PPT ON
ELECTRICAL MACHINES – I
III SEM (IARE-R18)

UNIT 1
MAGNETIC FIELDS AND MAGNETIC CIRCUITS

Principles of Electromechanical Energy Conversion

- Why do we study this?
  - Electromechanical energy conversion theory is the cornerstone for the analysis of electromechanical motion devices.
  - The theory allows us to express the electromagnetic force or torque in terms of the device variables such as the currents and the displacement of the mechanical system.
  - Since numerous types of electromechanical devices are used in motion systems, it is desirable to establish methods of analysis which may be applied to a variety of electromechanical devices rather than just electric machines.

PLAN

- Establish analytically the relationships which can be used to express the electromagnetic force or torque.
- Develop a general set of formulas which are applicable to all electromechanical systems with a single mechanical input.
- Detailed analysis of:
  - Elementary electromagnet
  - Elementary single-phase reluctance machine
  - Windings in relative motion

Lumped Parameters vs. Distributed Parameters

- If the physical size of a device is small compared to the wavelength associated with the signal propagation, the device may be considered lumped and a lumped (network) model employed.

$$\lambda = \frac{v}{f}$$

λ= wavelength (distance/cycle)
v = velocity of wave propagation (distance/second) f
= signal frequency (Hz)

-
  - 20 to 20,000 Hz is the audio range

$$\lambda = \frac{186{,}000 \text{ miles/second}}{20{,}000 \text{ cycles/second}} = 9.3 \text{ miles/cycle}$$

Conservative Force Field

- A force field acting on an object is called conservative if the work done in moving the object from one point to another is independent of the path joining the two points.

$$\int_C F\cdot dr \text{ is independent of path if and only if } \nabla\times F = 0 \text{ or } F = \nabla\phi$$

$$F\cdot dr \quad \text{is an exact differential}$$

$$F_1dx + F_2dy + F_3dz = d \qquad \text{where } \phi(x,y,z)$$

$$\int^{x,y,z)} F\cdot dr = \int_{(x_1,y_1,z_1} d\phi = \phi(x_2,y_2,z_2) - \phi(x_1,y_1,z_1$$

Energy Balance Relationships

- Electromechanical Syste
  1. Comprises
  2. Electric system
- Mechanical system
- Means whereby the electric and mechanical systems can interact

- Interactions can take place through any and all electromagnetic and electrostatic fields which are common to both systems, and energy is transferred as a result of this interaction.

- Both electrostatic and electromagnetic coupling fields may exist simultaneously and the system may have any number of electric and mechanical subsystems.

Electromechanical System in Simplified Form

Electric System ⟷ Coupling Field ⟷ Mechanical System

- Neglect electromagnetic radiation
- Assume that the electric system operates at a frequency sufficiently low so that the electric system may be considered as a lumped-parameter system
  - Energy Distribution

$$W_E = W_e + W_{eL} + W_{eS} \quad W_M = W_m + W_{mL} + W_{mS}$$

- W_E = total energy supplied *by* the electric source (+)
- W_M = total energy supplied *by* the mechanical source (+)

- WeL = heat loss associated with the electric system, excluding the coupling field losses, which occurs due to:

- the resistance of the current-carrying conductors

- the energy dissipated in the form of heat owing to hysteresis, eddy currents, and dielectric losses external to the coupling field

- We = energy transferred to the coupling field by the electric system
- WmS = energy stored in the moving member and the compliances of the mechanical system
- WmL = energy loss of the mechanical system in the form of heat due to friction
- Wm = energy transferred to the coupling field by the mechanical system

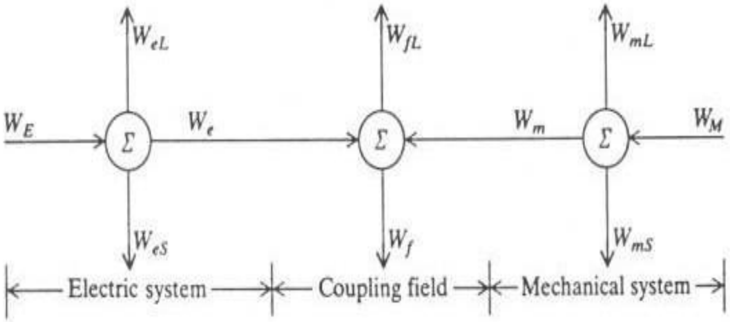
- WF = Wf + WfL = total energy transferred to the coupling field

- Wf = energy stored in the coupling field
- WfL = energy dissipated in the form of heat due to losses within the coupling field (eddy current, hysteresis, or dielectric losses)

- Conservation of Energy

$$W_f + W_{fL} = (W_E - W_{eL} - W_{eS}) + (W_M - W_{mL} - W_{mS})$$

$$W_f + W_{fL} = W_e + W_m$$



- The loss of energy in either the electric or the mechanical systems (W_{eL} and W_{mL})
- The energies stored in the electric or magnetic fields which are not in common to both systems (W_{eS})
- The energies stored in the mechanical system (W_{mS})

- If the losses of the coupling field are neglected, then the field is conservative and $W_f = W_e + W_m$.
- Consider two examples of elementary electromechanical systems
  - Magnetic coupling field
  - Electric field as a means of transferring energy

v = voltage of electric source

f = externally-applied mechanical force

f_e = electromagnetic or electrostatic force

r = resistance of the current-carrying conductor

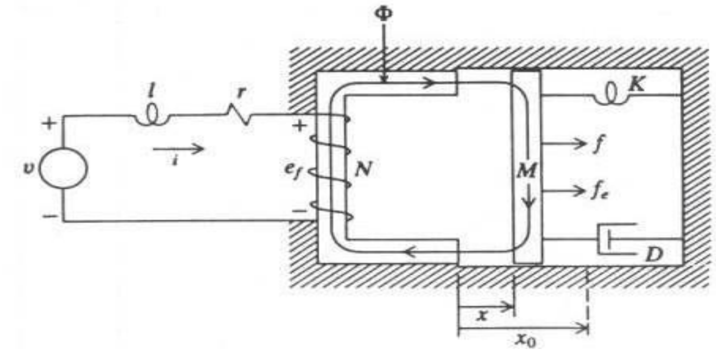
⍰= inductance of a linear (conservative) electromagnetic system which does not couple the mechanical system

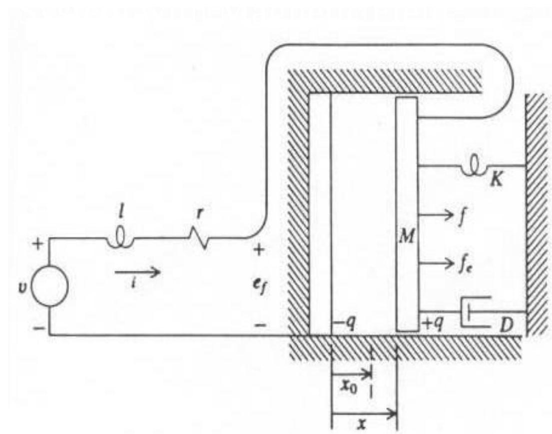
M = mass of moveable member

K = spring constant

D = damping coefficient

x_0 = zero force or equilibrium position of the mechanical system (f_e = 0, f = 0)





voltage equation that describes the electric systems; e_f is the voltage drop due to the coupling field

$$f = M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + K(x - x_0) - f_e$$

Newton’s Law of Motion

$$W_M = \int (f)\,dx = \int \left(\quad \frac{dx}{dt} \right) dt$$

Since power is the time rate of energy transfer, this is the total energy supplied by the electric and mechanical sources

$$v = ri + \Box\frac{di}{dt} + e_f$$

$$W_E = \int (vi)\,dt$$

$$W_E = r\int (i^2)\,dt + \Box\int \left(i\,\frac{di}{dt} \right) dt + \int (e_f\, i)\,dt$$

$$= W_{eL} + W_{eS} + W_e$$

$$f = M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + K(x - x_0) - f_e$$

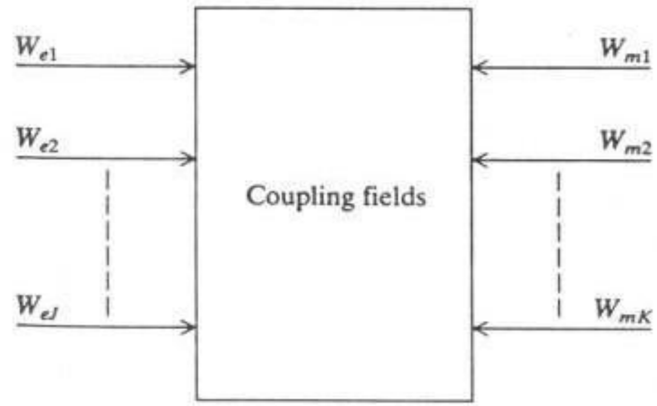
$$W_M = \int (f)dx = \int\left(f\,\frac{dx}{dt}\right)dt$$

$$W_M = M\int\left(\frac{d^2x}{dt^2}\right)dx + D\int\left(\frac{dx}{dt}\right)^2 dt + K\int(x - x_0)dx - \int(f_e)dx$$

Σ

W_{mS} W_{mL} W_m

- These equations may be readily extended to include an electromechanical system with any number of electrical and mechanical inputs and any number of coupling fields



- We will consider devices with only one mechanical input, but with possibly multiple electric inputs. In all cases, however, the multiple electric inputs have a common coupling field.

$$W_f = \sum_{j=1}^{J} W_{ej} + \sum_{k=1}^{K} W_{mk}$$

$$\sum_{j=1}^{J} W_{ej} = \int \sum_{j=1}^{J} e_{fj} i_j \, dt$$

- Total energy supplied to the coupling field from the electric inputs

$$\sum_{k=1}^{K} W_{mk} = -\int \sum_{k=1}^{K} f_{ek} \, dx_k$$

- Total energy supplied to the coupling field from the mechanical inputs

$$\left.\begin{aligned} W_f &= \int \sum_{j=1}^{J} e_{fj} i_j \, dt - \int f_e \, dx \\ dW_f &= \sum_{j=1}^{J} e_{fj} i_j \, dt - f_e \, dx \end{aligned}\right\}$$

- With one mechanical input and multiple electric inputs, the energy supplied to the coupling field, in both integral and differential form

Energy in Coupling Field

- We need to derive an expression for the energy stored in the coupling field before we can solve for the electromagnetic force f_e.
- We will neglect all losses associated with the electric or magnetic coupling field, whereupon the field is assumed to be conservative and the energy stored therein is a function of the state of the electrical and mechanical variables and not the manner in which the variables reached that state.
- This assumption is not as restrictive as it might first appear.

- Nearly all of the energy stored in the coupling field is stored in the air gap of the electromechanical device.Air is a conservative medium and all of the energy stored therein can be returned to the electric or mechanical systems.
- We will take advantage of the conservative field assumption in developing a mathematical expression for the field energy. We will fix mathematically the position of the mechanical system associated with the coupling field and then excite the electric system with the displacement of the mechanical system held fixed.

- During the excitation of the electric inputs, *dx = 0*, hence, W_m is zero even though electromagnetic and electrostatic forces occur.

  - Therefore, with the displacement held fixed, the energy stored in the coupling field during the excitation of the electric inputs is equal to the energy supplied to the coupling field by the
  - With dx = 0, the energy supplied from the electric

$$W_f = \int \sum_{j=1} e_{fj} i_j dt - \int f_e dx$$

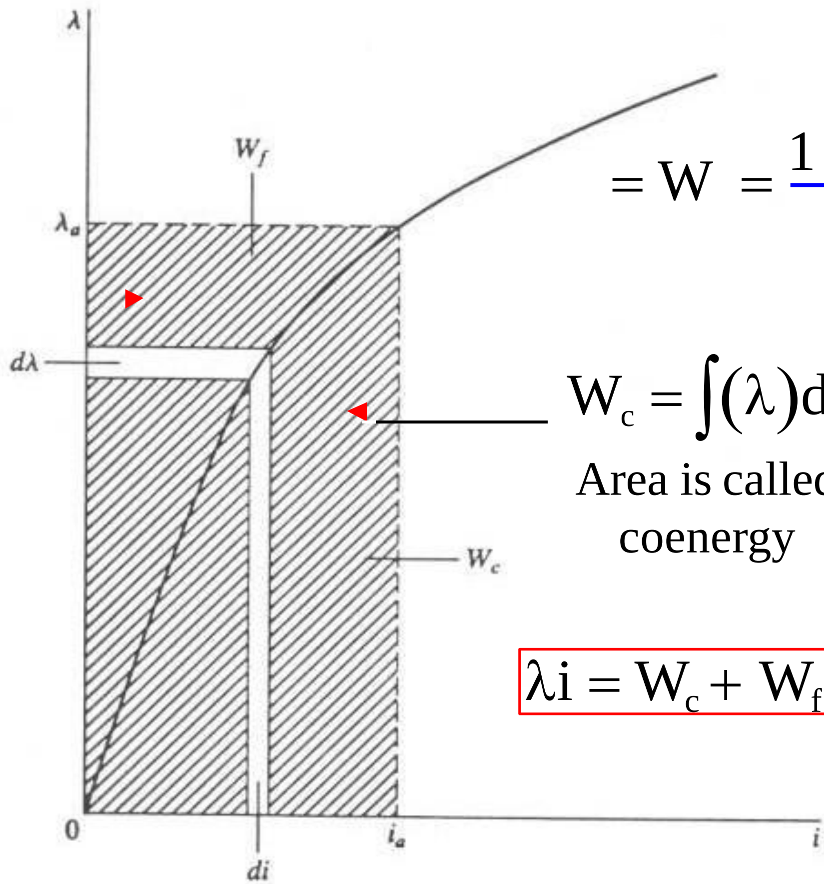
$$W_f = \int \sum_{j=1}^{J} e_{fj} i_j dt$$

For a singly excited electromagnetic system

$$W_f = \int (i)\,d\lambda$$

$$W_f = \int (i)\,d\lambda$$

Area represents energy stored in the field at the instant



$$= W = \frac{1}{\;}\lambda$$

$$W_c = \int (\lambda)\,di$$

Area is called coenergy

$$\boxed{\lambda i = W_c + W_f}$$

Graph
Stored energy and coenergy in a magnetic field of a singly excited electromagnetic device

- The i relationship need not be linear, it need only be single-valued, a property which is characteristic to a conservative or lossless field.

- Also, since the coupling field is conservative, the energy stored in the field with $\lambda = \lambda_a$ and $i = i_a$ is independent of the excursion of the electrical and mechanical variables before reaching this state.

- The displacement x defines completely the influence of the mechanical system upon the coupling field; however, since λ and i are related, only one is needed in addition to x in order to describe the state of the electromechanical system.

- If *i* and *x* are selected as the independent variables, it is convenient to express the field energy and the flux

$$\lambda = \lambda(i, x)$$

$$\frac{\partial\lambda(i,x)}{\partial i} di + \frac{\partial\lambda(i,x)}{\partial x} dx$$

$$\frac{\partial\lambda(i,x)}{\partial i} di \quad \text{with } dx = 0$$

$$\int \qquad \int i \frac{\partial\lambda(i,x)}{\partial i} di = \int_0^i \xi \frac{\partial\lambda(\xi,x)}{\partial \xi} d\xi$$

Energy stored in the field of a singly excited system

- The coenergy in terms of *i* and *x* may be evaluated as

$$W_c(i, x) = \int \lambda(i, x)\,di = \int_0^i \lambda(\xi, x)\,d\xi$$

- For a linear electromagnetic system, the λ-*i* plots are straightline relationships. Thus, for the singly excited magnetically linear system, $\lambda(i, x) = L(x)i$, where *L(x)* is the inductance.
  - Let's evaluate $W_f(i,x)$.

$$d\lambda = \frac{\partial\lambda(i,x)}{\partial i}\,di \quad \text{with } dx = 0$$

$$d\lambda = L(x)\,di$$

$$W_f(i,x) = \int_0^i \xi L(x)\,d\xi = \frac{1}{2}L(x)i^2$$

- The field energy is a state function and the expression describing the field energy in terms of the state variables is valid regardless of the variations in the system variables.
- W_f expresses the field energy regardless of the variations in *L(x)* and *i*. The fixing of the mechanical system so as to obtain an expression for the field energy is a mathematical convenience and not a restriction upon the result.

$$W \quad i,x \; = \quad L \;\; x \; d\xi = \;\; L(x)i$$

- In the case of a multiexcited electromagnetic system, an expression for the field energy may be obtained by evaluating the following relation with $dx = 0$:

$$W_f = \int \sum_{j=1} i_j d\lambda_j$$

- Since the coupling field is considered conservative, this expression may be evaluated independent of the order in which the flux linkages or currents are brought to their final values.
- Let's consider a doubly excited electric system with one mechanical input.

$$W_f(i_1, i_2, x) = \int \left[i_1 d\lambda_1(i_1, i_2, x) + i_2 d\lambda_2(i_1, i_2, x) \right]$$

- The result is:

$$W_f(i_1, i_2, x) = \int_0^{i_1} \xi \frac{\partial \lambda_1(\xi, 0, x)}{\partial \xi} d\xi +$$

$$\int_0^{i_2} \left[i_1 \frac{\partial \lambda_1(i_1, \xi, x)}{\partial \xi} + \xi \frac{\partial \lambda_2(i_1, \xi, x)}{\partial \xi} \right] d\xi$$

- The first integral results from the first step of the evaluation with i_1 as the variable of integration and with $i_2 = 0$ and $di_2 = 0$.
- The second integral comes from the second step of the evaluation with i_1 equal to its final value ($di_1 = 0$) and i_2 as the variable of integration. The order of allowing the currents to reach their final state is irrelevant.

- Let’s now evaluate the energy stored in a magnetically linear electromechanical system with two electrical inputs and one mechanical input.

$$\lambda_1(i_1, i_2, x) = L_{11}(x)i_1 + L_{12}(x)i_2$$

$$\lambda_2(i_1, i_2, x) = L_{21}(x)i_1 + L_{22}(x)i_2$$

- The self-inductances $L_{11}(x)$ and $L_{22}(x)$ include the leakage inductances.
- With the mechanical displacement held constant (dx = 0):

$$d\lambda\ (i\ , i\ \ , x) = L\ \ (x)di\ \ + L\ \ (x)di$$

$$d\lambda_2(i_1, i_2, x) = L_{21}(x)di_1 + L_{22}(x)di_2$$

- Substitution into:

$$W_f(i_1,i_2,x)=\int_0^{i_1}\xi\frac{\partial\lambda_1(\xi,0,x)}{\partial\xi}d\xi+\int_0^{i_2}\left[i_1\frac{\partial\lambda_1(i_1,\xi,x)}{\partial\xi}+\xi\frac{\partial\lambda_2(i_1,\xi,x)}{\partial\xi}\right]d\xi$$

-

$$W_f(i_1,i_2,x)=\int_0^{i_1}\xi L_{11}(x)d\xi+\int_0^{i_2}\left[i_1L_{12}(x)+\xi L_{22}(x)\right]d\xi$$

$$=\frac{1}{2}L_{11}(x)i_1^2+L_{12}(x)i_1i_2+\frac{1}{2}L_{22}(x)i_2^2$$

- Energy Balance Equation:

$$W_f = \int \sum_{j=1}^{J} e_{fj} i_j dt - \int f_e dx$$

$$dW_f = \sum_{j=1}^{J} e_{fj} i_j dt - f_e dx$$

$$f_e dx = \sum_{j=1}^{J} e_{fj} i_j dt - dW_f$$

- To obtain an expression for f_e, it is first necessary to express W_f and then take its total derivative. The total differential of the field energy is required here.

May be evaluated by employing:

$$dW_f = dW_e + dW_m$$

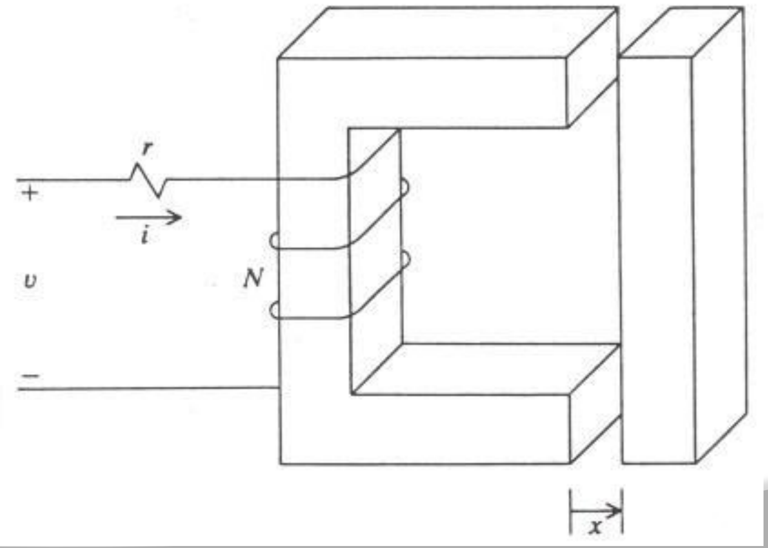
- The force or torque in any electromechanical system
- We will derive the force equations for electro-mechanical systems with one mechanical input and *J*
  - For an electromagnetic system:
    - Select i_j and x as independent variables:

$$dW_f = \sum_{j=1}^{J} \left[\frac{f}{\partial i_j} di_j \right] + \frac{f}{\partial x} dx$$

$$d\lambda_j = \sum_{n=1}^{J} \left[\frac{\partial \lambda_j (i, x)}{\partial i_n} di_n \right] + \frac{\partial \lambda_j (i, x)}{\partial x} dx$$

Elementary Electromagnet

- The system consists of:
  - stationary core with a winding of N turns
  - block of magnetic material is free to slide relative to the stationary member



$$v = ri + \frac{d\lambda}{dt}$$

voltage equation that describes the electric system

$$\lambda = N\phi$$

$$\phi = \phi_{\ell} + \phi_m$$

ϕ_{ℓ} = leakage flux

ϕ_m = magnetizing flux

flux linkages

(the magnetizing flux is common to both stationary and rotating members)

$$\phi_{\ell} = \frac{Ni}{\Re_{\ell}}$$

$$\phi_m = \frac{Ni}{\Re_m}$$

If the magnetic system is considered to be linear (saturation neglected), then, as in the case of stationary coupled circuits, we can express the fluxes in terms of reluctances.

flux linkages

$$\lambda = \left(\frac{N^2}{\Re_{\ell}} + \frac{N^2}{\Re_m} \right) i$$

$$= (L_{\ell} + L_m) i$$

L_{ℓ} = leakage inductance

L_m = magnetizing inductance

$$\Re_m = \Re_i + 2\Re_g$$

reluctance of the magnetizing path

$\Re_i$ total reluctance of the magnetic material of the stationary and movable members

$\Re_g$ reluctance of one of the air gaps

$$\Re_i = \frac{\ell_i}{\mu_{ri}\mu_0 A_i}$$

$$\Re_g = \frac{x}{\mu_0 A_g}$$

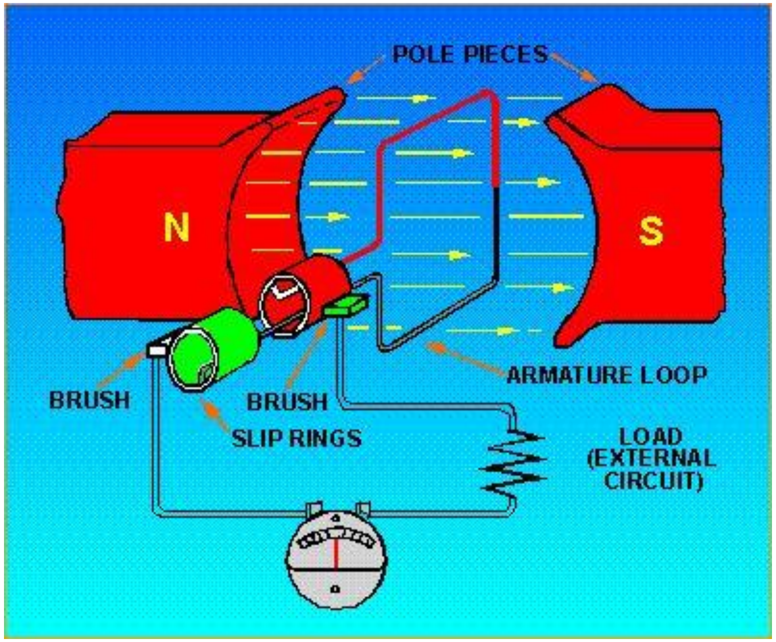
Assume that the cross-sectional areas of the stationary and movable members are equal and of the same material

UNIT 2
DC GENERATORS

INTRODUCTION

- What is a generator?

➢ It is a machine that converts mechanical energy into electrical energy.



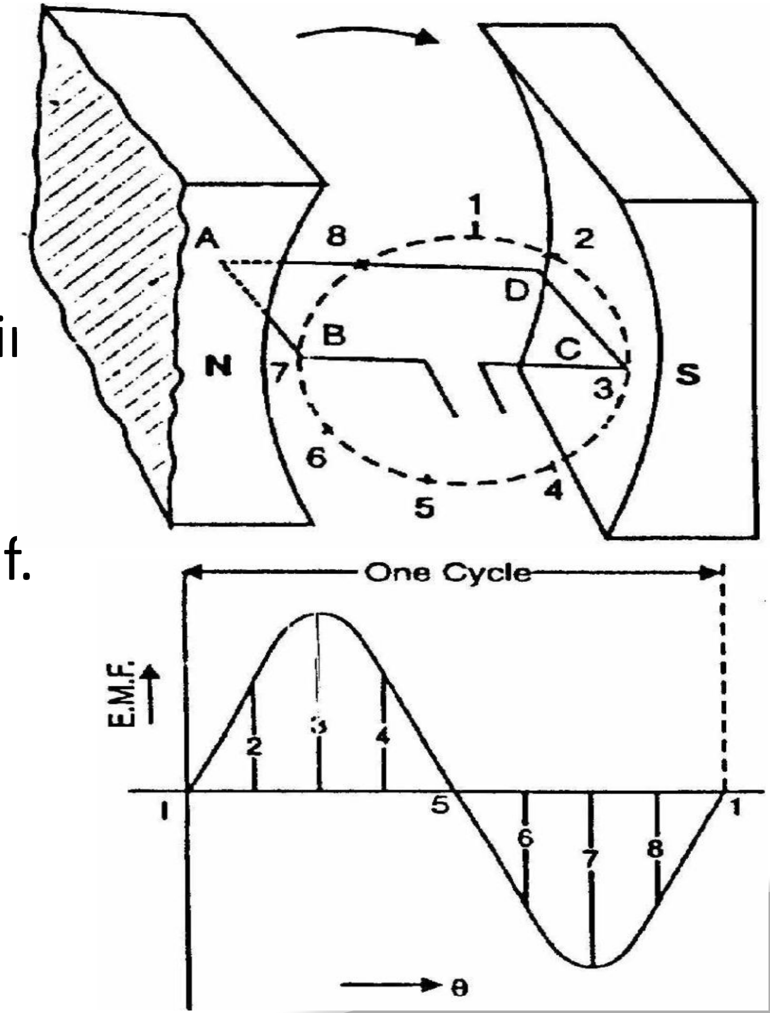
Working Principle

- The energy conversion is based on the principle of the production of dynamically induced emf.
- Whenever a conductor cuts magnetic flux, dynamically induced emf is produced according to faraday's law of electromagnetic induction.
- This emf causes a current to flow if the conductor circuit is closed.
- Hence two basic essential parts if an electrical generator are:

1. magnetic field
2. a conductor or conductors which can so move as to cut the flux.

