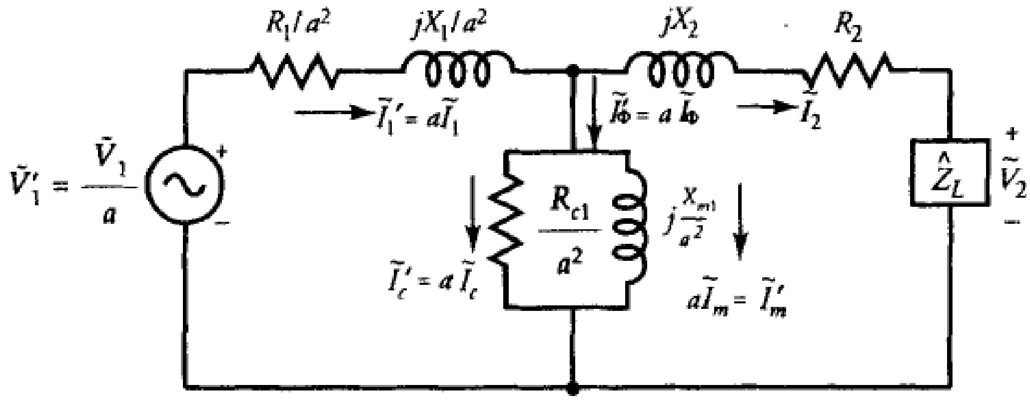


Figure 4.9 An exact equivalent circuit as viewed from the secondary side of the transformer

Phasor Diagram of Non-Ideal Transformer:

When a transformer operates under steady-state conditions, an insight into its currents, voltages, and phase angles can be obtained by sketching its phasor diagram.

Let V_2 be the voltage across the load impedance Z_2, and I_2 be the load current. Depending upon Z_L, I_2 may be leading, in phase with, or lagging V_2. In this particular case, let us assume that I_2 lags V_2, by an angle θ_2. We first draw a horizontal line from the origin of magnitude V_2 to represent the phasor V_2, as shown in Figure 2.11. The current I_2, is now drawn lagging V_2, by θ_2. From circuit 4.10, we have

$$E_2 = V_2 + (R_2 + jX_2)I_2$$

Since the voltage drop I_2R_2, is in phase with I_2, and it is to be added to V_2, we draw a line of magnitude I_2R_2 starting at the tip of V_2, and parallel to I_2. The length of the line from the origin to the tip of I_2R_2, represents the sum of V_2 and I_2R_2. We can now add the voltage drop jI_2X_2

at the tip of $I_2 R_2$ by drawing a line equal to its magnitude and leading I_2 by 90^0. A line from the origin to the tip of $jI_2 X_2$ represents the magnitude of E_2. This completes the phasor diagram for the secondary winding.

The current I_c is in phase with E_1, and I_m lags E_1 by 90^0. These currents are drawn from the origin as shown. The sum of these currents yields the excitation current I_Φ. The source current I_1, is now constructed using the currents I_Φ and I_1 / a, as illustrated in the figure. The voltage drop across the primary-winding impedance $Z_1 = R_1 + jX_1$ is now added to obtain the phasor V_1. The phasor diagram is now complete. In this case, the source current I_1, lags the source voltage V_1.

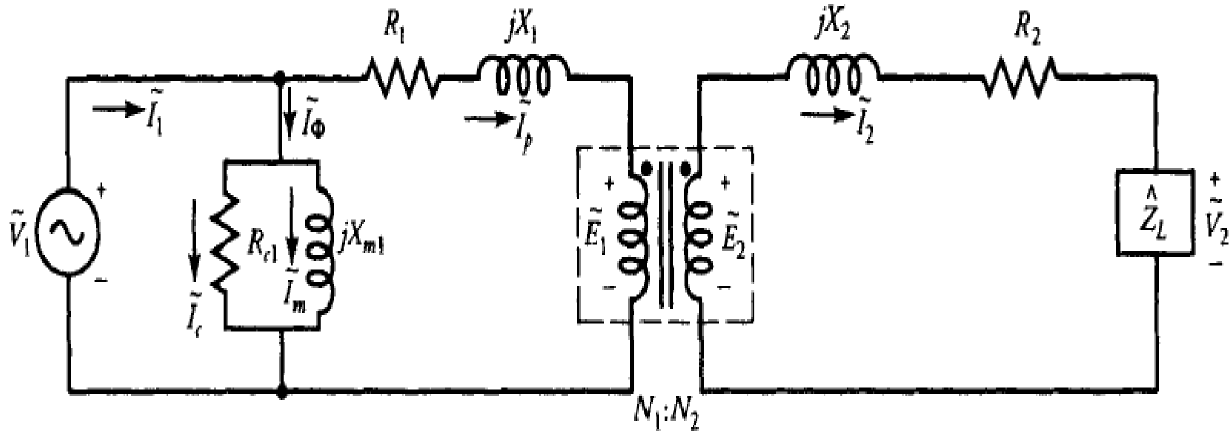


Figure **4.10 An** approximate equivalent circuit of a transformer embodying an ideal transformer.

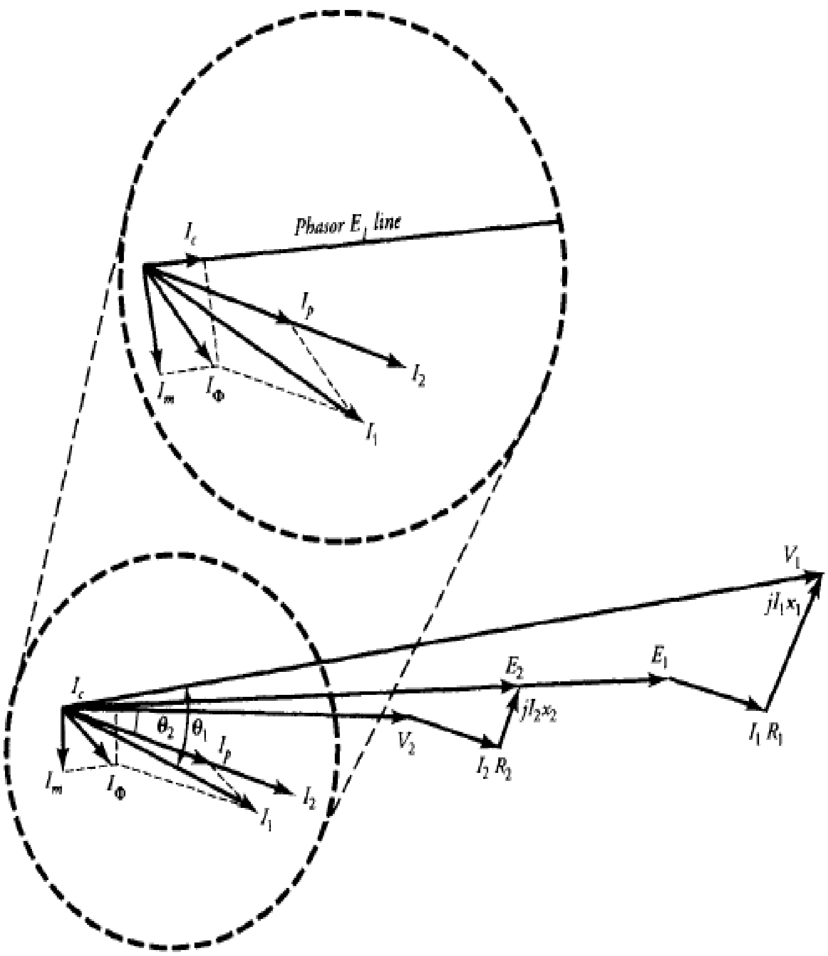


Figure 4.11 The phasor diagram of a non-ideal transformer of Figure 4.8.

Voltage Regulation:

Consider a transformer whose primary winding voltage is adjusted so that it delivers the rated load at the rated secondary terminal voltage. If we now remove the load, the secondary terminal voltage changes because of the change in the voltage drops across the winding resistances and leakage reactances. A quantity of interest is the net change in the secondary winding voltage from no load to full load for the same primary winding voltage. When the change is expressed as a percentage of its rated voltage, it is called the voltage regulation *(VR)* of the transformer. As a percent, it may be written as

$$\%VR = \frac{V_{2NL} - V_{2FL}}{V_{2FL}}$$

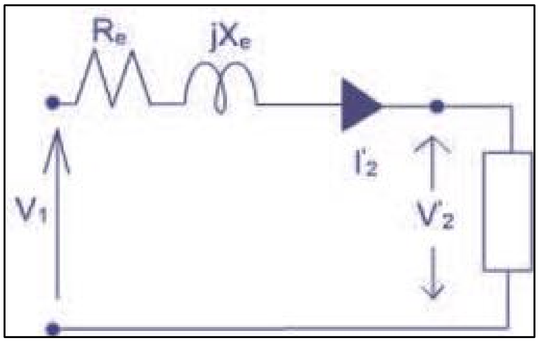
where V_{2NL} and V_{2FL} are the effective values of no-load and full-load voltages at the secondary terminals. The voltage regulation is like the figure-of-merit of a transformer. **For** an ideal transformer, the voltage regulation is zero. The smaller the voltage regulation, the better the operation of the transformer.

The expressions for the percent voltage regulation for the approximate equivalent circuits as viewed from the primary and the secondary sides are

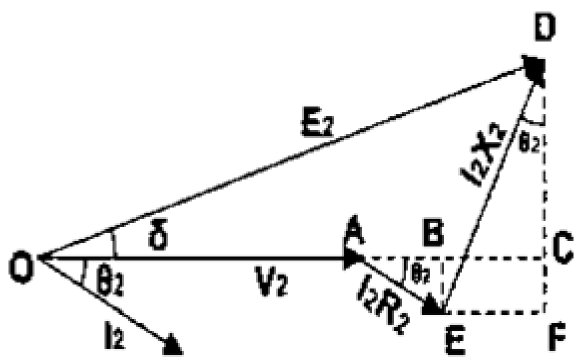
$$\%VR = \frac{V_1 - aV_2}{aV_2}$$

$$\%VR = \frac{(V_1 / a) - V_2}{V_2}$$

where V_1, is the full-load voltage on the primary side and V_2 is the rated voltage at the secondary.



