Chapter one

((Electromagnetic Basics))

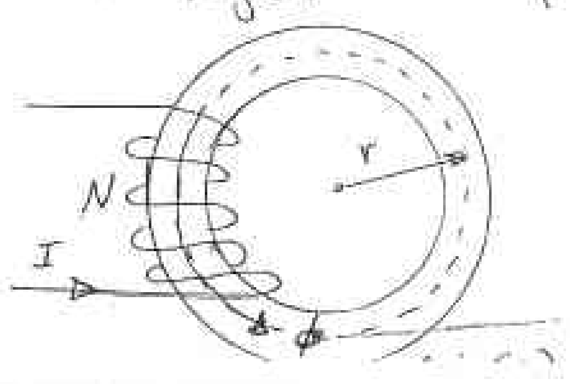
اساسيات الكهرومغناطيسية

Ferromagnetic Materials:

The usage of iron Core is very Common in electrical equipments such as motors, transformers, ...etc., because the Iron is a ferromagnetic material, and such materials have an ability to increase the flux density inside the Coil which is turned around it. That is due to electrons motion of the individual atoms, where each atom acts like a miniature bar magnet. These magnets over a region of many atoms tend to orient themselves parallel to each other with north poles pointing to one way. This region is called "domain" and it is spontaneously magnetized. When this material affected by a magnetic field, these domains aligned parallel to it causing an increase in the flux density hundreds or thousands times.

The Magnetic Circuit:

It is defined as the path followed by the magnetic flux. The magnetic circuit in fig(1) has a path of length $l = 2\pi r$.



Magnetic Flux (ϕ)

It represents the lines of magnetic force. and in the SI system of units it has the unit of, Webers (Wb).

Magnetic flux Density (B):

It is defined as the ratio of the magnetic flux divided by the area perpendicular to the flux. and the unit of it in SI system of units is the Tesla (T)

$$B = \frac{\phi}{A}$$

Faraday's law:

It states that the EMF induced in a circuit is proportional to the rate of change of flux linkages.

$$e = \frac{d\phi}{dt}$$

Lenz's Law:

It states that any current produced by the EMF tends to oppose the flux change.

$$e = -\frac{d\phi}{dt}$$

and if there is N turns in the circuit then

$$e = -N\frac{d\phi}{dt}$$

$$e = -\frac{d(N\phi)}{dt}$$

MagnetoMotive Force (mmf) (F):

It is given by the product of the winding's current (i) times its number of turns (N). and its unit is (ampere-turns) At.

$$mmf = N i$$

Magnetic field Intensity: (H)

It is given by the ratio of the mmf divided by the length of the mean magnetic path. and its unit is (ampere-turns/meter) (At/m)

$$H = \frac{N i}{l}$$

Reluctance: (R)

It is the ratio of the applied magnetic potential divided by the flux through the magnetic path under consideration. and its unit is (At/Wb)

$$R = \frac{NI}{\phi} \quad , \quad R = \frac{l}{\mu_o \mu_r A}$$

Permeability: (μ)

It is an intrinsic property of all materials.

$$\mu = \mu_o \mu_r$$

μ_r: is the relative permeability of the material

μ_o: is the permeability of free space.

$$\mu_o = 4\pi \times 10^{-7} \ H/m$$

$$\mu = \frac{B}{H}$$

Magnetization Curve:

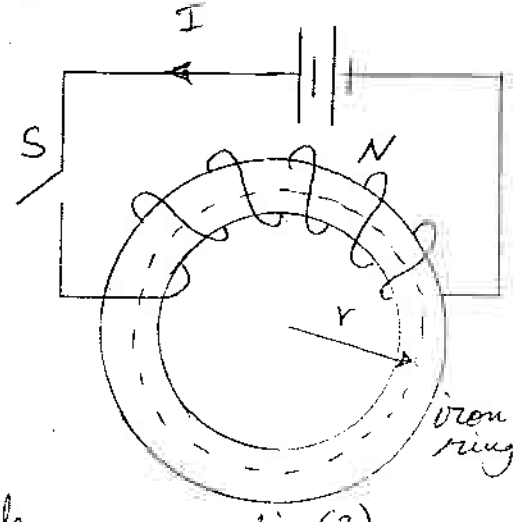


fig (2)

In the circuit shown in fig (2), if the switch S is closed and the voltage increased gradually, the core will be affected by a magnetizing force (H) and the domains become unstable and a few of them may rotate so that they have the same direction as the field. With further increase of the field more domains change over each as an individual unit, until all the domains are in the same direction, the magnetic saturation is reached.

Then the magnetic field density (B) increases gradually as (H) increases. The relation between B and H is shown in fig (3). B is directly proportional to H, and the relation starts approximately linear up to a certain point then the saturation starts.

This relation is called the magnetization curve.

$B \propto H$

$B = \mu H$

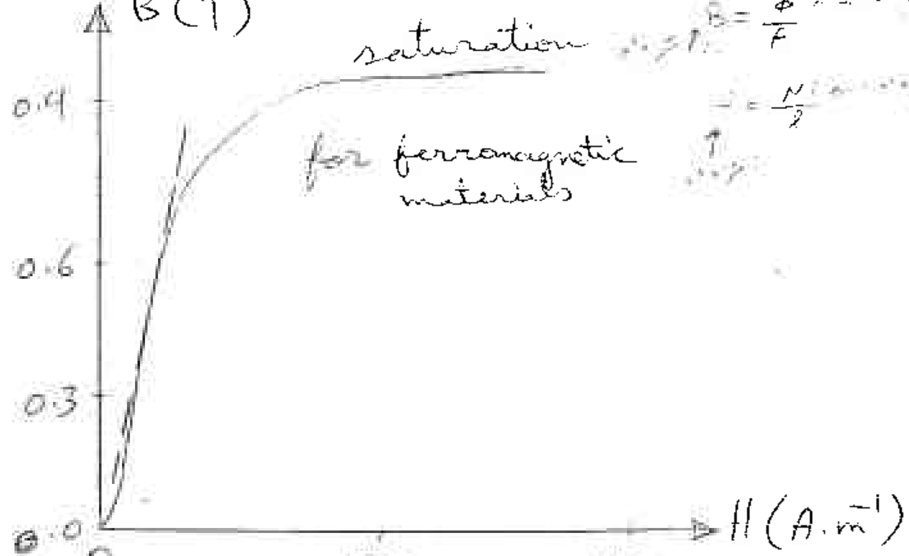


fig (3)

Hysteresis Loop:

When the magnetic flux density varies from (0 to 1) the relation follows the ordinary B – H curve. When the magnetic flux density decreases to Zero (1 → 2), the core is still magnetized and this is called the residual magnetization. Then the magnetic flux density increases in reverse direction up to 3 at which the flux density is equals Zero. This part periodically is closed loop (1234561) which is called hysteresis loop. The area of this loop gives an idea about the losses of the material.

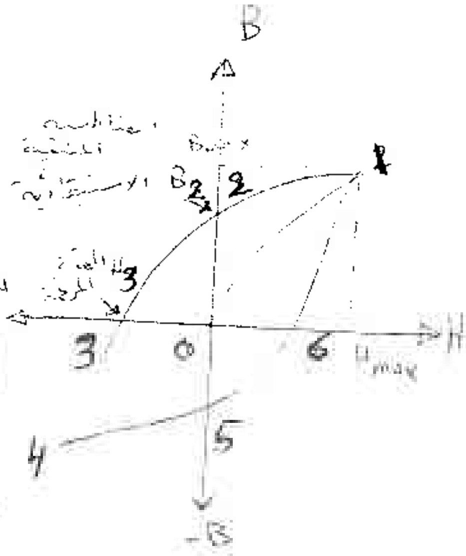


fig (4)

Inductance:

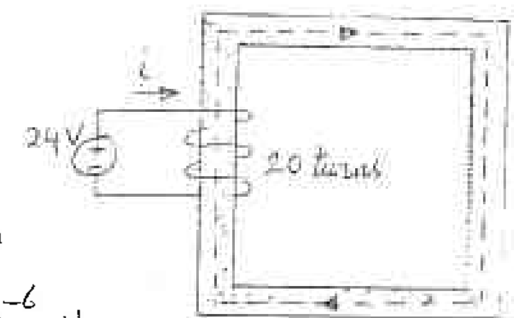
$$L = \frac{N\phi}{I} \quad (Henry)\ (H)$$

$\lambda = N\phi$: flux linkage (wbt)

Examples:

① The mean magnetic path of the material in fig(1) is 0.3m, and its effective cross-sectional area is $5\times10^{-4}\,m^2$. The flux density is 0.008 T, and the dc resistance of the winding at the operating temperature is 2 Ω. Determine:

a) The current drawn from the 24V dc supply.
b) The magnetic field intensity.
c) The flux.



fig(1)

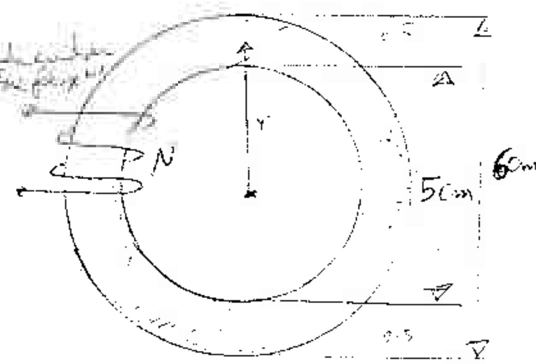
solution:

a) $i = \frac{V}{R} = \frac{24}{2} = 12\,A$

b) $H = \frac{NI}{l} = \frac{20(12)}{0.3} = 800\,A/m$

c) $\phi = AB = 5\times10^{-4}(0.008) = 4\times10^{-6}\,wb$

② A coil of 50 turns is wound around the toroid shown in fig(1) when a certain voltage is applied across the coil, its inductance is found to be 200 μH. Determine the relative permeability of the magnetic material from which the toroid is made.



fig(1)

solution: The cross-sectional area perpendicular to the flux is

$$A = \frac{\pi}{4}(0.5\times10^{-2})^2 = 0.196\times10^{-4}\,m^2$$

$$l = 2\pi r = 2\pi(0.0275) = 0.17\,m$$

$$\mu = \frac{Ll}{N^2A} = \frac{(200\times10^{-6})(0.17)}{(50)^2(0.196\times10^{-4})} = 0.7\,mH/m$$

$$\mu_r = \frac{\mu}{\mu_o} = \frac{0.7\times10^{-3}}{4\pi\times10^{-7}} = 560.27$$

② For Cast steel path:

$$H = \frac{B}{\mu_0 \mu_r} = \frac{0.5}{4\pi \times 10^{-7} \times 825} = 482 \ AT/m$$

The cast steel path length $= \pi r = \pi \frac{D}{2}$

$$= \pi \frac{21 \times 10^{-2}}{2} = 0.33 m$$

$\therefore$ mmf $= Hl = 482 \times 0.33$

$= 159 \ AT$

③ For Cast iron path:

$$H = \frac{B}{\mu_0 \mu_r} = \frac{0.5}{4\pi \times 10^{-7} \times 165} = 2411 \ AT/m$$

Cast iron path length $= \frac{\pi D}{2} = \frac{\pi (21 \times 10^{-2})}{2} = 0.33 m$

$\therefore$ mmf $= Hl = 2411 \times 0.33 = 795.6 \ AT$

$\therefore$ The total mmf = The total AT $= AT_{total}$

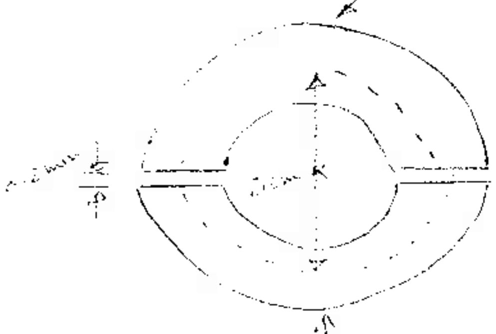
$$AT_{total} = 159 + 159 + 795.6$$

$$= 1113.6 \ AT$$

example3:

A ring of mean diameter 21 cm and cross section of 10 cm^2 is made up of a semi-circular section of Cast steel and Cast iron. If each joint has a reluctance equals to an air-gap of 0.2mm Find the A.T required to produce a flux of 5×10^{-4} wb in the magnetic circuit. Take μ_r for steel and iron as 825 and 165 respectively. neglect leakage and fringing.

solution.



$B = \phi / A$

$= 5 \times 10^{-4} / 10 \times 10^{-4}$

$= 0.5 \ wb/m^2$.