Simple loop generator

- Consider a single turn loop ABCD rotating clockwise in a uniform magnetic
- field with a constant speed as shown in Fig. As the loop rotates, the flux
- linking the coil sides AB and CD changes continuously. Hence the e.m.f.
- induced in these coil sides also changes but the e.m.f. induced in one coil side
- adds to that induced in the other.



Working of simple loop generator

- When the loop is in position no. 1 [See Fig. In above slide], the generated e.m.f. Is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it
- (ii) When the loop is in position no. 2, the coil sides are moving at an angle to the flux and, therefore, a low e.m.f. is generated as indicated by point 2 in Fig. In above slide.
- When the loop is in position no. 3, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate. Hence at this instant, the generated e.m.f. is maximum as indicated by point 3 in Fig in above slide.
- At position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle.

Types of generators

- Separately excited generators
- Self excited generators

  (1) Shunt wound

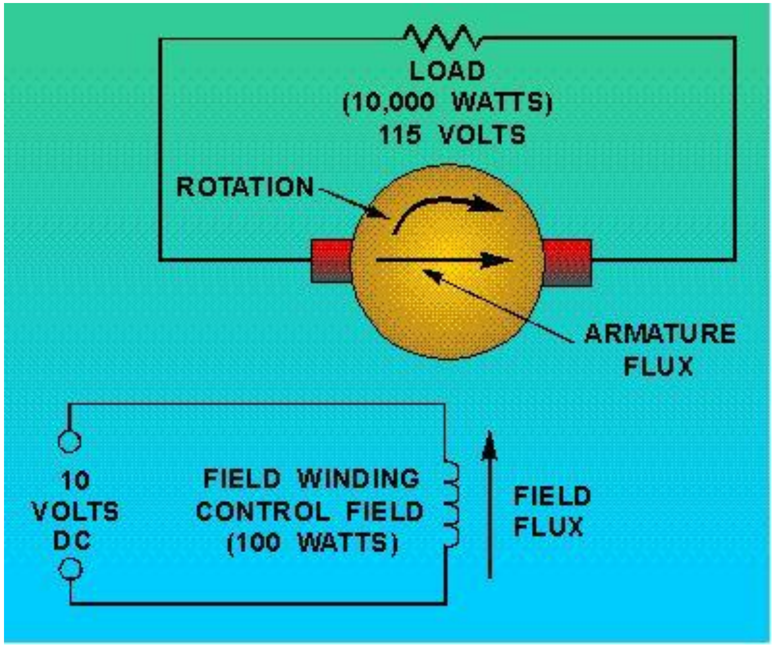
  (2) Series wound

  (3) Compound wound

Separately excited generators

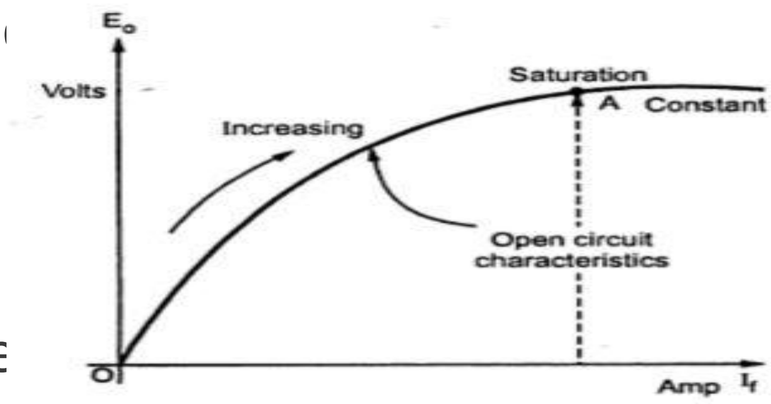
- In separately excited generators ,the fill flux is derived from a separately power source independent of the generator itself .

- Its field current is supplied by a separately external dc voltage source .



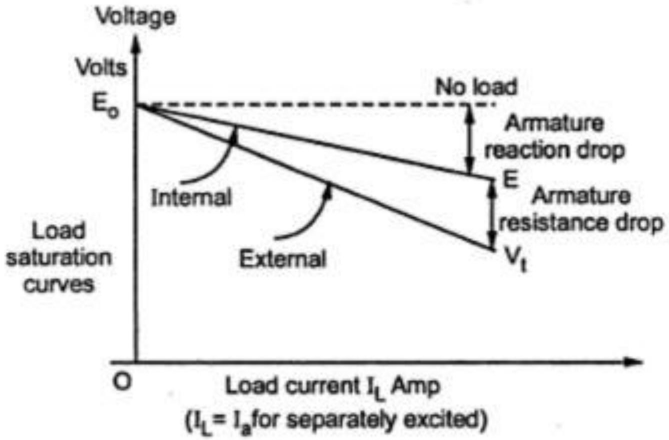
Characteristics of a Separately Excited DC Generator

- For DC generator , the output quantities are its terminal voltage and line current . The terminal voltage is
- Since the internal generated voltage E_A is independent of I_A, the terminal characteristic of the separately excited generator is a straight line.
- When the load is supplied by the generator is increased, I_L (and therefore I_A) increase. As the armature current increase, the IARA drop increase, so the terminal voltage of the generator falls.



Characteristic of a separately excited generators

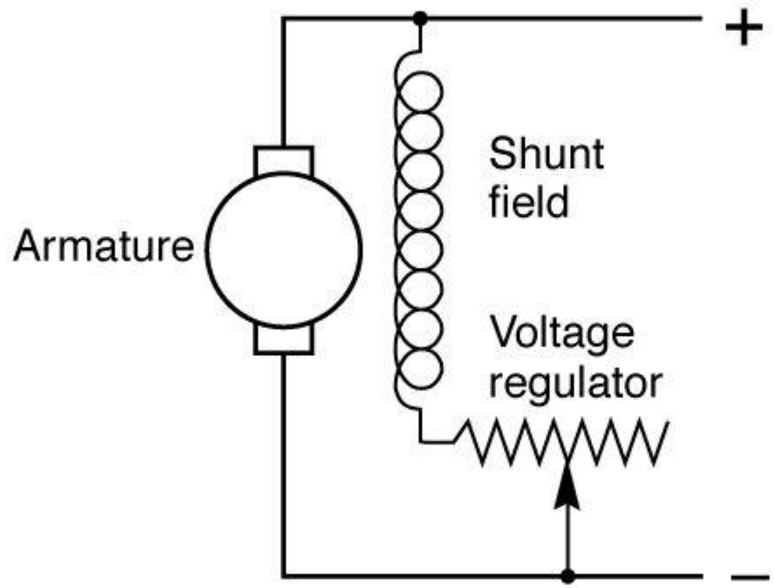
- This terminal characteristic is not always entirely accurate. In the generators without compensating windings, an increase in I_A causes an increase in the armature reaction, and armature reaction causes flux weakening. This flux weakening causes a decrease in $E_A = K\Phi\downarrow \omega$ which further decreases the terminal voltage of the generator.



Self excited generators

- Self excited generators are those whose field magnets are energised by the current produced by the generators themselves . Due to residual magnetism there is always present some flux in the poles .

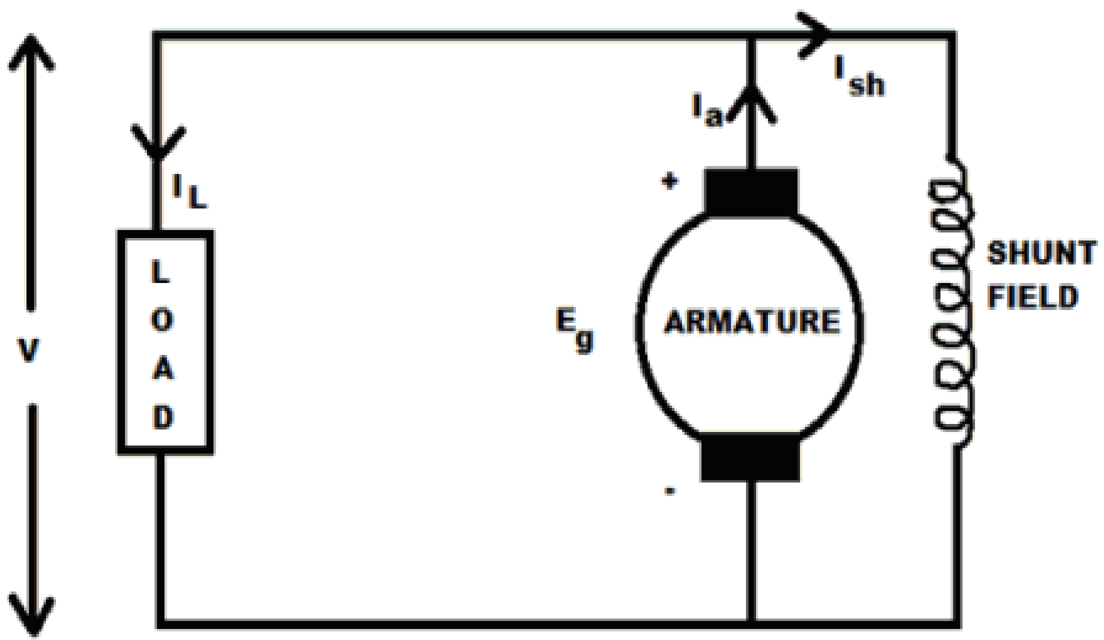
- When the armature is rotated some emf and hence some induced current is produced which is partly or fully passed through the field coils thereby strengthening the residual pole flux .



self-excited generator

Shunt wound

- DC generator that supplies its own field current by having its field connected directly across the terminals of the machine.



Shunt Wound Generator

Voltage Buildup in A Shunt Generator

- Assume the DC generator has no load connected to it and that the prime mover starts to turn the shaft of the generator.
- The voltage buildup in a DC generator depends on the presence of a residual flux in the poles of the generator.

$$\boxed{E_A = K\Phi_{res}\,\omega}$$

- This voltage, E_A (a volt of two appears at terminal of generators), and it causes a current I_F to flow in the field coils. This field current produces a magnetomotive force in the poles, which increases the flux in them.

- $\Phi\uparrow \Rightarrow E_A\uparrow$, then V_T increase and cause further increase $I_F\uparrow$, which further increasing the flux $\Phi\uparrow$ and so on.

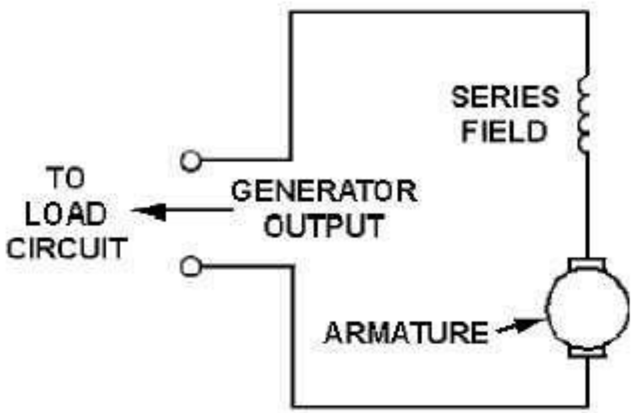
- The final operating voltage is determined by intersection of the field resistance line and saturation curve. This voltage buildup process is depicted in the next slide

Conditions for build-up of a shunt generator

- There must be some residual magnetism in the generator poles.
- For the given direction of rotation, the shunt field coils should be correctly connected to the armature.
- If excited on open circuit, its shunt field resistance should be less than the critical resistance.

Series generator

- In a series generator, the field flux is produced by connecting the field circuit in series with the armature of the generator.

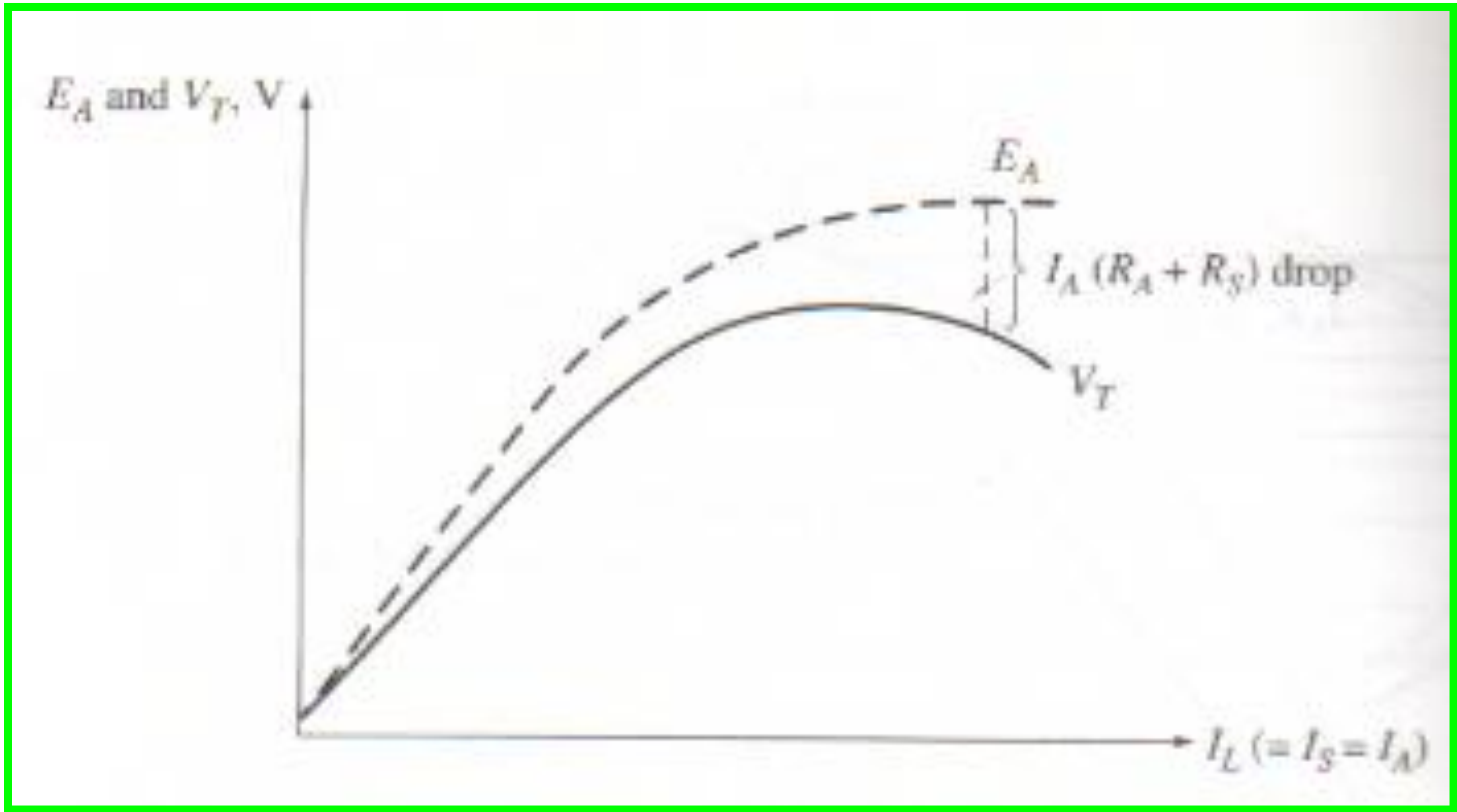


Characteristics of series generator

- The magnetization curve of a series DC generator looks very much like the magnetization curve of any other generator. At no load, however, there is no field current, so V_T is reduced to a very small level given by the residual flux in the machine.

- As the load increases, the field current rises, so E_A rises rapidly. The I_A $(R_A + R_S)$ drop goes up too, but at the first the increase in E_A goes up more rapidly than the $I_A(R_A + R_S)$ drop rises, so V_T increases. After a while, the machine approaches saturation, and E_A becomes almost constant. At that point, the resistive drop is the predominant effect, and V_T starts to fall.

Characteristics of series generator



Compound wound generator

- The compound generator prevents the terminal voltage of a dc generator from decreasing with increasing load.
- A compound generator is similar to a shunt generator except that it has additional field coils connected in series with the armature.
- This series field coils are composed of a few turns of heavy wire big enough to carry the armature current.
- The total resistance of the series coils is therefore small.

- When the generator runs at no load the current in the series coil is zero.
- The shunt coils however carry exciting current I_x ;which produces field flux, just as in a standard self excited shunt generator.
- As the generator is loaded the terminal voltage tends to drop but load current I_c now flows through the series field coils.
- The mmf developed by this coil act in the same direction as the mmf of the shunt field.

- Consequently the field flux under load rise above its original no load value which rise the value of E_0 if the series coils are properly designed the terminal voltage remains practically constant from no load to full load.

EMF equation of generator

Notations for equations

f = flux/pole in Wb

Z = total number of armature conductors

P = number of poles

A = number of parallel paths = 2 ... for wave winding

= P ... for lap winding

N = speed of armature in rpm

Eg = e.m.f of the generator = e.m.f /parallel path

Derivation of equation

Flux cut by one conductor in one revolution of the armature,

$d\Phi = P\Phi$ webers

Time taken to complete one revolution,

$dt = 60/N$ second

EMF generated/conductor $= d\Phi/dt = p\Phi N/60$ volts

EMF of generated,

E_g = EMF per parallel

= (emf/conductor)*no, of conductor in series per parallel path

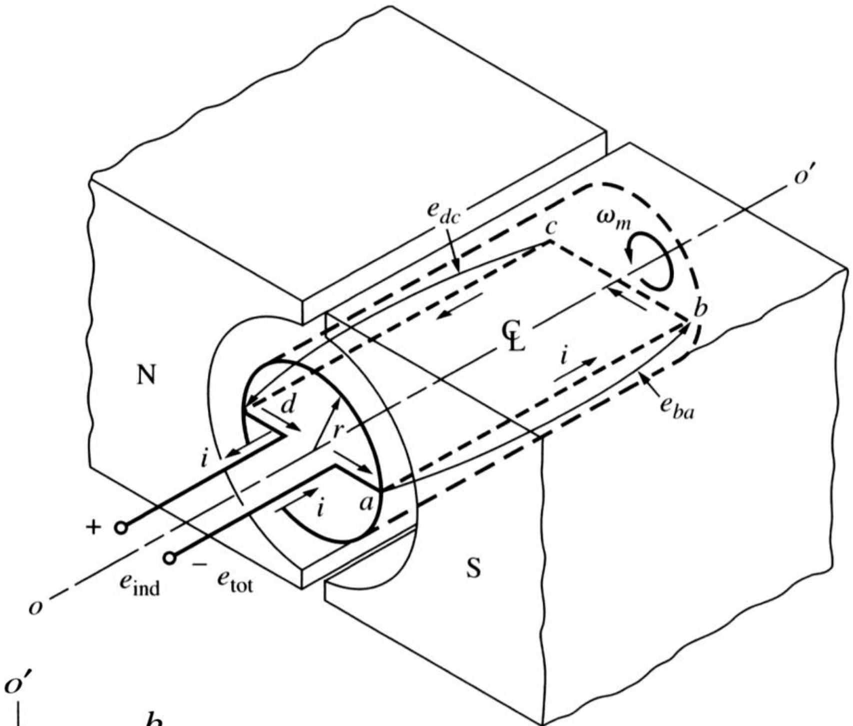
$= P\Phi NZ/60A$

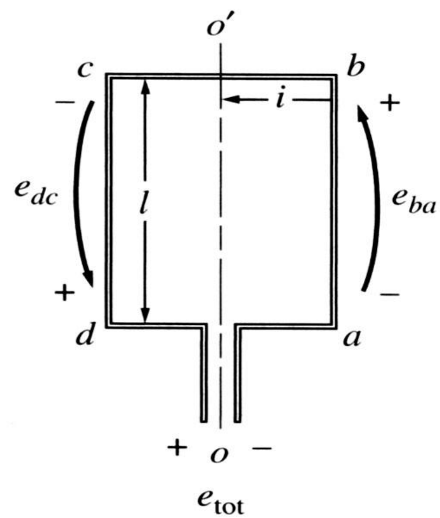
Therefore $E_{g=}\ P\Phi NZ/60A$

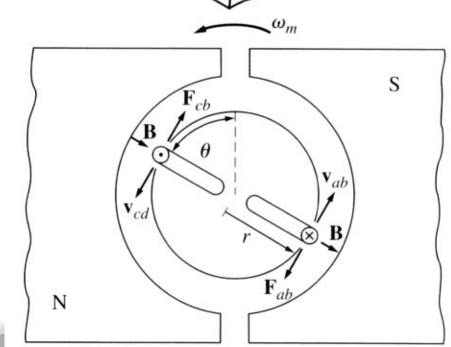
UNIT 3
DC MOTORS

The simplest DC machine

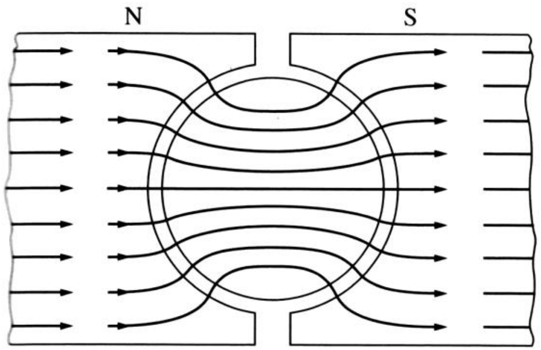
- The simplest DC rotating machine consists of a single loop of wire rotating about a fixed axis. The magnetic field is supplied by the North and South poles of the magnet.
- Rotor is the rotating part; Stator is the stationary part.







The simplest DC machine



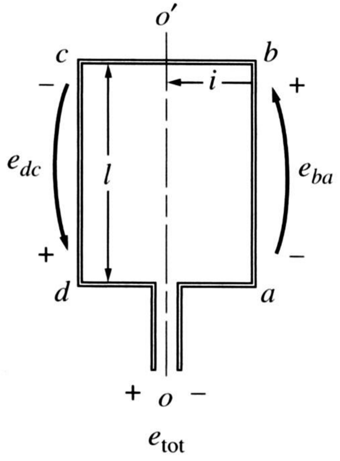
•We notice that the rotor lies in a slot curved in a ferromagnetic stator core, which, together with the rotor core, provides a constant-width air gap between the rotor and stator.

•The reluctance of air is much larger than the reluctance of core. Therefore, the magnetic flux must take the shortest path through the air gap.

•consequence, the magnetic flux is perpendicular to the rotor surface everywhere under the pole faces.

•Since the air gap is uniform, the reluctance is constant everywhere under the pole faces. Therefore, magnetic flux density is also constant everywhere under the pole faces.

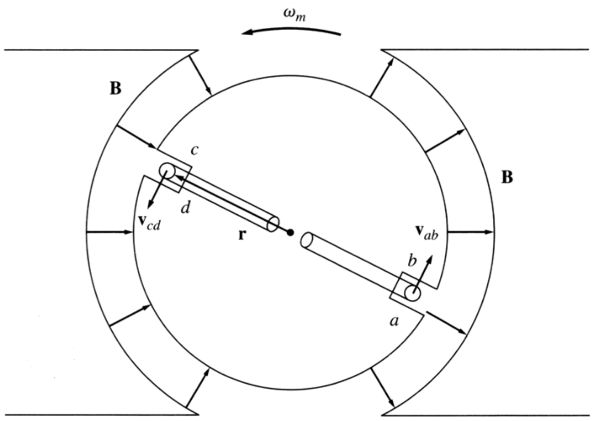
1. Voltage induced in a rotating loop



If a rotor of a DC machine is rotated, a voltage will be induced…

The loop shown has sides *ab* and *cd* perpendicular to the figure plane, *bc* and *da* are parallel to it.

The total voltage will be a sum of voltages induced on each segment of the loop.



Voltage on each segment is:

1) *ab*: In this segment, the velocity of the wire is tangential to the path of rotation. Under the pole face, velocity *v* is perpendicular to the magnetic field *B*, and the vector product *v* x *B* points into the page. Therefore, the voltage is

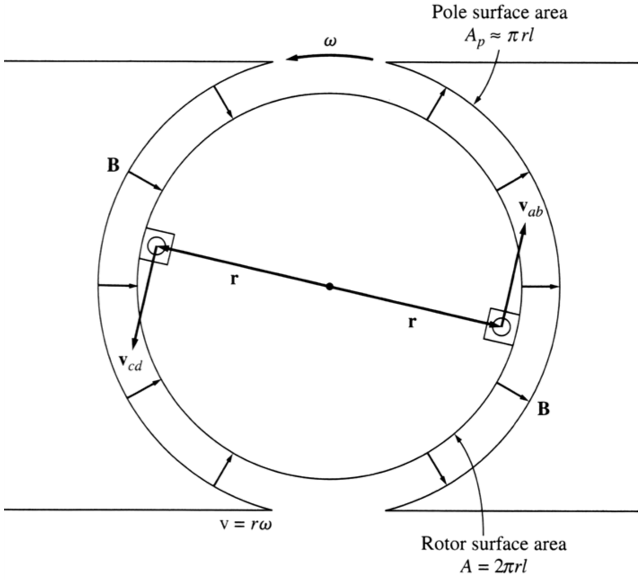
2) *bc*: In this segment, vector product *v* x *B* is perpendicular to *l*. Therefore, the voltage is zero.

3) *cd*: In this segment, the velocity of the wire is tangential to the path of rotation. Under the pole face, velocity *v* is perpendicular to the magnetic flux density *B*, and the vector product *v* x *B* points out of the page. Therefore, the voltage is

4) *da*: In this segment, vector product *v* x *B* is perpendicular to *l*. Therefore, the voltage is zero.

The tangential velocity of the loop's edges is (5.8.1)

where *r* is the radius from the axis of rotation to the edge of the loop. The total induced voltage: (5.8.2)



The rotor is a cylinder with surface area $2\pi rl$. Since there are two poles, the area of the rotor under each pole is $A_p = \pi rl$. Therefore:

$$e_{tot} = \begin{cases} \dfrac{2}{\pi} A_p B\omega & \textit{under the pole faces} \\ 0 & \textit{beyond the pole edges} \end{cases}$$

Assuming that the flux density B is constant everywhere in the air gap under the pole faces, the total flux under each pole is

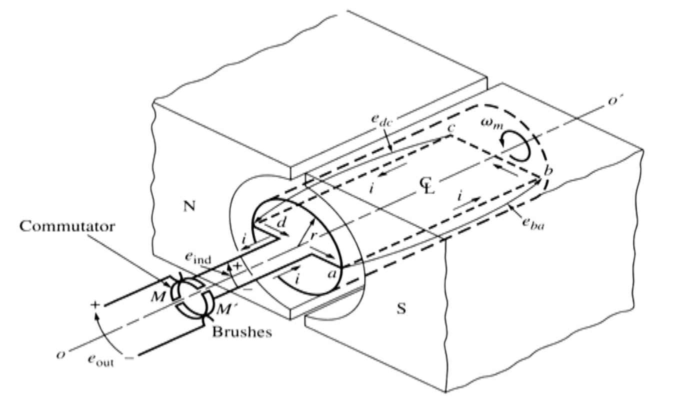
The voltage generated in any real machine depends on the following factors:

1. The flux inside the machine;

2. The rotation speed of the machine;

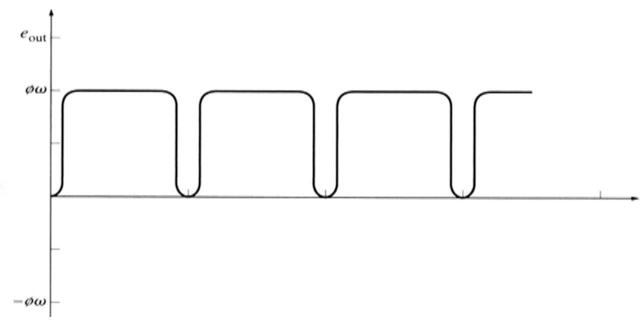
3. A constant representing the construction of the machine.