Equivalent Circuit



Voltage regulation at lagging power factor

In the case of transformers both definitions result in more or less the same value for the regulation as the transformer impedance is very low and the power factor of operation is quite high. The power factor of the load is defined with respect to the terminal voltage on load. Hence a convenient starting point is the load voltage. Also the full load output voltage is taken from the name plate. Hence regulation up has some advantage when it comes to its application. Figure above shows the phasor diagram of operation of the transformer under loaded condition. The no-load current I_0 is neglected in view of the large magnitude of I_2' .Then $I_1 = I_2'$

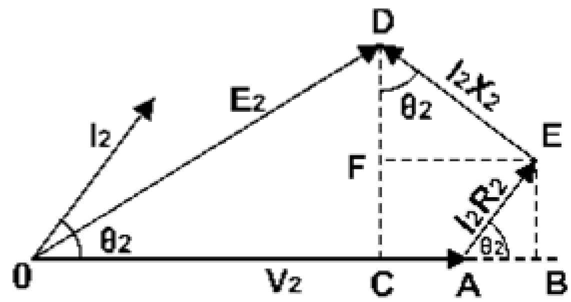
$$OC = OA + AB + BC$$
$$Here,\ OA = V_2$$
$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$
$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$

Angle between OC & OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB + BC$$
$$E_2 = OC = V_2 + I_2 R_2 cos\theta_2 + I_2 X_2 sin\theta_2$$

Voltage regulation of transformer at lagging power factor,

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



Voltage Regulation at Leading Power Factor

$$OC = OA + AB - BC$$
$$Here,\ OA = V_2$$
$$Here,\ AB = AE\cos\theta_2 = I_2 R_2 \cos\theta_2$$
$$and,\ BC = DE\sin\theta_2 = I_2 X_2 \sin\theta_2$$

Angle between OC & OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

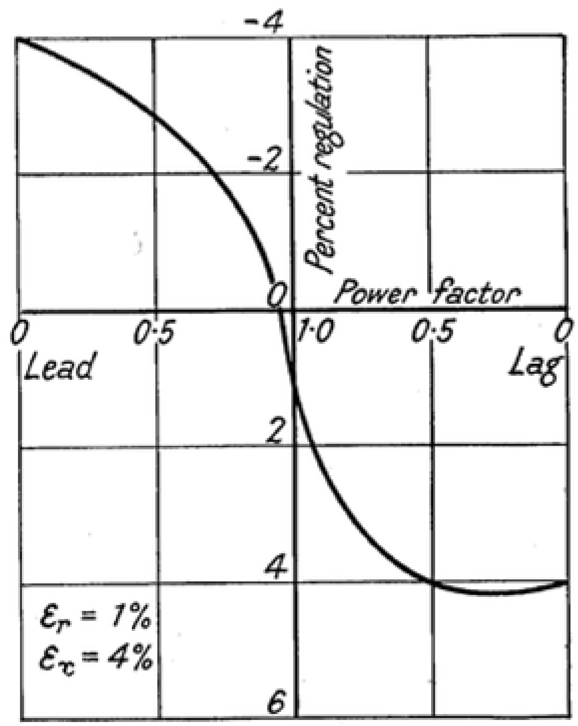
$$E_2 = OC = OA + AB - BC$$
$$E_2 = OC = V_2 + I_2 R_2 cos\theta_2 - I_2 X_2 sin\theta_2$$

Voltage regulation of transformer at leading power factor,

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

It can be seen from the above expression, the full load regulation becomes zero when the power factor is leading or the power factor angle $\Phi = \tan^{-1}(\frac{R_e}{X_e})$ leading.

Similarly, the value of the regulation is maximum at a power factor angle $\Phi = \tan^{-1}(\frac{R_e}{X_e})$ lagging.



Regulation Curve

It is seen from Figure above that the full load regulation at unity power factor is nothing but the percentage resistance of the transformer. It is therefore very small and negligible. Only with low power factor loads the drop in the series impedance of the transformer contributes substantially to the regulation.

Efficiency:

Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. Putting in the form of an expression,

$$\text{Efficiency } \eta = \frac{OutputPower}{InputPower} = \frac{InputPower - Losses}{InputPower} = 1 - \frac{losses}{Input}$$

More conveniently the efficiency is expressed in percentage.

$$\%\eta = \frac{Output}{Input}$$

A typical curve for the variation of efficiency as a function of output is given in Figure below. The losses that take place inside the machine expressed as a fraction of the input is sometimes termed as deficiency. Except in the case of an ideal machine, a certain fraction of the input power gets lost inside the machine while handling the power. Thus the value for the efficiency is always less than one.. The losses taking place inside a transformer can be enumerated as below:

1. Primary copper loss
2. Secondary copper loss
3. Iron loss

These are explained in sequence below.
Primary and secondary copper losses take place in the respective winding resistances due to the ow of the current in them.

$$P_c = I_1^2 r_1 + I_2^2 r_2 = I_2'^2 R_e$$

The primary and secondary resistances differ from their d.c. values due to skin effect and the temperature rise of the windings. While the average temperature rise can be approximately used, the skin effect is harder to get analytically. The short circuit test gives the value of R_e taking into account the skin effect. The iron losses contain two components - Hysteresis loss and Eddy current loss. The Hysteresis loss is a function of the material used for the core.

$$P_h = K_h f B_m^{1.6}$$

For constant voltage and constant frequency operation this can be taken to be constant. The eddy current loss in the core arises because of the induced emf in the steel lamination sheets and the eddies of current formed due to it. This again produces a power loss Pe in the lamination.

$$P_e = K_e f^2 B_m^2 t^2$$

where t is the thickness of the steel lamination used. As the lamination thickness is much smaller than the depth of penetration of the field, the eddy current loss can be reduced by reducing the thickness of the lamination. Present day laminations are of 0.25 mm thickness and are capable of operation at 2 Tesla. These reduce the eddy current losses in the core. This loss also remains constant due to constant voltage and frequency of operation.

The expression for the efficiency of the transformer operating at a fractional load x of its rating, at a load power factor of θ_2, can be written as

$$\eta = \frac{xS\cos\theta_2}{xS\cos\theta_2 + P_{const} + x^2 P_{\text{var}}}$$

Here S in the volt ampere rating of the transformer ($V_2' I_2'$ at full load), P_{const} being constant losses and P_{var} the variable losses at full load. For a given power factor an expression for η in terms of the variable x is thus obtained. By differentiating η with respect to x and equating the same to zero, the condition for maximum efficiency is obtained. In the present case that condition comes out to be

$$P_{const} = x^2 P_{\text{var}}$$

That is, when constant losses equal the variable losses at any fractional load x the efficiency reaches a maximum value. The maximum value of that efficiency at any given power factor is given by,

$$\eta = \frac{xS\cos\theta_2}{xS\cos\theta_2 + 2P_{const}}$$

$$\eta_{\max} = \frac{xS\cos\theta_2}{xS\cos\theta_2 + 2x^2 P_{\text{var}}}$$

From the expression for the maximum efficiency it can be easily deduced that this maximum value increases with increase in power factor and is zero at zero power factor of the load.

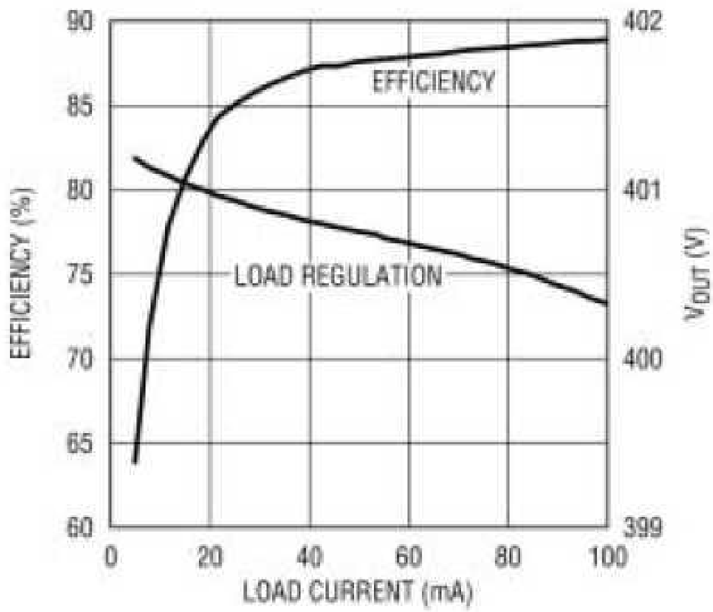


Figure 3b: Efficiency Curve with Secondary-Side Output Sense

All Day Efficiency:

Large capacity transformers used in power systems are classified broadly into Power transformers and Distribution transformers. The former variety is seen in generating stations and large substations. Distribution transformers are seen at the distribution substations.
The basic diference between the two types arise from the fact that the power transformers are switched in or out of the circuit depending upon the load to be handled by them. Thus at 50% load on the station only 50% of the transformers need to be connected in the circuit. On the other hand a distribution transformer is never switched off.
on the transformer continuously changes. This has been presented by a stepped curve for convenience. The average load can be calculated by

Average load over a day $= \sum_{i=1}^{n} P_i / 24 = \dfrac{S_n \sum_{i=1}^{n} x_i^2 t_i}{24}$

where P_i is the load during an interval i. n intervals are assumed. x_i is the fractional load. $S_i = x_i S_n$ where S_n is nominal load. The average loss during the day is given by

$$\text{Average load over a day} = P_i + \frac{P_c \sum_{i=1}^{n} x_i^2 t_i}{24}$$

Testing of Transformer:

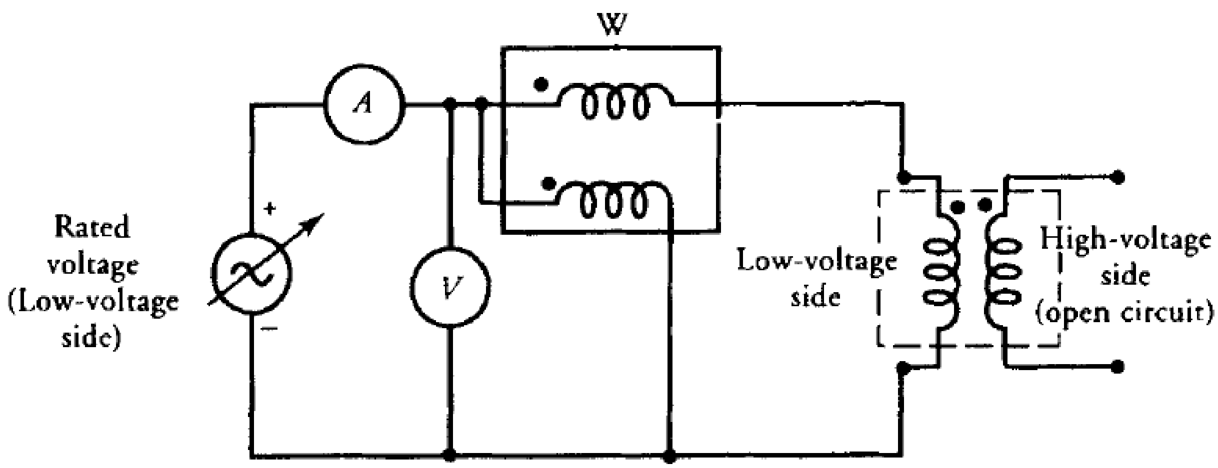
Open Circuit Test:

one winding of the transformer is left open while the other is excited by applying the rated voltage. The frequency of the applied voltage must be the rated frequency of the transformer. Although it does not matter which side of the transformer is excited, it is safer to conduct the test on the low-voltage side. Another justification for performing the test on the low-voltage side is the availability of the low-voltage source in any test facility. Figure 2.21 shows the connection diagram for the open-circuit test with ammeter, voltmeter, and wattmeter inserted on the low-voltage side.

$$S_{oc} = V_{oc} I_{oc} \text{ at a lagging power-factor angle of } \Phi_{oc} = \cos^{-1}\left(\frac{P_{oc}}{S_{oc}}\right)$$

The core-loss and magnetizing currents are

$$I_c = I_{oc}\cos(\Phi_{oc}) \;\&\; I_m = I_{oc}\sin(\Phi_{oc})$$



A two-winding transformer wired with instruments for open-circuit test.