For the air gap:

$H = B / \mu_0$

$= 0.5 / 4\pi \times 10^{-7}$

$H = 3.97 \times 10^5 \ AT/m$

The length of the airgap is:

$l_{airgap} = 0.2 \times 2 = 0.4 \ mm = 4 \times 10^{-4} \ m$

$\therefore \ mmf = Hl$

$= 3.97 \times 10^5 \times 4 \times 10^{-4}$

$= 159 \ AT$

د. شريف

Leakage flux (ϕ_L):

It is the flux which follows a path not intended for it.

Fig (5) shows the main flux, leakage flux and the air-gap.

The flux in the air-gap is known as the useful flux.

main flux = ϕ_m (useful flux)
leakage flux = ϕ_L
total flux = ϕ

$$\therefore \phi = \phi_m + \phi_L$$

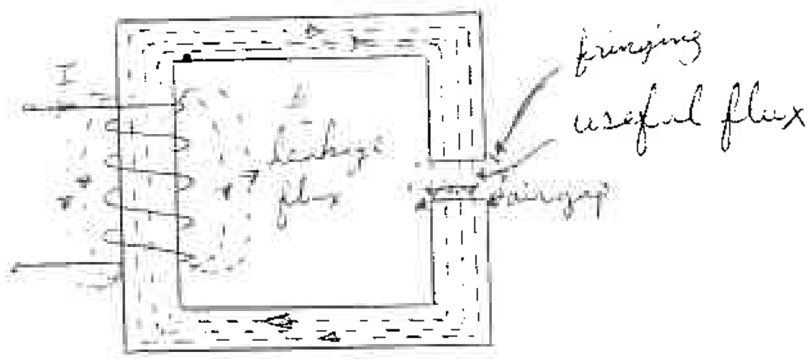


fig (5)

$$\text{leakage coefficient } (K_L) = \frac{\text{total flux}}{\text{useful flux}} = \frac{\phi}{\phi_m}$$

$$= \frac{\phi_m}{\phi_m} + \frac{\phi_L}{\phi_m} = 1 + \frac{\phi_L}{\phi_m}$$

$$K_L > 1$$

Chapter two
((DC Machines Fundamentals))
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DC Generator:

The generation of electricity achived by moving a conductor in a magnetic field, therefore to built a generator, a rotational movement is considered as follow: let us assume the generator to be shown in fig (1)

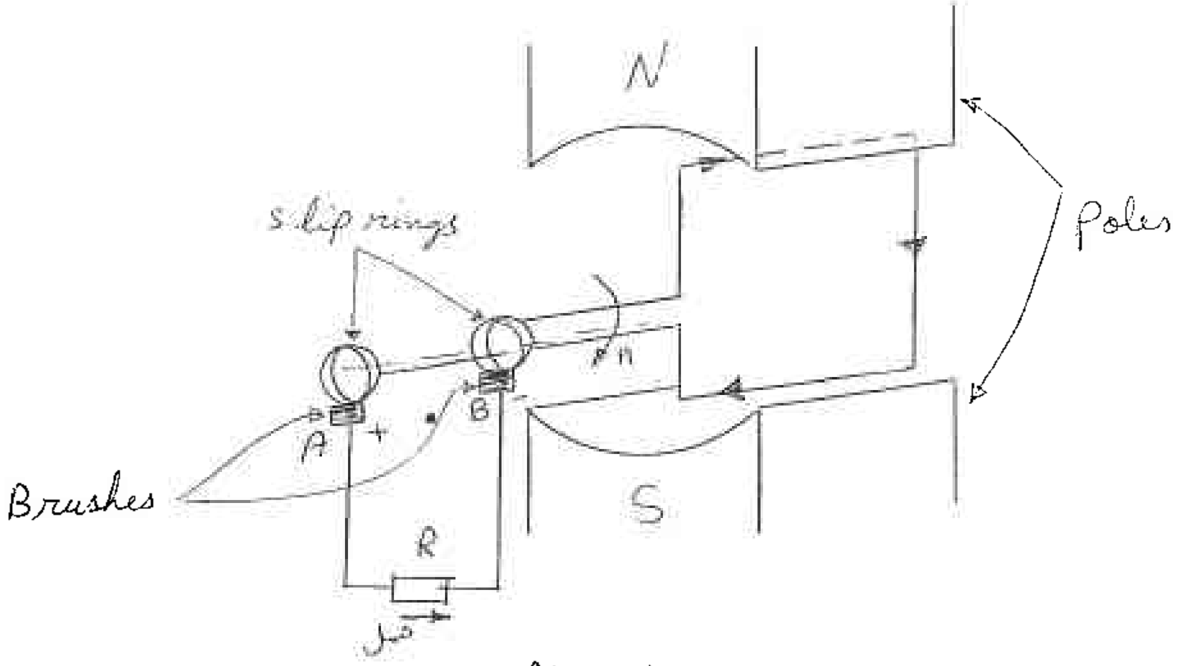
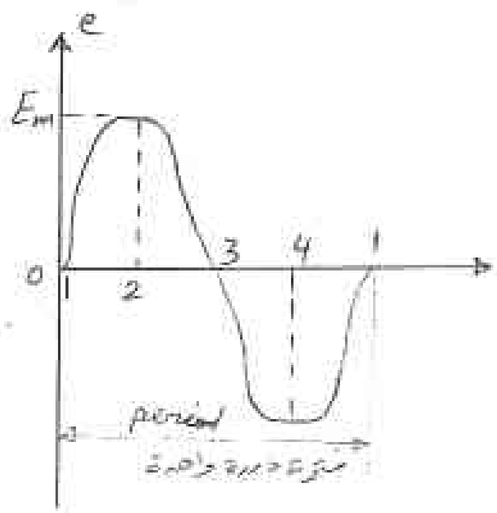
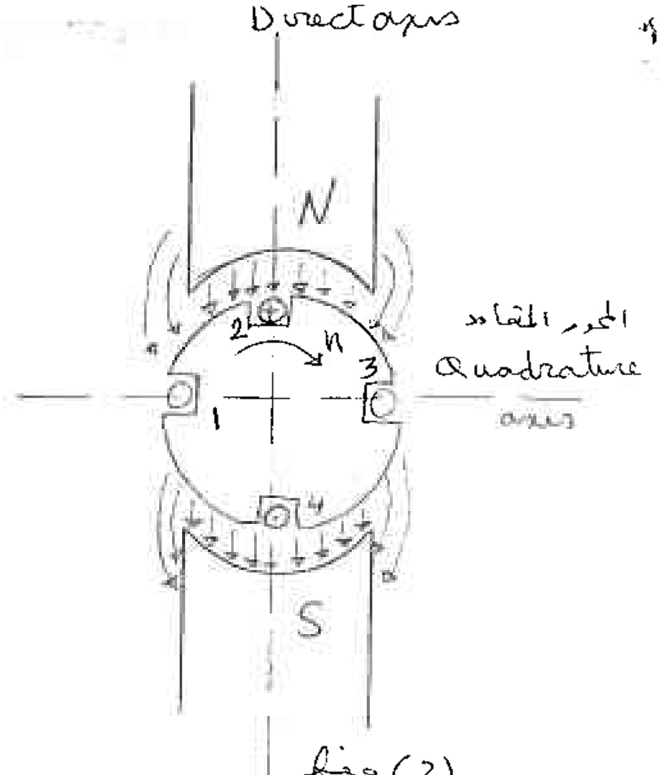


fig (1)

The magnetic field which the poles construct distributed ununiformly around the rotor. The density of magnetic field is max (maximum) in the direct axis but minimum in the quadrature axis as shown in fig (2).
This produce maximum induced emf in 2 & 4 and minimum induced emf in 1 & 3 as shown in fig (3)



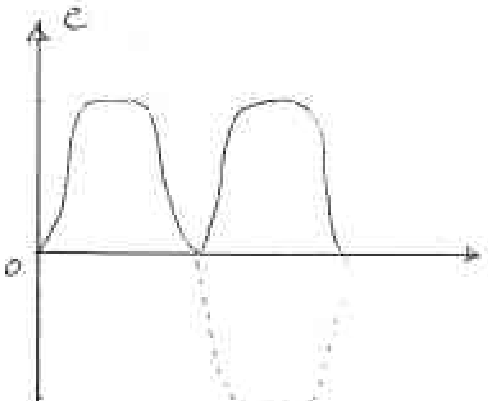
fig(3)



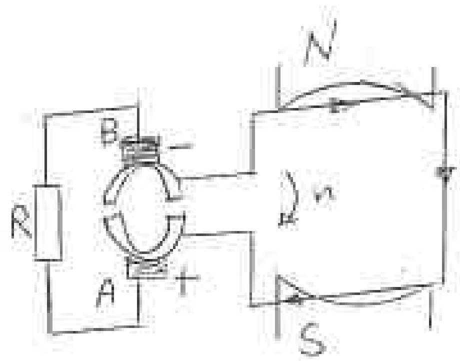
fig(2)

distrution of magnetic field

In order to generate a "Unidirectional Voltage" the slip rings replaced by two segments as shown in fig(4) this mean that the brush A its polarity always positive while brush B its polarity always negative. These segments generates the waveform shown in fig (5).



fig(5)



fig(4)

$$E = \frac{Z}{a} P \phi N = K_e \phi N$$

$$K_e = \frac{Z}{a} P$$

It is clear that the output voltage is not of Constant value always. In order to achive such a voltage a perpendicular turn will be added to the generator, In such Case the commutator Consist of four segments, as shown in fig(6)

fig (7) shows that we Can obtain d.c voltage by using this arrangment.