2. Getting DC voltage out of a rotating loop

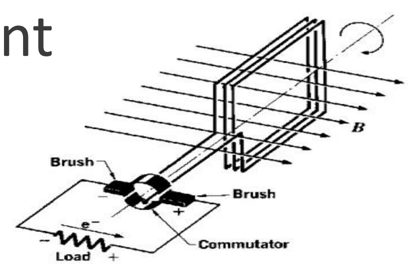


(a)

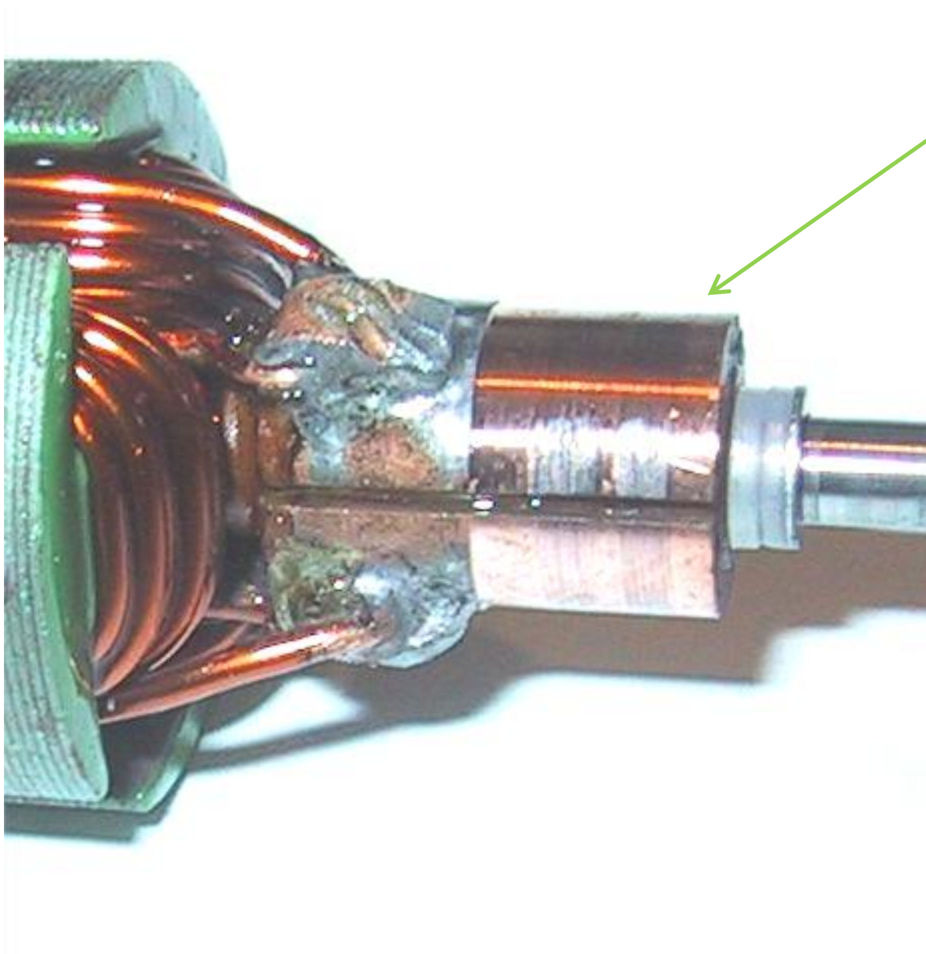
A voltage out of the loop is alternatively a constant positive value and a constant negative value.



One possible way to convert an alternating voltage to a constant voltage is by adding



commutator segment/brush circuitry to the end of the loop. Every time the voltage of the loop switches direction, contacts switch connection.




H27

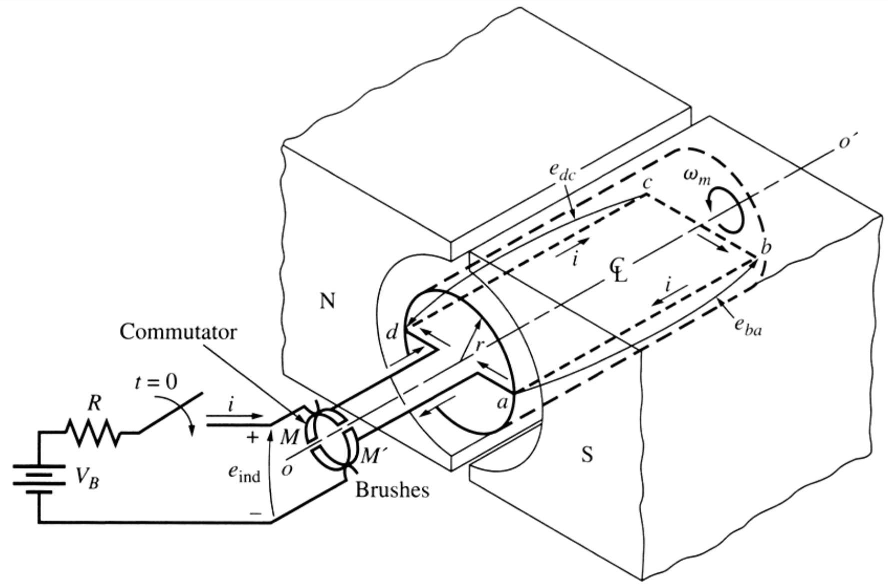
TORQUE

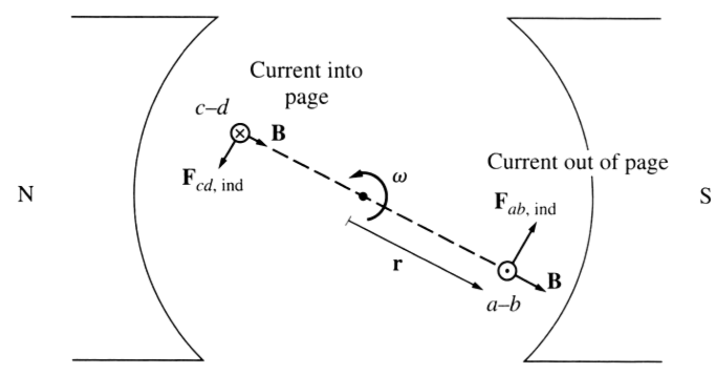
The induced torque in the rotating

Assuming that a battery is connected to the DC machine, the force on a segment of a loop is:

And the torque on the segment is

Where θ is the angle between r and F. Therefore, the torque is zero when the loop is beyond the pole edges.



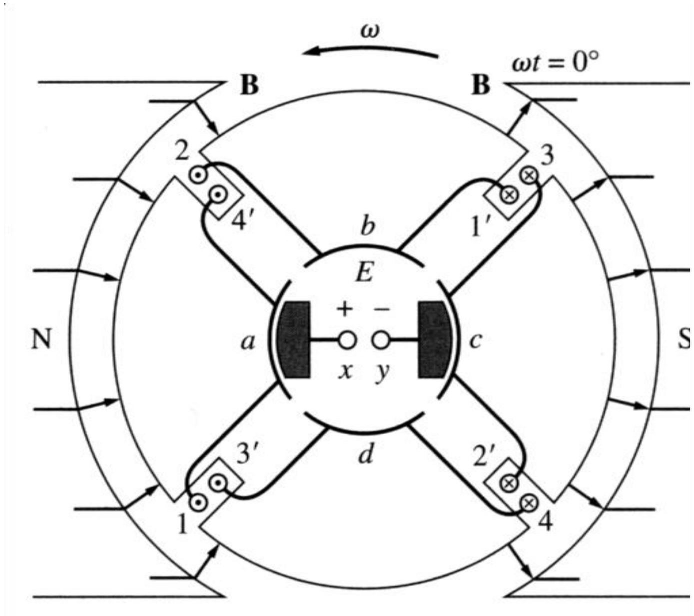


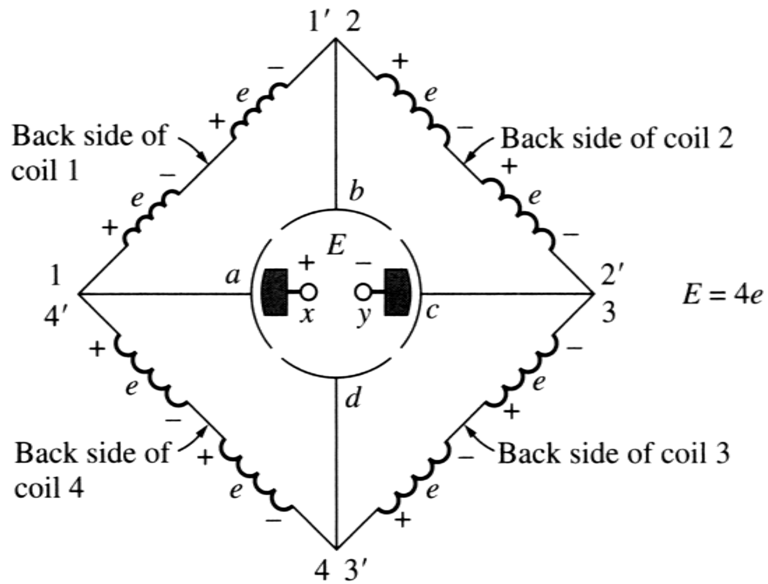
Commutation in a simple 4-loop DC machine

•Commutation is the process of converting the AC voltages and currents in the rotor of a DC machine to DC voltages and currents at its terminals.

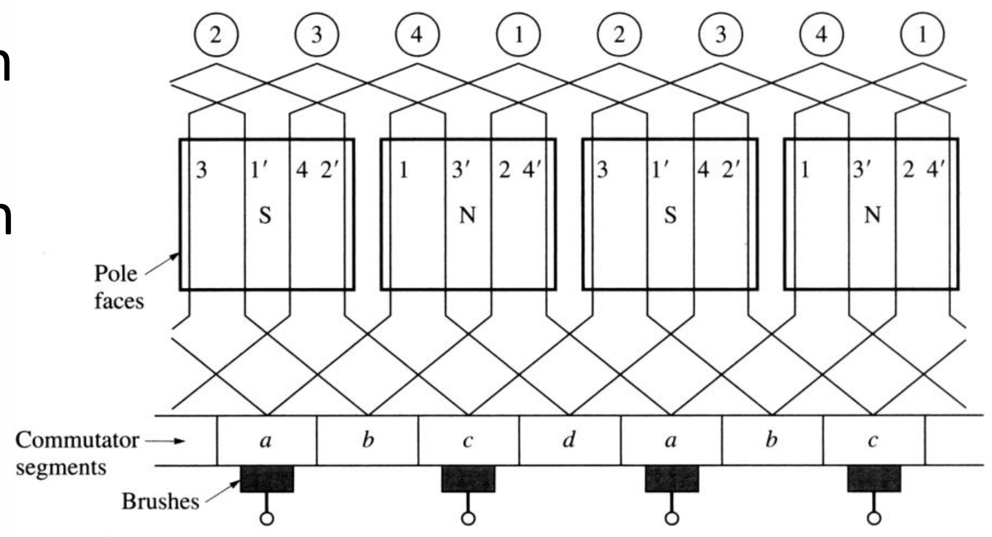
•A simple 4-loop DC machine has four complete loops buried in slots curved in the laminated steel of its rotor. The pole faces are curved to make a uniform air-gap. The four loops are laid into the slots in a special manner: the innermost wire in each slot (end of each loop opposite to the "unprimed") is indicated by a prime.

•Loop 1 stretches between commutator segments *a* and *b*, loop 2 stretches between segments *b* and *c*…


ω
ωt = 0°
B
B
N
S
2
3
4′
1′
b
E
+ −
a
c
x y
3′
2′
d
1
4


1′ 2
Back side of coil 1
Back side of coil 2
b
E
a
c
x
y
1
4′
2′
3
E = 4e
d
Back side of coil 4
Back side of coil 3
4 3′

At a certain time instance, when $\omega t = 0^0$, the 1, 2, 3', and 4' ends of the loops are under the north pole face and the 1', 2', 3, and 4 ends of the loops are under the south pole face. The voltage in each of 1, 2, 3', and 4' ends is given by

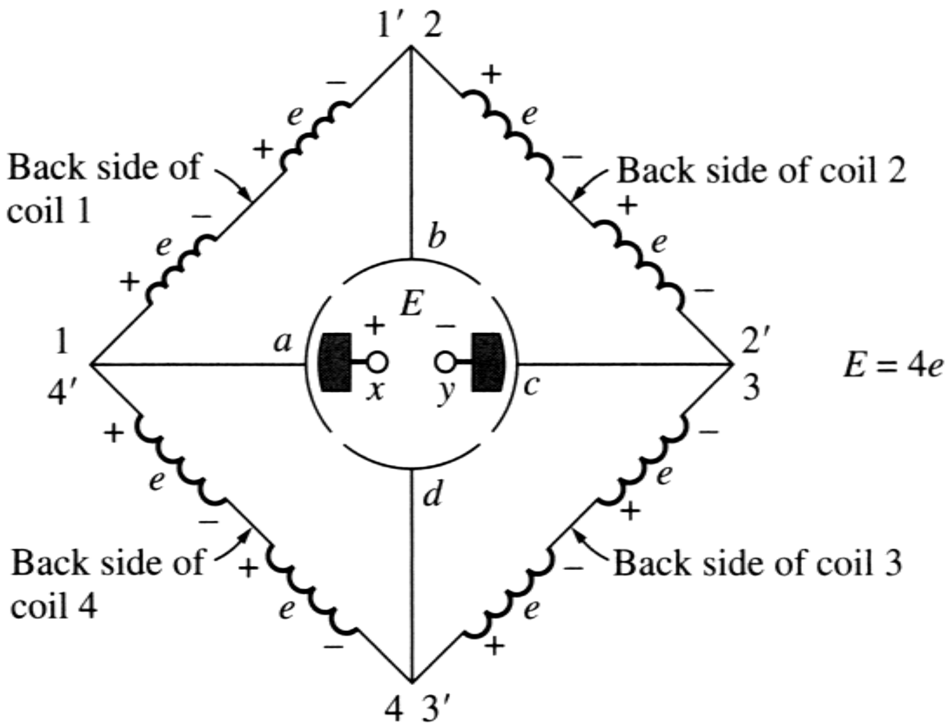


The voltage in each of 1', 2', 3, and 4 ends is

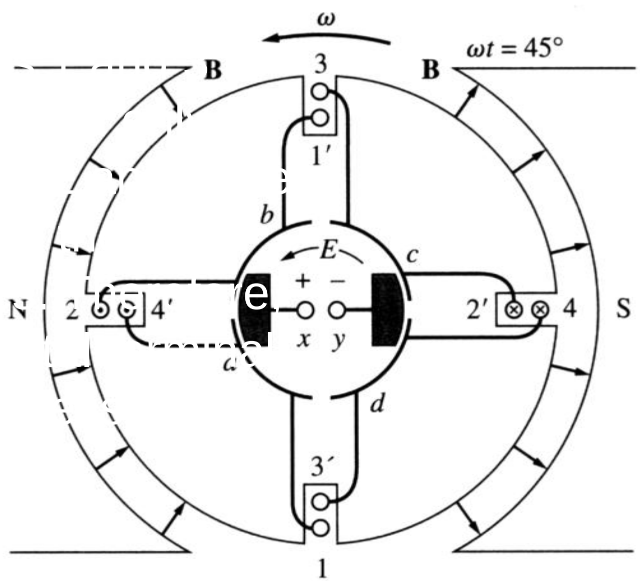
If the induced voltage on any side of a loop is (5.16.1), the total voltage at the brushes of the DC machine is

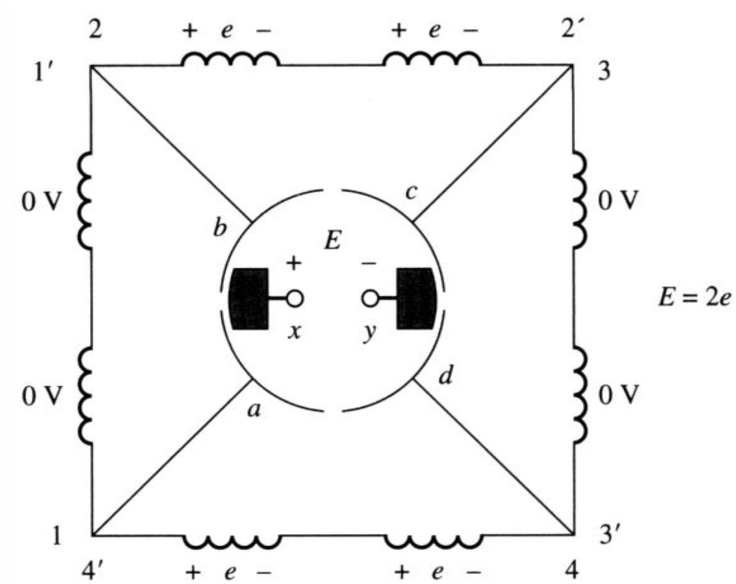
$$E = 4e \qquad at\ \omega t = 0^\circ \tag{5.16.3}$$

We notice that there are two parallel paths for current through the machine! The existence of two or more parallel paths for rotor current is a common feature of all commutation schemes.



If the machine keeps rotating, at ωt = 45^0, loops 1 and 3 have rotated into the gap between poles, so the voltage across each of them is zero. At the same time, the brushes short out the commutator segments *ab* and *cd*.



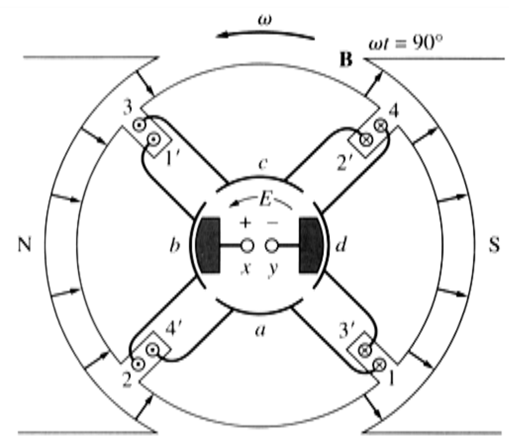


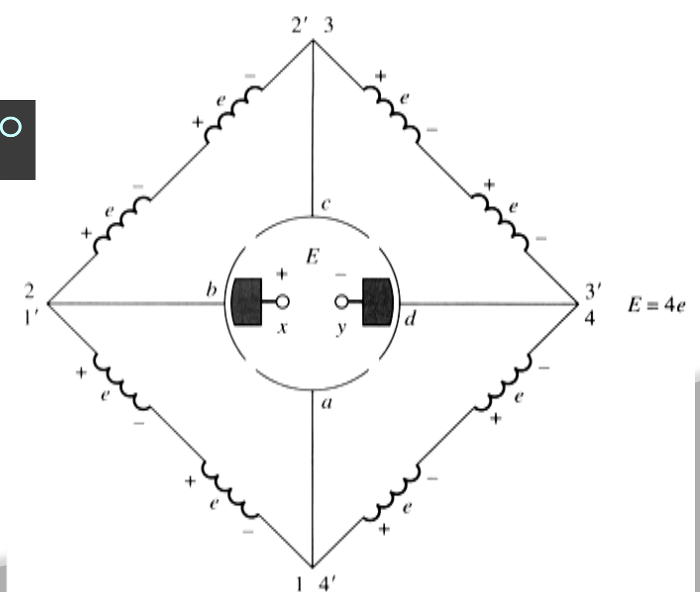
$$E = 2e \qquad \text{at } \omega t = 45^\circ \tag{5.18.1}$$

At ωt = 90^0, the loop ends 1’, 2, 3, and 4’ are under the north pole face, and the loop ends 1, 2’, 3’, and 4 are under the south pole face. The voltages are built up out of page for the ends under the north pole face and into the page for the ends under the south pole face. Four voltage-carrying ends in each parallel path through the machine lead to the terminal voltage of

$$E = 4e \qquad at\ \omega t = 90^\circ \qquad (5.163)$$

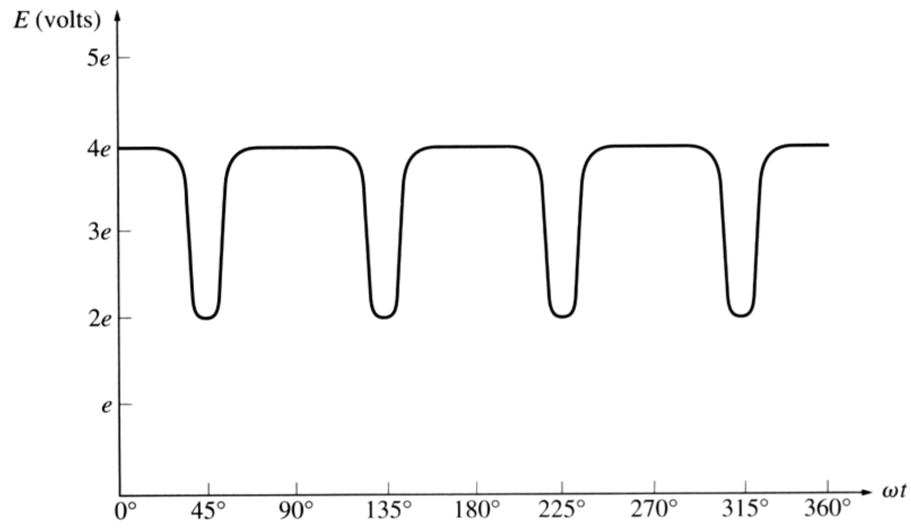
We notice that the voltages in loops 1 and 3 have reversed compared to ωt = 0^0. However, the loops’ connections have also reversed, making the total voltage being of the same polarity.





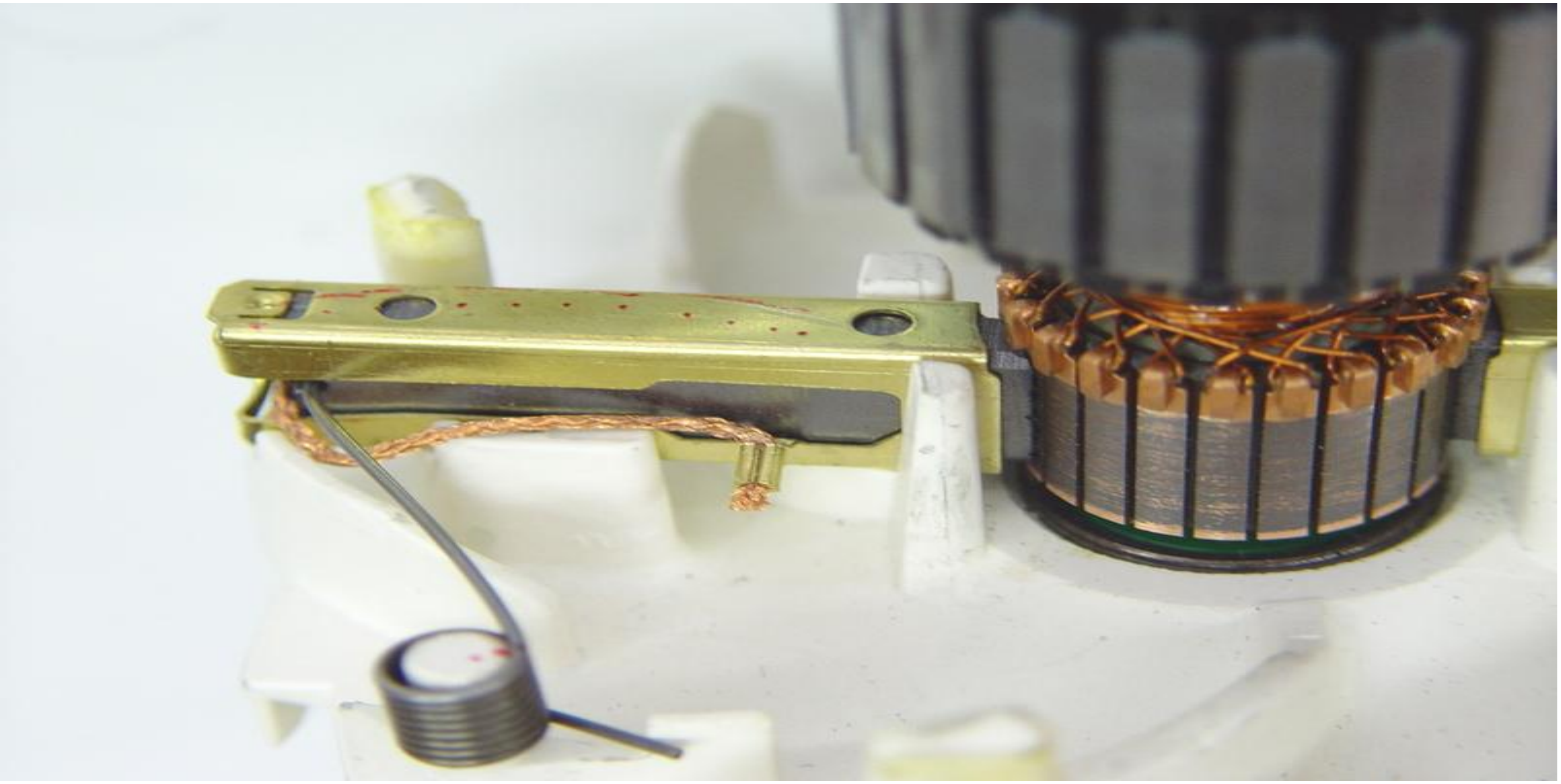
When the voltage reverses in a loop, the connections of the loop are also switched to keep the polarity of the terminal voltage the same.

The terminal voltage of this 4-loop DC machine is still not constant over time, although it is a better approximation to a constant DC level than what is produced by a single rotating loop.



Increasing the number of loops on the rotor, we improve our approximation to perfect DC voltage.

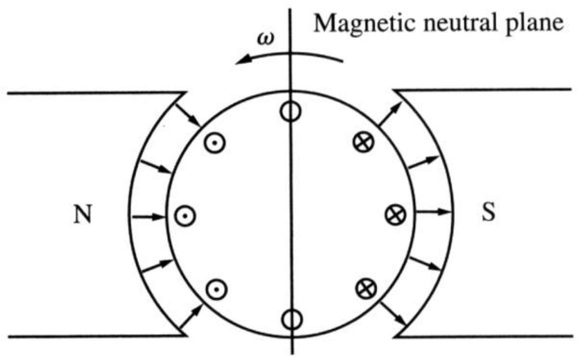
Commutator segments are usually made out of copper bars and the brushes are made of a mixture containing graphite to minimize friction between segments and brushes.