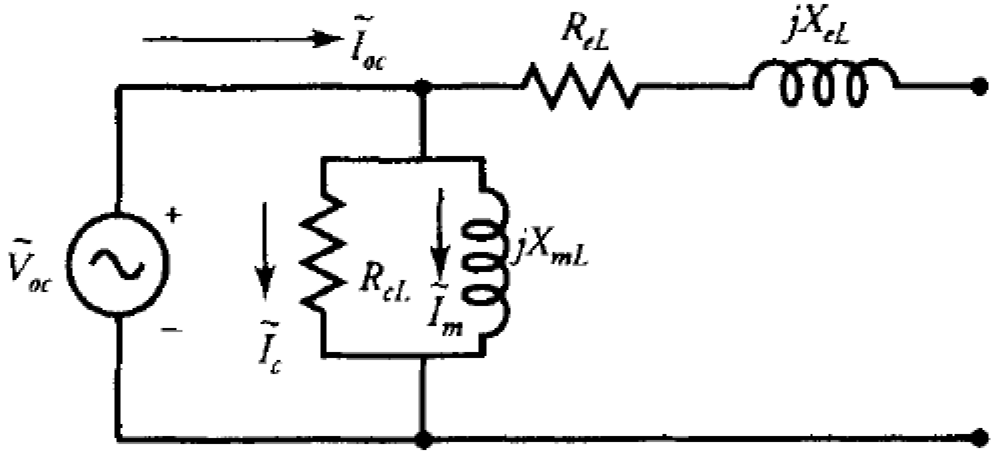


Figure 4.12 The approximate equivalent circuit of a two-winding transformer under open-circuit test.

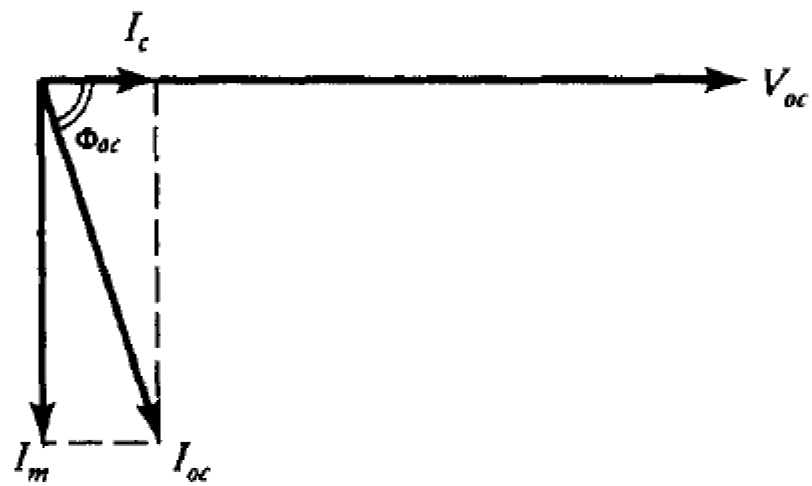


Figure **4.13** The phasor diagram of a **two-winding** transformer under open-circuit test.

Thus, the core-loss resistance and the magnetizing reactance as viewed from the low-voltage side are

$$R_{cL} = \frac{V_{oc}}{I_c} = \frac{V_{oc}^{\ 2}}{P_{oc}} \text{ and } X_{mL} = \frac{V_{oc}}{I_m} = \frac{V_{oc}^{\ 2}}{Q_{oc}}$$

$$Q_{oc} = \sqrt{S_{oc}^2 - P_{oc}^2}$$

Short Circuit test:

This test is designed to determine the winding resistances and leakage reactances. The short-circuit test is conducted by placing a short circuit across one winding and exciting the other from an alternating-voltage source of the frequency at which the transformer is rated. Since the short circuit constrains the power output to be zero, the power input to the transformer is low. The low

power input at the rated current implies that the applied voltage is a small fraction of the rated voltage. Therefore, extreme care must be exercised in performing this test.
. In this case, the wattmeter records the copper loss at full load.
If V_{sc}, I_{sc} and P_{sc} are the readings on the voltmeter, ammeter, and wattmeter, then

$$R_{eH} = \frac{P_{sc}}{I_{sc}^2}$$

$$X_{eH} = \sqrt{Z_{eH}^2 - R_{eH}^2}$$

$$Z_{eH} = \frac{V_{sc}}{I_{sc}}$$

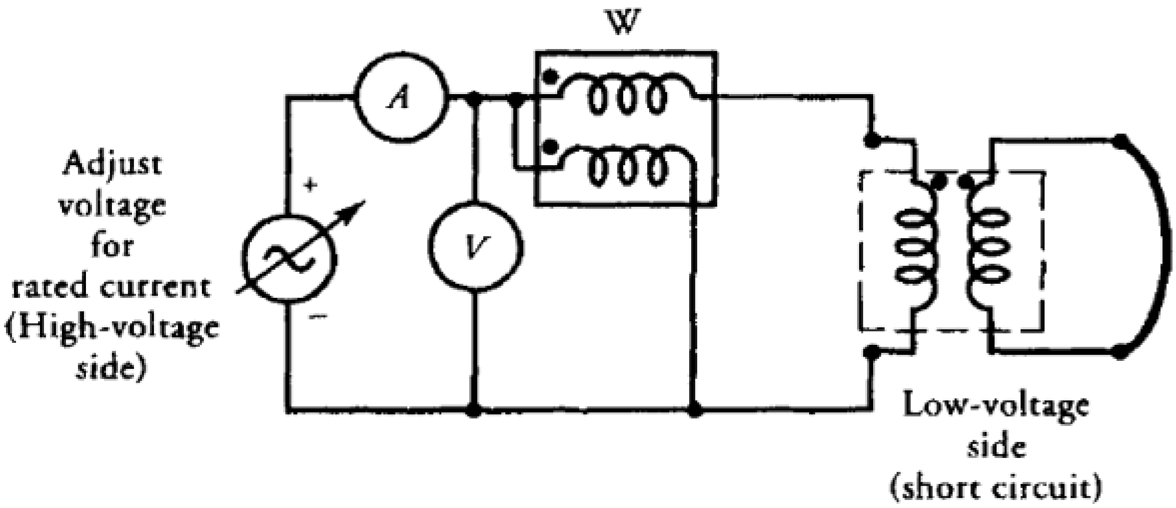


Figure 4.14 A two-winding transformer wired for short-circuit test.

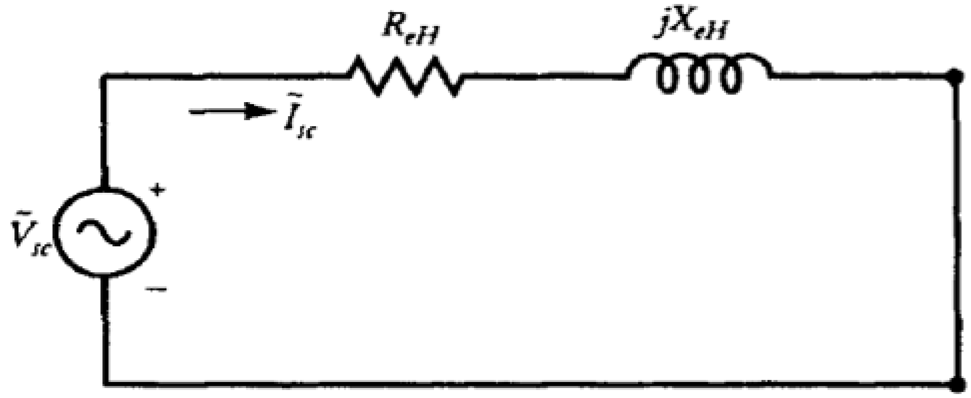


Figure 4.15 An approximate equivalent circuit of a two-winding transformer under short-circuit condition.

Then

$$I_H^2 R_H = I_L^2 R_L$$

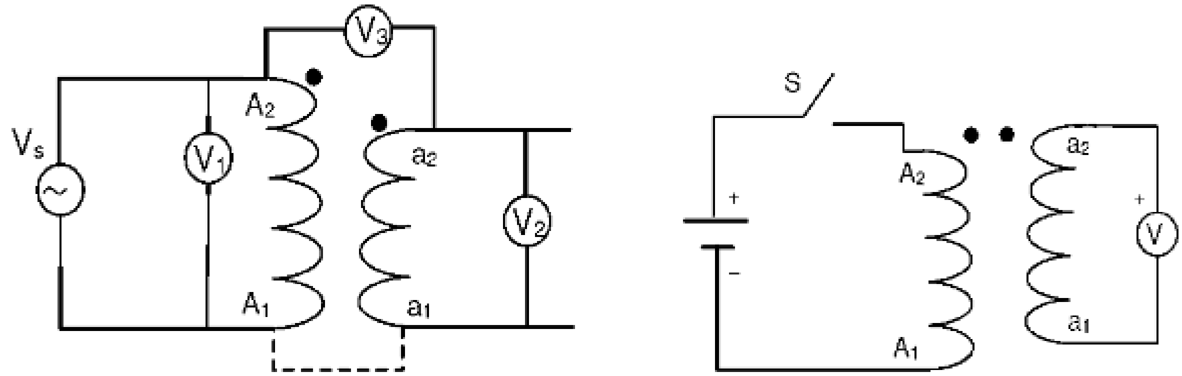
$$R_{eH} = R_H + a^2 R_L$$

$$X_{eH} = X_H + a^2 X_L$$

Where R_H is the resistance of the high-voltage winding, R_L, is the resistance of the low-voltage winding, X_H is the leakage reactance of the high-voltage winding, and X_L, is the leakage reactance of the low-voltage winding.

Polarity Test:

This is needed for identifying the primary and secondary phasor polarities. It is a must for poly phase connections. Both a.c. and d.c methods can be used for detecting the polarities of the induced emfs. The dot method discussed earlier is used to indicate the polarities. The transformer is connected to a low voltage a.c. source with the connections made as shown in the figure below. A supply voltage Vs is applied to the primary and the



(a)A.C.test (b)D.C.test

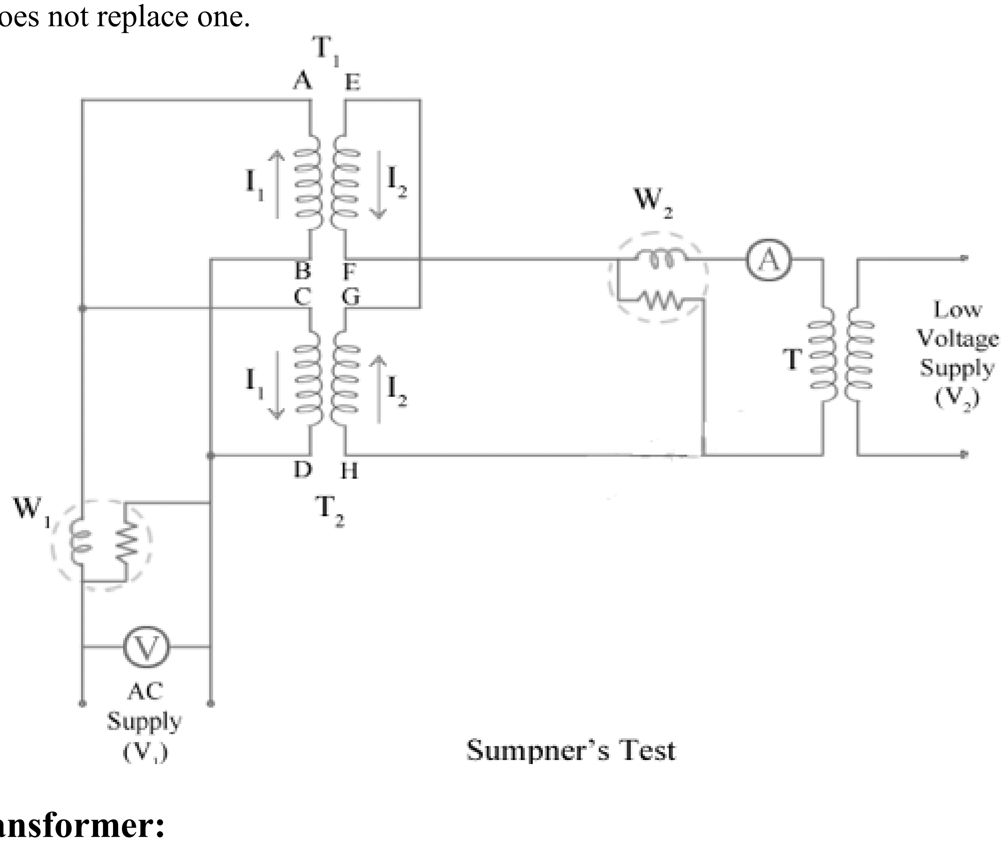
readings of the voltmeters V1, V2 and V3 are noted. V1 : V2 gives the turns ratio. If V3 reads V1-V2 then assumed dot locations are correct (for the connection shown). The beginning and end of the primary and secondary may then be marked by A1,A2 and a1,a2 respectively. If the voltage rises from A1 to A2 in the primary, at any instant it does so from a1 to a2 in the secondary. If more secondary terminals are present due to taps taken from the windings they can be labeled as a3; a4; a5; a6. It is the voltage rising from smaller number towards larger ones in each winding. The same thing holds good if more secondaries are present. Figure above shows the d.c. method of testing the polarity. When the switch S is closed if the secondary voltage shows a positive reading, with a moving coil meter, the assumed polarity is correct. If the meter kicks back the assumed polarity is wrong.