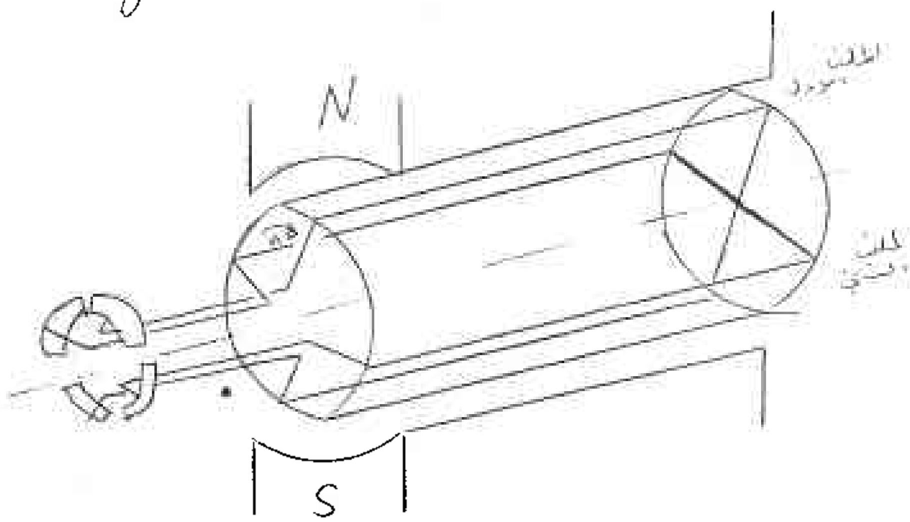
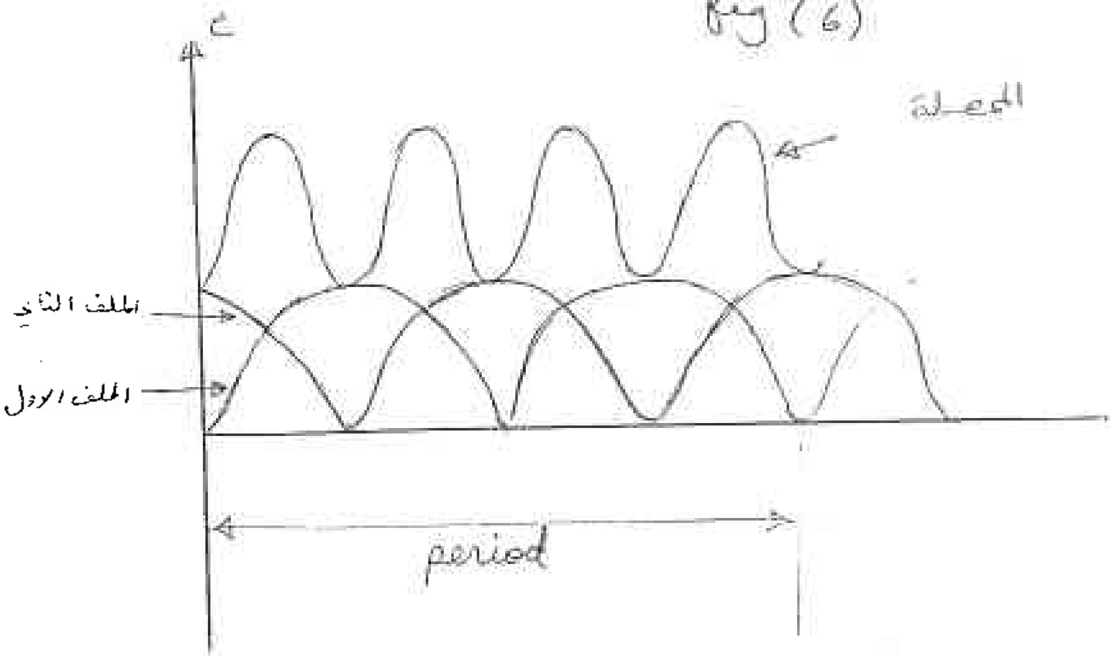
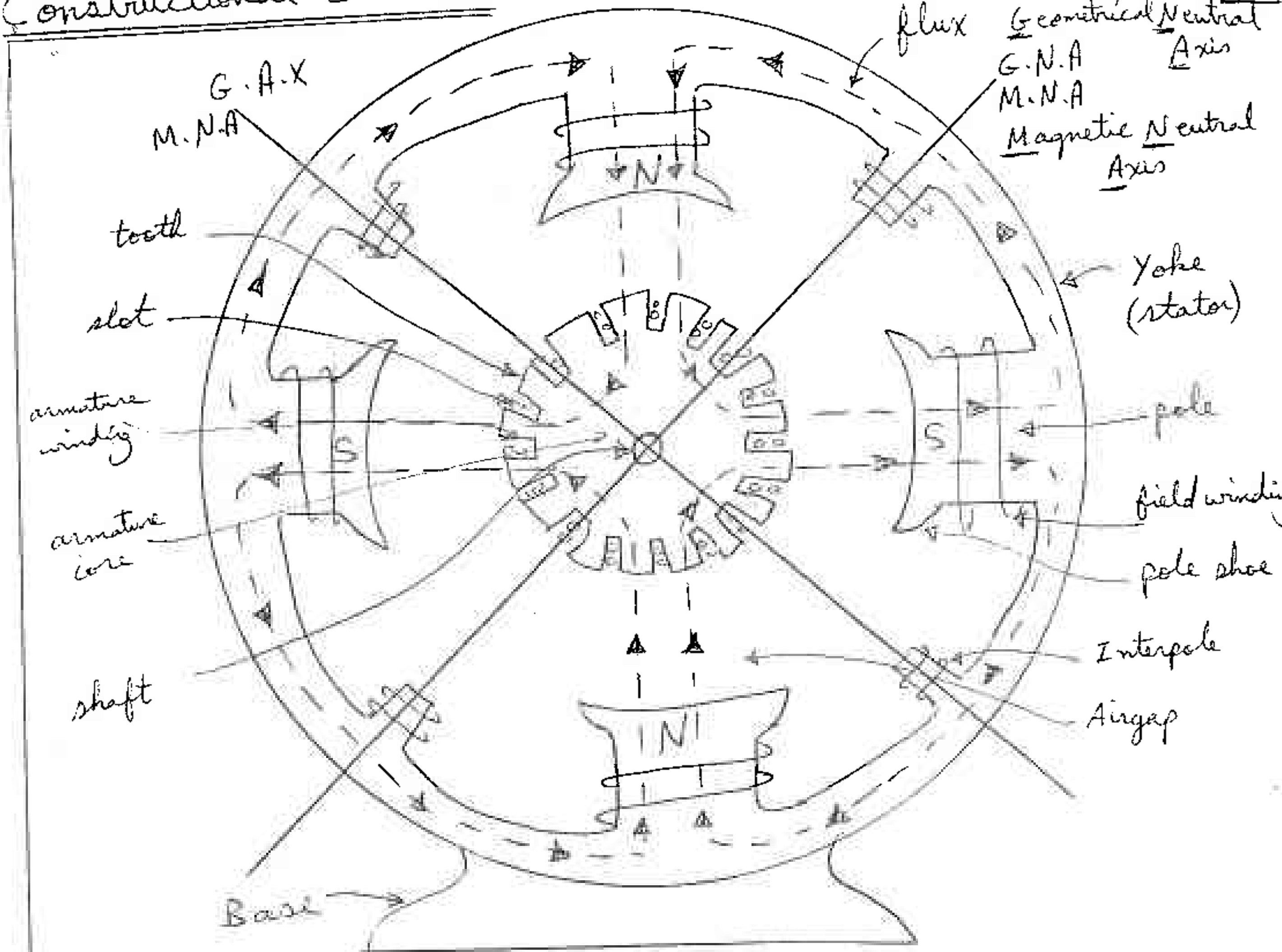


fig (6)



fig(7)

Constructional Elements:



fig(8)

Fig(8) represents a cross-section in a typical d-c machine showing its parts in the stator and the inside parts of the rotor.
In general the machine composed of two parts; the stator and the rotor, The stator (is the stationary part) of hollow cylindrical shape (in general) carrying machine poles and interpoles, also it fixes the brushes arrangment and contains the bearings of the machine rotor. Normaly the stator inclose the machine but it permit an air circulation (or water circulation in large machines) for the purpose of heat dissipation and cooling.
The rotor (is the rotating part) composed of armature winding, commutator, rotating shaft, fan arrangment.

Description of machine parts:

1. pole: each pole Composed of three parts as shown in fig (9) field winding, pole body & pole shoe.

The pole shoes serve two purposes

(a) they spread out the flux in the airgap being of larger cross-section, reduce the reluctance of the magnetic path.

(b) they support the coils.

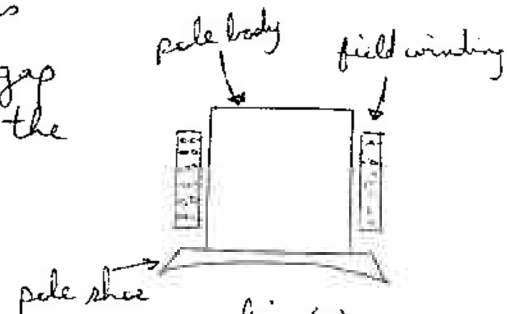
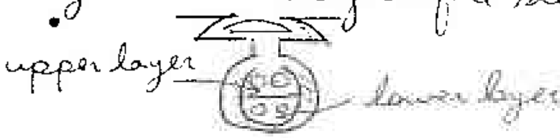


fig (9)

2. Interpole: is a small pole, its position between the poles. in order to reduce the commutation problem.

3. Slot: is a long deep to occupy the Conductors in many layers and to protect them from mechanical effect during operation. fig (10) shows the general design of a slot.

fig (10)



4. Commutator: The function of the commutator is to facilitate collection of current from the armature conductors, as shown in fig (11)

fig (11)

Side View ⇒

⇐ front View

5. Brush: As shown in fig (11) it is a part Connecting the commutator segments to the electric circuit, they are usually made of carbon and are in the shape of a rectangular block

6. Armature Core: It houses the armature conductors or coils, and Causes them to rotate and hence cut the magnetic flux of the field magnets.

7 Yoke: it provides mechanical support for the poles and acts as a protecting cover for the whole machine.

((D.C Machine Windings))

Introduction:

As shown in the previous section, the armature composed slots carrying two layers of Conductors. These bundled Conductor are Connected to each other and to the Commutator segments in a Certain way such that, the machine can use them totally and in the whole time of rotation

In machine winding we have two main types of windings these are (a) lap winding. (b) Wave winding. In each type there are two modes (Progressive and Retrogressive).

In the following only the simplex, two layers types will be discussed in order to declear the main ideas.

Definitions & Rules:

Pole pitch (τ) : is the region effected by the pole. also it is equal to the number of armature slots per pole.

$$\tau = \frac{S}{P}$$

Distance between brushes = τ

Coil : is a winding of wire composed of many turns with two Common terminals only.

Number of brushes = Number of Poles

Number of commutator segments C = Number of slots S

Lap Winding :

This type of winding used to achive low voltage high current d-c generator or low voltage high torque d-c motor, as will be shown. In the winding we have many definitions to be known.

خطوة الملف

Back Pitch (y_b): it is the distance measured in number of slots between the back ends of the coil.

Front Pitch (y_f): it is the distance between the end of the coil and the begining of the follower coil from the front side of the armature

Commutator Pitch (y_c): it is the distance between the begining of each cascaded two coils

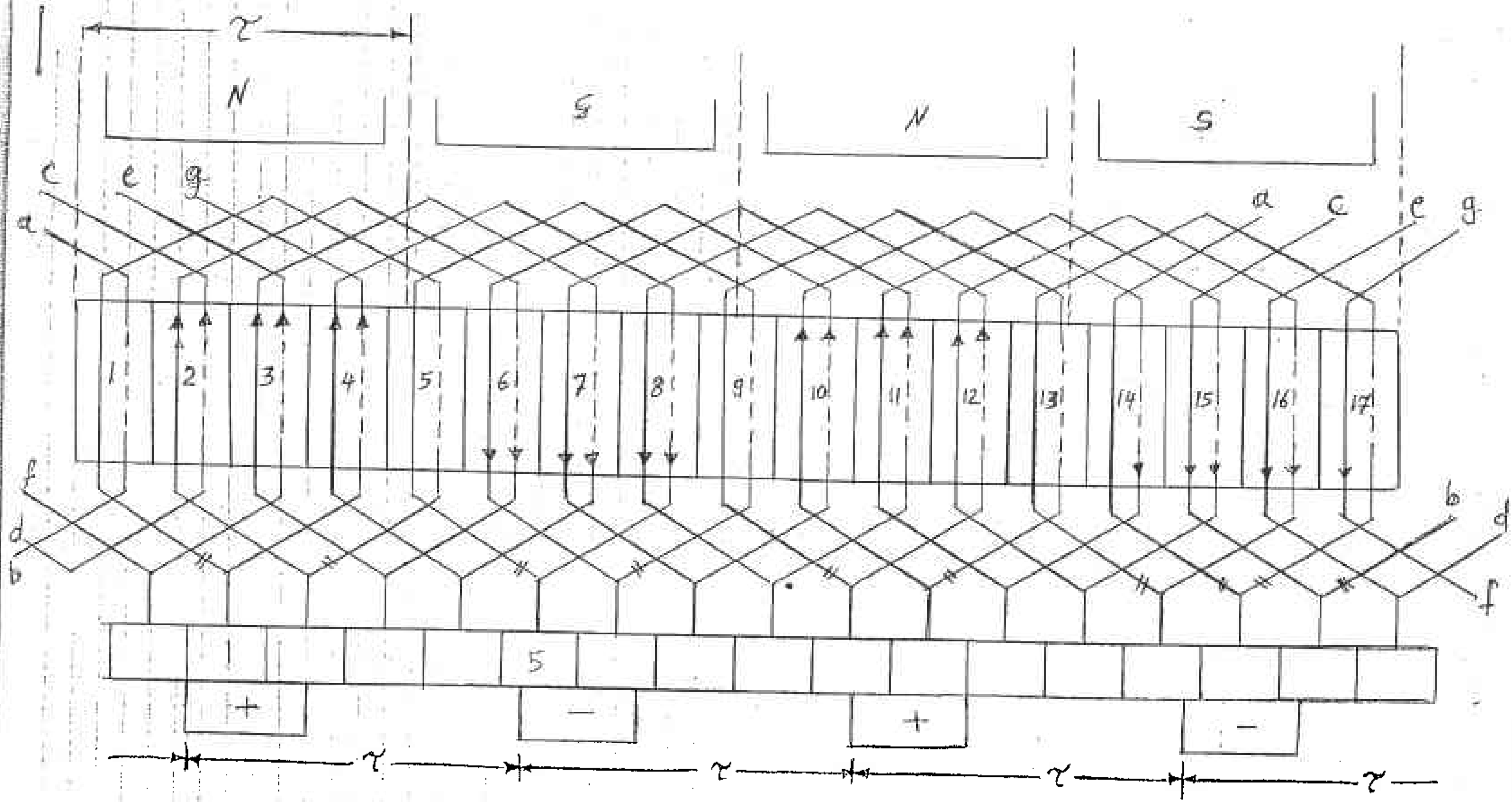
In lap winding.

$$y_b = \left|\frac{S}{P}\right| = |\tau|$$

$$y_c = \pm 1 \quad \text{(+ progressive)}$$

$$y_f = y_b - y_c$$

Example: Draw a developed diagram of armature in a 4 pole d-c machine lap winded (Progressive) (two layers), knowing that number of slots = 17. Draw also the equivalent armature circuit and the sequence diagram of the armature. Assign the direction of currents when operates as a motor.