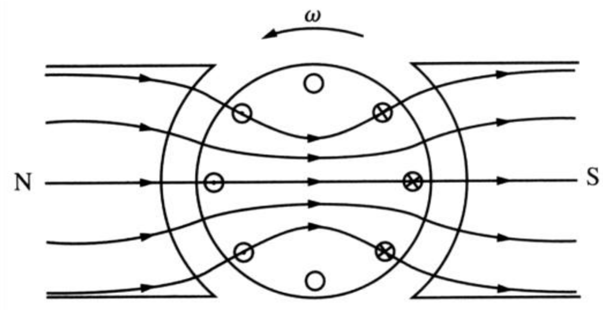
Problems with commutation in DC machines

If the magnetic field windings of a DC machine are connected to the power source and the rotor is turned by an external means, a voltage will be induced in the conductors of the rotor. This voltage is rectified and can be supplied to external loads. However, if a load is connected, a current will flow through the armature winding. This current produces its own magnetic field that distorts the original magnetic field from the machine's poles. This distortion of the machine's flux as the load increases is called armature reaction and can cause two problems:

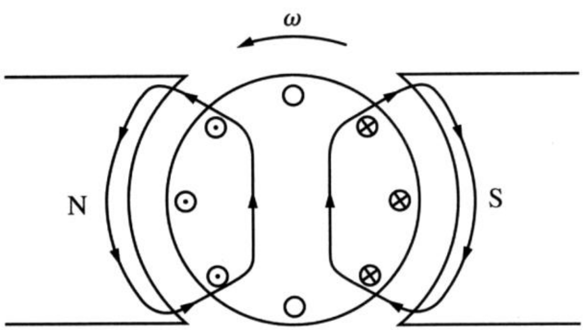
1) neutral-plane shift: The magnetic neutral plane is the plane within the machine where the velocity of the rotor wires is exactly parallel to the magnetic flux lines, so that the induced voltage in the conductors in the plane is exactly zero.



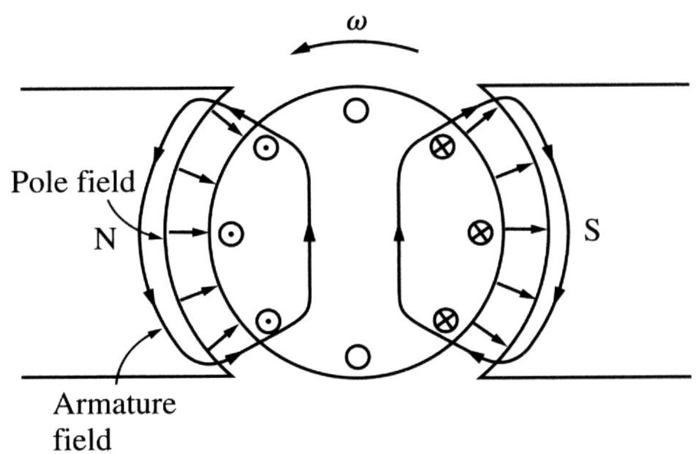
A two-pole DC machine: initially, the pole flux is uniformly distributed and the magnetic neutral plane is vertical.

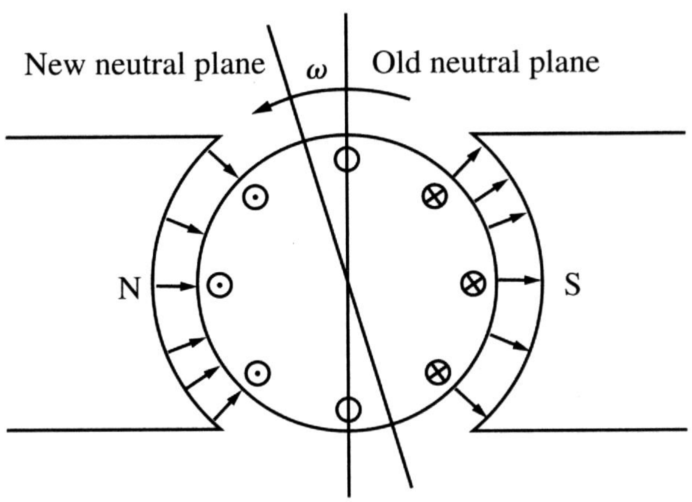


The effect of the air gap on the pole flux.



When the load is connected, a current – flowing through the rotor – will generate a magnetic field from the rotor windings.



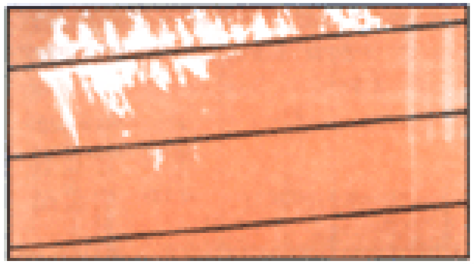


This rotor magnetic field will affect the original magnetic field from the poles. In some places under the poles, both fields will sum together, in other places, they will subtract from each other

Therefore, the net magnetic field will not be uniform and the neutral plane will be shifted.

In general, the neutral plane shifts in the direction of motion for a generator and opposite to the direction of motion for a motor. The amount of the shift depends on the load of the machine.

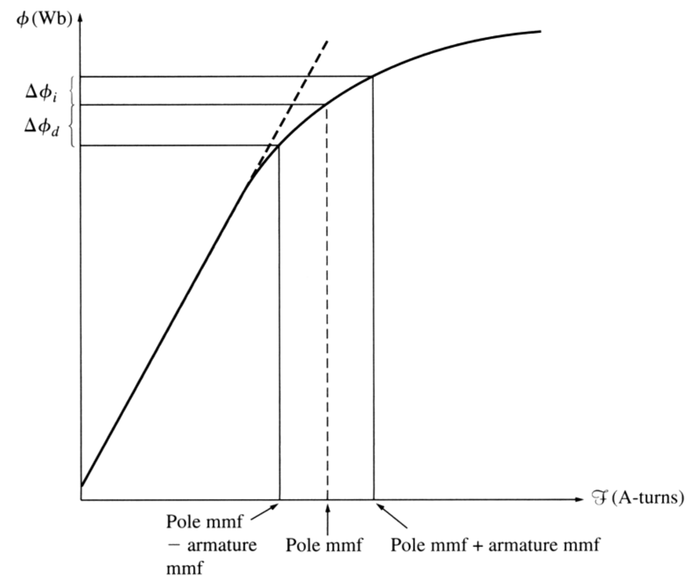
The commutator must short out the commutator segments right at the moment when the voltage across them is zero. The neutral-plane shift may cause the brushes short out commutator segments with a non-zero voltage across them. This leads to arcing and sparkling at the brushes!



2) Flux weakening.

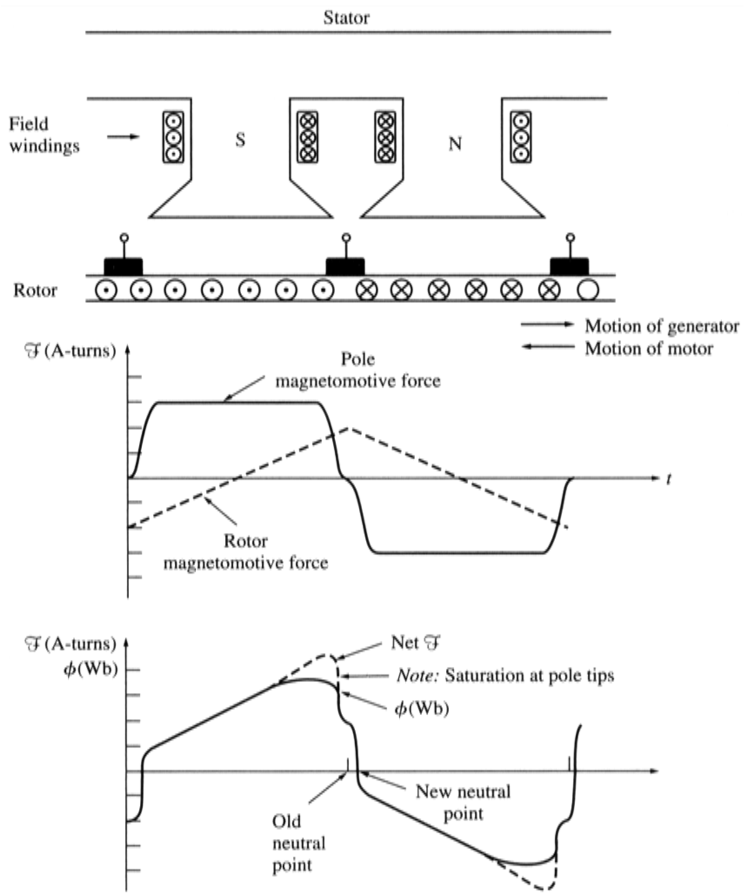
Most machines operate at flux densities near the saturation point.

- At the locations on the pole surfaces where the rotor mmf adds to the pole mmf, only a small increase in flux occurs (due to saturation).
- However, at the locations on the pole surfaces where the rotor mmf subtracts from the pole mmf, there is a large decrease in flux.
- Therefore, the total average flux under the entire pole face decreases.



$\Delta\phi_i \equiv$ flux increase under reinforced sections of poles

$\Delta\phi_d \equiv$ flux decrease under subtracting sections of poles

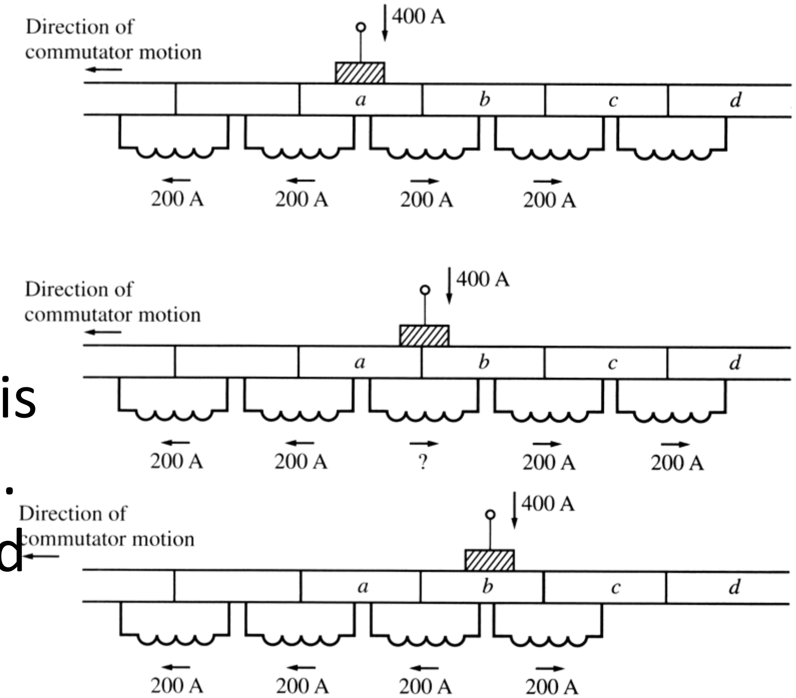


In generators, flux weakening reduces the voltage supplied by a generator.

In motors, flux weakening leads to increase of the motor speed. Increase of speed may increase the load, which, in turns, results in more flux weakening. Some shunt DC motors may reach runaway conditions this way…

Observe a considerable decrease in the region where two mmfs are subtracted and a saturation…

This problem occurs in commutator segments being shorten by brushes and is called sometimes an inductive kick.

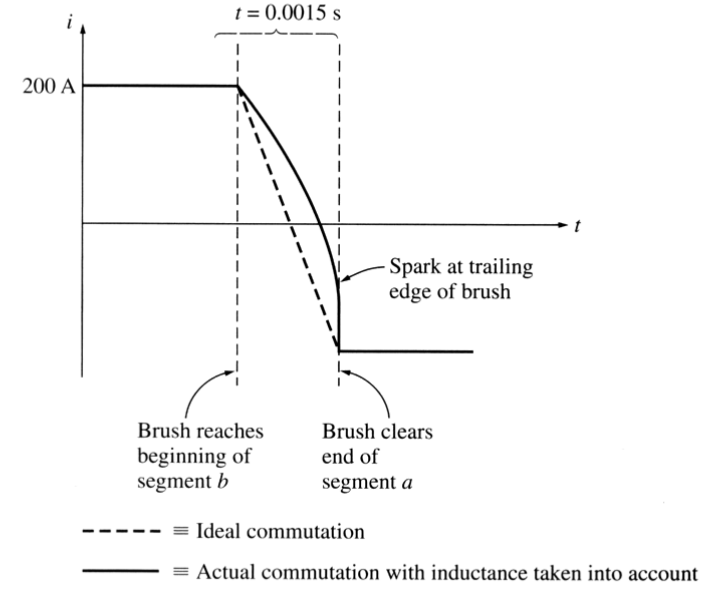


Assuming that the current in the brush is 400 A, the current in each path is 200 A. When a commutator segment is shorted out, the current flow through that segment must reverse.

Assuming that the machine is running at 800 rpm and has 50 commutator segments, each segment moves under the brush and clears it again in 0.0015 s

The rate of change in current in the shorted loop averages

Therefore, even with a small inductance in the loop, a very large inductive voltage kick *L di/dt* will be induced in the shorted commutator segment.



This voltage causes sparkling at the brushes.

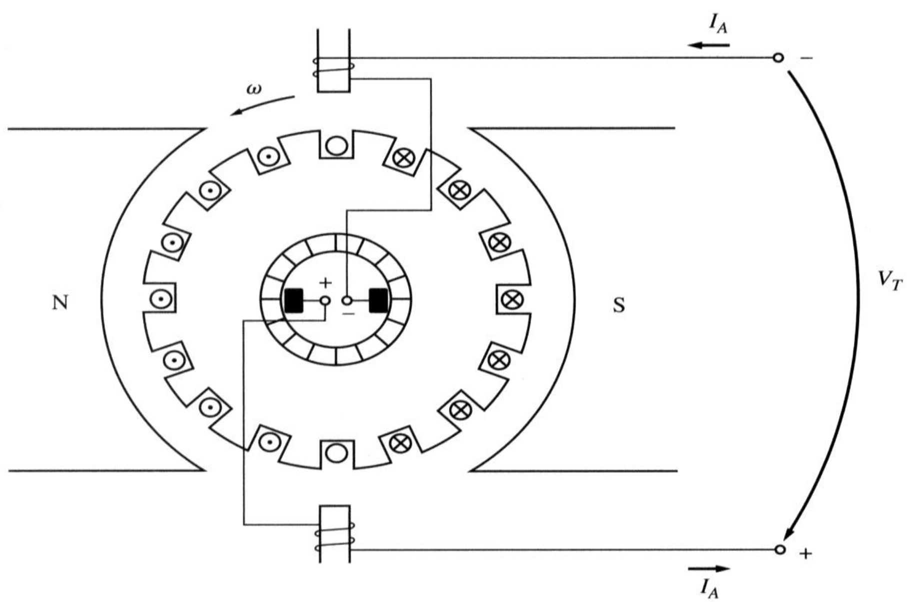
Solutions to the problems with commutation

1. Commutating poles or interpoles

To avoid sparkling at the brushes while the machine's load changes, instead of adjusting the brushes' position, it is possible to introduce small poles (commutating poles or interpoles) between the main ones to make the voltage in the commutating wires to be zero. Such poles are located directly over the conductors being commutated and provide the flux that can exactly cancel the voltage in the coil undergoing commutation. Interpoles do not change the operation of the machine

since they are so small that only affect few conductors being commutated. Flux weakening is unaffected.

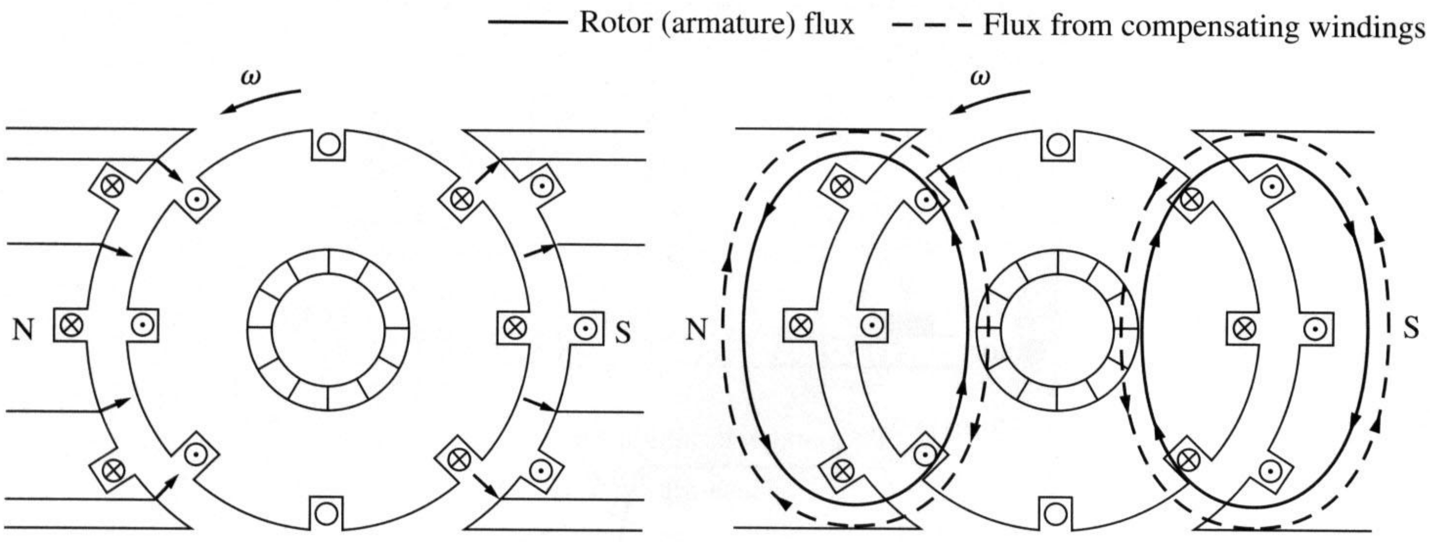
Interpole windings are connected in series with the rotor windings. As the load increases and the rotor current increases, the magnitude of neutral-plane shift and the size of *Ldi/dt* effects increase too increasing the voltage in the conductors undergoing commutation



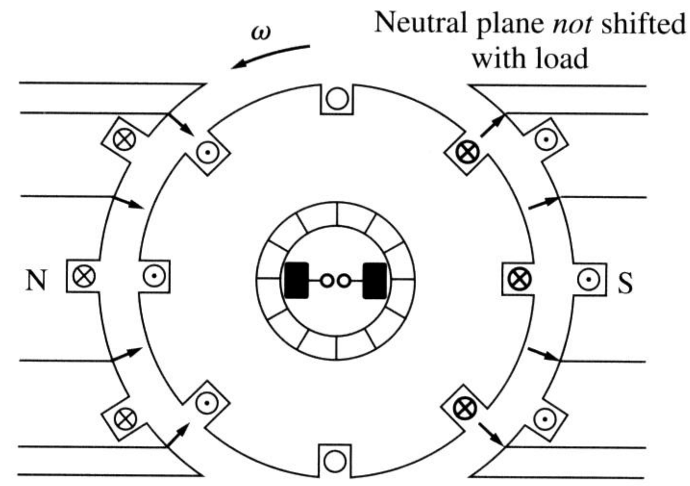
- However, the interpole flux increases too producing a larger voltage in the conductors that opposes the voltage due to neutral-plane shift. Therefore, both voltages cancel each other over a wide range of loads. This approach works for both DC motors and generators.
- The interpoles must be of the same polarity as the next upcoming main pole in a generator;
- The interpoles must be of the same polarity as the previous main pole in a motor.
- The use of interpoles is very common because they correct the sparkling problems of DC machines at a low cost. However, since interpoles do nothing with the flux distribution under the pole faces, flux-weakening problem is still present.

2. Compensating windings

The flux weakening problem can be very severe for large DC motors. Therefore, compensating windings can be placed in slots carved in the faces of the poles parallel to the rotor conductors. These windings are connected in series with the rotor windings, so when the load changes in the rotor, the current in the compensating winding changes too…

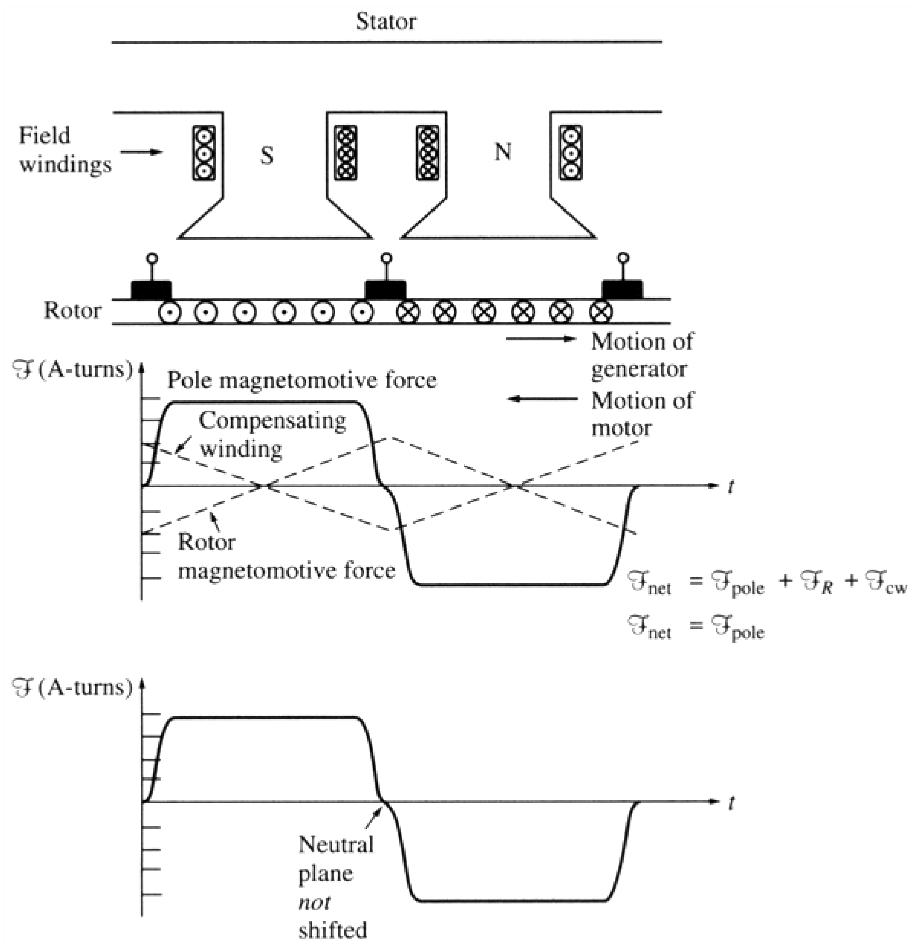


Sum of these three fluxes equals to the original pole flux.



The mmf due to the compensating windings is equal and opposite to the mmf of the rotor. These two mmfs cancel each other, such that the flux in the machine is unchanged.

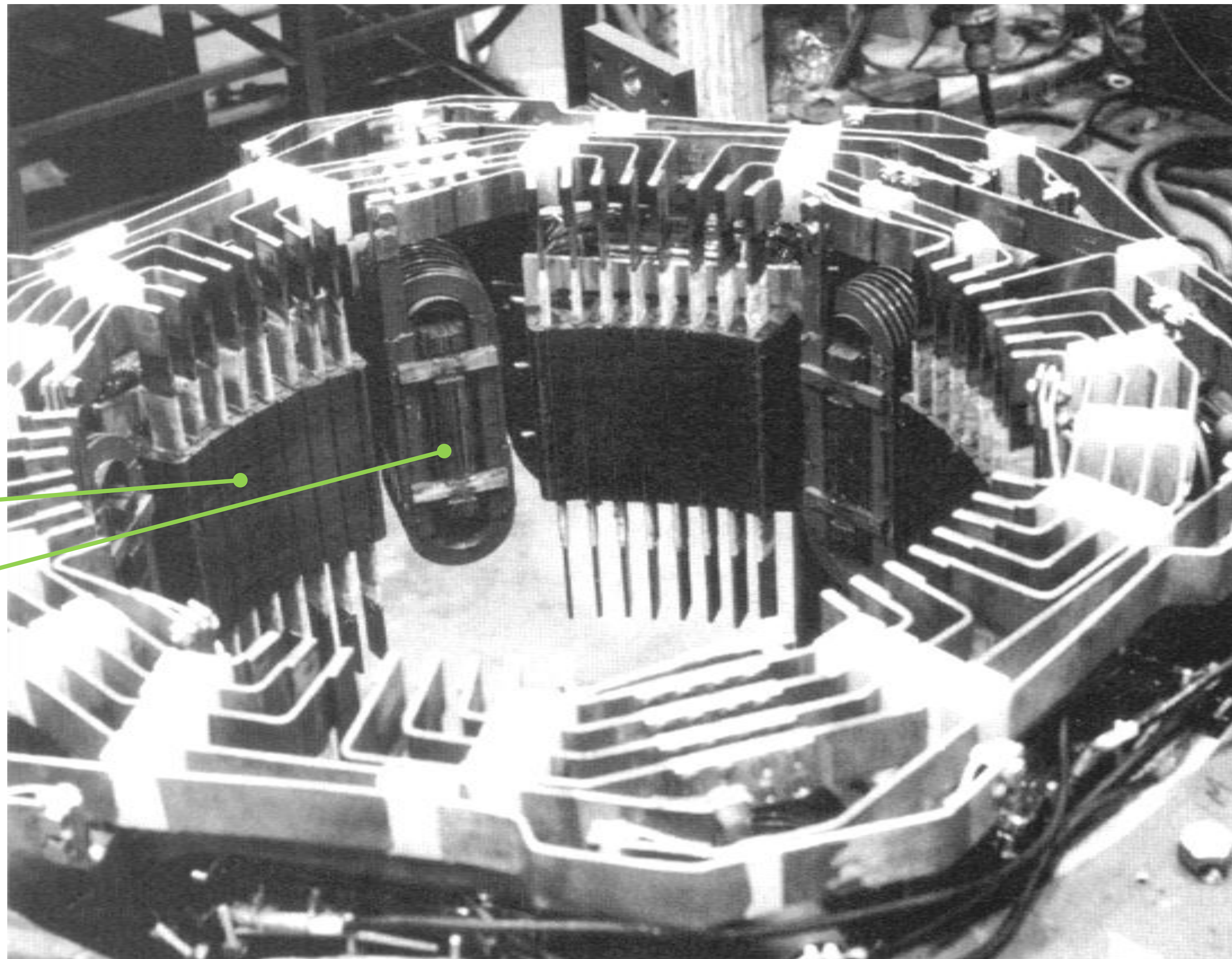
The main disadvantage of compensating windings is that they are expensive since they must be machined into the faces of the poles. Also, any motor with compensative windings must have interpoles to cancel *L di/dt* effects.



A stator of a six-pole DC machine with interpoles and compensating windings.

pole

interpole



The losses in DC machines

Brush (drop) losses – the power lost across the contact potential at the brushes of the machine.

Where I_A is the armature current and V_{BD} is the brush voltage drop. The voltage drop across the set of brushes is approximately constant over a large range of armature currents and it is usually assumed to be about 2 V.