Sumpner's Test (Back to Back test):

Load Test helps to determine the total loss that takes place, when the transformer is loaded. Unlike the tests described previously, in the present case nominal voltage is applied across the primary and rated current is drown from the secondary. Load test is used mainly

1. to determine the rated load of the machine and the temperature rise
2. To determine the voltage regulation and efficiency of the transformer.

Rated load is determined by loading the transformer on a continuous basis and observing the steady state temperature rise. The losses that are generated inside the transformer on load appear as heat.
This heats the transformer and the temperature of the transformer increases. The insulation of the transformer is the one to get a_ected by this rise in the temperature. Both paper and oil which are used for insulation in the transformer start getting degenerated and get decomposed. If the ash point of the oil is reached the transformer goes up in ames.
Hence to have a reasonable life expectancy the loading of the transformer must be limited to that value which gives the maximum temperature rise tolerated by the insulation. This aspect of temperature rise cannot be guessed from the electrical equivalent circuit. Further, the losses like dielectric losses and stray load losses are not modeled in the equivalent circuit and the actual loss under load condition will be in error to that extent.
In the equivalent loss method a short circuit test is done on the transformer. The short circuit current is so chosen that the resulting loss taking place inside the transformer is equivalent to the sum of the iron losses, full load copper losses and assumed stray load losses. By this method even though one can pump in equivalent loss inside the transformer, the actual distribution of this loss vastly differs from that taking place in reality. Therefore this test comes close to a load test but does not replace one.



Sumpner's Test

Autotransformer:

When the two windings of a transformer are interconnected electrically, it is called autotransformer. The direct electrical connection between the windings ensures that a part of the energy is transferred from the primary to the secondary by conduction. The magnetic coupling between the windings guarantees that some of the energy is also delivered by induction. Autotransformers may be used for almost all applications in which we use a two-winding transformer. The only disadvantage in doing so is the loss of electrical isolation between the high- and low-voltage sides of the autotransformer. Listed below are some of the advantages of an autotransformer compared with a two-winding transformer.

1. It is cheaper in first cost than a conventional two-winding transformer of a similar rating.
2. It delivers more power than a two-winding transformer of similar physical dimensions.
3. For a similar power rating, an autotransformer is more efficient than a twowinding transformer.
4. An autotransformer requires lower excitation current than a two-winding transformer to establish the same flux in the core.

The two-winding transformer is connected as a step-down autotransformer. Note that the secondary winding of the two-winding transformer is now the common winding for the autotransformer. Under ideal conditions,

$$\tilde{V}_{1a} = \tilde{E}_{1a} = \tilde{E}_1 + \tilde{E}_2$$

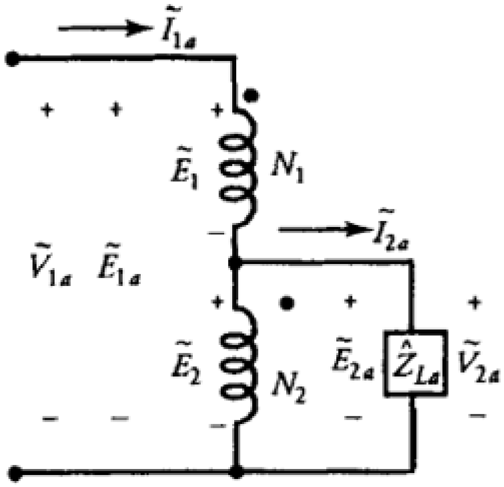
$$\tilde{V}_{2a} = \tilde{E}_{2a} = \tilde{E}_2$$

$$\frac{\tilde{V}_{1a}}{\tilde{V}_{2a}} = \frac{\tilde{E}_{1a}}{\tilde{E}_{2a}} = \frac{\tilde{E}_1 + \tilde{E}_2}{\tilde{E}_2} = \frac{N_1 + N_2}{N_2} = 1 + a = a_T$$

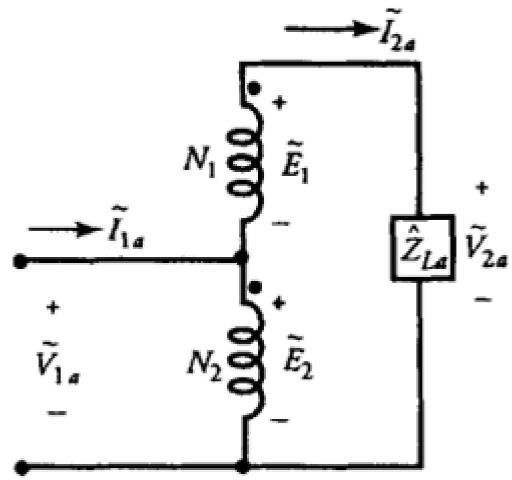
where $a = N_1/N_2$ is the a-ratio of a two-winding transformer, and $a_T = 1 + a$ is the a-ratio of the autotransformer under consideration. The a-ratio for the other connections should also be computed in the same way. Note that a_T is not the same for all connections.

In an ideal autotransformer, the primary mmf must be equal and opposite to the secondary mmf. That is,

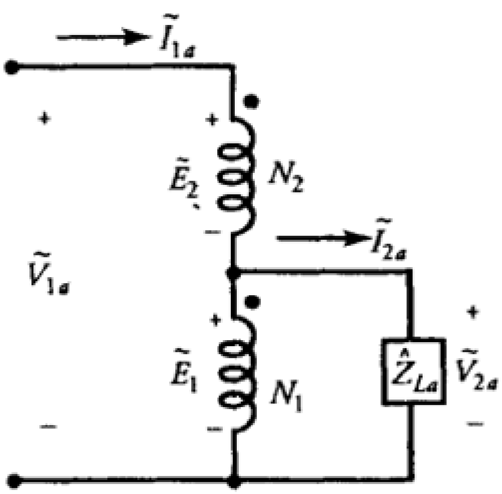
$$(N_1 + N_2)I_{1a} = N_2 I_{2a}$$



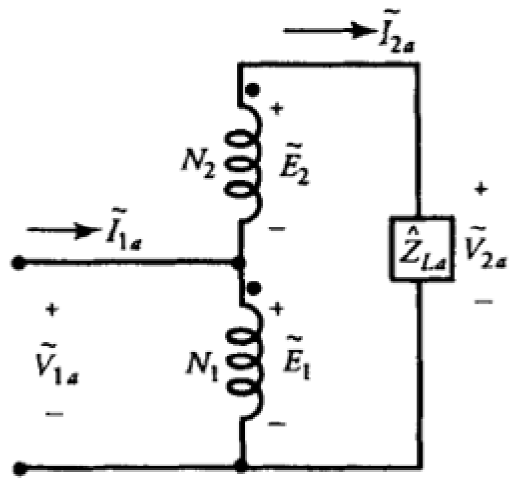
(a) $(V_1 + V_2)/\ V_2$ step-down connection.



(b) $V_2/(V_1 + V_2)$ step-up connection.



(c) $(V_1 + V_2)/\ V_1$ step-down connection.



(d) $V_1/(V_1 + V_2)$ step-up connection.

Possible ways to connect two winding transformer as an Auto Transformer

From this equation we obtain,

$$\frac{I_{2a}}{I_{1a}} = \frac{N_1 + N_2}{N_2} = 1 + a = a_T$$

Thus apparent power supplied by an ideal transformer to load is

$$\begin{aligned} S_{oa} &= V_{2a} I_{2a} \\ &= \left[\frac{V_{1a}}{a_T}\right][a_T\, I_{1a}] \\ &= V_{1a} I_{1a} \\ &= S_{ina} \end{aligned}$$

Let us now express the apparent output power in terms of the parameters of a two-winding transformer. For the configuration under consideration,

$$V_{2a} = V_2$$

and

$$I_{2a} = a_T I_{1a} = (a + 1)I_{1a}$$

However, for the rated load, $I_{1a} = I_1$. Thus,

$$\begin{aligned} S_{oa} &= V_2 I_1(a + 1) \\ &= V_2 I_2 \frac{a + 1}{a} = S_o \left[1 + \frac{1}{a}\right] \end{aligned}$$

where $S_o = V_2 I_2$ is the apparent power output of a two-winding transformer. This power is associated with the common winding of the autotransformer. This, therefore, is the power transferred to the load by induction in an autotransformer. The rest of the power, S_o / a in this case, is conducted directly from the source to the load and is called the **conduction power**. Hence, a two-winding transformer delivers more power when connected as an autotransformer.

Unit 5

Transformers

Three Phase Transformers:

Since most **of** the power generated and transmitted over long distances is of the three-phase type, **we** can use three exactly alike single-phase transformers to form a single three-phase transformer. For economic reasons, however, a three-phase transformer is designed to have all **six** windings on a common magnetic core. **A** common magnetic core, three-phase transformer can also be either a core type (Figure **3.1)** or a shell type (Figure **3.2).**