fig(12) lap winding

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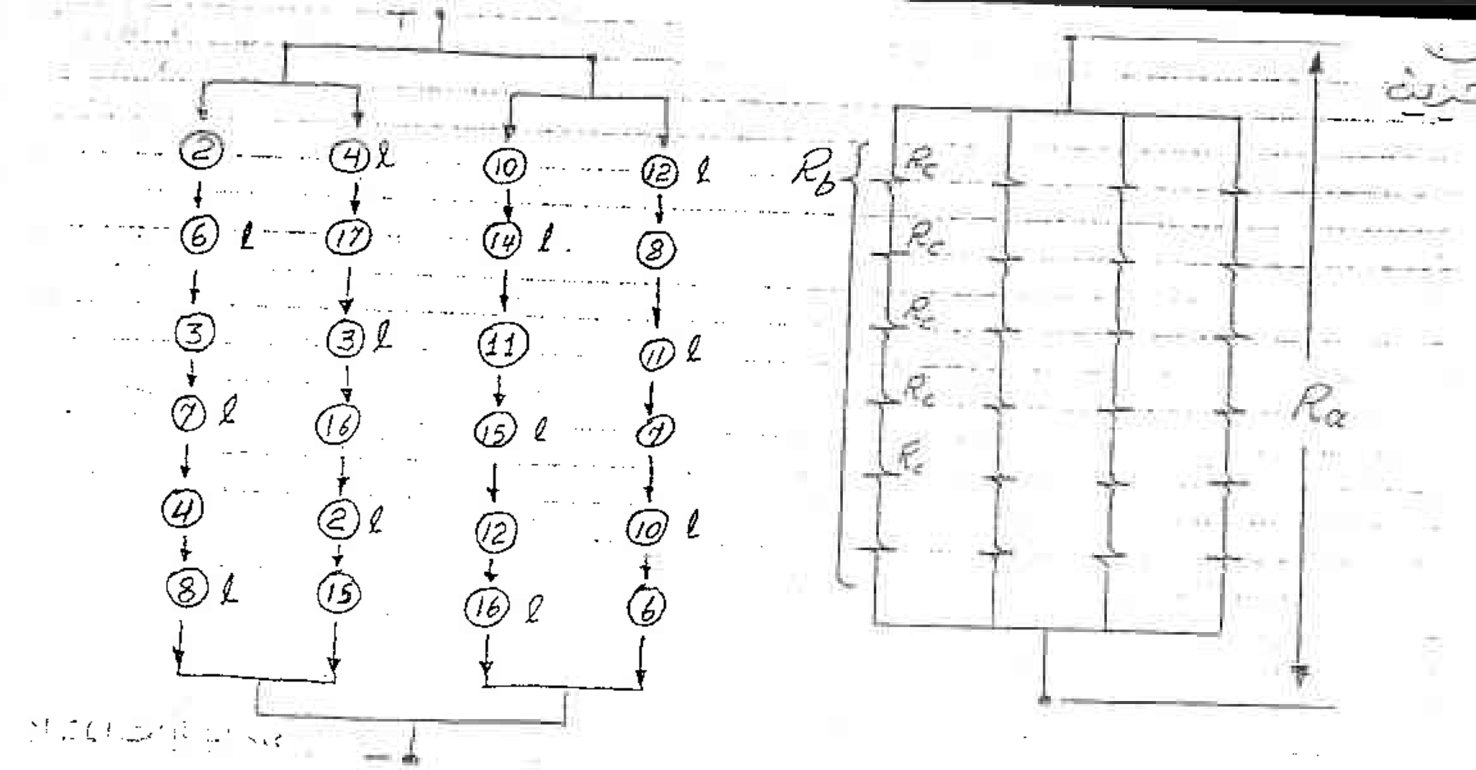

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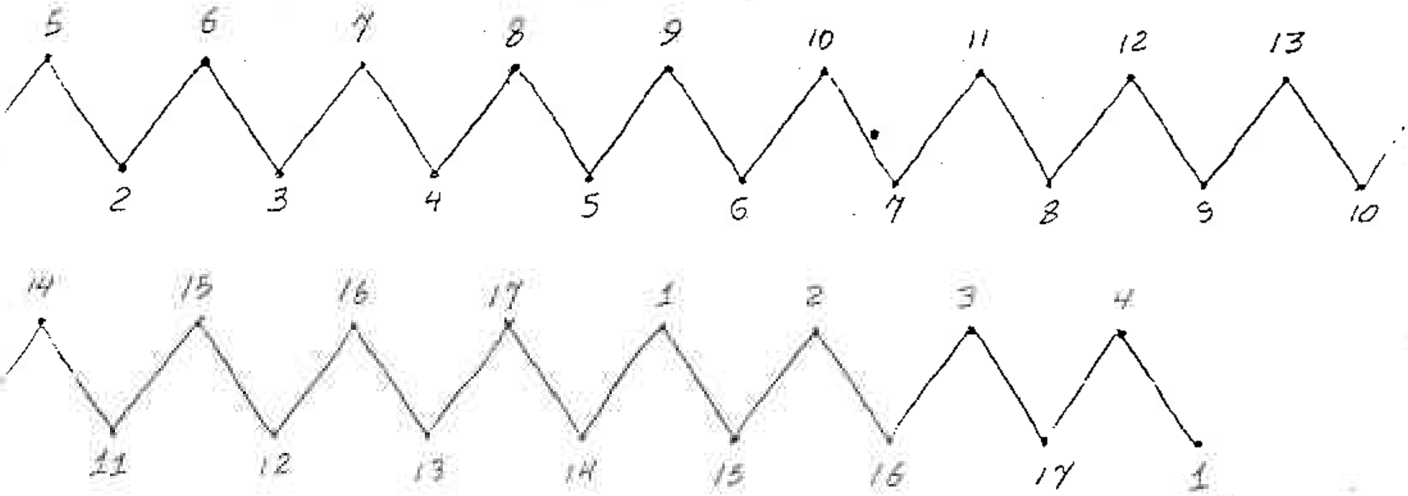
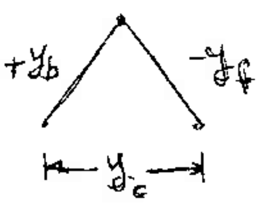
fig(13) Equivalent circuit





fig(14)
Sequence Diagram

Discussion of lap winding:

Fig (12) show this winding clearly, it is a progressive type of winding. Many important results and procedures should be considered as follows:

* The direction of currents shown in figure represent a motor operation.

* The brush width = 1.5 Commutator segment. The bursh position should be such as to be connected to the commutator segment which is connected to coil sides laying in slots exists at the interpole regions.

* Fig (13) represents the current distribution inside the armature in order to understand the machine operation and to draw the armature equivalent circuit. This circuit represents that the armature is divided into four parallel paths or branches each contains equal number of coil sides connected in series and the branches are connected in parallel so it leads to:

ⓐ The machine voltage is the branch voltage or

$$V_t = V_b$$

where

V_t = terminal voltage & V_b = branch voltage

ⓑ The armature rated current, "which is the motor or generator rated current", equal to the sum of the branch currents (I_b). But, it is clear

that number of parallel branches equal to the number of poles. Hence

$$I_a = P I_b$$

where I_a = Armature current.

(c) The armature resistance can be calculated as

$$R_a = \frac{R_b}{P}$$

Since (a) represent the number of parallel branches in the armature then ($a = P$) in such a type of winding.

(d) Fig (14) represents the "Sequence Diagram" which is useful during machine winding.

Wave Winding:

This type of winding is useful in case of generating high voltage low current using the same armature previously winded by lap winding as will be shown later. In this type:

$y_b = |\tau|$, $y_c = 2\left(\frac{S \mp 1}{P}\right)$ + for progressive
− for retogressive

$y_f = y_c - y_b$

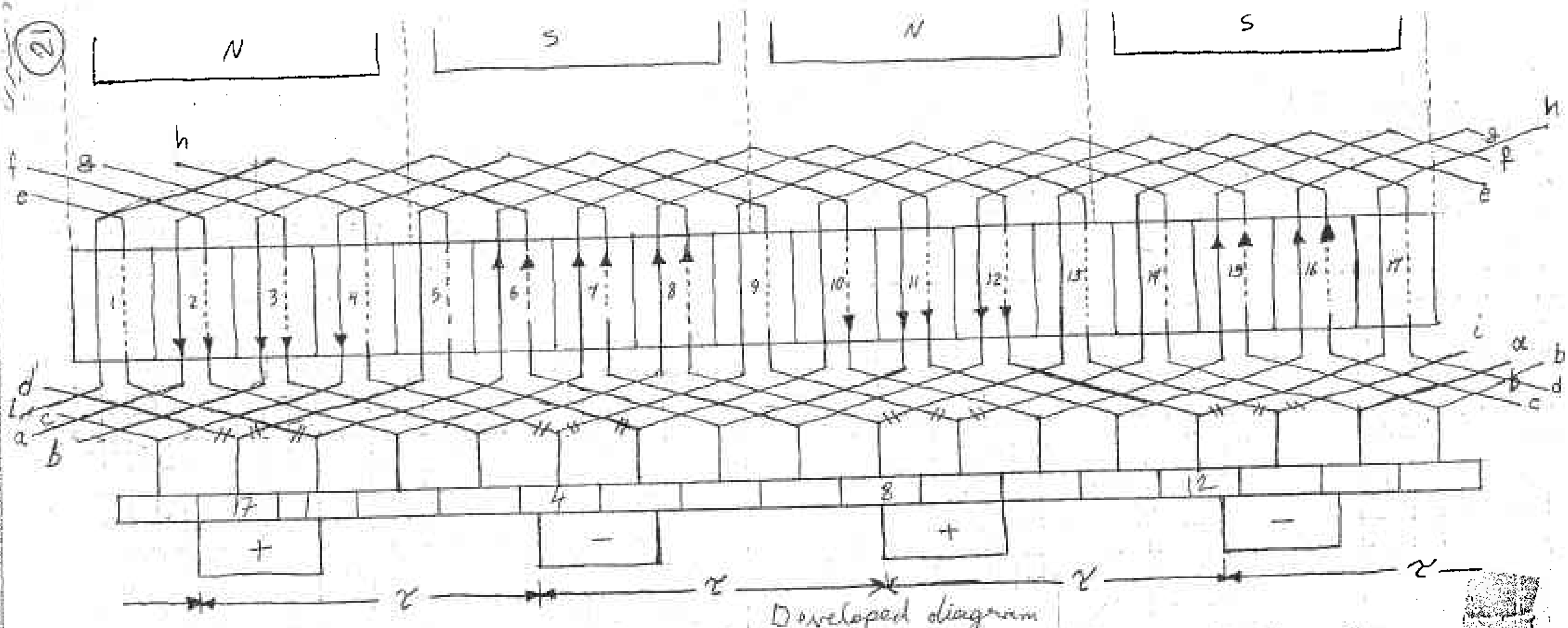
Hence for 4 pole, 17 slots machine, progressive wave

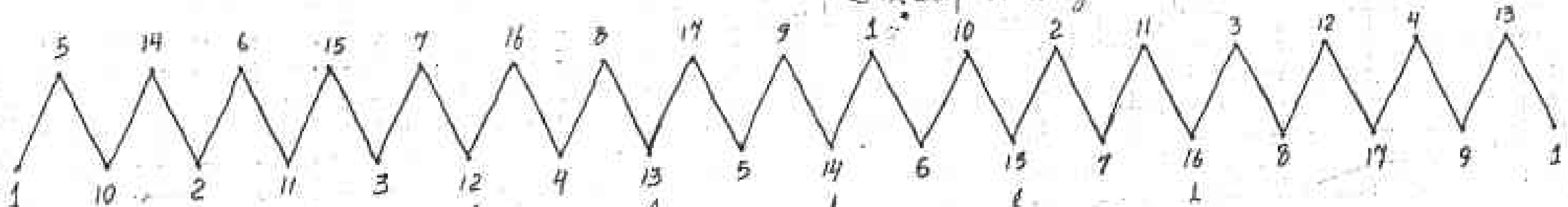
$$y_b = \left|\frac{S}{P}\right| = \left|\frac{17}{4}\right| = |4.25| = 4$$

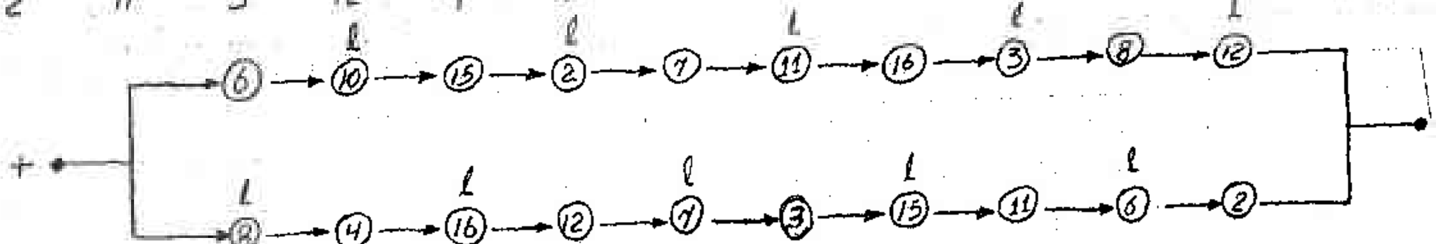
$$y_c = 2\left(\frac{17+1}{4}\right) = 9$$

$$y_f = 9 - 4 = 5$$

Fig (15) show the winding completely (the developed diagram, sequence diagram, and equivalent circuit). From the equivalent circuit it is clear that there is only two parallel branches whatever the number of poles is, and the voltage of the generator increased about twice that of the lap in this case (only). This means that the output power is constant in both cases.