Other losses are exactly the same as in AC machines…

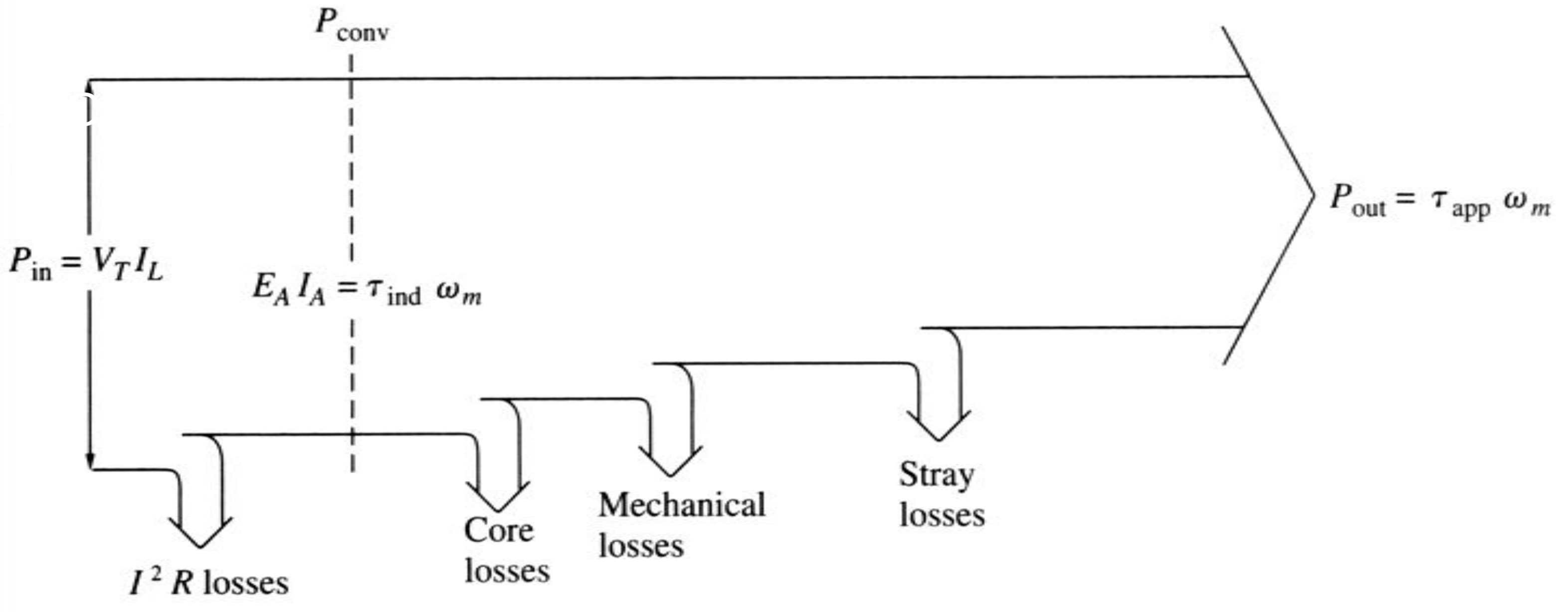
Core losses – hysteresis losses and eddy current losses. They vary as B^2 (square of flux density) and as $n^{1.5}$ (speed of rotation of the magnetic field).

Mechanical losses – losses associated with mechanical effects: friction (friction of the bearings) and windage (friction between the moving parts of the machine and the air inside the casing). These losses vary as the cube of rotation speed n^3.

Stray (Miscellaneous) losses – losses that cannot be classified in any of the previous categories. They are usually due to inaccuracies in modeling. For many machines, stray losses are assumed as 1% of full load.

The power-flow diagram

On of the most convenient technique to account for power losses in a machine is the power-flow diagram.

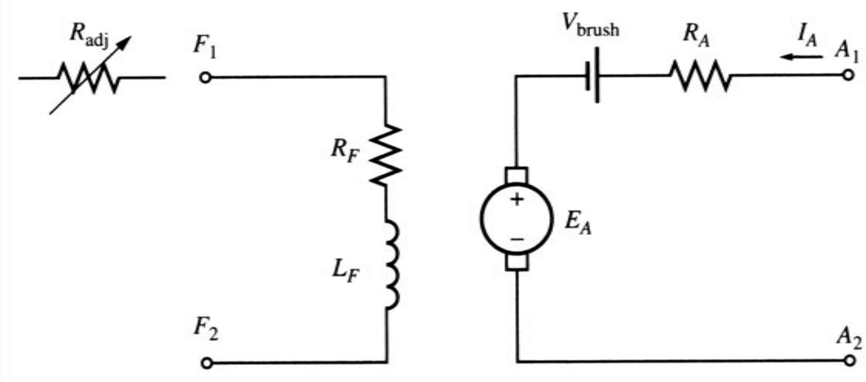


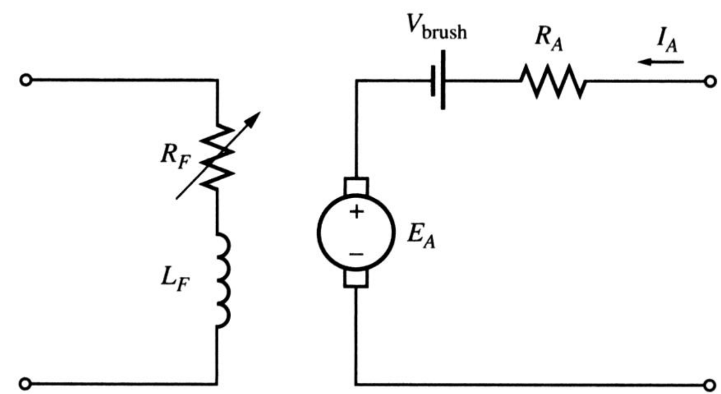
Electrical power is input to the machine, and the electrical and brush losses must be subtracted. The remaining power is ideally converted from electrical to mechanical form at the point labeled as P_{conv}.

Equivalent circuit of a DC motor

•The armature circuit (the entire rotor structure) is represented by an ideal voltage source E_A and a resistor R_A. A battery V_{brush} in the opposite to a current flow in the machine direction indicates brush voltage drop.

•The field coils producing the magnetic flux are represented by inductor L_F and resistor R_F. The resistor R_{adj} represents an external variable resistor (sometimes lumped together with the field coil resistance) used to control the amount of current in the field circuit.





Sometimes, when the brush drop voltage is small, it may be left out. Also, some DC motors have more than one field coil.

The internal generated voltage in the machine is

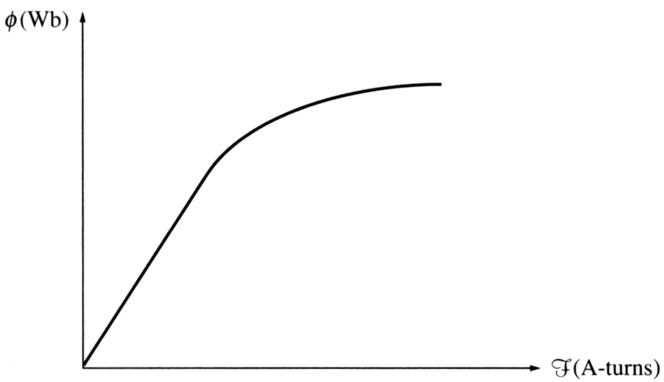
The induced torque developed by the machine is

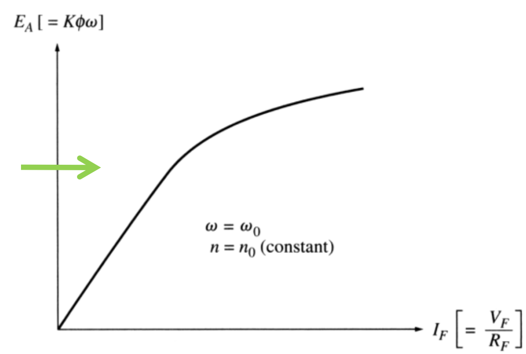
Here K is the constant depending on the design of a particular DC machine (number and commutation of rotor coils, etc.) and ϕ is the total flux inside the machine.

Note that for a single rotating loop $K = \pi/2$.

Magnetization curve of a DC machine

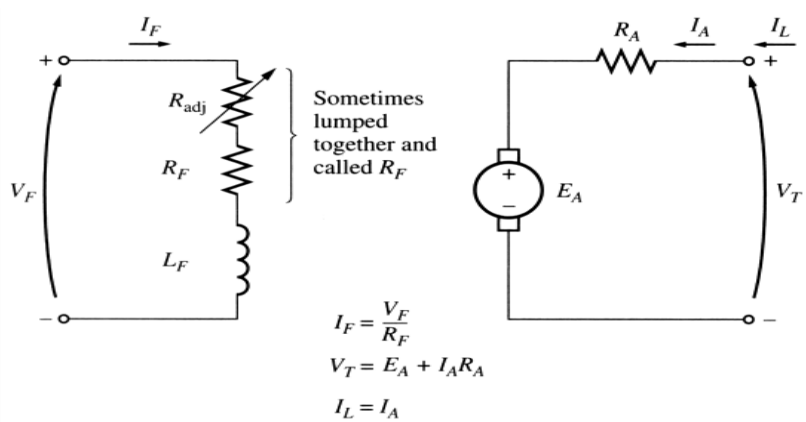
The internal generated voltage E_A is directly proportional to the flux in the machine and the speed of its rotation.
The field current in a DC machine produces a field mmf $F = N_F I_F$, which produces a flux in the machine according to the magnetization curve

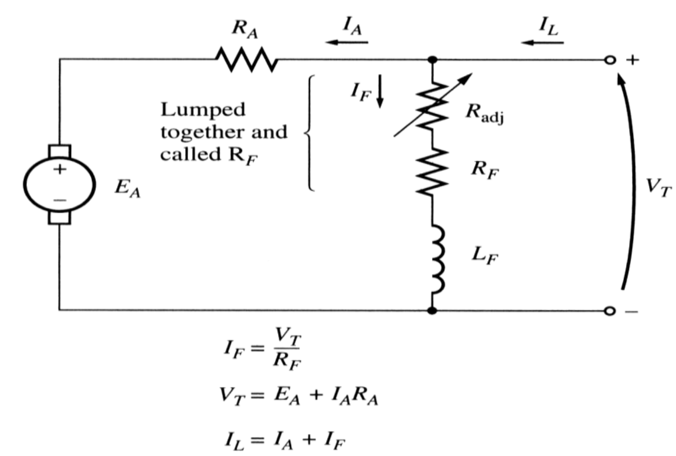




To get the maximum possible power per weight out of the machine, most motors and generators are operating near the saturation point on the magnetization curve. Therefore, when operating at full load, often a large increase in current I_F may be needed for small increases in the generated voltage E_A.

Separately excited and Shunt DC motors





Separately excited DC motor:
a field circuit is supplied from a separate constant voltage power source.

For the armature circuit of these motors:

$$V_T = E_A + I_A R_A \tag{5.45.1}$$

Shunt DC motor:
a field circuit gets its power from the armature terminals of the motor.

Shunt motor: terminal characteristic

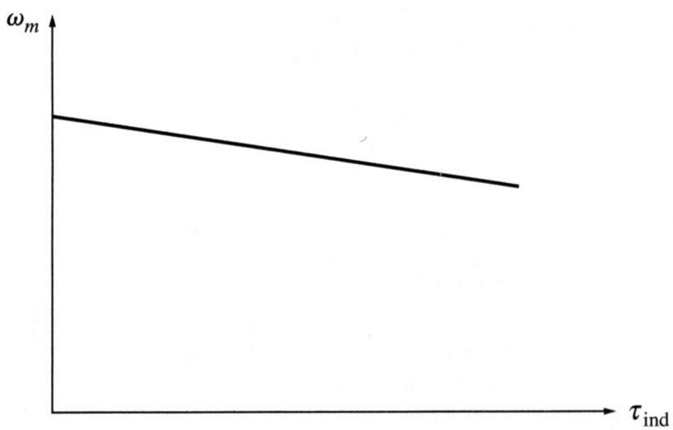
A terminal characteristic of a machine is a plot of the machine's output quantities vs. each other.

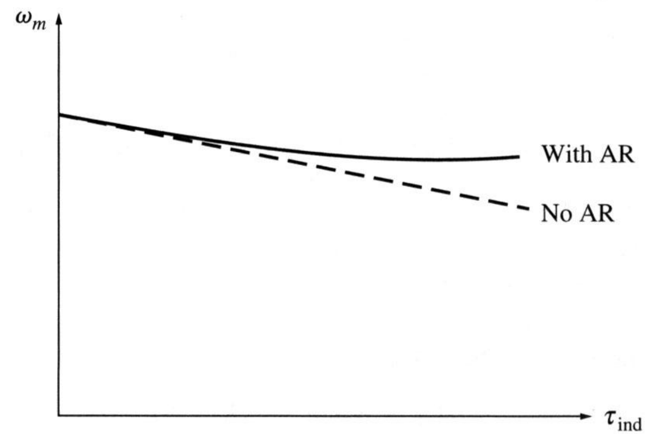
For a motor, the output quantities are shaft torque and speed. Therefore, the terminal characteristic of a motor is its output torque vs. speed.

If the load on the shaft increases, the load torque τ_{load} will exceed the induced torque τ_{ind}, and the motor will slow down. Slowing down the motor will decrease its internal generated voltage (since $E_A = K\phi\omega$), so the armature current increases ($I_A = (V_T - E_A)/R_A$). As the armature current increases, the induced torque in the motor increases (since $\tau_{ind} = K\phi I_A$), and the induced torque will equal the load torque at a lower speed ω.

$$\omega = \frac{V_T}{K\phi} - \frac{R_A}{(K\phi)^2}\tau_{ind}$$

Assuming that the terminal voltage and other terms are constant, the motor's speed vary linearly with torque.





However, if a motor has an armature reaction, flux-weakening reduces the flux when torque increases. Therefore, the motor's speed will increase. If a shunt (or separately excited) motor has compensating windings, and the motor's speed and armature current are known for any value of load, it's possible to calculate the speed for any other value of load.

Shunt motor: Nonlinear analysis

•The flux ϕ and, therefore the internal generated voltage E_A of a DC machine are nonlinear functions of its mmf and must be determined based on the magnetization curve. Two main contributors to the mmf are its field current and the armature reaction (if present).

•Since the magnetization curve is a plot of the generated voltage vs. field current, the effect of changing the field current can be determined directly from the magnetization curve.

•If a machine has armature reaction, its flux will reduce with increase in load. The total mmf in this case will be

•It is customary to define an equivalent field current that would produce the same output voltage as the net (total) mmf in the machine:

•Conducting a nonlinear analysis to determine the internal generated voltage in a DC motor, we may need to account for the fact that a motor can be running at a speed other than the rated one.

The voltage induced in a DC machine is

•For a given effective field current, the flux in the machine is constant and the internal generated voltage is directly proportional to speed:

- •Where E_{A0} and n_0 represent the reference (rated) values of voltage and speed, respectively. Therefore, if the reference conditions are known from the magnetization curve and the actual E_A is computed, the actual speed can be determined.

Shunt motor: Speed control

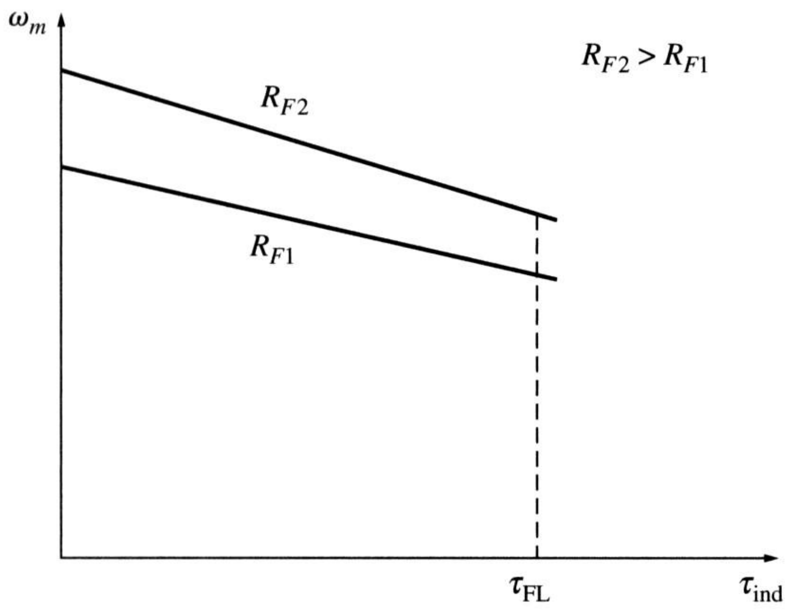
There are two methods to control the speed of a shunt DC motor:

1. Adjusting the field resistance R_F (and thus the field flux)
2. Adjusting the terminal voltage applied to the armature

1. Adjusting the field resistance

1) Increasing field resistance R_F decreases the field current ($I_F = V_T/R_F$);
2) Decreasing field current I_F decreases the flux ϕ;
3) Decreasing flux decreases the internal generated voltage ($E_A = K\phi\omega$);
4) Decreasing E_A increases the armature current ($I_A = (V_T - E_A)/R_A$);
5) Changes in armature current dominate over changes in flux; therefore, increasing I_A increases the induced torque ($\tau_{ind} = K\phi I_A$);
6) Increased induced torque is now larger than the load torque τ_{load} and, therefore, the speed ω increases;
7) Increasing speed increases the internal generated voltage E_A;
8) Increasing E_A decreases the armature current I_A…
9) Decreasing I_A decreases the induced torque until $\tau_{ind} = \tau_{load}$ at a higher speed ω.

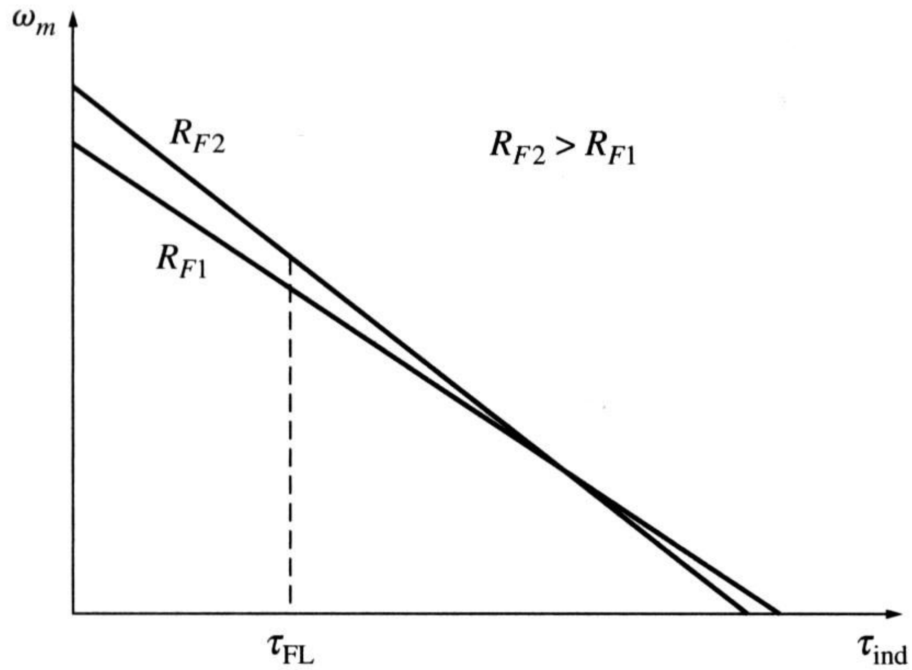
The effect of increasing the field resistance within a normal load range: from no load to full load.



Increase in the field resistance increases the motor speed. Observe also that the slope of the speed-torque curve becomes steeper when field resistance increases.

The effect of increasing the field resistance with over an entire load range: from no-load to stall.

At very slow speeds (overloaded motor), an increase in the field resistance decreases the speed. In this region, the increase in armature current is no longer large enough to compensate for the decrease in flux.

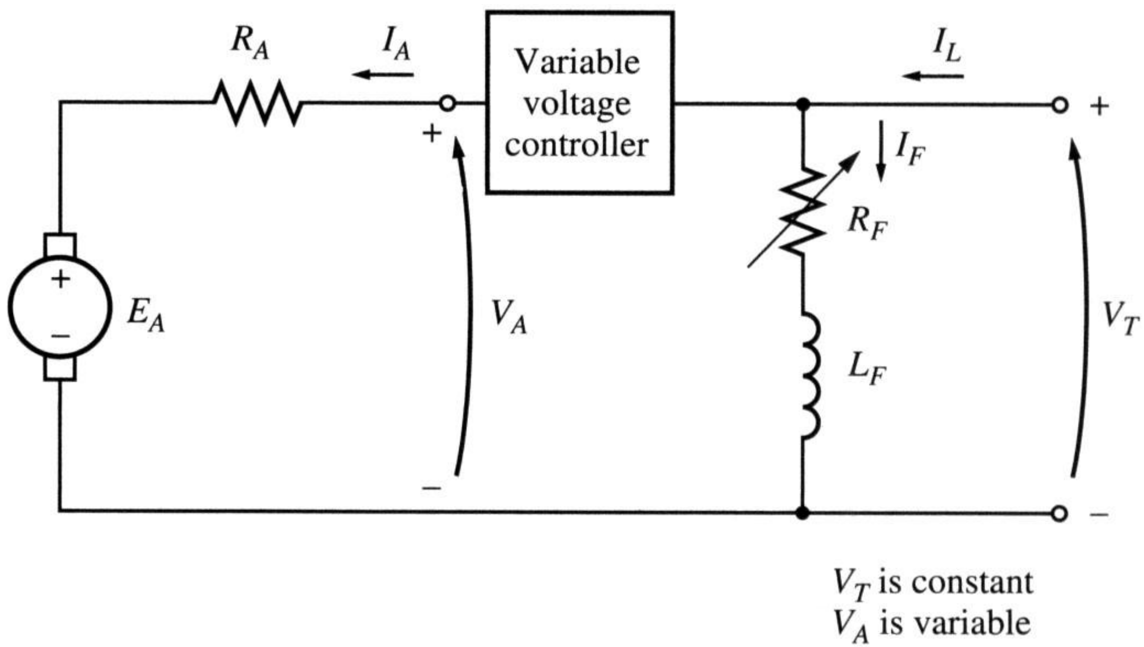


Some small DC motors used in control circuits may operate at speeds close to stall conditions. For such motors, an increase in field resistance may have no effect (or opposite to the expected effect) on the motor speed. The result of speed control by field resistance is not predictable and, thus, this type of control is not very common.

2. Changing the armature voltage

This method implies changing the voltage applied to the armature of the motor without changing the voltage applied to its field. Therefore, the motor must be separately excited to use armature voltage control.

Armature voltage speed control



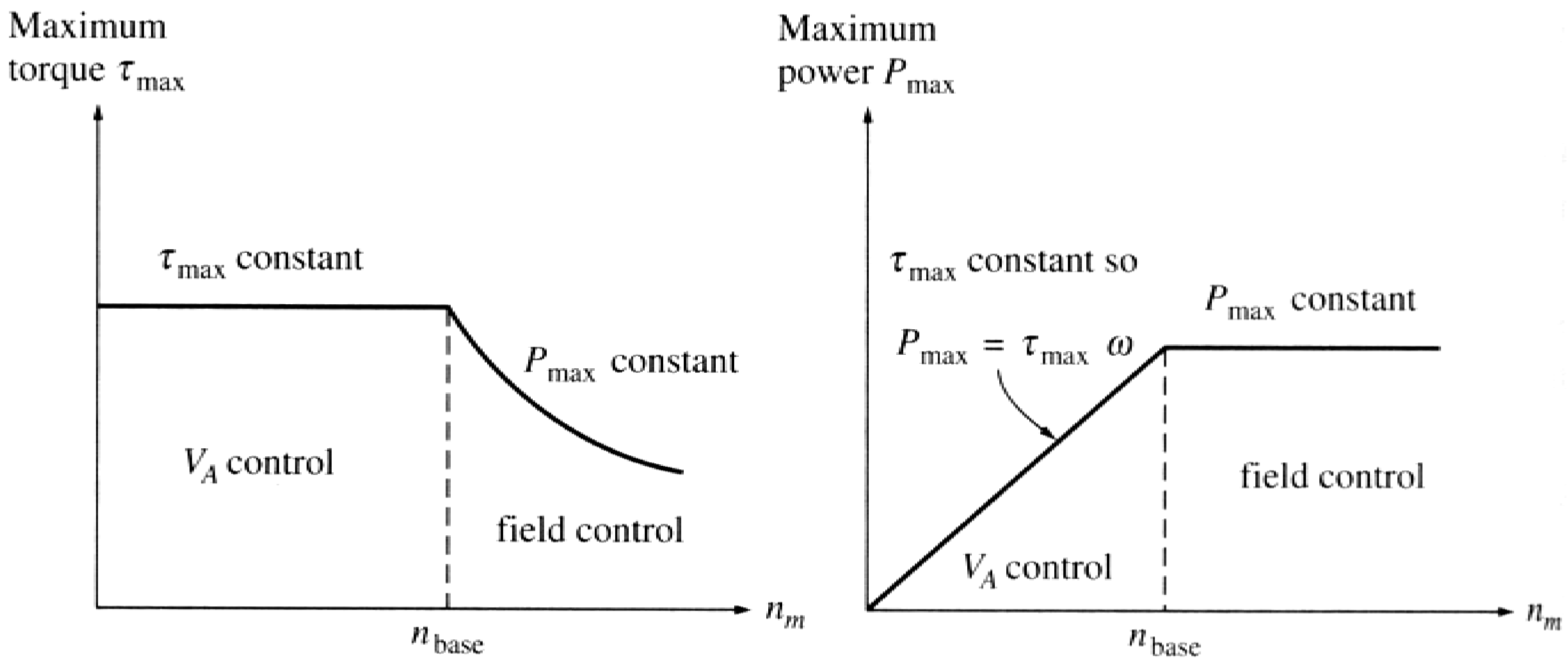
•If a motor is operated at its rated terminal voltage, power, and field current, it will be running at the rated speed also called a base speed.
•Field resistance control can be used for speeds above the base speed but not below it. Trying to achieve speeds slower than the base speed by the field circuit control, requires large field currents that may damage the field winding.
•Since the armature voltage is limited to its rated value, no speeds exceeding the base speed can be achieved safely while using the armature voltage control.
•Therefore, armature voltage control can be used to achieve speeds below the base speed, while the field resistance control can be used to achieve speeds above the base speed.
•Shunt and separately excited DC motors have excellent speed control characteristic.

For the **armature voltage control**, the flux in the motor is constant. Therefore, the maximum torque in the motor will be constant too regardless the motor speed:

Since the maximum power of the motor is

The maximum power out of the motor is directly proportional to its speed.

For the **field resistance control**, the maximum power out of a DC motor is constant, while the maximum torque is reciprocal to the motor speed.



Torque and power limits as functions of motor speed for a shunt (or separately excited) DC motor.

Shunt motor: The effect of an open field circuit

•If the field circuit is left open on a shunt motor, its field resistance will be infinite. Infinite field resistance will cause a drastic flux drop and, therefore, a drastic drop in the generated voltage. The armature current will be increased enormously increasing the motor speed.

•A similar effect can be caused by armature reaction. If the armature reaction is severe enough, an increase in load can weaken the flux causing increasing the motor speed. An increasing motor speed increases its load, which increases the armature reaction weakening the flux again. This process continues until the motor overspeeds. This condition is called runaway.

Motor types: The permanent-magnet DC motor

A permanent magnet DC (PMDC) motor is a motor whose poles are made out of permanent magnets.

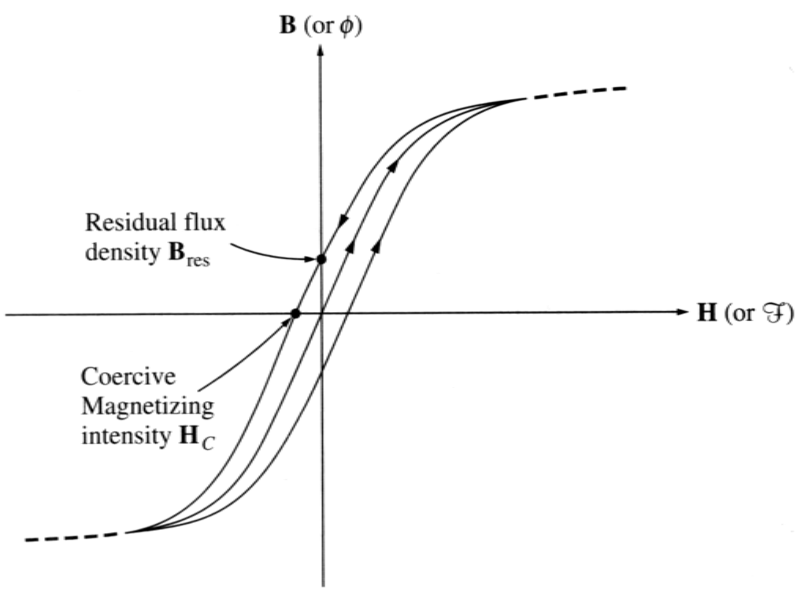
Advantages:

1. Since no external field circuit is needed, there are no field circuit copper losses;
2. Since no field windings are needed, these motors can be considerable smaller.