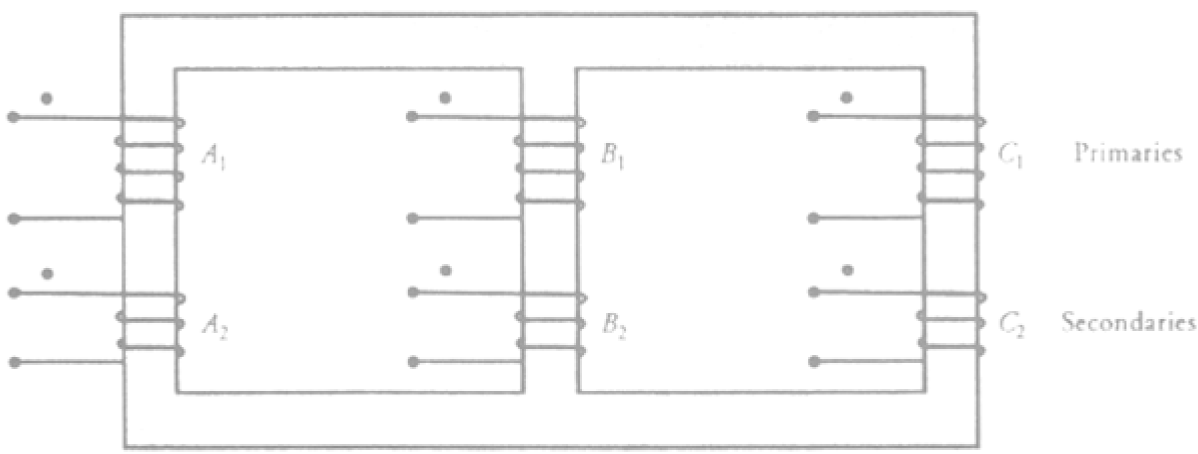


Figure 3.1 Core Type

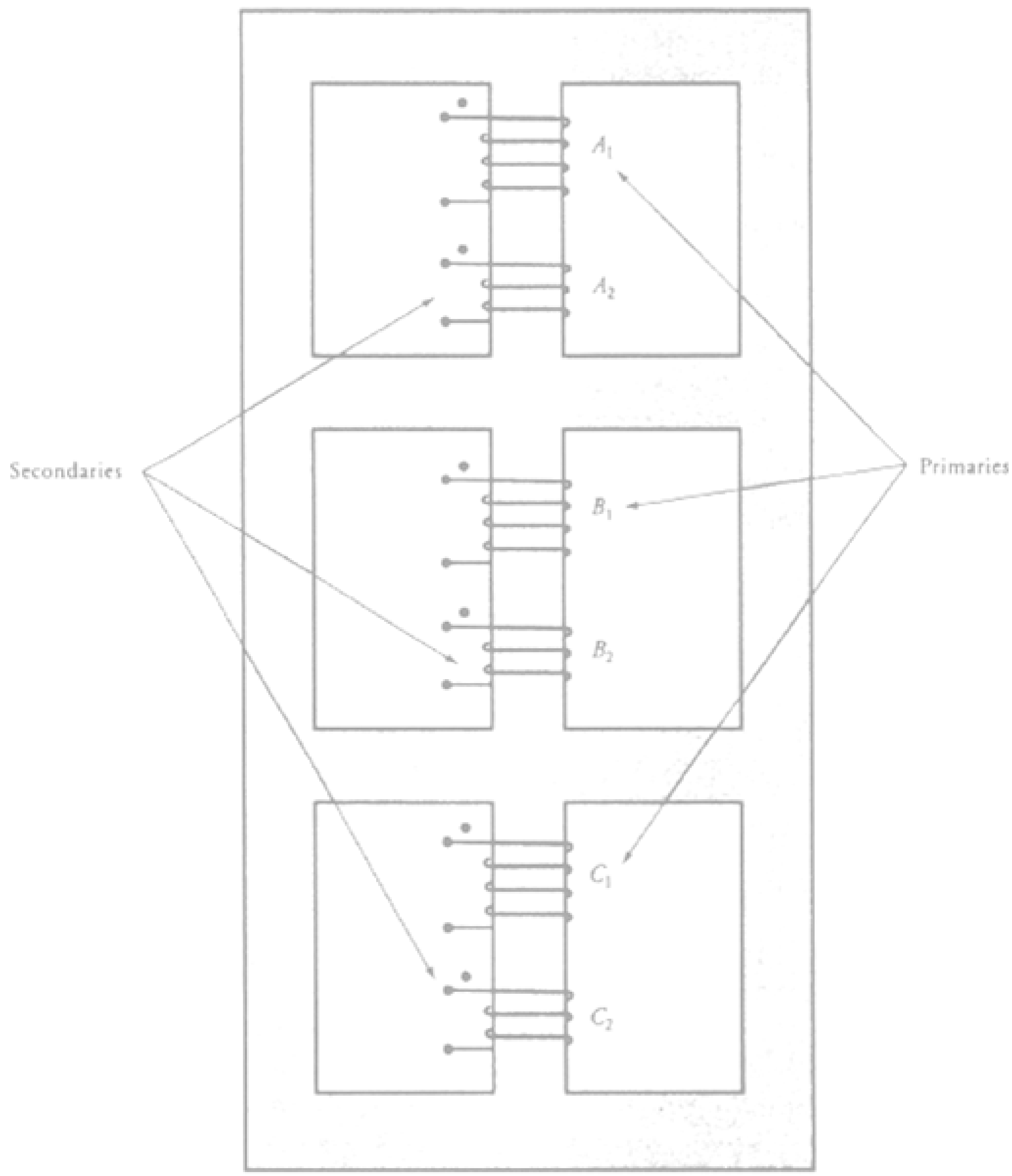
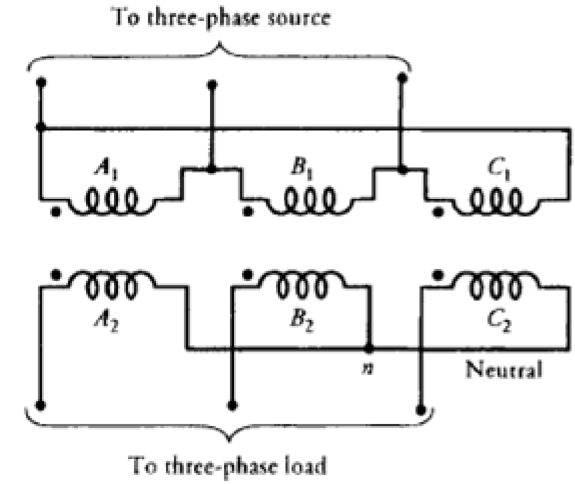
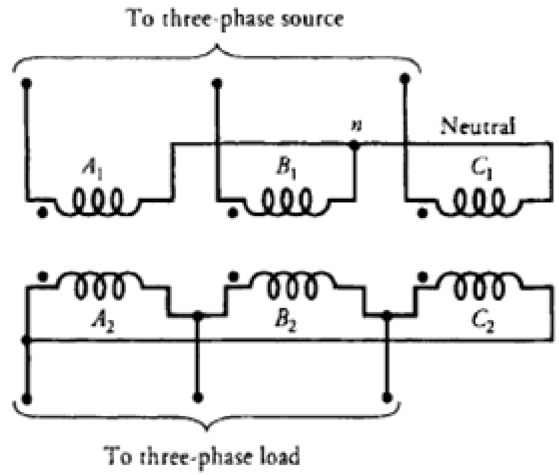


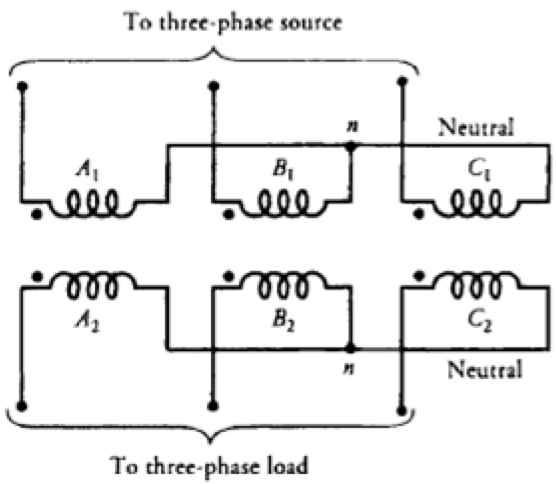
Figure 3.2 Shell Type

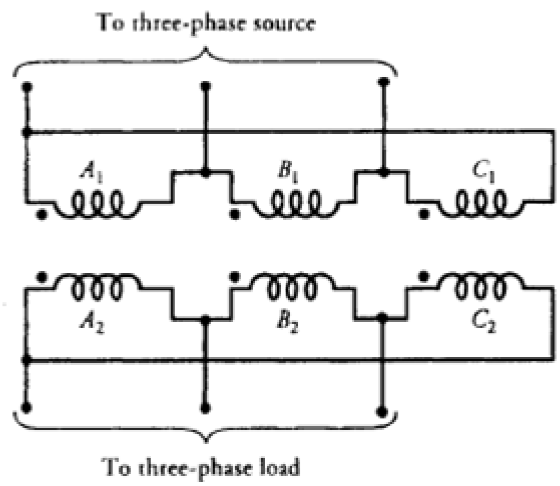
Since the third harmonic flux created by each winding is in phase, a shell-type transformer is preferred because it provides an external path for this flux. In other words, the voltage waveforms are less distorted for a shell-type transformer than for a core-type transformer of similar ratings. The three windings on either side of a three-phase transformer can be connected either in wye (Y) or in delta (A). Therefore, a three-phase transformer can be connected in four possible ways: Y/Y, Y/A, A/Y, and A/A.

Star and mesh connections are very commonly used. Apart from these, vee or open delta connections, zig zag connections , T connections, auto transformer connections, multi winding transformers etc. are a few of the many possibilities. A few of the common connections and the technical and economic considerations that govern their usage are discussed here. Literature abounds in the description of many other. Apart from the characteristics and advantages of these,









one must also know their limitations and problems, to facilitate proper selection of a con_guration for an application. Many polyphase connections can be formed using single phase transformers. In some cases it may be preferable to design, develop and deploy a polyphase transformer itself. In a balanced two phase system we encounter two voltages that are equal in magnitude di_ering in phase by 90 degree. Similarly, in a three phase system there are three equal voltages di_ering in phase 120 electrical degrees. Further there is an order in which they reach a particular voltage magnitude. This is called the phase sequence. In some applications like a.c. to d.c. conversion, six phases or more may be encountered. Transformers used in all these applications must be connected properly for proper functioning.
. These connections are broadly classi_ed into 4 popular vector groups.

1. Group I: zero phase displacement between the primary and the secondary.
2. Group II: 180^0 phase displacement.
3. Group III: 30^0 lag phase displacement of the secondary with respect to the primary.
4. Group IV: 30^0 lead phase displacement of the secondary with respect to the primary.

The capital letters indicates primary and the small letters the secondary. D/d stand for mesh, Y/y for star, Z/z for zig-zag. The angular displacement of secondary with respect to the primary are shown as clock position, 0^0 referring to 12 o'clock position. These vector groups are especially important when two or more transformers are to be connected in parallel.

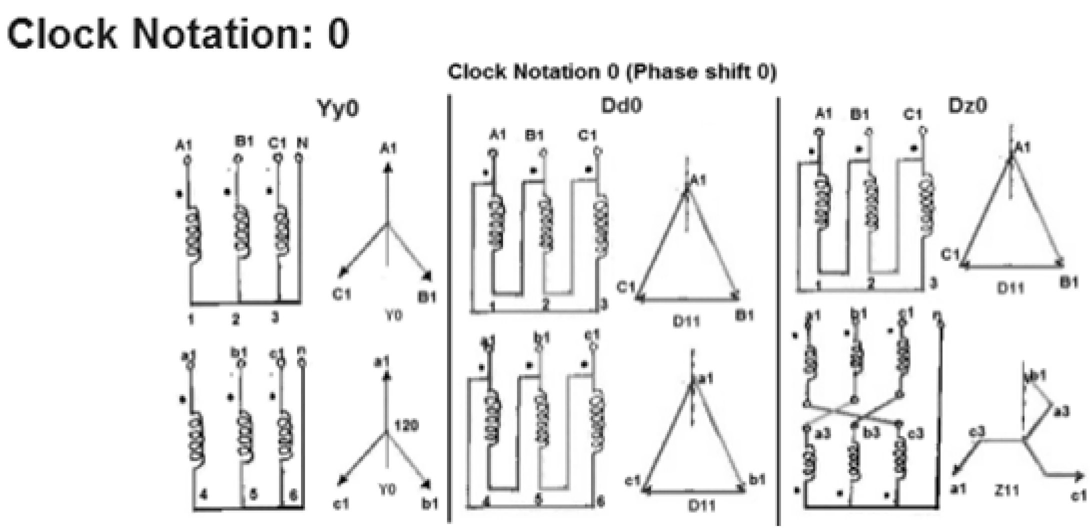
Star connection is normally cheaper as there are fewer turns and lesser cost of insulation. The advantage becomes more with increase in voltage above 11kv. In a star connected winding with earthed-neutral the maximum voltage to the earth is ($\frac{1}{\sqrt{3}}$)of the line voltage. Also star connection permits mixed loading due to the presence of the neutral. Mesh connections are advantageous in low voltage transformers as insulation costs are insignificant and the conductor size becomes ($\frac{1}{\sqrt{3}}$) of that of star connection and permits ease of winding. The common polyphase connections are briefly discussed now.