Equivalent circuit

fig (15) Wave winding

((Armature Reaction))

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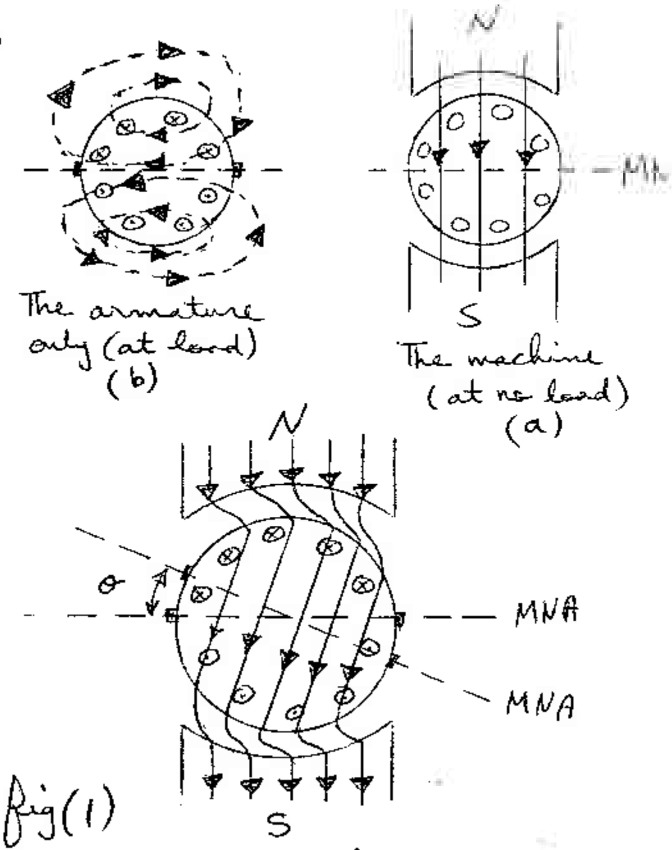
Armature Reaction:

This term is used to describe the effects of the armature mmf on the excitation field of the poles. This armature mmf has two effects:

(a) It demagnetises or weakens the main flux.
(b) It cross-magnetises or distorts it.

When the machine (motor or generator) loaded, a considrable current will pass through the armature and this current will produce magnetic field. To declear this fig(1) is showing a 2 pole machine at no-load and at load. fig(a) shows the normal distribution of field lines of d.c machine at no load, but at loading the current pass through armature winding, and this current will produce a flux as shown in fig(b), hence this will deflect the resultant flux as shown in fig(c).



The armature only (at load) (b)

The machine (at no load) (a)

fig(1)

The machine (at load) (c)

It is clear in (c) that the new field direction rotates the magnetic neutral axis an angle θ in CW direction.

If the burshes are shifted clockwise (cw) by an electrical angle (θ) as shown in fig (2), it can be seen that the armature mmf (F_a) = $\frac{I_c Z}{4P}$ can be resolved into two components:

(a) one along the quadrature axis (F_{aq}) = $\left(1 - \frac{2\theta}{\pi}\right) F_a$

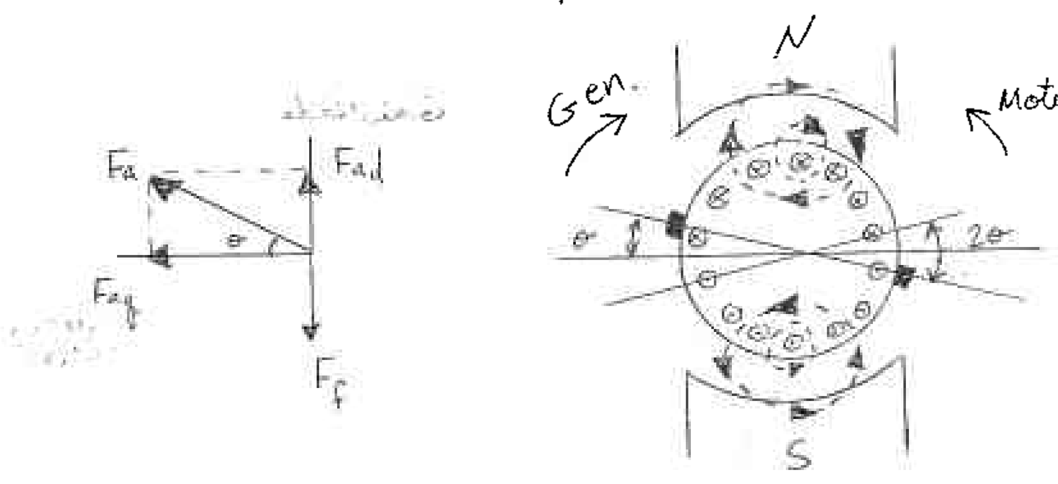
(b) the other along the direct axis (F_{ad}) = $\frac{2\theta}{\pi} F_a$

Because the mmf is not sinusoidally distributed, these components are only approximately equal to $F_a \cos\theta$ and $F_a \sin\theta$ respectively. The quadrature component is the little different in practice from F_a and is cross magnetising. The direct-axis component on the other hand is directly demagnetising.

where:

Z : the total number of conductors in armature.

I_c = armature current per conductor.



fig(2)

where:

F_f : field winding mmf

$\theta_e = \frac{P}{2} \theta_m$ θ_e = electrical degrees

θ_m = mechanical degrees

Compensating Windings:

If the machine load changes continuously, the flux will be suddenly shifting backward and forward with every change in load, therefore compensating winding is used which is a winding located in slots in the pole faces and are connected in series with armature in such a way that the current in them flows in opposite direction to that flowing in armature conductors directly below the pole face and produce an mmf equal in magnitude, opposite in direction to that of the armature mmf.

Compensating windings is shown in fig (3).

$$F_{cw} = \frac{Z I_c}{4P} \frac{\text{Pole arc}}{\text{Pole pitch}}$$

By the experience of the designer the impirical formula of c.w

$$F_{cw} = 0.7 \frac{Z I_c}{2p}$$

where:

F_{cw}: Compensating winding mmf

direct $F_{ad} = Z I \frac{\theta_m}{360}$

quadrature $F_{aq} = Z I \left(\frac{1}{2p} - \frac{\theta_m}{360}\right)$

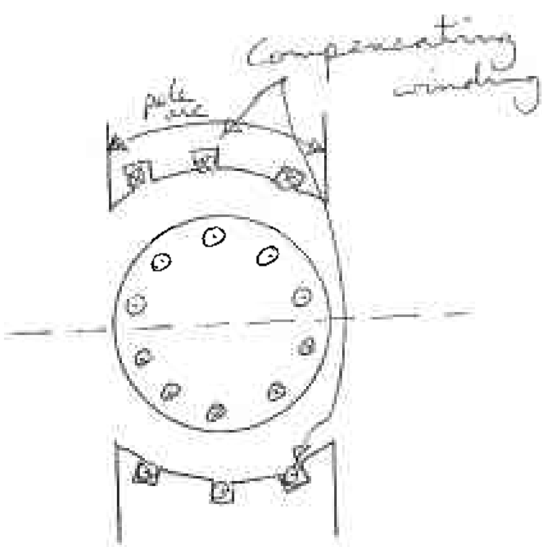


fig (3)

((Commutation))

التبديل

Commutation problem :

A problem arises in d.c machines during loading only, that a spark generates between the trailing edge of brushes and the commutator segment behind. This spark generates a high temperature in commutator region leads to damage the commutator and brushes, and if the spark is very high sometimes leads to a short circuit between brushes, So it is a serious problem and should be solved.

To solve this problem one should know the mechanical and electromagnetic reasons of this spark :

1. The elliptcal surface of the commutator lead to bad contact between the commutator and the brush as shown in fig.
2. Wear of the copper parts as a result of continous friction.
3. The vibration of the brushes lead to bad contact.
4. The ununiformely distribution of the current density through the brush as shown in fig (4)
5. The distortion of armature reaction to the ~~magnet~~ field as shown in fig(5).

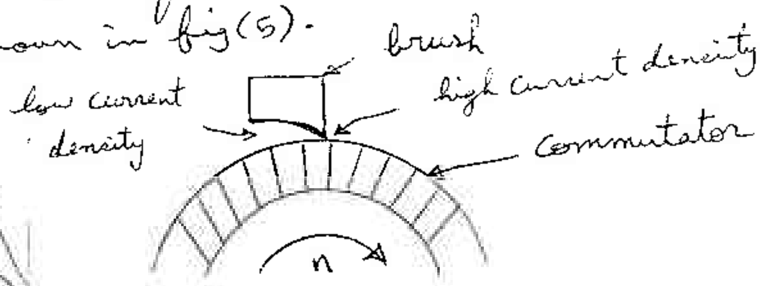
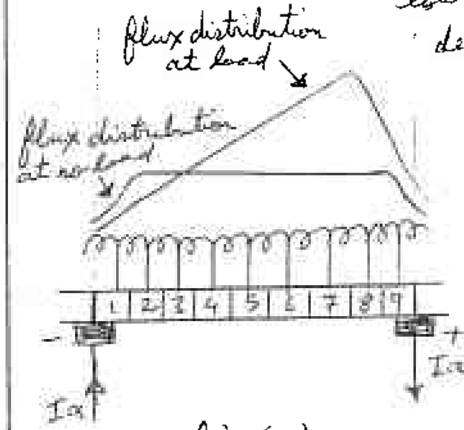


fig (4)



fig(5)

6. The Commutation, if it is not in the ideal case, it will cause a spark

From the function of the Commutator, it is expected that the Coil in Contact to the brushes will be subjected to change in the direction of current flows through it, as will be explained with the aid of fig(6.a, b, c) which shows the ideal Case of Commutation by Considering coil B which is the coil under Commutation. In fig (a) the Current in Coil B is from left to right, while that in fig (c) flowing from right to left. The value of this Current in a two-pole is (I/2), so the current in coil B changes from I/2 to − I/2 as shown in fig (7). So Commutation: is the reversal of the armature current during half the period of its cycles, While during the time elapsed to pass one commutator segment under the brush denote by (T). The bold line in the figure represents the ideal Case at which the current of coil B changes from I/2 at t=0 to −I/2 at t=T while the Current of coil B reaches Zero at t = T/2 which is the Case of no sparking during commutation.