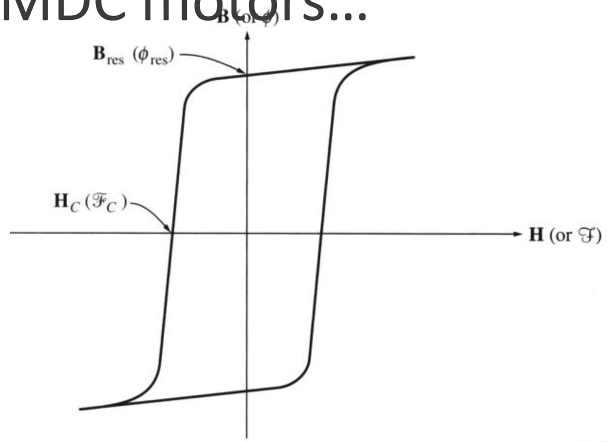
Disadvantages:

1. Since permanent magnets produces weaker flux densities then externally supported shunt fields, such motors have lower induced torque.
2. There is always a risk of demagnetization from extensive heating or from armature reaction effects (via armature mmf).

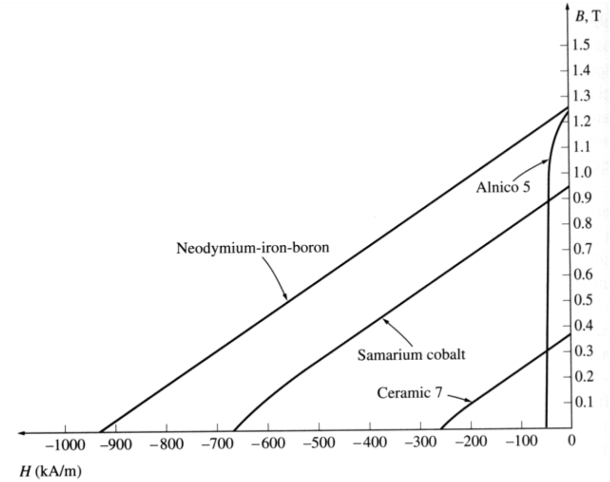
Normally (for cores), a ferromagnetic material is selected with small residual flux B_{res} and small coercive magnetizing intensity H_C.



However, a maximally large residual flux B_{res} and large coercive magnetizing intensity H_C are desirable for permanent magnets forming the poles of PMDC motors…



•A comparison of magnetization curves of newly developed permanent magnets with that of a conventional ferromagnetic alloy (Alnico 5) shows that magnets made of such materials can produce the same residual flux as the best ferromagnetic cores.



•Design of permanent-magnet DC motors is quite similar to the design of shunt motors, except that the flux of a PMDC motor is fixed. Therefore, the only method of speed control available for PMDC motors is armature voltage control.

Series motor: Speed control

•The only way to control speed of a series DC motor is by changing its terminal voltage, since the motor speed is directly proportional to its terminal voltage ***for any given torque***.

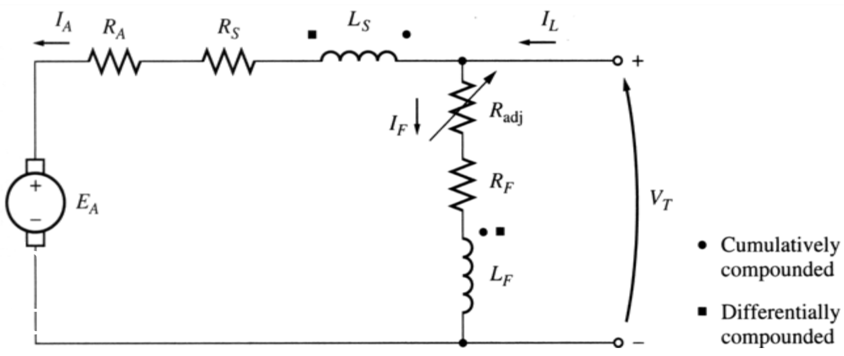
Compounded DC motor

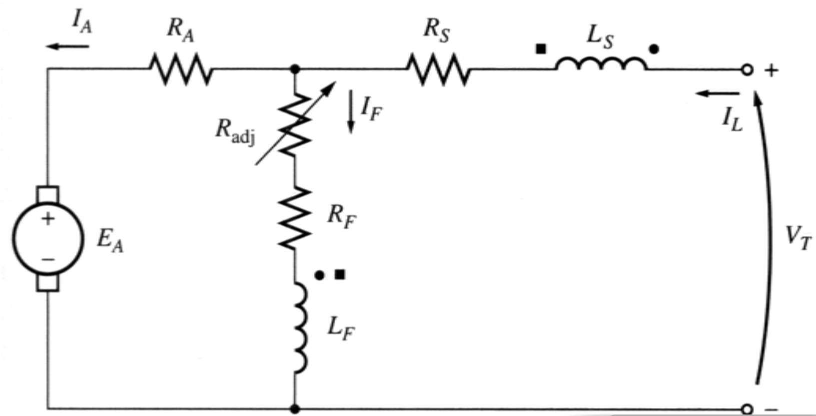
A compounded DC motor is a motor with both a shunt and a series field.

Current flowing into a dotted end of a coil (shunt or series) produces a positive mmf.

If current flows into the dotted ends of both coils, the resulting mmfs add to produce a larger total mmf – cumulative compounding.

one coil and out of the dotted end of another coil, the resulting mmfs subtract – differential compounding.



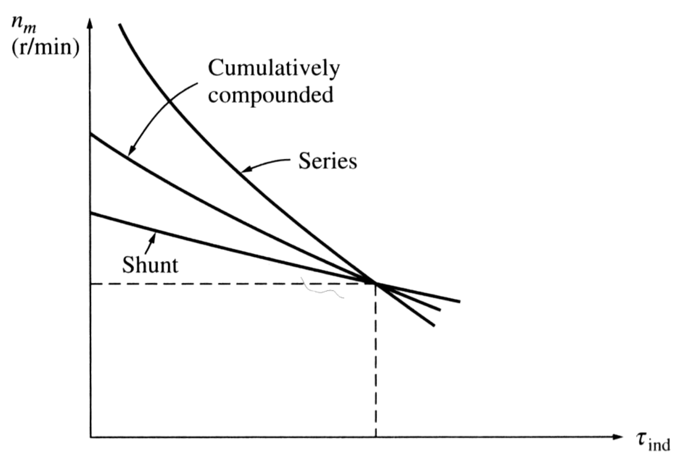


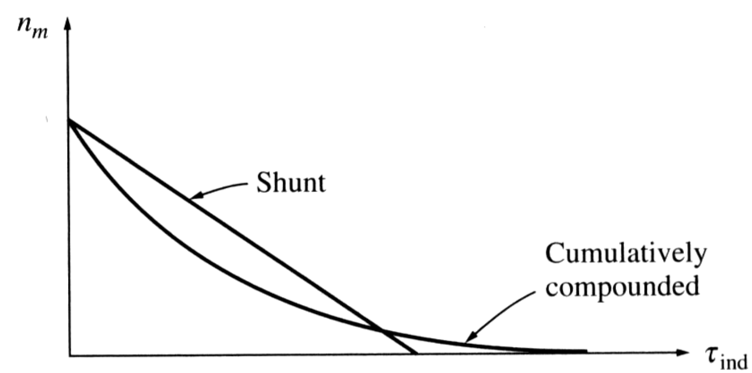
Short-shunt connection

Cumulatively compounded motors: torque-speed characteristic

In a cumulatively compounded motor, there is a constant component of flux and a component proportional to the armature current (and thus to the load). These motors have a higher starting torque than shunt motors (whose flux is constant) but lower than series motors (whose flux is proportional to the armature current).

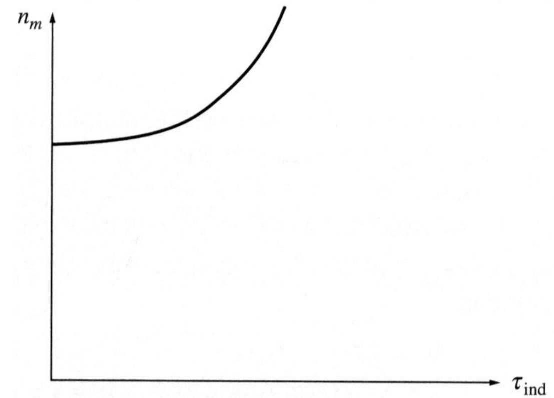
The series field has a small effect at light loads – the motor behaves as a shunt motor. The series flux becomes quite large at large loads – the motor acts like a series motor.





Differentially compounded motors: torque-speed characteristic

Since the shunt mmf and series mmf subtract from each other in a differentially compounded motor, increasing load increases the armature current I_A and decreases the flux. When flux decreases, the motor speed increases further increasing the load. This results in an instability (much worse than one of a shunt motor) making differentially compounded motors unusable for any applications.



In addition to that, these motors are not easy to start… The motor typically remains still or turns very slowly consuming enormously high armature current.
Stability problems and huge starting armature current lead to these motors being never used **intentionally**.

Cumulatively compounded motors: speed control

The same two techniques that have been discussed for a shunt motor are also available for speed control of a cumulatively compounded motor.

1. Adjusting the field resistance R_F;
2. Adjusting the armature voltage V_A.

The details of these methods are very similar to already discussed for shunt DC motors.

DC motor starters

In order for DC motors to function properly, they must have some special control and protection equipment associated with them. The purposes of this equipment are:

1. To protect the motor against damage due to short circuits in the equipment;
2. To protect the motor against damage from long-term overloads;
3. To protect the motor against damage from excessive starting currents;
4. To provide a convenient manner in which to control the operating speed of the motor.

DC motor efficiency calculations

To estimate the efficiency of a DC motor, the following losses must be determined:

1. Copper losses;
2. Brush drop losses;
3. Mechanical losses;
4. Core losses;
5. Stray losses.

To find the copper losses, we need to know the currents in the motor and two resistances. In practice, the armature resistance can be found by blocking the rotor and a small DC voltage to the armature terminals: such that the armature current will equal to its rated value. The ratio of the applied voltage to the armature current is approximately R_A.
The field resistance is determined by supplying the full-rated field voltage to the field circuit and measuring the resulting field current. The field voltage to field current ratio equals to the field resistance.

Brush drop losses are frequently lumped together with copper losses. If treated separately, brush drop losses are a product of the brush voltage drop V_{BD} and the armature current I_A.

The core and mechanical losses are usually determined together. If a motor is running freely at no load and at the rated speed, the current I_A is very small and the armature copper losses are negligible. Therefore, if the field copper losses are subtracted from the input power of the motor, the remainder will be the mechanical and core losses. These two losses are also called the no-load rotational losses. As long as the motor's speed remains approximately the same, the no-load rotational losses are a good estimate of mechanical and core losses in the machine under load.

UNIT -IV
Single-Phase Transformers

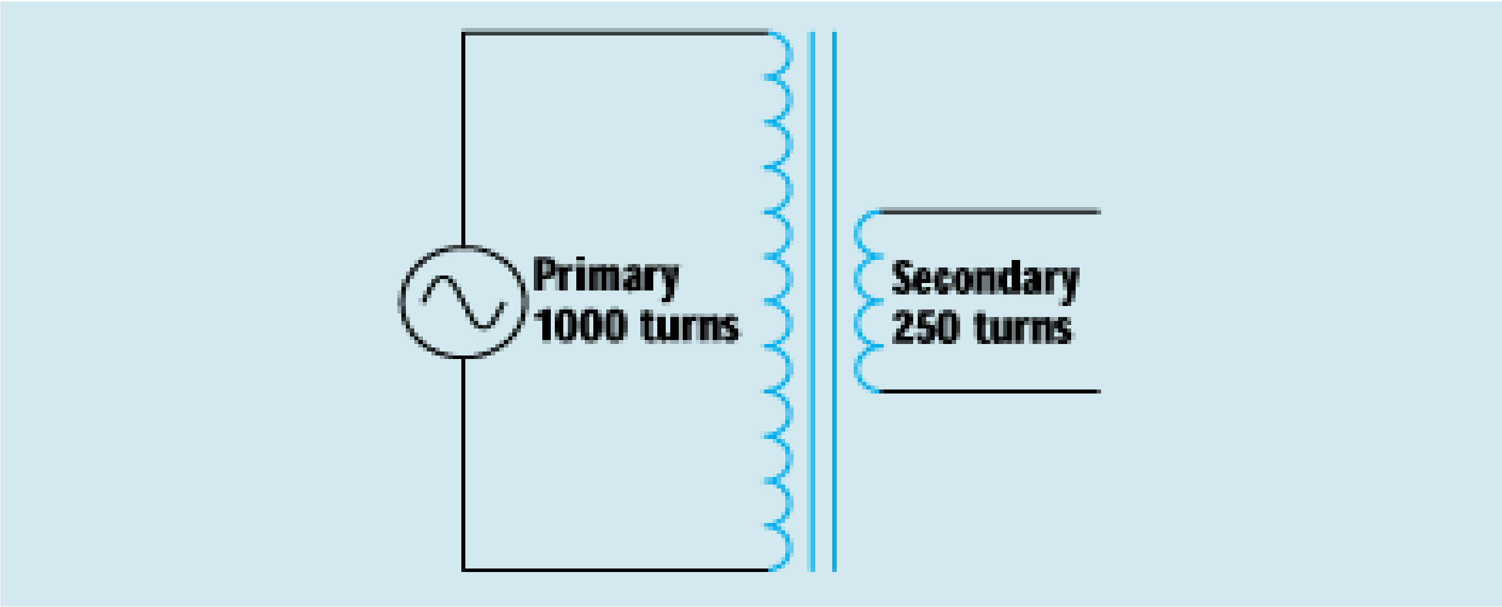
UNIT 4
SINGLE PHASE TRANSFORMERS

Single-Phase Transformers

Objectives:

- Discuss the different types of transformers.
- List transformer symbols and formulas.
- Discuss polarity markings.

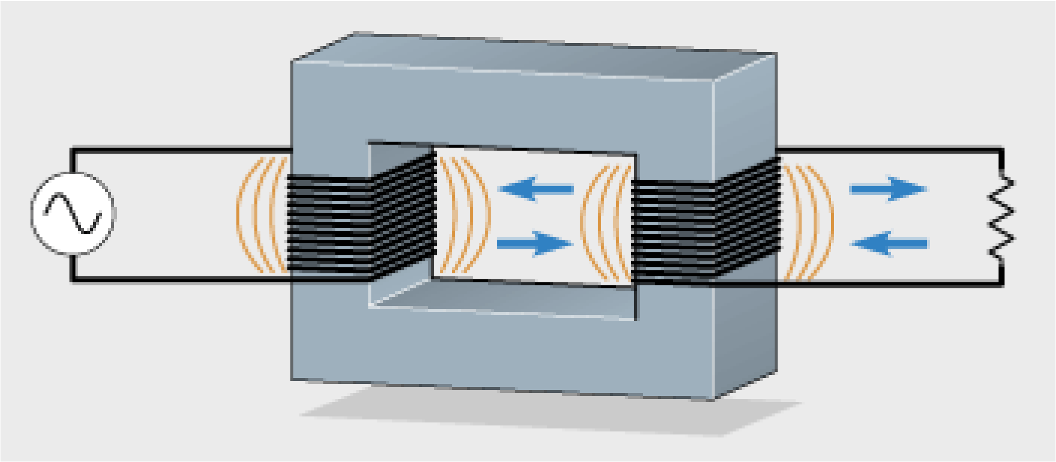
Single-Phase Transformers



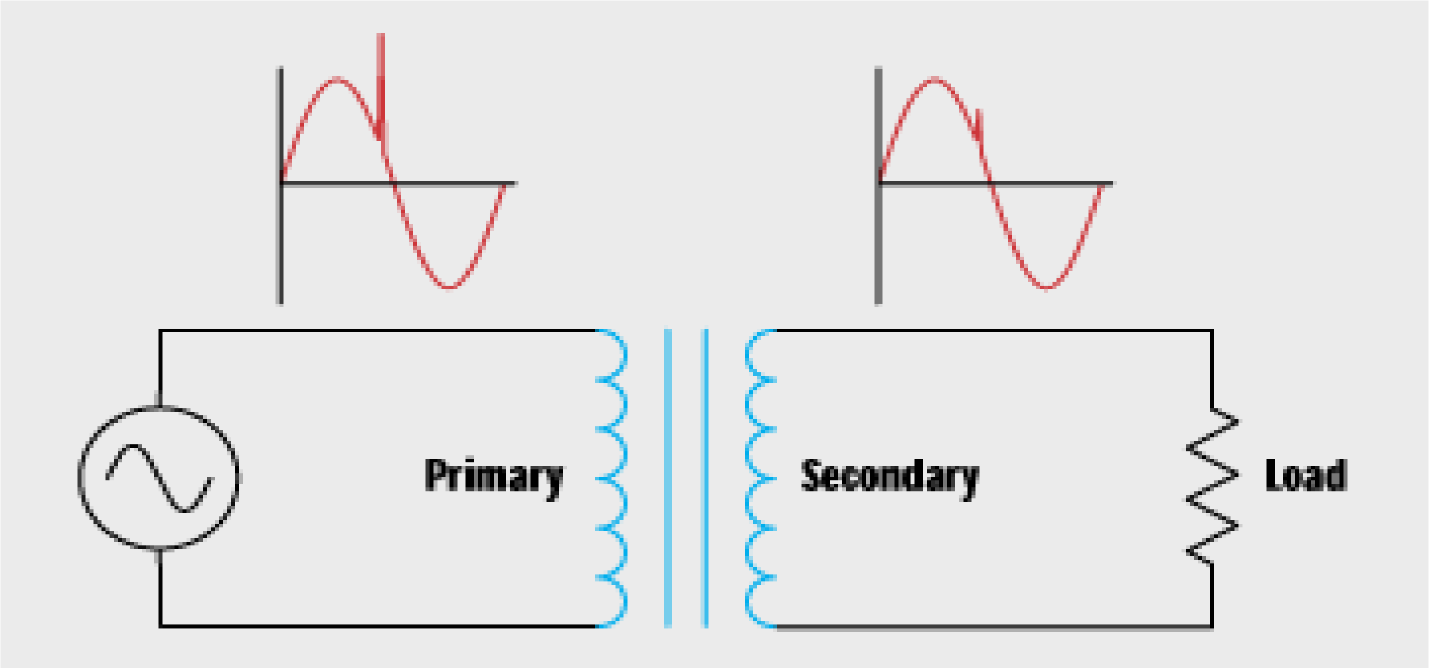
- A transformer is a magnetically operated machine.
- All values of a transformer are proportional to its turns ratio.

- The **primary winding** is connected to the incoming power supply.
- The **secondary winding** is connected to the driven load.

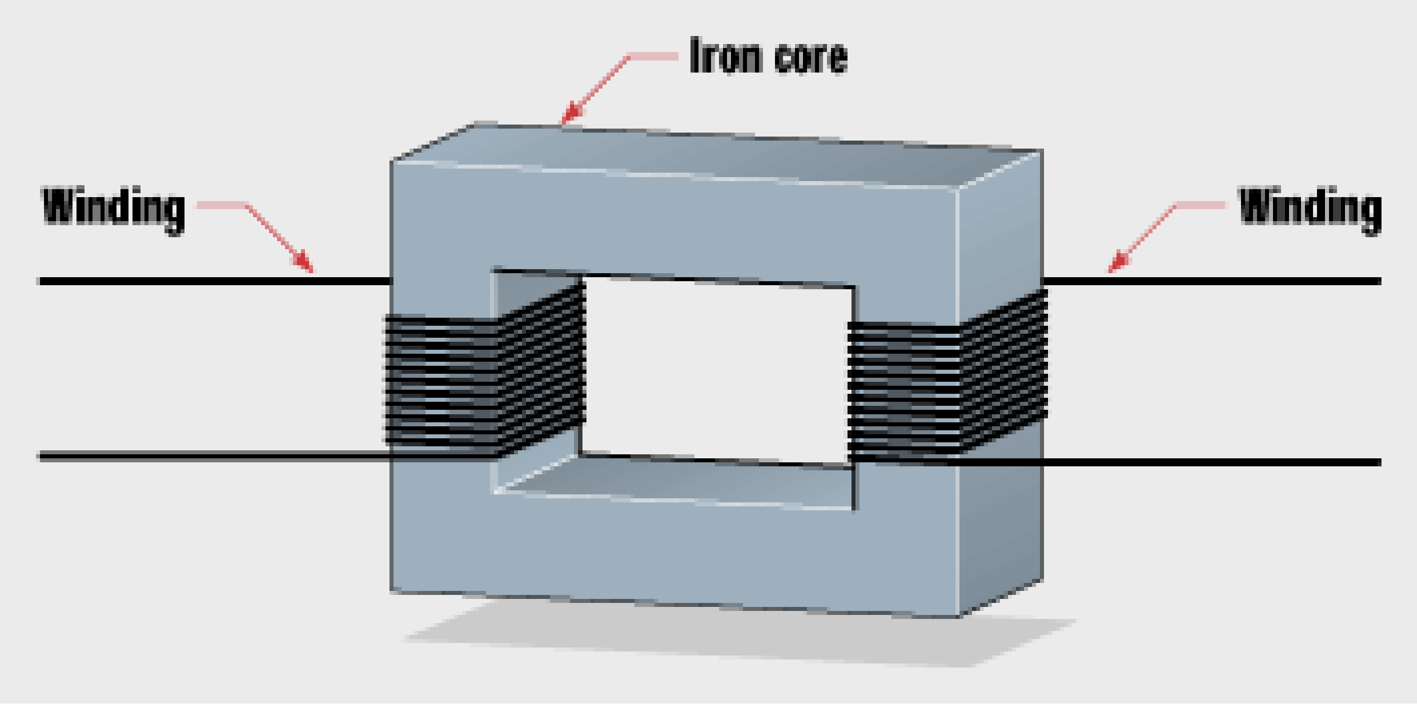
- This is an **isolation transformer**. The secondary winding is physically and electrically isolated from the primary winding.



- The two windings of an isolation transformer are linked together by the magnetic field.



- The isolation transformer greatly reduces voltage spikes.



- Basic construction of an isolation transformer.

- Each set of windings (primary and secondary) is formed from loops of wire wrapped around the core.
- Each loop of wire is called a **turn**.
- The ratio of the primary and secondary voltages is determined by the ratio of the number of turns in the primary and secondary windings.
- The volts-per-turn ratio is the same on both the primary and secondary windings.

N_P = number of turns in the primary

N_S = number of turns in the secondary

E_P = voltage of the primary

E_S = voltage of the secondary

I_P = current in the primary

I_S = current in the secondary

$$E_P / E_S = N_P / N_S$$

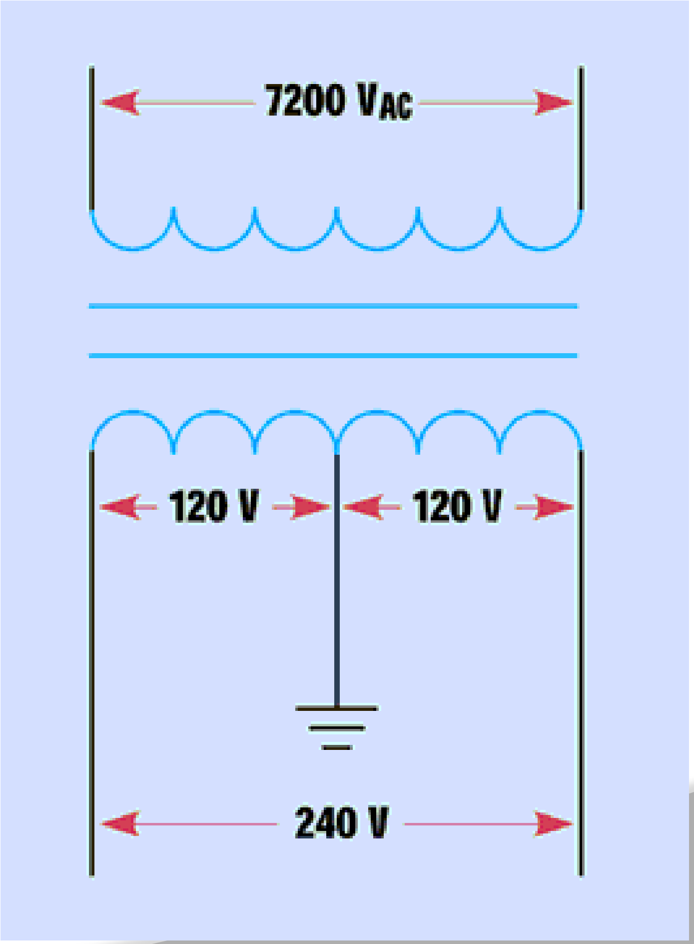
$$E_P \times N_S = E_S \times N_P$$

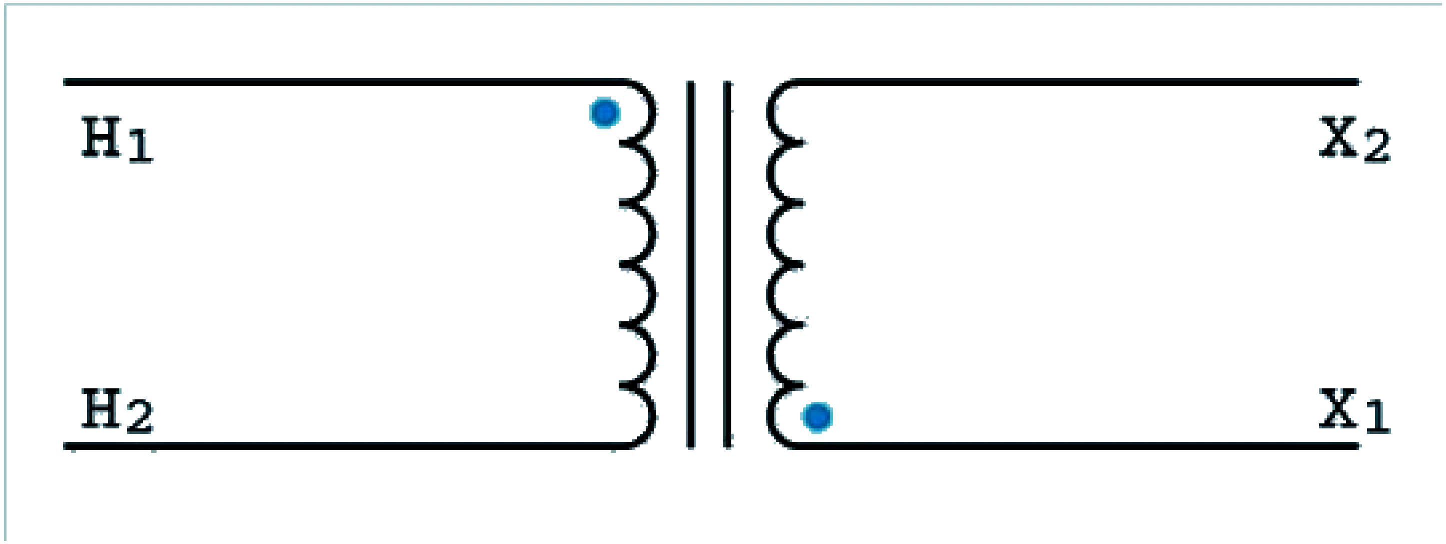
$$E_P \times I_P = E_S \times I_S$$

$$N_P \times I_P = N_S \times I_S$$

- The distribution transformer is a common type of isolation transformer. This transformer changes the high voltage from the power company to the common 240/120 V.