Star/star (Yy0, Yy6)connection

This is the most economical one for small high voltage transformers. Insulation cost is highly reduced. Neutral wire can permit mixed loading. Triplen harmonics are absent in the lines. These triplen harmonic currents cannot flow, unless there is a neutral wire. This connection produces oscillating neutral. Three phase shell type units have large triplen harmonic phase voltage. However three phase core type transformers work satisfactorily. A tertiary mesh connected winding may be required to stabilize the oscillating neutral due to third harmonics in three phase banks.

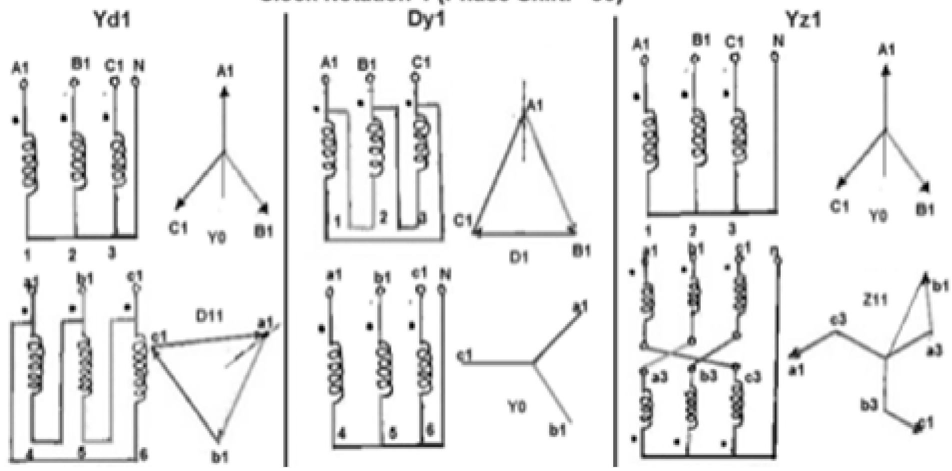
Mesh/mesh (Dd0, Dd6)

This is an economical con_guration for large low voltage transformers. Large amount of unbalanced load can be met with ease. Mesh permits a circulating path for triplen harmonics thus attenuates the same. It is possible to operate with one transformer removed in open delta or Vee connection meeting 58 percent of the balanced load. Three phase units cannot have this facility. Mixed single phase loading is not possible due to the absence of neutral.



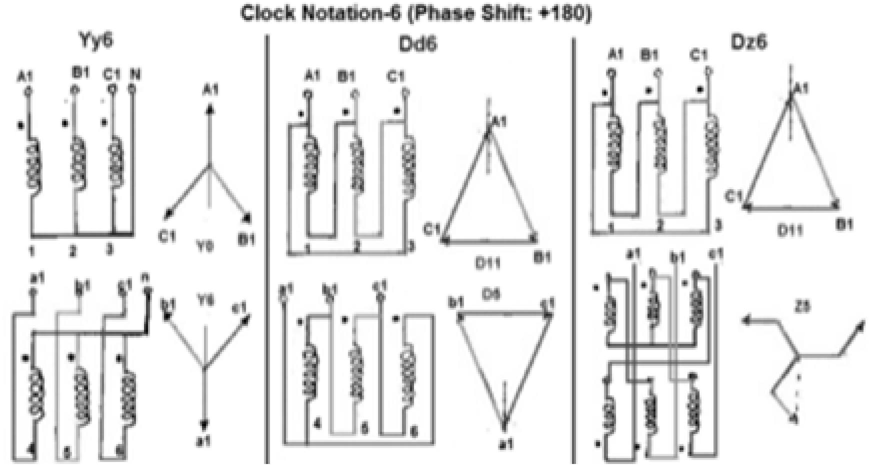
Clock Notation : 1

Clock Notation-1 (Phase Shift: -30)



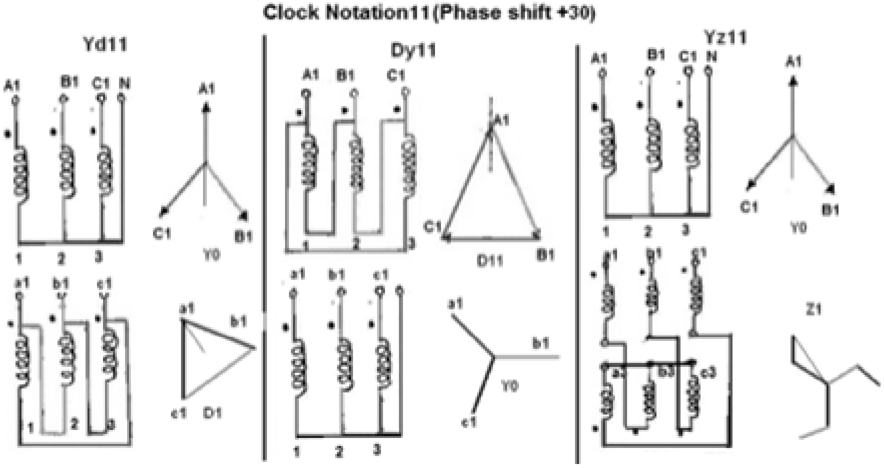
Clock Notation: 6

Clock Notation-6 (Phase Shift: +180)



Clock Notation: 11

Clock Notation11(Phase shift +30)



Star/mesh(Dy or Yd)

This arrangement is in general used for power supply transformers. The delta winding permits triplen harmonic currents to circulate in the closed path and attenuates them.

Zig zag/ star (ZY1 or Zy11)

Zigzag connection is obtained by inter connection of phases.4-wire system is possible on both sides. Unbalanced loading is also possible. Oscillating neutral problem is absent in this connection. This connection requires 15% more turns for the same voltage on the zigzag side and hence costs more. Generally speaking a bank of three single phase transformers cost about 15% more than their 3-phase counterpart. Also, they occupy more space. But the spare capacity cost will be less and single phase units are easier to transport.

Application of Transformer according to Vector Group:

(1) (Dy11, Dy1, YNd1, Yd11)

- Common for distribution transformers.
- Normally Dy11 vector group using at distribution system. Because Generating Transformer are Yd1 for neutralizing the load angle between 11 and 1.
- We can use Dy1 at distribution system, when we are using Generator Transformer are Yd11.
- In some industries 6 pulse electric drives are using due to this 5thharmonics will generate if we use Dy1 it will be suppress the 5th harmonics.
- Star point facilitates mixed loading of three phase and single phase consumer connections.
- The delta winding carry third harmonics and stabilizes star point potential.
- A delta-Star connection is used for step-up generating stations. If HV winding is star connected there will be saving in cost of insulation.
- But delta connected HV winding is common in distribution network, for feeding motors and lighting loads from LV side.

(2) Star-Star (Yy0 or Yy6)

- Mainly used for large system tie-up Transformer.
- Most economical connection in HV power system to interconnect between two delta systems and to provide neutral for grounding both of them.
- The neutral condition is stabilized by using tertiary winding. The load can be connected in star connected transformers, between line and neutral, only if (a) the source side transformers is delta connected or (b) the source side is star connected with neutral connected back to the source neutral.
- In This Transformers. Insulation cost is highly reduced. Neutral wire can permit mixed loading.

- Triple harmonics are absent in the lines. These triple harmonic currents cannot flow, unless there is a neutral wire. This connection produces oscillating neutral.
- Three phase shell type units have large triple harmonic phase voltage. However three phase core type transformers work satisfactorily.
- A tertiary mesh connected winding may be required to stabilize the oscillating neutral due to third harmonics in three phase banks.

(3) Delta – Delta (Dd 0 or Dd 6)

- This is an economical connection for large low voltage transformers.
- Large unbalance of load can be met without difficulty.
- Delta permits a circulating path for triple harmonics thus attenuates the same.
- It is possible to operate with one transformer removed in open delta or" V" connection meeting 58 percent of the balanced load.
- Three phase units cannot have this facility. Mixed single phase loading is not possible due to the absence of neutral.

(4) Star-Zig-zag or Delta-Zig-zag (Yz or Dz)

- These connections are employed where delta connections are weak. Interconnection of phases in zigzag winding effects a reduction of third harmonic voltages and at the same time permits unbalanced loading.
- This connection may be used with either delta connected or star connected winding either for step-up or step-down transformers. In either case, the zigzag winding produces the same angular displacement as a delta winding, and at the same time provides a neutral for earthing purposes.
- The amount of copper required from a zigzag winding in 15% more than a corresponding star or delta winding. This is extensively used for earthing transformer.
- Due to **zigzag** connection (interconnection between phases), third harmonic voltages are reduced. It also allows unbalanced loading. The zigzag connection is employed for LV winding. For a given total voltage per phase, the zigzag side requires 15% more turns as compared to normal phase connection. In cases where delta connections are weak due to large number of turns and small cross sections, then zigzag star connection is preferred. It is also used in rectifiers.

(5) Zig- zag/ star (ZY1 or Zy11)

- Zigzag connection is obtained by inter connection of phases.4-wire system is possible on both sides. Unbalanced loading is also possible. Oscillating neutral problem is absent in this connection.
- This connection requires 15% more turns for the same voltage on the zigzag side and hence costs more. Hence a bank of three single phase transformers cost about 15% more than their 3-phase counterpart. Also, they occupy more space. But the spare capacity cost will be less and single phase units are easier to transport.

- Unbalanced operation of the transformer with large zero sequence fundamental mmf content also does not affect its performance. Even with Yy type of poly phase connection without neutral connection the oscillating neutral does not occur with these cores. Finally, three phase cores themselves cost less than three single phase units due to compactness.

Application of Transformer according according to Uses:

- **Step up Transformer:** It should be Yd1 or Yd11.
- **Step down Transformer:** It should be Dy1 or Dy11.
- **Grounding purpose Transformer:** It should be Yz1 or Dz11.
- **Distribution Transformer:** We can consider vector group of Dzn0 which reduce the 75% of harmonics in secondary side.
- **Power Transformer:** Vector group is deepen on application for Example : Generating Transformer : Dyn1 , Furnace Transformer: Ynyn0.