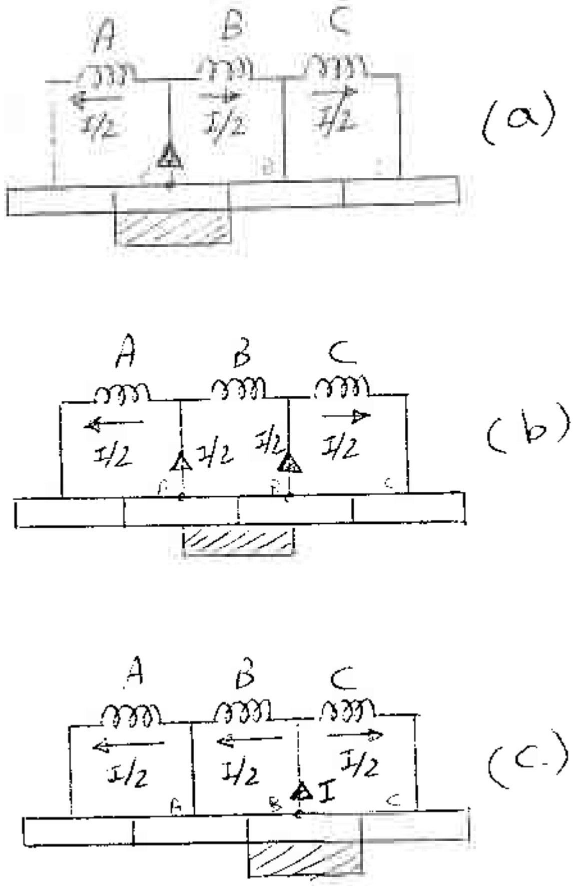


fig (6)

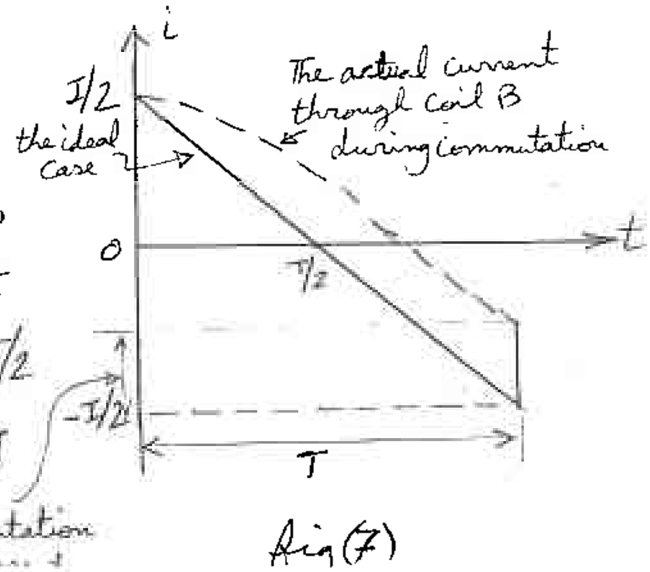


fig (7)

What factors stand in the way of our achieving ideal Commutation?

The main cause which retards or delays this quick reversal is the production of self-induced emf in the coil undergoing commutation. This self induced emf is known as reactance voltage, this voltage, even though of a small magnitude, produces a large current through the coil whose resistance is very low due to short-circuit.

Solution of Commutation Problem:

From the analysis of the spark reason it is clear that if T increased the commutation current will be reduced. This can be achived by increasing the brush width, but as shown previously (the short circuited conductors will be increased during operation). so in small machines, a brush width of about 1.5 commutator segment will be expected, while in medium and large machines the interpoles are considered to eleminate the induced voltage in the coil under commutatio by generating a motional emf against it and equal to its value leads to make the commutation ideal. For that reason the interpole position is in the G.N.A and will be narrow in order to effect on the coil under commutation only. It is short, in order, not to increase the armatu reaction which is discussed previously.

د. ....

(Chapter three)

((Types of D-c Generators))

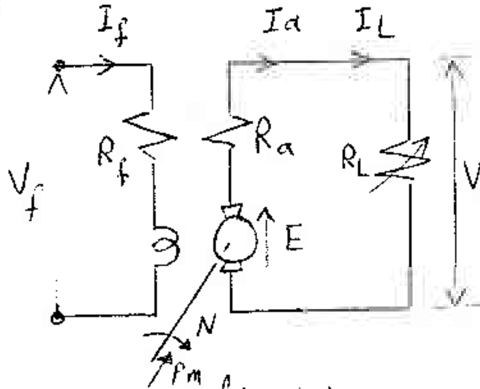
انواع مولدات التيار المستمر

There are different types of d-c generators in order to cover the demand in d-c power for different loads.

The generators classified due to their excitation in it, so there are two main types, the self excited and the separately excited d-c generators.

1. Separately-excited d-c Gen:

The field winding in this type excited from an isolated source of voltage, so the field circuit is separated and not effected by the armature circuit and load.



fig(1)

$I_f = \frac{V_f}{R_f}$ $\quad I_a = I_L$

$V_t = E - I_a R_a$

So the voltage equation of a d-c Gen is:

$$E = \frac{Z}{a} p \phi N \quad \text{———} \quad (1)$$

where

Z = total number of conductors

a = Number of parallel paths in armature

In equation (1) the parameters Z, a, & p are constants for each generator while ϕ & N are variables. The flux ϕ is function of I_f (field current), and N (speed of rota in r.p is determined by prime mover. So the emf equation can be written as:

$$E = K_e \phi N \quad \text{———} \quad (2)$$

where $K_e = \frac{Z}{a} p$

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The Open-Circuit Characteristics (O.C.C.):

The relation between E and I_f at constant speed (N = constant) when the load is open circuited ($R_L = \infty$) (the no-load condition) is called the open-circuit characteristics (O.C.C). The shape of this relation effected by the shape of the (B-H) curve of the ferromagnetic material used to build the machine as shown in fig (2). So the terminal voltage of this type at no-load ($V_t = E$) determined by two factors (I_f & N).

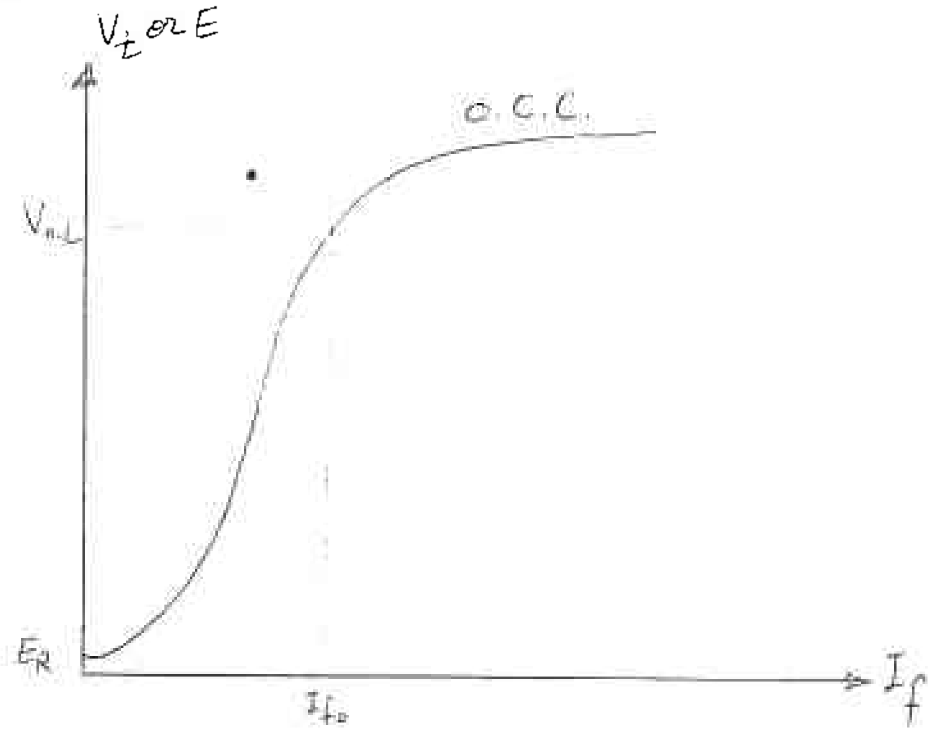

fig (2)

Note: ميزة

The specification of using two separate circuits is the perfect control on the magnetic flux, so these generators is suitable to generate voltage exceed (500 V), and also it is suitable to generate voltage less than (10 V).

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The internal & external Characteristics:

The external characteristics is the relation between the terminal voltage & the load current.

In the circuit shown in fig(1) & due to K.V.L.

$$V_t = E - I_a R_a$$

where:

$I_a = I_L$ in sep. excited d-c gen.

R_a = Armature resistance.

Let us consider a separately-excited generator giving its rated no-load voltage (E_o) for a certain constant field current (I_f = constant). If there were no armature reaction and armature voltage drop, then this voltage would have remained constant as shown in fig(3) (the line 1). But when the generator is loaded, the voltage falls due to these two causes. If we subtract from E_o the values of voltage drops due to armature reaction for different loads, then we get curve 2 (internal characteristic). If we get the value of E - the emf actually induced in the armature under load conditions, then we get curve 3 (external characteristic).

<u>Voltage regulation</u> (V.R): is the change in voltage from no-load to full-load under constant speed.

$$\% V.R = \frac{V_{n.L} - V_{f.L}}{V_{f.L}} \times 100$$

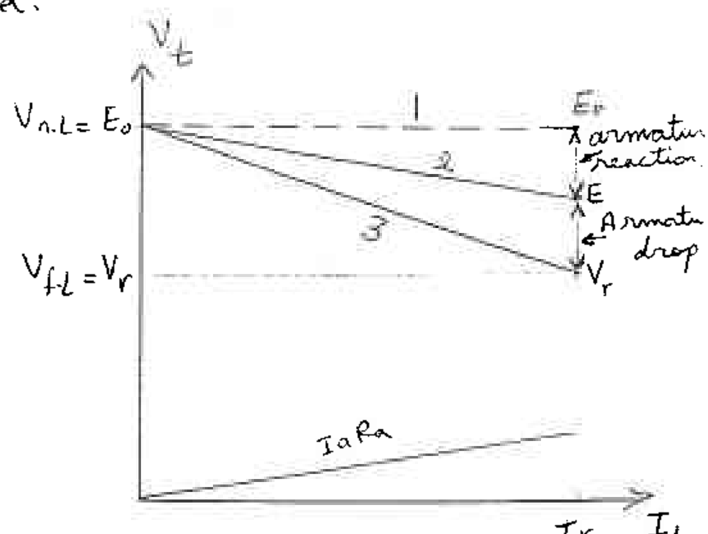

fig (3)

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2. Self-Excited d-c generators:

These generators fed their field winding by their generate voltage, so they don't need to external d-c voltage source.
These types are: shunt, series & Compound.

2.1 Shunt generator:

In this type the field winding connected in parallel (shunt) to the armature circuit as shown in fig (4). and construct f high number of turns and high resistance.

In self-excited gen. the primary generated voltage depends on the residual flux in iron poles, but in shunt-gen there are four conditions should be fulfilled in order to build-up the terminal voltage these are:

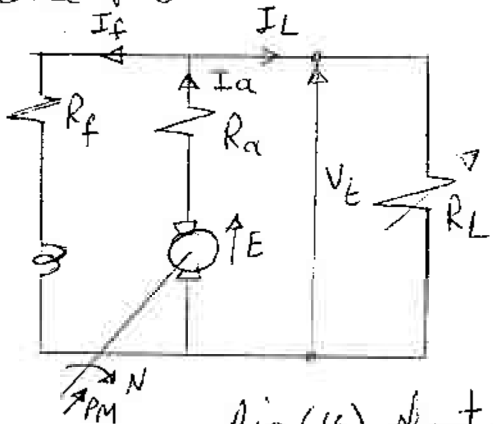

fig (4) shunt gen

$I_a = I_L + I_f$

$V_t = E - I_a R_a$

1. There must be some residual magnetism in the poles.
2. For the given direction of rotation, the shunt field coils should be correctly connected to the armature, i.e they should be so connected that the induced current reinforces the e.m.f. produced initially due to residual magnetism.
3. If excited on open circuit, its shunt field resistance should be less than the critical resistance.
4. The speed should be greater than critical speed.

The Open Circuit Characteristics (O.C.C.)

It is similar to the curve of separately excited dc gen., as shown in fig (5).

The voltage will be increased gradually as shown in fig (5) which represents the method of voltage build-up in steps, that, when $I_f = 0$ at starting and the prime mover starts up a small value of voltage E_R will be generated, this is due to residual flux.

This value will initiate a low current I_{f1}

$$I_{f_1} = \frac{E_R}{R_f} \qquad \text{(Note: } R_L = \infty \text{ i.e O.C.C)}$$

I_{f1} will increase the flux and generate E_1, -- and so on until a balance will be reached of the operating point at which field current and no-load voltage will be sustained.

This method shows the importance of the polarity of (field current, generated voltage, direction of rotation, and the field coil terminals).