- The control transformer is another common type of isolation transformer. This transformer reduces high voltage to the value needed by control circuits.





- Polarity dots are placed on transformer schematics to indicate points that have the same polarity at the same time.

Review:

1. All values of voltage, current, and impedance in a transformer are proportional to the turns ratio.
2. The primary winding of a transformer is connected to the source voltage.
3. The secondary winding is connected to the load.

4. An isolation transformer has its primary and secondary voltage electrically and mechanically separated.
5. Isolation transformers help filter voltage and current spikes.
6. Polarity dots are often added to schematic diagrams to indicate transformer polarity.

Transformer Regulation

- Loading changes the output voltage of a transformer.

Definition of % Regulation

$$= \frac{|V_{no-load}| - |V_{load}|}{|V_{load}|} * 100$$

$V_{no\text{-}load}$ =RMS voltage across the load terminals without load
V_{load} = RMS voltage across the load terminals with a specified load

Maximum Transformer Regulation

Maximum Transformer Regulation

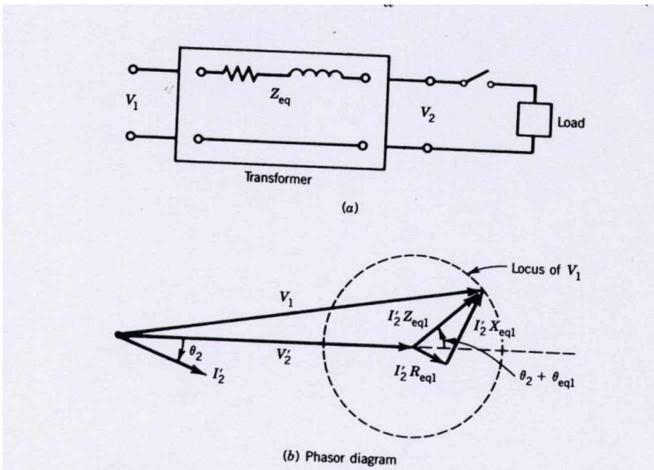


FIGURE 2.14 Voltage regulation.

$$V_1 = V_2' \angle 0^0 + I_2' \angle \theta_2{}^0 . Z_{eq1} \angle \theta_{eq1}{}^0$$

$$Clearly\ \ V_1\ \ is\ \max imum\ when$$

$$\theta_2 + \theta_{eq1} = 0; or\ \theta_2 = -\theta_{eq1}$$

- Transformer Losses
    - Core/Iron Loss $= V_1^2 / R_{c1}$
    - Copper Loss $= I_1^2 R_1 + I_2^2 R_2$

Definition of % efficiency

$$= \frac{V_2 I_2 Cos\theta_2}{Losses + V_2 I_2 Cos\theta_2} * 100$$

$$= \frac{V_2 I_2 Cos\theta_2}{V_1^2 / R_{c1} + I_1^2 R_1 + I_2^2 R_2 + V_2 I_2 Cos\theta_2} * 100$$

$$= \frac{V_2 I_2 Cos\theta_2}{V_1^2 / R_{c1} + I_2^2 R_{eq2} + V_2 I_2 Cos\theta_2} * 100$$

$$Cos\theta_2$$

Maximum Transformer Efficiency

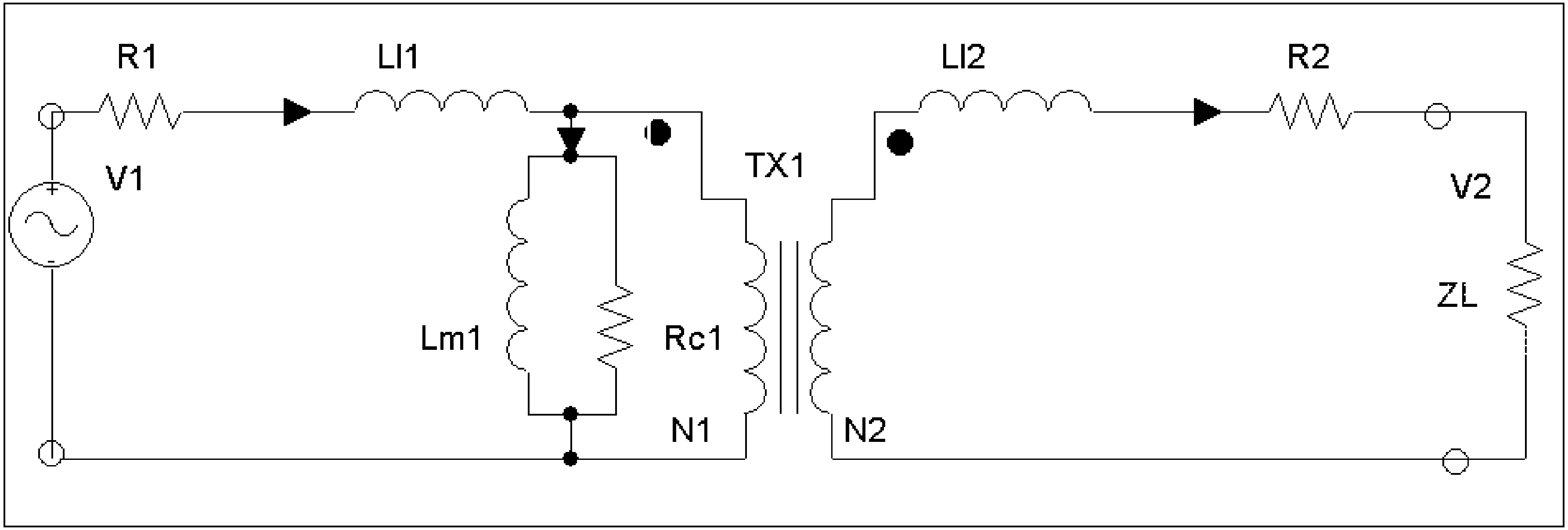
The efficiency varies as with respect to 2 independent quantities namely, current and power factor

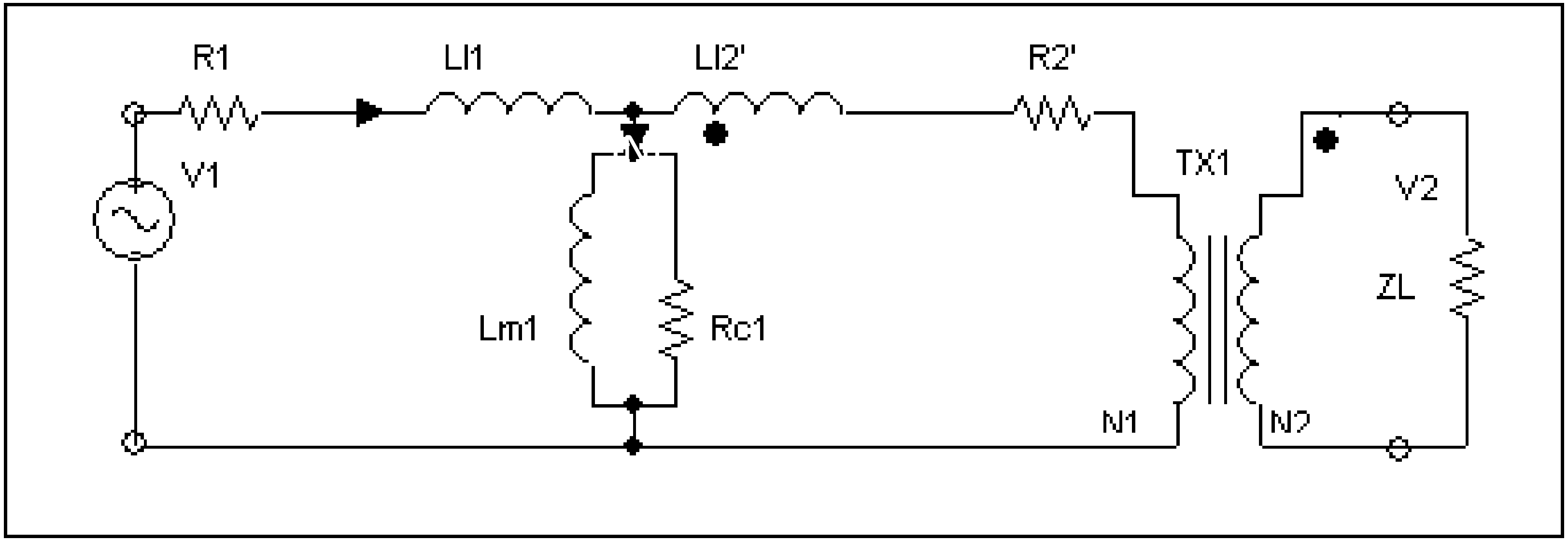
- Thus at any particular power factor, the efficiency is maximum if core loss = copper loss .This can be obtained by differentiating the expression of efficiency with respect to I_2 assuming power factor, and all the voltages constant.

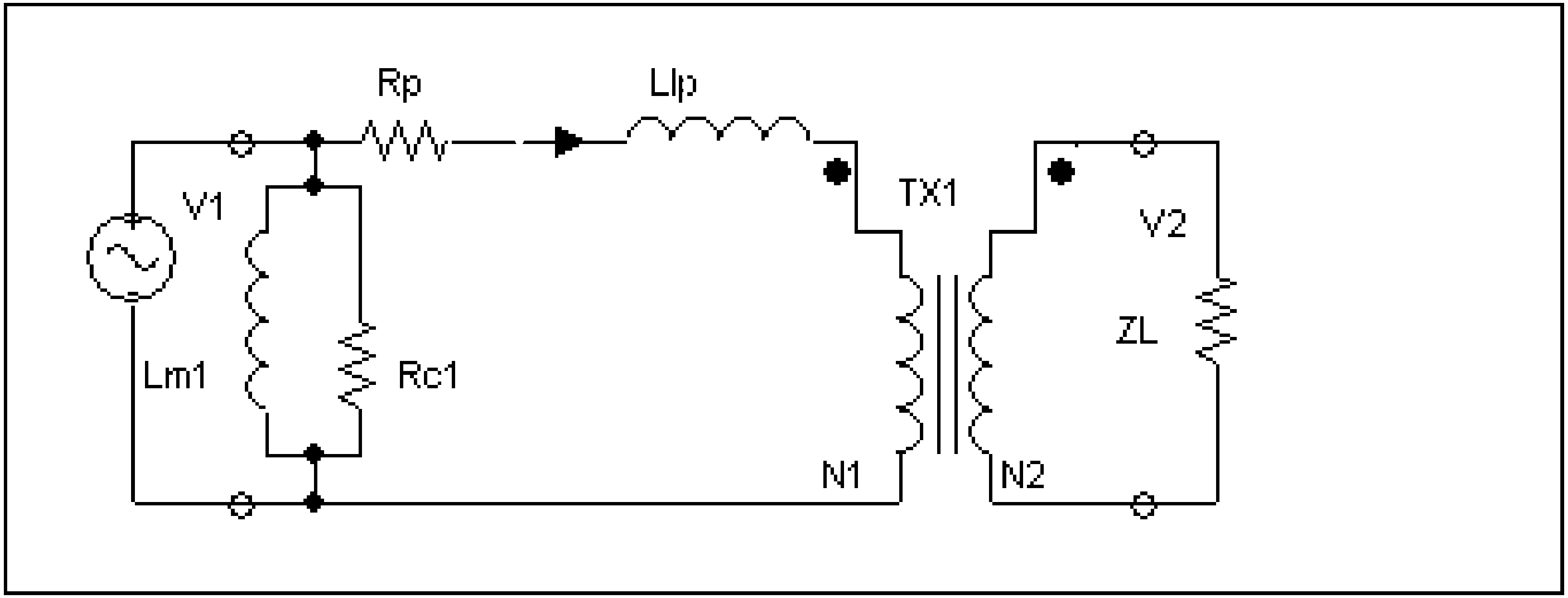
- At any particular I_2 maximum efficiency happens at unity power factor. This can be obtained by differentiating the expression of efficiency with respect to power factor, and assuming I_2 and all the voltages constant.

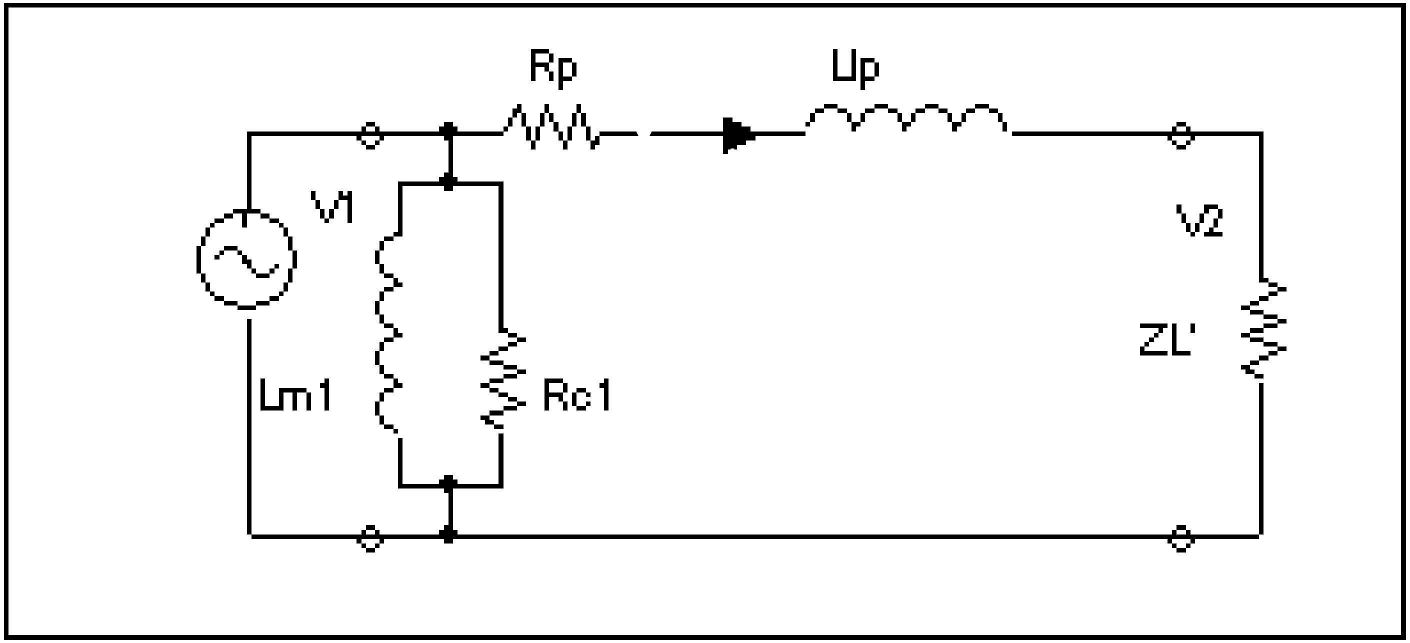
- Maximum efficiency happens when both these conditions are satisfied.

Transformer Equivalent circuit

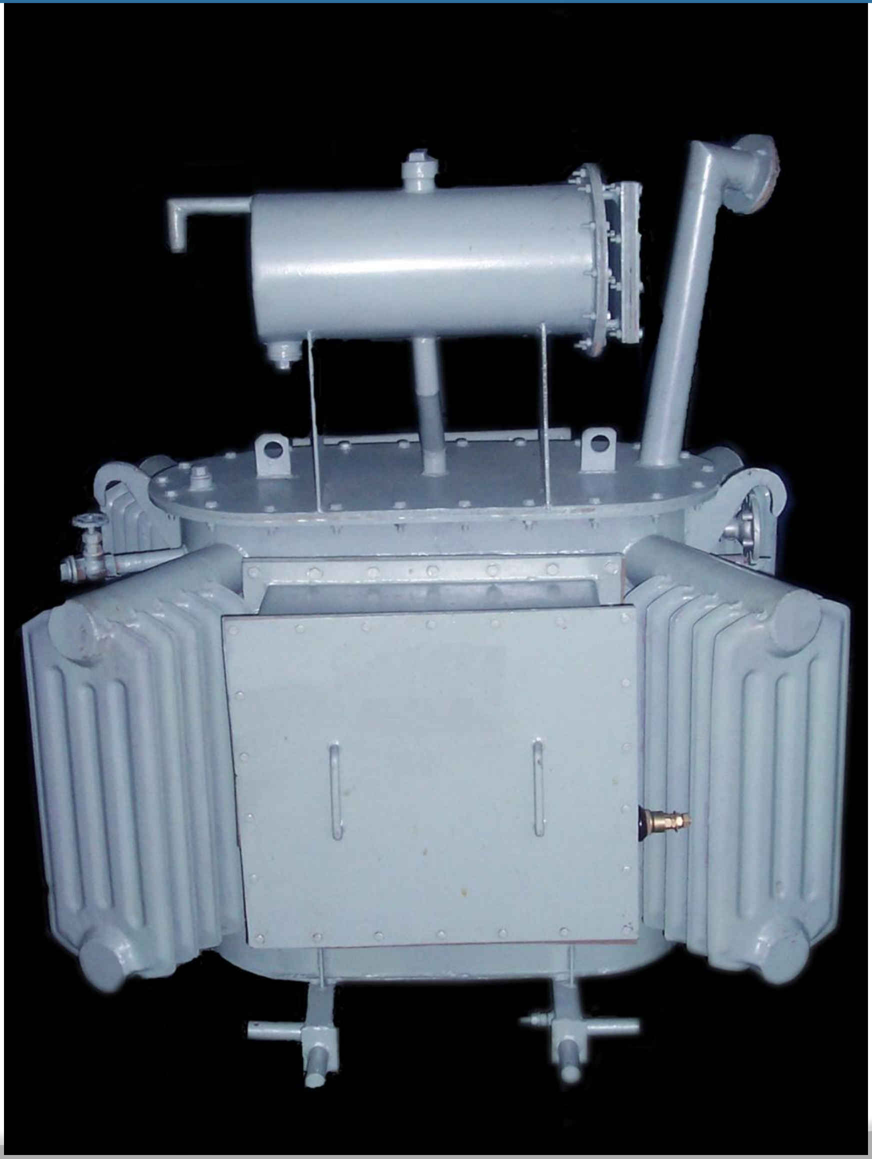



R1
Ll1
Ll2'
R2'
V1
TX1
V2
ZL
Lm1
Rc1
N1
N2


Rp
Llp
V1
TX1
V2
ZL
Lm1
Rc1
N1
N2


Rp
Lp
V1
V2
ZL'
Lm1
Rc1

PARTS OF TRANSFORMER



- MAIN TANK
- RADIATORS
- CONSERVATOR
- EXPLOSION VENT
- LIFTING LUGS
- AIR RELEASE PLUG
- OIL LEVEL INDICATOR
- TAP CHANGER
- WHEELS
- HV/LV BUSHINGS
- FILTER VALVES
- OIL FILLING PLUG
- DRAIN PLUG
- CABLE BOX

TESTING OF TRANSFORMER

- Testing of single phase Transformers

  1. OC Test
  2. SC test
  3. Sumpner’s Test or Back to Back Test

Open circuit Test

- It is used to determine L_{m1} (X_{m1})and R_{c1}
- Usually performed on the low voltage side
- The test is performed at rated voltage and frequency under no load
- This test gives the values of core losses in a transformer

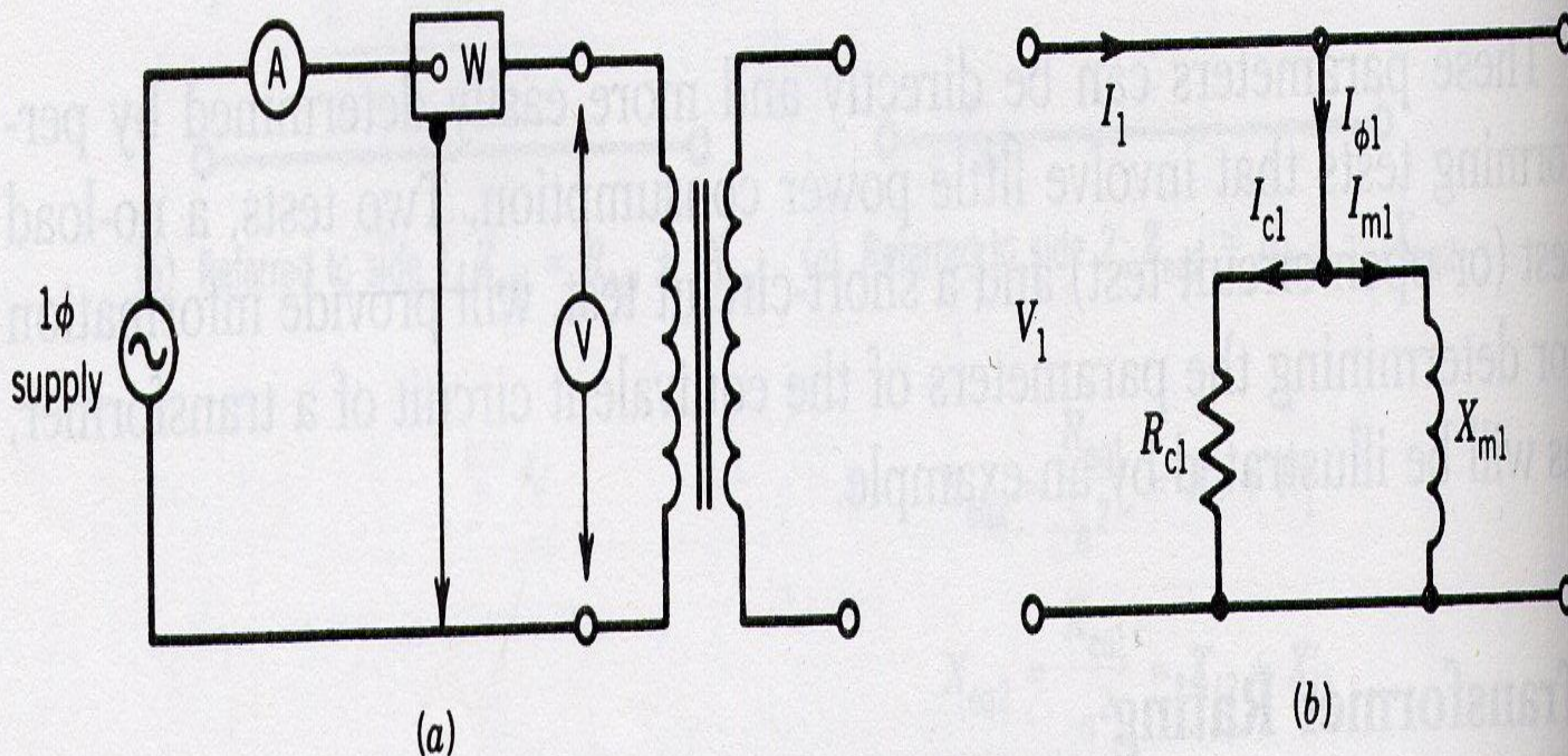


FIGURE 2.12 No-load (or open-circuit) test. (*a*) Wiring diagram for open-circuit test. (*b*) Equivalent circuit under open circuit.

Woc= Core loss of the transformer

From the data

Cosø= Woc/(Voc*Ioc)

Iw=IocCosø

Ių = Ioc Sinø

Rcl=Voc/Iw

Xml=Voc/I ų

Short circuit Test

- It is used to determine Ll_p (X_{eq}) and R_p(R_{eq})

- Usually performed on the high voltage side

- This test is performed at *reduced* voltage and rated frequency with the output of the low voltage winding short circuited such that rated current flows on the high voltage side.

- This test gives copper loss of the transformer.

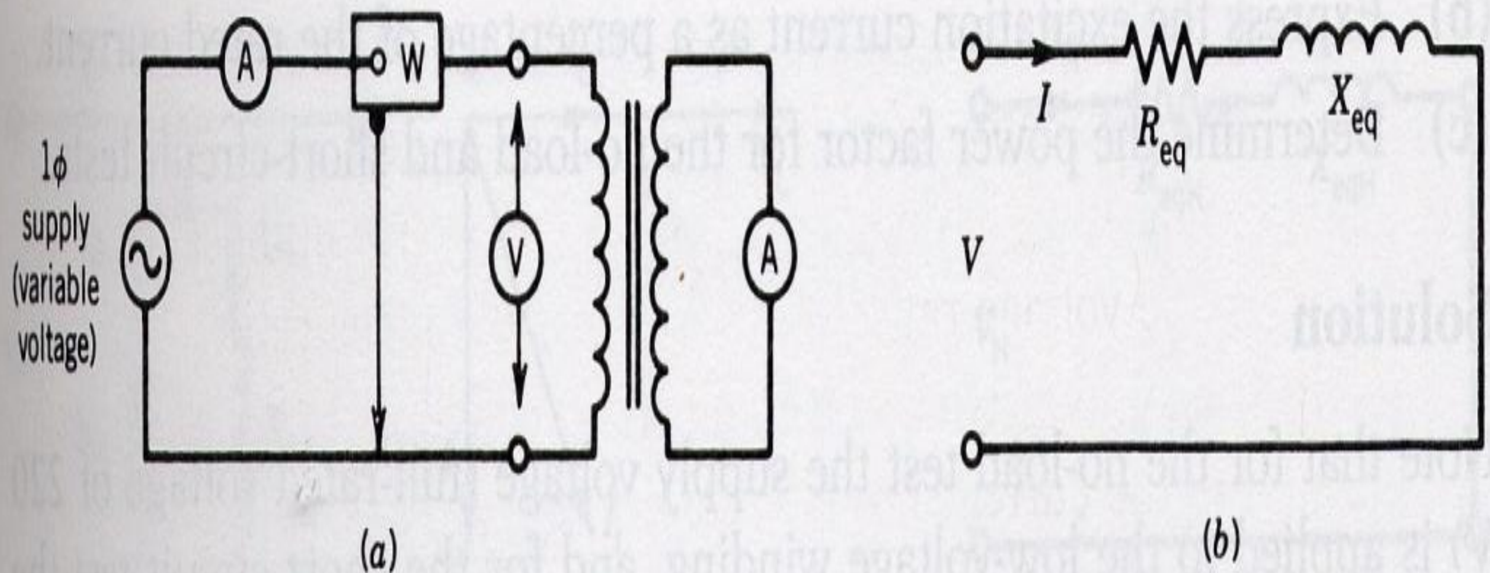


FIGURE 2.13 Short-circuit test. (*a*) Wiring diagram for short-circuit test. (*b*) Equivalent circuit at short-circuit condition.

W_{sc}= copper losses of the transformer.