Parallel Operation of Single Phase Transformer:

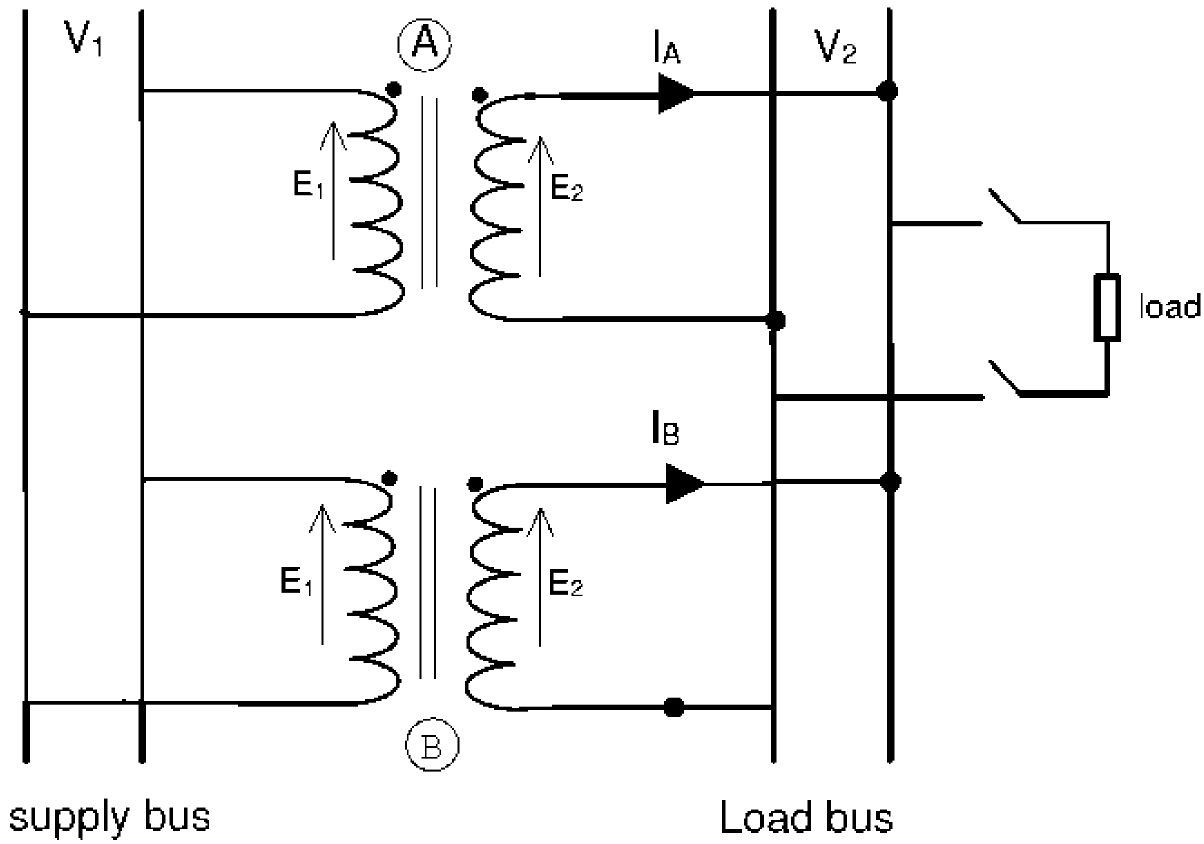
- For supplying a load in excess of the rating of an existing transformer, two or more transformers may be connected in parallel with the existing transformer. The transformers are connected in parallel when load on one of the transformers is more than its capacity. The reliability is increased with parallel operation than to have single larger unit. The cost associated with maintaining the spares is less when two transformers are connected in parallel.
- It is usually economical to install another transformer in parallel instead of replacing the existing transformer by a single larger unit. The cost of a spare unit in the case of two parallel transformers (of equal rating) is also lower than that of a single large transformer. In addition, it is preferable to have a parallel transformer for the reason of reliability. With this at least half the load can be supplied with one transformer out of service.

Condition for Parallel Operation of Transformer:

- For parallel connection of transformers, primary windings of the Transformers are connected to source bus-bars and secondary windings are connected to the load bus-bars.
- Various conditions that must be fulfilled for the successful parallel operation of transformers:

1. Same voltage Ratio & Turns Ratio (both primary and secondary Voltage Rating is same).
2. Same Percentage Impedance and X/R ratio.
3. Identical Position of Tap changer.
4. Same KVA ratings.
5. Same Phase angle shift (vector group are same).
6. Same Frequency rating.
7. Same Polarity.
8. Same Phase sequence.

- Some of these conditions are convenient and some are mandatory.
- The convenient are: Same voltage Ratio & Turns Ratio, Same Percentage Impedance, Same KVA Rating, Same Position of Tap changer.
- The mandatory conditions are: Same Phase Angle Shift, Same Polarity, Same Phase Sequence and Same Frequency.
- When the feasible conditions are not met the paralleled operation is possible but not optimal.

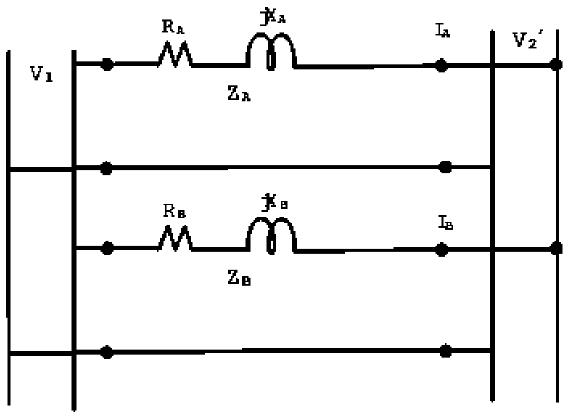


Two Single Phase Transformer in Parallel

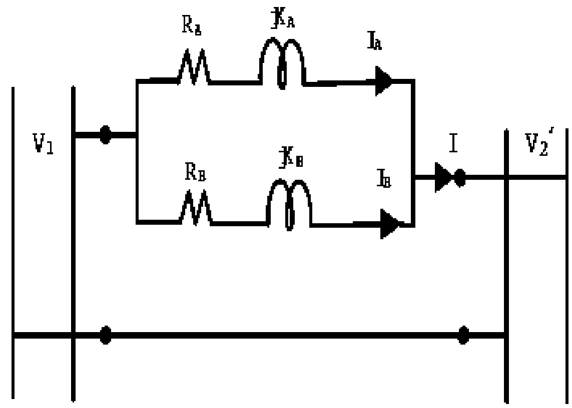
Load Sharing of Two Single Phase transformer:

Equal Voltage Ratio:

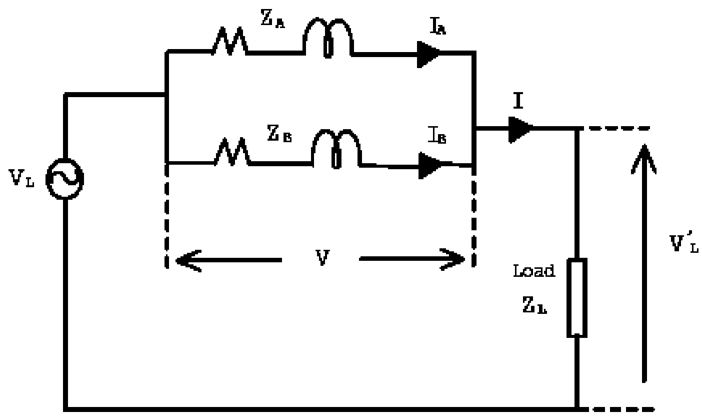
Always two transformers of equal voltage ratios are selected for working in parallel. This way one can avoid a circulating current between the transformers. Load can be switched on subsequently to these bus bars. Neglecting the parallel branch of the equivalent circuit the above connection can be shown as in Figure (a),(b). The equivalent circuit is drawn in terms of the secondary parameters. This may be further simplified as shown under Figure (c). The voltage drop across the two transformers must be the same by virtue of common connection at input as well as output ends. By inspection the voltage equation for the drop can be



(a)



(b)



(c)

written as

$$I_A Z_A = I_B Z_B = IZ = v \quad (say)$$

$$\text{Here} I = I_A + I_B$$

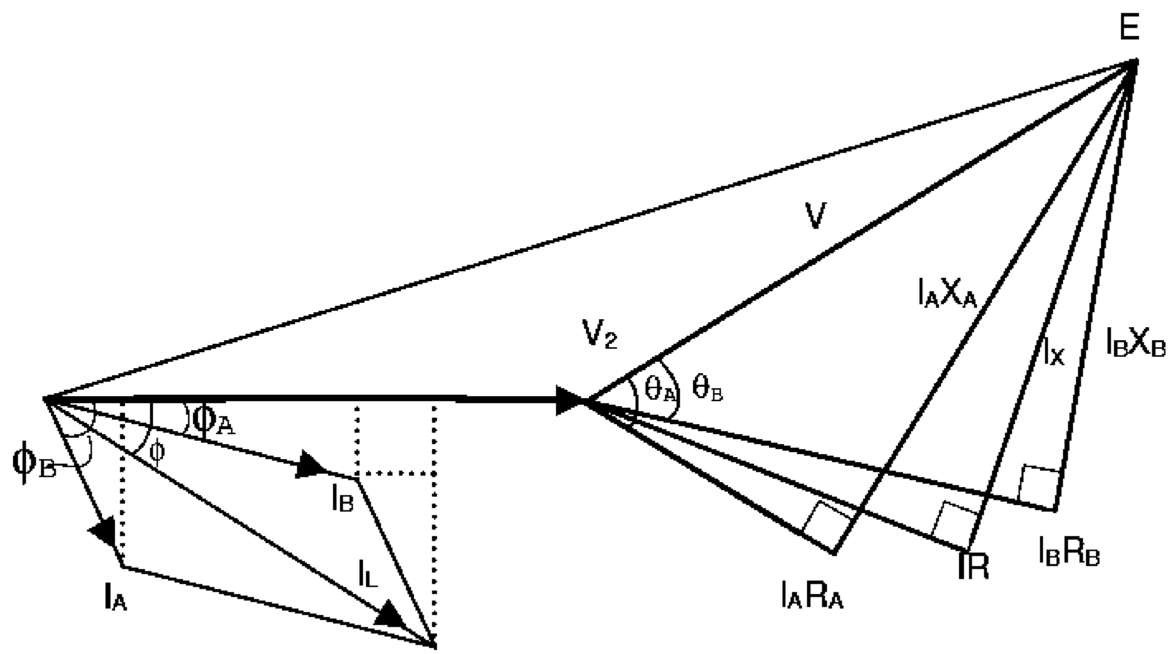
And Z is the equivalent impedance of the two transformers given by,

$$Z = \frac{Z_A Z_B}{Z_A + Z_B}$$

$$\begin{aligned} \text{Thus} \quad I_A &= \frac{v}{Z_A} = \frac{IZ}{Z_A} = I.\frac{Z_B}{Z_A + Z_B} and \\ I_B &= \frac{v}{Z_B} = \frac{IZ}{Z_B} = I.\frac{Z_A}{Z_A + Z_B} \end{aligned}$$

If the terminal voltage is $V = IZ_L$ then the active and reactive power supplied by each of the two transformers is given by

From the above it is seen that the transformer with higher impedance supplies lesser load current and vice versa. If transformers of dissimilar ratings are paralleled the transformer with larger rating shall have smaller impedance as it has to produce the same drop as the other transformer, at a larger current. Thus the ohmic values of the impedances must be in the inverse ratio of the ratings of the transformers. $I_A Z_A = I_B Z_B$), hence, $I_A/I_B= Z_B/Z_A$.
Expressing the voltage drops in p.u basis, we aim at the same per unit drops at any load for the transformers. The per unit impedances must therefore be the same on their respective bases. Figure below shows the phasor diagram of operation for these conditions. The drops are magnified and shown to improve clarity. It is seen that the total voltage drop inside the transformers is v but the currents I_A and I_B are forced to have a different phase angle due to the difference in the internal power factor angles θ_A and θ_B.