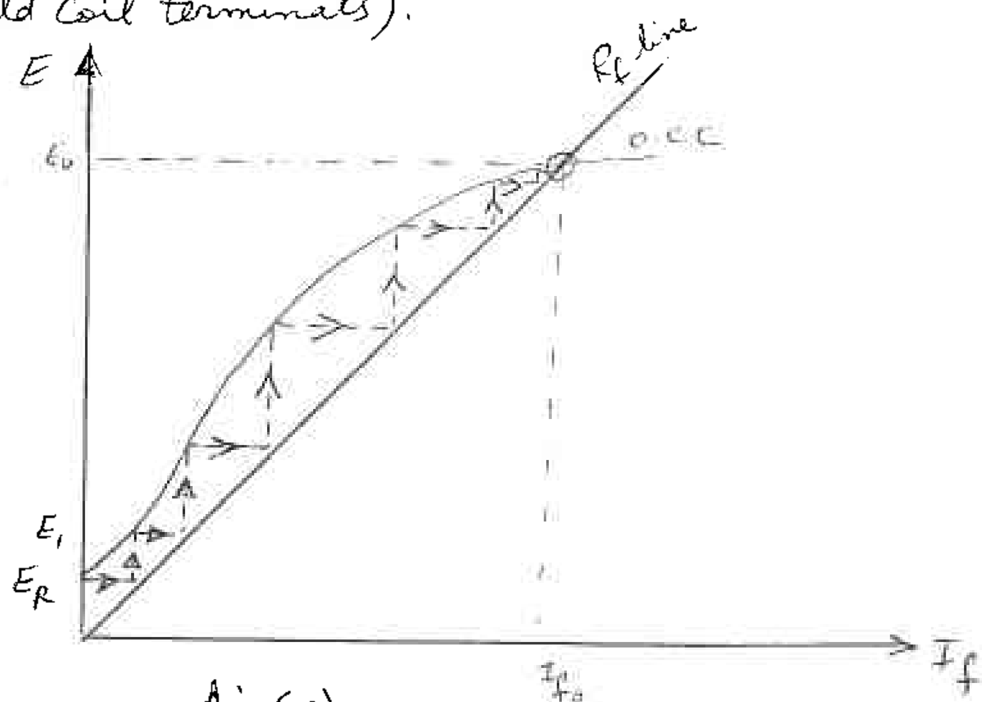

fig (5)

steps of voltage build-up during starting of shunt gen.

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The external Characteristics:

It means the relation between terminal voltage & load current when the speed and total resistance of field are constants.

When the load is connected to the generator fig (4) the terminal voltage will obey the quation:

$$V_t = E - I_a R_a$$

Which is the same formula used in separately-excited generator, but the difference here is in the fact that:

$$V_f = V_t$$

Which lead to reduce V_f during loading and this will lead to reduce I_f and then ϕ is reduced also. Since $E = K_e \phi N$, it will be reduced due to reduction in ϕ, as shown in fig (6).

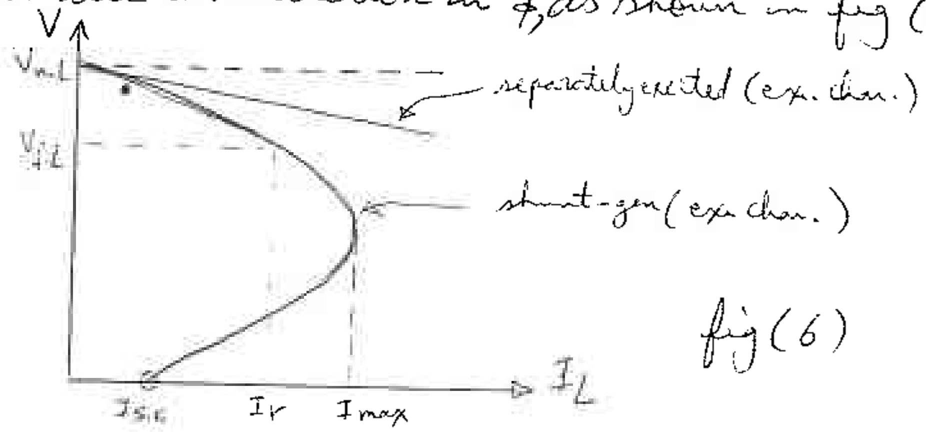

fig (6)

The critical resistance (for constant speed): is the value of field resistance in which the resistance line will be asymptotic to the linear part of the O.C.C. as shown in fig (7)

Application: with field regulators
These gen. are used for ordinary lighting and power supply purposes and for charging batteries

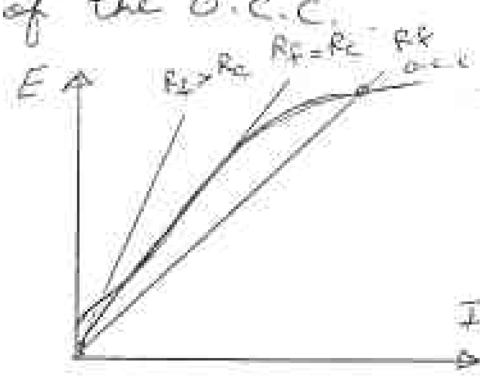

fig (7)

2.2 Series generator:

As shown in fig (8), the field winding of this type is connected in series with the armature, so such a winding will be constructed from low number of turns and high cross-sectional area wire.

The characteristic of this type is quite different compared to others, that the terminal voltage of this gen. will be very low and equal $E_R = K_e \phi_R N$, at no load. and it start to increase with I_L until the saturation, then it starts to decrease as shown in fig (9) and reaches zero when $I_L = I_{sc}$ (the short circuit current).

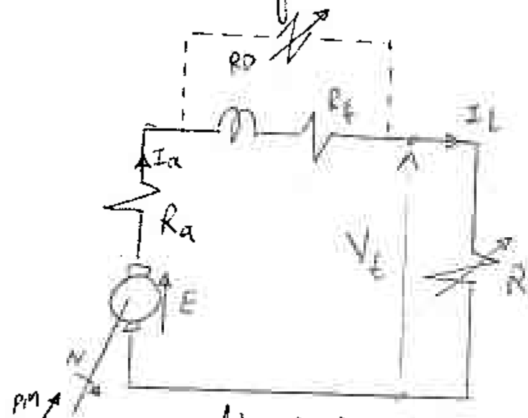

fig (8)

To control this voltage a diverting resistance R_D will be connected in parallel with the field winding to regulate the field current.

This generator used in special application. It is used a a heavy current supply in welding machines, and as a compensator or booster in long d-c voltage feeders.

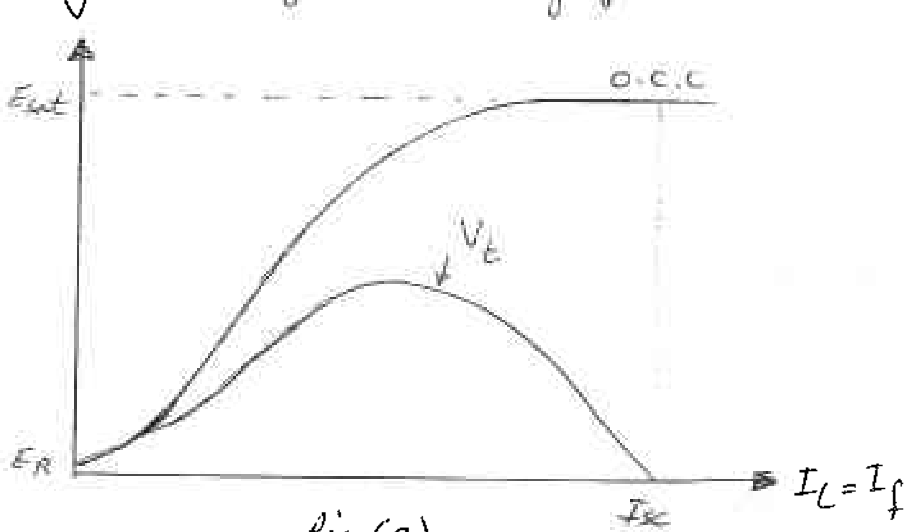

fig (9)

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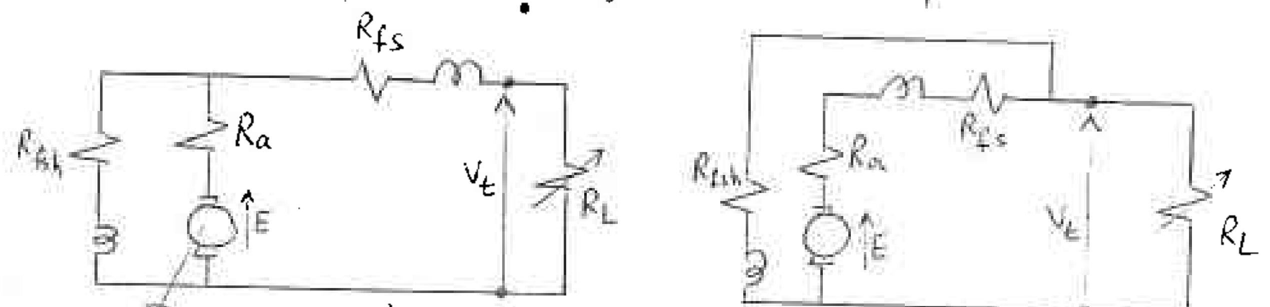
2.3 Compound generator:

This type of generator designed to get ideal external characteristics by compensating the drop in terminal voltage in shunt gen. due to loading by the increase in terminal voltage of the series gen. during load increase as shown in fig (10)

Hence, by regulating series and field currents in Compound gen., a group of different ext. characteristics can be achived as shown in fig (11).

Three different ext. c/c's of cummulative compound gen there are, over compound, flat compound & under com. These c/c's furnishes suitable power supply for different loads. The differential gen. used in special control circuit



(a) short compound

(b) long compound

fig(10)

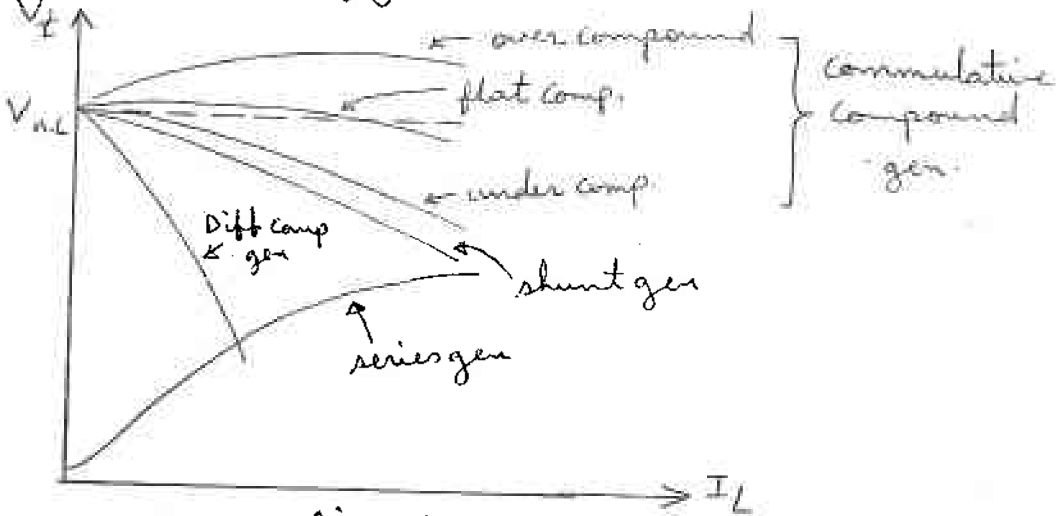


fig (11)

Parallel Operation of Shunt Generators:

Power plants, in d-c stations, will be generally found to have several smaller generators running in parallel rather than large single units capable of supplying the maximum peak load. These smaller units can be run singly or in various parallel combinations to suit the actual load demand. Such practice is considered extremely desirable for the following reasons:

1. Continuity of Service.
2. Efficiency.
3. Maintenance and Repair.
4. Additions to plant.

Load Sharing:

Because of their slightly drooping voltage charactoristic shunt generators are most suited for stable parallel operation. Their satisfactory operation is due to the fact that any tendency on the part of a generator to take more or less than its proper share of load results in certain changes of voltage in the system which immediately oppose this tendency thereby restoring the original division of load. Hence, once paralleled, they are automatically held in parallel.

Whenever generators are in parallel, their +ve and -ve terminals are respectively connected to the +ve and -ve sides of the bus bars. These bus-bars are heavy thick Copper bars and they act as +ve and -ve terminals for the whole power station.

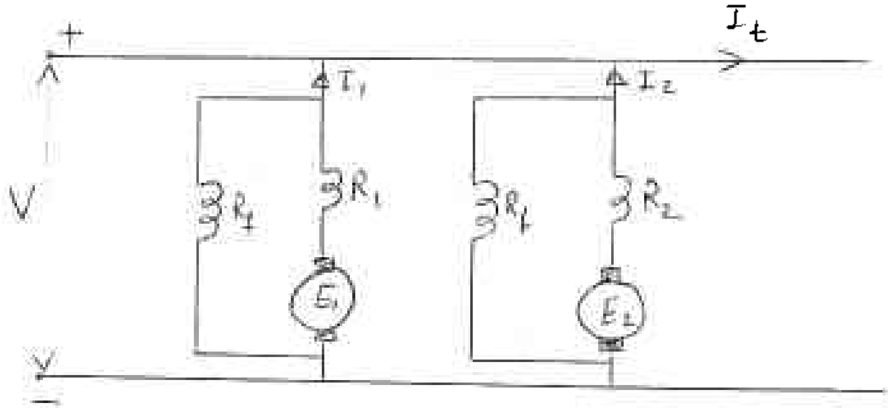


fig (12)

Let us discuss the load sharing of two generators which have unequal no-load voltages.