$Z_{eq}=V_{sc}/I_{sc}$

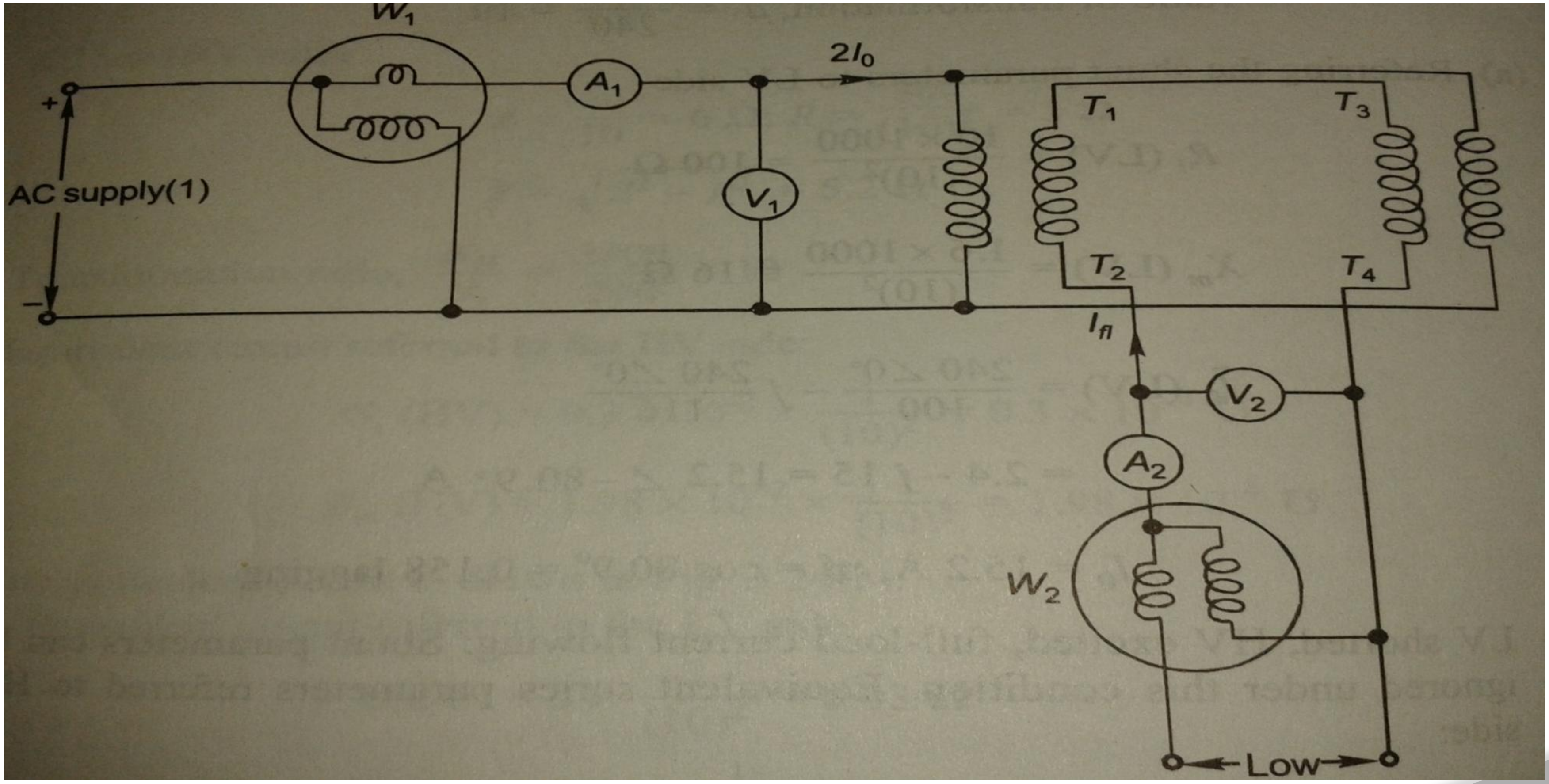
$R_{eq}=W_{sc}/I_{sc}^2$

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

Efficiency of the transformer

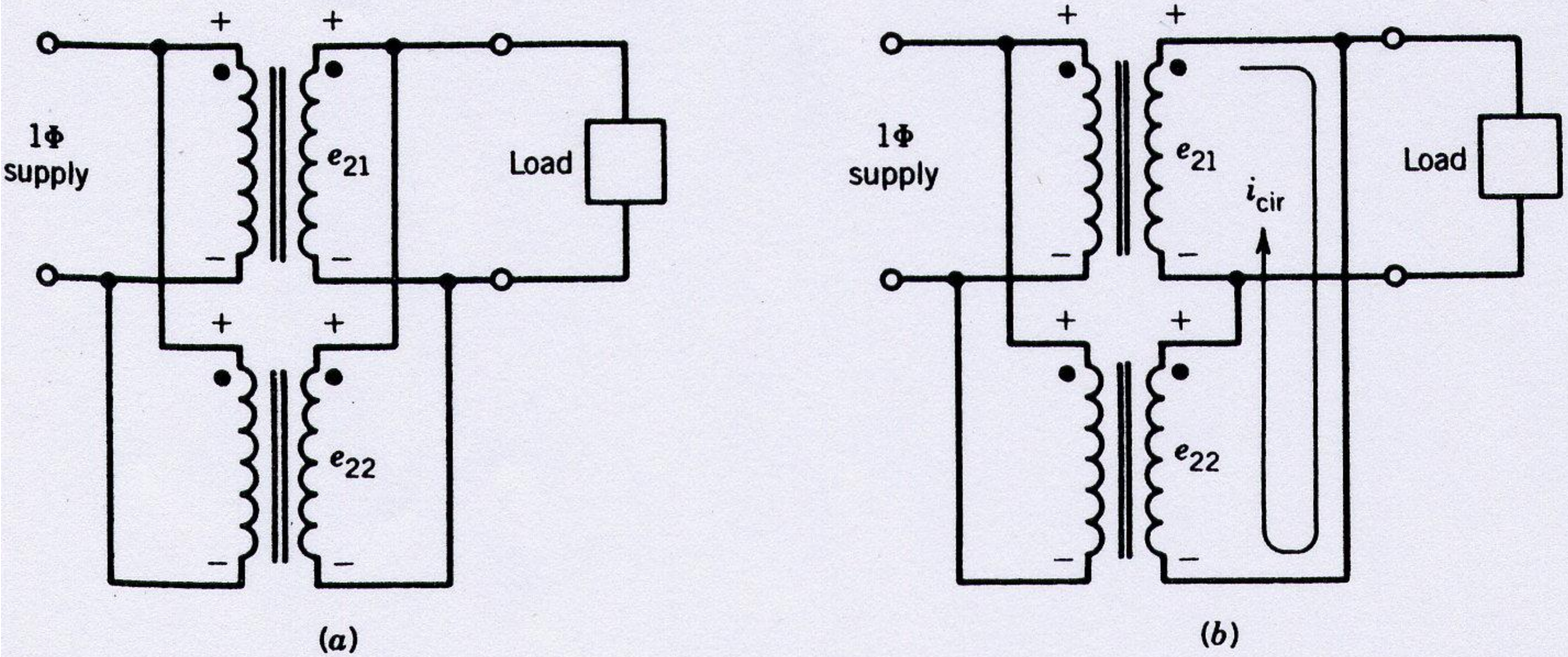
Ŋ = output Power/ Input power

$Ŋ = XVI\cos\phi/(XVI\cos\phi + P_c + x^2 P_{cu})$



From this test Losses and Efficiency of the two transformers can be determined

Parallel operation of transformers



Wrong connections give circulating between the windings that can destroy transformers.

FIGURE 2.9 Parallel operation of single-phase transformers. (a) Correct connection. (b) Wrong connection.

To connect the transformers in parallel the following conditions must be satisfied

i. Transformers must be of same rating.

ii. Transformers should have the same phase sequence.

iii. voltage ratio must be same.

iv. Per unit impedence of the transformers must be same.

UNIT 5
POLY PHASE TRANSFORMERS

Star (Y) connection

- Line current is same as phase current
- Line-Line voltage is $\sqrt{3}$ phase-neutral voltage
- Power is given by $\sqrt{3}\, V_{L-L} I_L \cos\theta$ or $3 V_{ph} I_{ph} \cos\theta$

Delta connection

- Line-Line voltage is same as phase voltage
- Line current is $\sqrt{3}$ phase current
- Power is given by $\sqrt{3}\ V_{L-L} I_{L} \cos\theta$ or $3 V_{ph} I_{ph} \cos\theta$

Typical three phase transformer connections

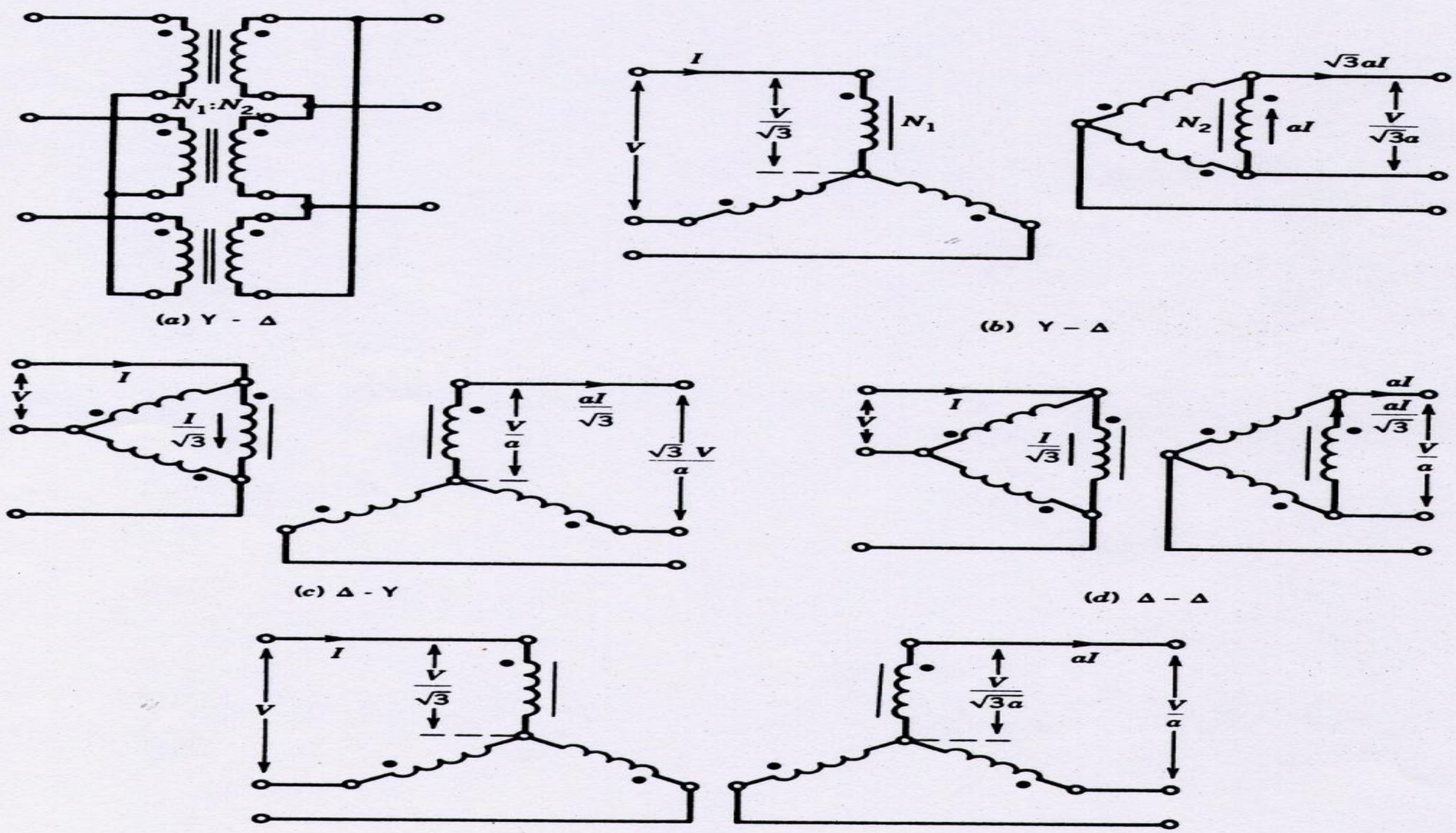


FIGURE 2.17 Three-phase transformer connections.

Other possible three phase transformer Connections

- Y- zigzag
- Δ- zigzag
- Open Delta or V
- Scott or T

How are three phase transformers made?

phase banks.

- Or by having coils mounted on a single core with multiple limbs
- The bank configuration is better from repair perspective, whereas the single three phase unit will cost less ,occupy less space, weighs less and is more efficient

Phase-shift between line-line voltages in transformers

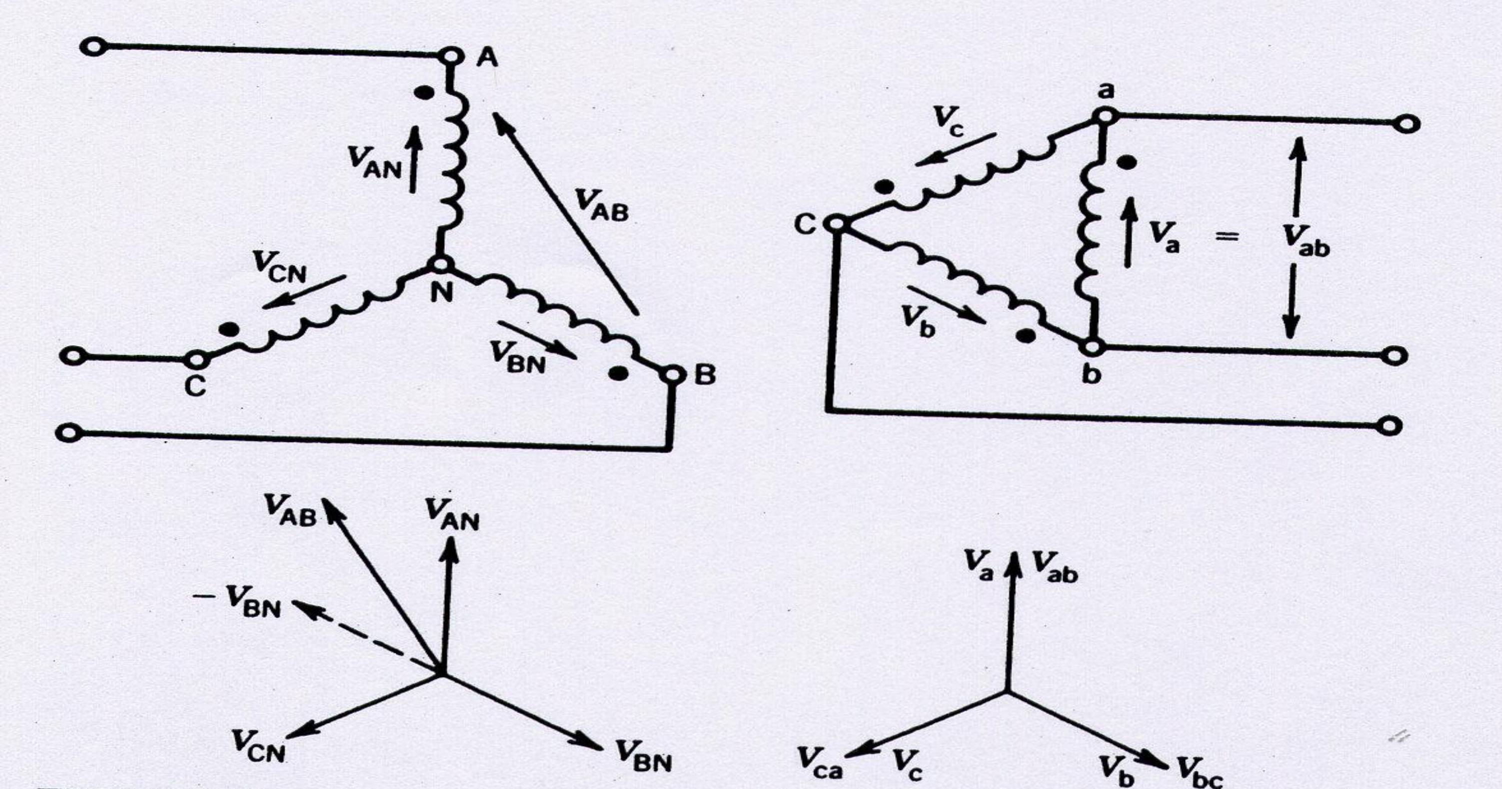


FIGURE 2.18 Phase shift in line-to-line voltages in a three-phase transformer.

Vector grouping of transformers

Depending upon the phase shift of line-neutral voltages between primary and secondary; transformers are grouped. This is done for ease of paralleling. Usually transformers between two different groups should not be paralleled.

- Group 1 :zero phase displacement (Yy0, Dd0,Dz0)
- Group 2 :180^0 phase displacement (Yy6, Dd6,Dz6)
- Group 3 : 30^0 lag phase displacement (Dy1, Yd1,Yz1)
- Group 4 : 30^0 lead phase displacement (Dy11, Yd11,Yz11)

(Y=Y; D= Δ; z=zigzag)

Open –delta or V connection

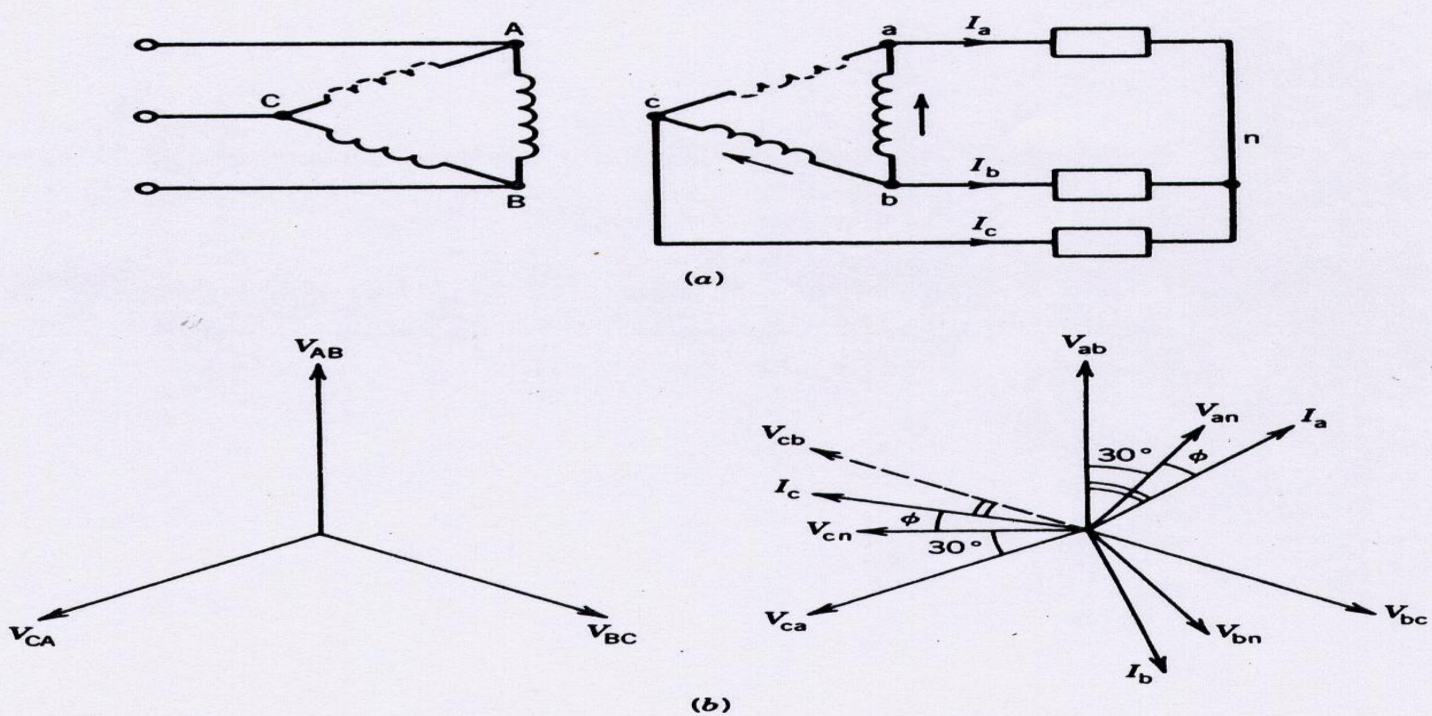


FIGURE 2.20 V connection.

Power from winding ‘ab’

is $P_{ab}=V_{ab}I_a\cos(30^0+\phi)$

Power from winding ‘bc’

is $P_{cb}=V_{cb}I_c\cos(30^0-\phi)$

Therefore total power is

$=2V_{L-L}I_L\cos30^0\cos\phi$ or 57.7% of total power from 3 phases

Harmonics in 3-phaseTransformer Banks

- In absence of neutral connection in a Y-Y transformers 3rd harmonic current cannot flow

- This causes 3rd harmonic distortion in the phase voltages (both primary and secondary) but not line-line voltages, as 3rd harmonic voltages get cancelled out in line-line connections

- Remedy is either of the following :
  a) Neutral connections, b) Tertiary winding c) Use zigzag secondary d) Use star-delta or delta-delta type of transformers.

a) The phenomenon is explained using a star-delta transformer.

Harmonics in 3-phaseTransformer Banks

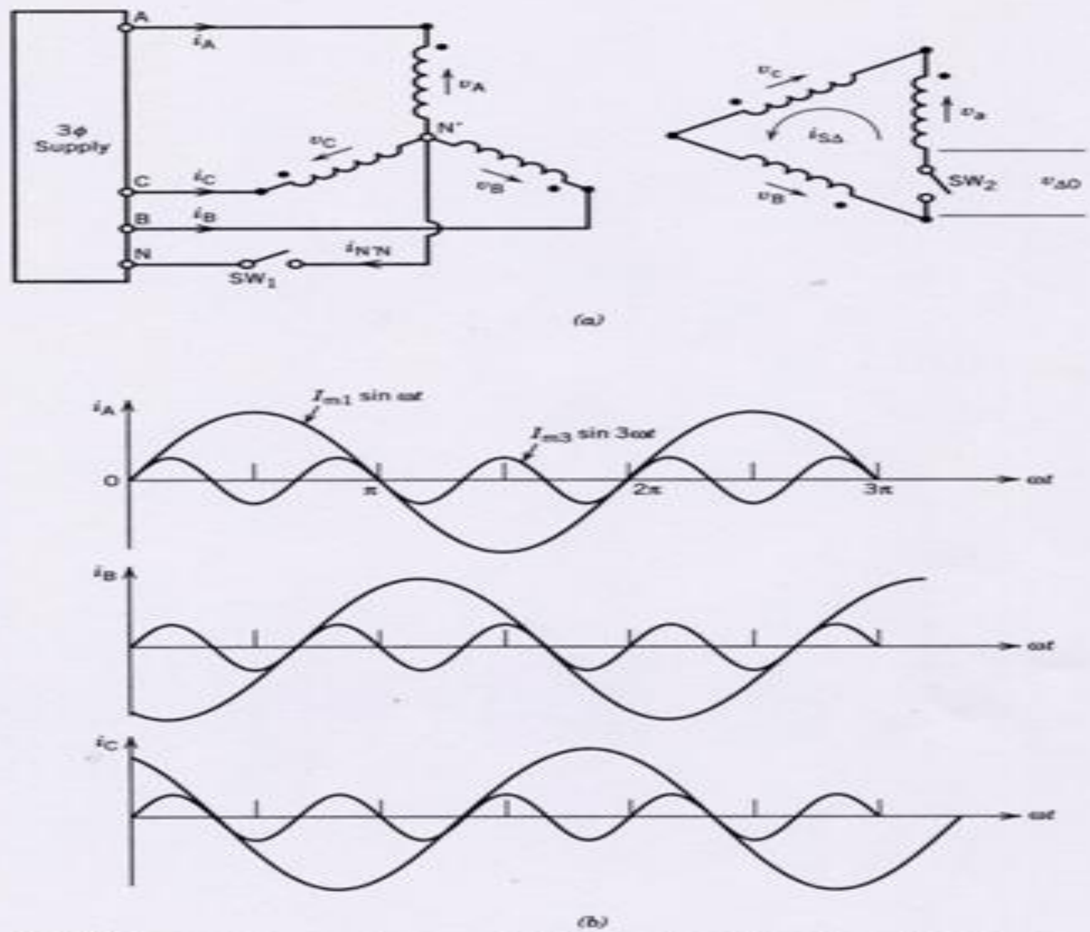
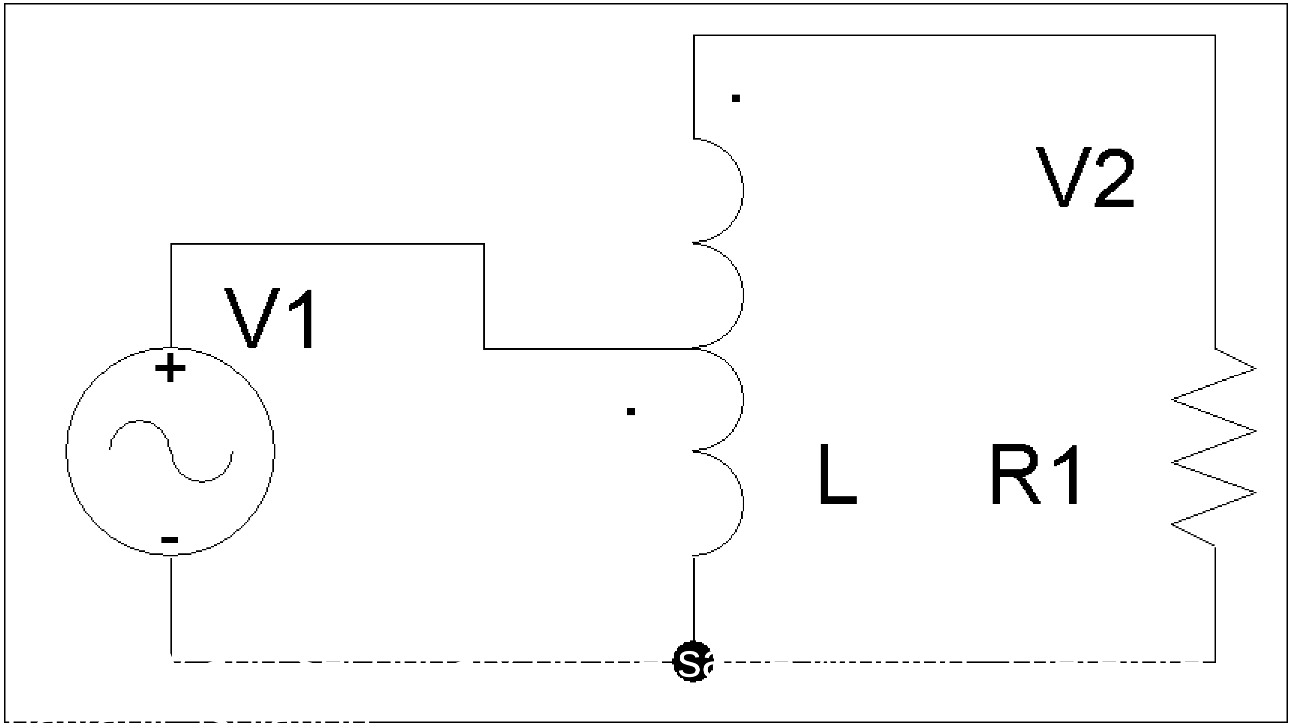


FIGURE Harmonic current in three-phase transformer connections. (*a*) Y–Δ connection. (*b*) Waveforms of exciting currents.

Autotransformer



Features of Autotransformer

✓ Lower leakage

✓Lower losses

✓Lower magnetizing current

✓Increase kVA rating

× No galvanic Isolation