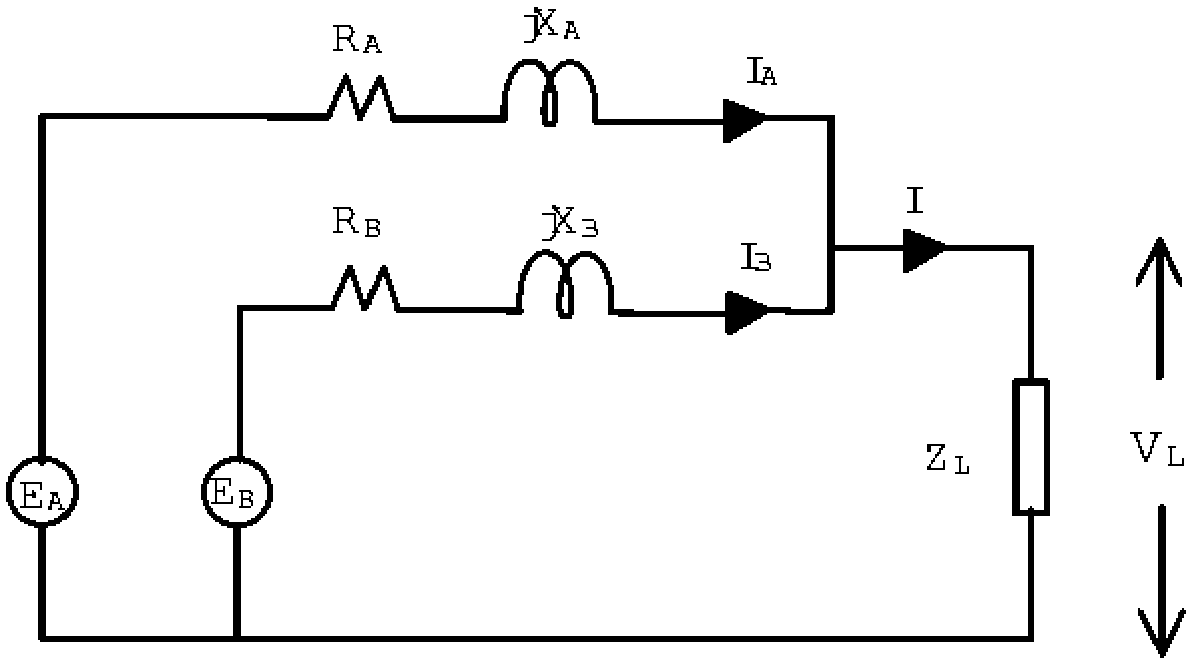


Phasor Diagram of Operation for two Transformers working in Parallel

This forces the active and reactive components of the currents drawn by each transformer to be different (even in the case when current in each transformer is the same). If we want them to share the load current in proportion to their ratings, their percentage (or p.u) impedances must be the same. In order to avoid any divergence and to share active and reactive powers also properly, $\theta_A = \theta_B$. Thus the condition for satisfactory parallel operation is that the p.u resistances and p.u reactance must be the same on their respective bases for the two transformers. To determine the sharing of currents and power either p.u parameters or ohmic values can be used.

Case B : unequal voltage ratios:

One may not be able to get two transformers of identical voltage ratio in spite of ones best efforts. Due to manufacturing differences, even in transformers built as per the same design, the voltage ratios may not be the same. In such cases the circuit representation for parallel operation will be different as shown in Figure below.



Equivalent Circuit for unequal Voltage Ratio

In such cases the circuit representation for parallel operation will be different as shown in Figure above. In this case the two input voltages cannot be merged to one, as they are different. The load brings about a common connection at the output side. E_A and E_B are the no-load secondary emf. Z_L is the load impedance at the secondary terminals. By inspection the voltage equation can be written as below:

$$E_A = I_A Z_A + (I_A + I_B) Z_L = V + I_A Z_A$$

$$E_B = I_B Z_B + (I_A + I_B) Z_L = V + I_B Z_B$$

Solving the two equations the expression for I_A and I_B can be obtained as

$$I_A = (E_A Z_B + (E_A - E_B) Z_L)/(Z_A Z_B + Z_L (Z_A + Z_B))$$

and

$$I_B = (E_B Z_A + (E_B - E_A) Z_L)/ (Z_A Z_B + Z_L (Z_A + Z_B))$$

Z_A and Z_B are phasors and hence there can be angular di_erence also in addition to the di_erence in magnitude. When load is not connected there will be a circulating current between the transformers. The currents in that case can be obtained by putting $Z_L = 1$ (after dividing the numerator and the denominator by Z_L). Then,

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

If the load impedance becomes zero as in the case of a short circuit, we have,
$I_A = E_A/Z_A$ and $I_B = E_B/Z_B$.

Excitation Phenomenon in Transformer:

In addition to the operation of transformers on the sinusoidal supplies, the harmonic behavior becomes important as the size and rating of the transformer increases. The effects of the harmonic currents are

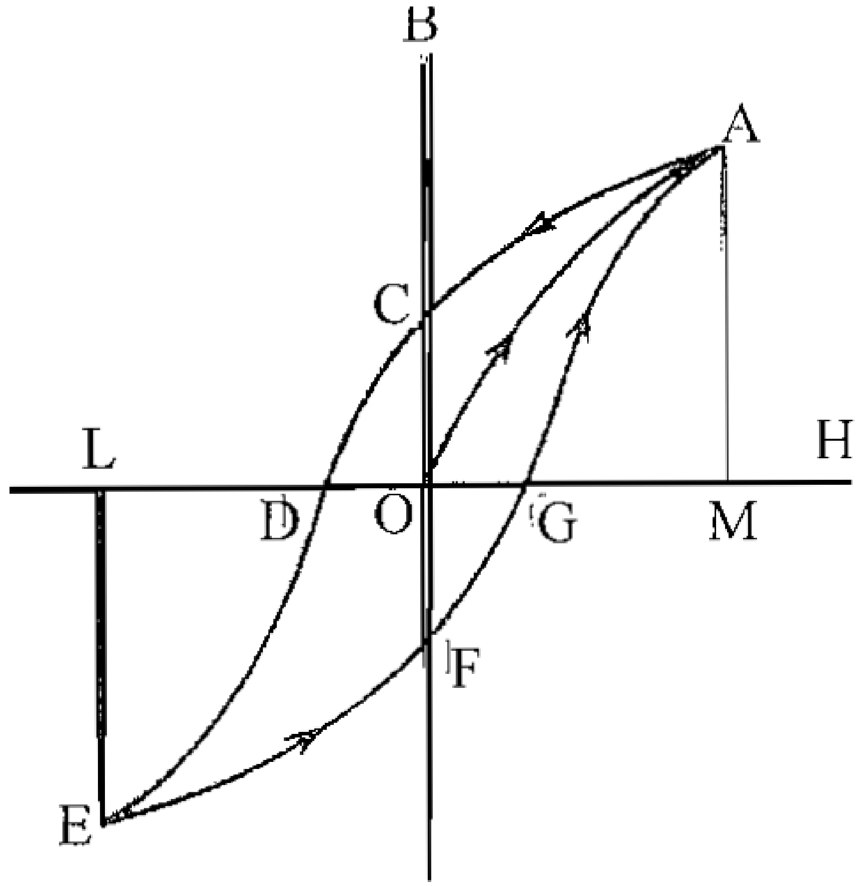
1. Additional copper losses due to harmonic currents
2. Increased core losses
3. Increased electro magnetic interference with communication circuits.

On the other hand the harmonic voltages of the transformer cause

1. Increased dielectric stress on insulation
2. Electro static interference with communication circuits.
3. Resonance between winding reactance and feeder capacitance.

In the present times a greater awareness is generated by the problems of harmonic voltages and currents produced by non-linear loads like the power electronic converters. These combine with non-linear nature of transformer core and produce severe distortions in voltages and currents and increase the power loss. Thus the study of harmonics is of great practical significance in the operation of transformers. The discussion here is confined to the harmonics generated by transformers only.

Modern transformers operate at increasing levels of saturation in order to reduce the weight and cost of the core used in the same. Because of this and due to the hysteresis,the transformer core behaves as a highly non-linear element and generates harmonic voltages and currents. This is explained below. Fig. 34 shows the manner in which the shape of the magnetizing current can be obtained and plotted. At any instant of the flux density wave the ampere turns required to establish the same is read out and plotted, traversing the hysteresis loop once per cycle. The sinusoidal flux density curve represents the sinusoidal applied voltage to some other scale. The plot of the magnetizing current which is peaky is analyzed using Fourier analysis. The harmonic current components are obtained from this analysis. These harmonic currents produce harmonic fields in the core and harmonic voltages in the windings. Relatively small value of harmonic fields generate considerable magnitude of harmonic voltages. For example a 10% magnitude of 3rd harmonic flux produces 30%magnitude of 3rd harmonic voltage. These effects get even more pronounced for higher order harmonics. As these harmonic voltages get short circuited through the low impedanceof the supply they produce harmonic currents. These currents produce effects according toLenz's law and tend to neutralize the harmonic flux and bring the flux wave to a sinusoid.Normally third harmonic is the largest in its magnitude and hence the discussion is based onit. The same can be told of other harmonics also. In the case of a single phase transformer the harmonics are confined mostly to the primary side as the source impedance is much smaller compared to the load impedance. The understanding of the phenomenon becomes more clear if the transformer is supplied with a sinusoidal current source. In this case current has to be sinusoidal and the harmonic currents cannot be supplied by the source and hence the induced emf will be peaky containing harmonic voltages. When the load is connected on the secondary side the harmonic currents flow through the load and voltage tends to become sinusoidal. The harmonic voltages induce electric stress on dielectrics and increased electro static interference. The harmonic currents produce losses and electromagnetic interference as already noted above.



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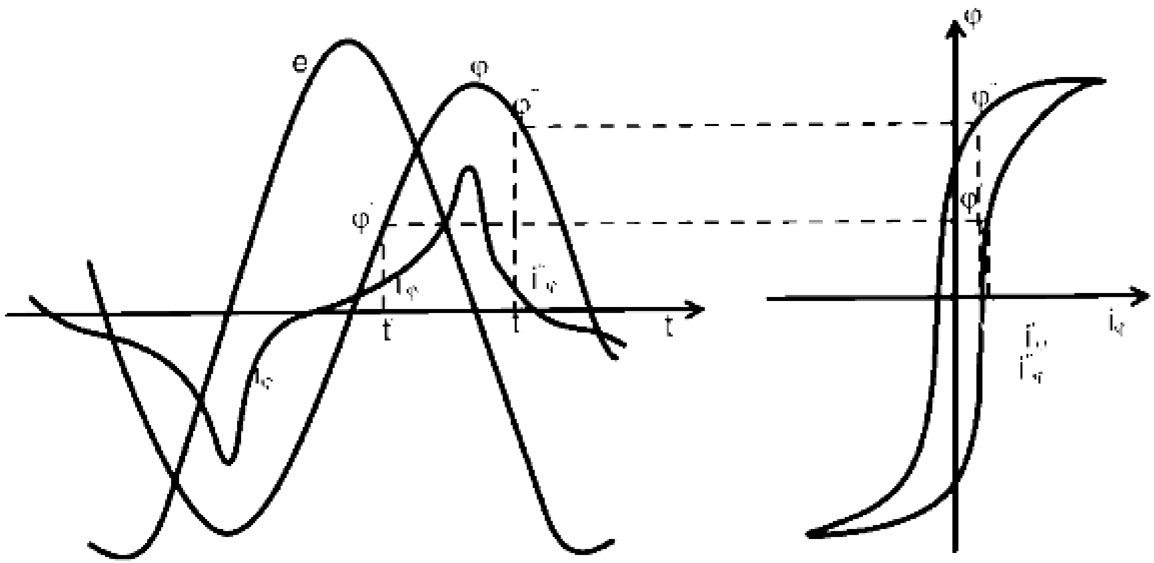

Harmonics generated by Transformer