Let E_1, E_2 = no load voltages of two generators.
R_1, R_2 = their armature resistances
V = terminal voltage (bus-bar voltage)
I_1, I_2 = output current of two generators.

Then $I_1 = \dfrac{E_1 - V}{R_1}$ and $I_2 = \dfrac{E_2 - V}{R_2}$

$$\therefore \frac{I_2}{I_1} = \frac{E_2 - V}{E_1 - V} \cdot \frac{R_1}{R_2} = \frac{K_2 N_2 \phi_2 - V}{K_1 N_1 \phi_1 - V} \cdot \frac{R_1}{R_2}$$

when R_f has a low value.

From the above equation it is clear that bus-bar voltage can be kept constant. and load can be transferred from 1 to 2 by increasing ϕ_2 or N_2 or by reducing N_1 and ϕ_1.

Generated E.M.F or E.M.F Equation of a Generator:

Let: ϕ = flux/pole in weber
Z = total number of armature conductors = No. of slots X No. of conductors/slot.
P = No. of poles
A = No. of parallel paths in armature
N = armature rotation in r.p.m.
E = e.m.f induced in any parallel path in armature

Generated e.m.f = e.m.f generated in one of the parallel paths.

$$\text{Average e.m.f generated/conductor} = \frac{d\phi}{dt} \text{ volt.}$$

Now, flux cut/conductor in one revolution, $d\phi = \phi P$ wb

No. of rev/second = $N/60$

$\therefore$ time for one revolution, $dt = 60/N$ second.

Hence, according to Faraday's laws of electromagnetic induction,

$$\text{E.M.F. generated/conductor} = \frac{d\phi}{dt} = \frac{\phi P N}{60} \text{ volt}$$

For a wave-wound generator:

No. of parallel paths = 2

No. of conductors (in series) in one path = $Z/2$

$$\therefore \text{E.M.F. generated path} = \frac{\phi P N}{60} \times \frac{Z}{2} = \frac{\phi Z P N}{120} \text{ volt}$$

For a lap-wound generator:

No. of parallel paths = P

No. of conductors (in series) in one path = Z/P

$\therefore$ E.M.F generated/path $= \dfrac{\phi P N}{60} \times \dfrac{Z}{P} = \dfrac{\phi Z N}{60}$ volt

In general, generated e.m.f., $E = \dfrac{\phi Z N}{60}\left(\dfrac{P}{A}\right)$ volt

where

$A = 2$ for wave-winding

$= P$ for lap-winding

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((D-C Motors))

محركات التيار المستمر

The construction, winding connections and types of motors are the same as that of d-c generators, the only difference is the energy conversion. In gen. mechanical power converted to electrical power, while in motors electrical power converted to mechanical power.

Main Equations:

$E < V$

Applying KVL fig (1) to the armature circuit results in:

$$V_t = E + I_a R_a \qquad \text{---} \quad (1)$$

$$E = K_e \phi N$$

where $K_e = \frac{PZ}{a}$

$$\therefore \; V_t = K_e \phi N + I_a R_a$$

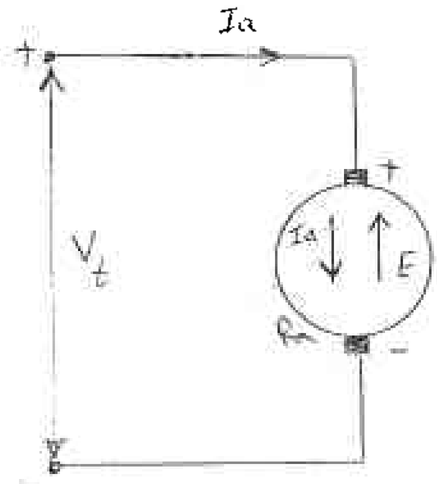

fig (1) motor

$$N = \frac{V_t - I_a R_a}{K_e \phi}$$

$$N = \frac{V_t}{K_e \phi} - \frac{R_a}{K_e \phi} I_a \qquad \text{---} \quad (2)$$

$$P_{em} = E I_a$$

$$= K_e \phi N I_a$$

$$T_{em} = \frac{P_{em}}{\omega} = \frac{K_e \phi N I_a}{2 \pi N} = \frac{K_e \phi}{2 \pi} I_a$$

, where $\omega = 2 \pi N$

$$I_a = \frac{2 \pi}{K_e \phi} T_{em} \qquad \text{---} \quad (3)$$

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where:

N: speed (r.p.m)

ω: angular velocity (rad/sec) = $2\pi n$

P_{EM}: electromagnetic power.

T_{em}: electromagnetic torque = T

$$T = \frac{K_e}{2\pi} \phi I_a \qquad (4)$$

This equation can be written as:

$$T = K_t \phi I_a \qquad (5)$$

where $K_t = \frac{K_e}{2\pi}$

sub. (3) in (2) results in:

$$n = \frac{V_t}{K_e\phi} - \frac{R_a 2\pi}{K_e^2 \phi^2} T$$

$$n = \frac{V_t}{K_e\phi} - \frac{R_a}{2\pi K_t^2 \phi^2} T \qquad (6)$$

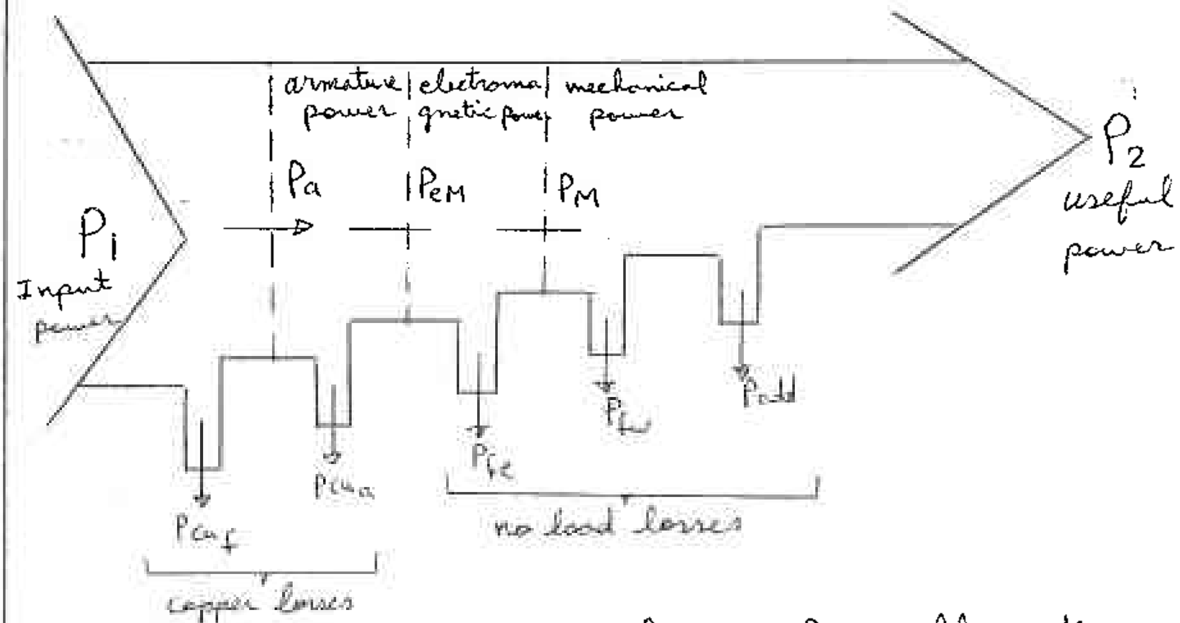
$\because \omega = 2\pi n$

$$\therefore \omega = \frac{2\pi V_t}{K_e\phi} - \frac{R_a}{K_t^2 \phi^2} T$$

$$\omega = \frac{V_t}{K_t\phi} - \frac{R_a}{K_t^2 \phi^2} T \qquad (7)$$

د. شريف

Power flow diagram (PFD):



fig(2) Power flow diagram

From fig(2):

$P_1 = V_t I_a$

① Electrical losses:

(a) $P_{Cu_f} = I_f^2 R_f$ = Copper losses in field winding

(b) $P_{Cua} = I_a^2 R_a$ = Copper losses in armature winding.

$P_a = P_1 - P_{cu_f}$

$P_{em} = P_1 - P_{cu_f} - P_{cua}$

$P_M = P_{em} - P_{fe} = P_1 - P_{cu_f} - P_{cua} - P_{fe}$

② Rotational losses:

(a) Iron losses (P_{fe}):

These losses occures in the iron of rotor only, and these are two types:

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(i) Eddy current losses (P_{ed})
(ii) Hysteresis losses (P_h)

$$P_{fe} = P_{ed} + P_h$$

(b) Mechanical losses (P_{fw}):
There are due to two different reasons:
(i) Friction losses (P_f)
(ii) Windage losses (P_w): Friction with air inside the machine.
$P_{fw} = P_f + P_w$
(c) Additional losses (P_{add}): its value very low so it can be neglected

P_{fe} & P_{fw} are function of speed (n), so when the speed is constant, there losses are considered constant.

$$P_2 = P_M - P_{fw} - P_{add}$$

$$P_2 = P_1 - P_{cuf} - P_{cua} - P_{fe} - P_{fw} - P_{add}$$

$$P_2 = T_2 \omega$$

$$\eta = \frac{P_2}{P_1}$$

where P_1 : input power
P_2 : useful power

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Types of motors:

1. Seperately - Excited d-c Motor:

- For this motor, the same series of eqn's (from 1 to 7) can be applied to this type of motor.

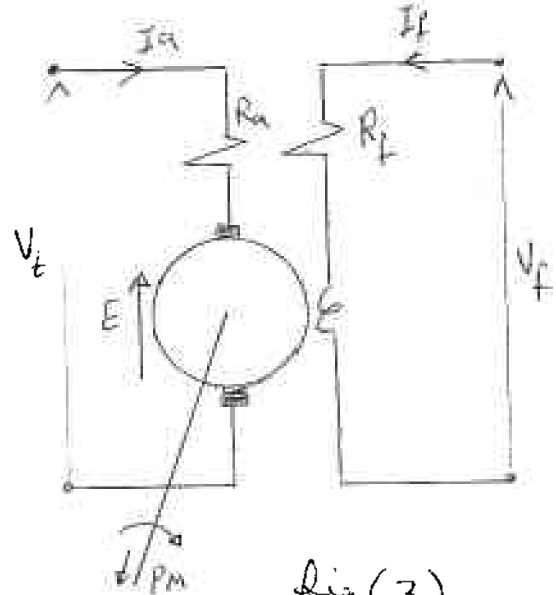


fig (3)

1. N/Ia Characteristics:

Eqn (2) represents the relation between the speed of the motor and the armature current (n versus Ia). This relation is shown in fig (4)

$$n = \frac{V_t}{K e \phi} - \frac{R_a}{K e \phi} I_a \quad ---(2)$$

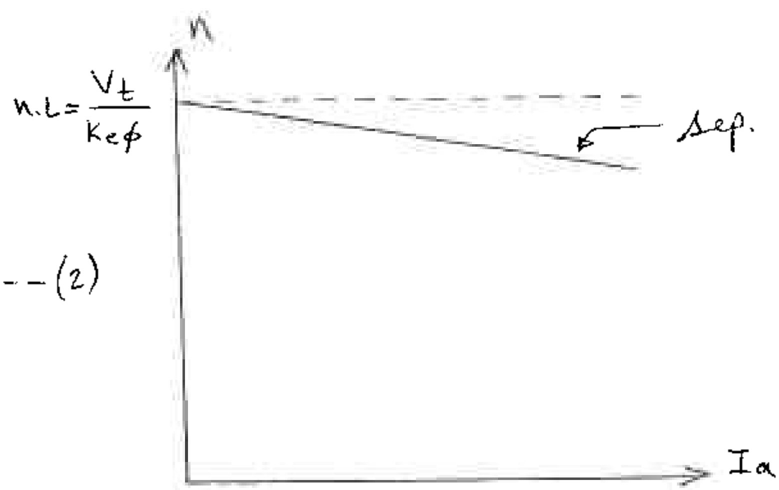
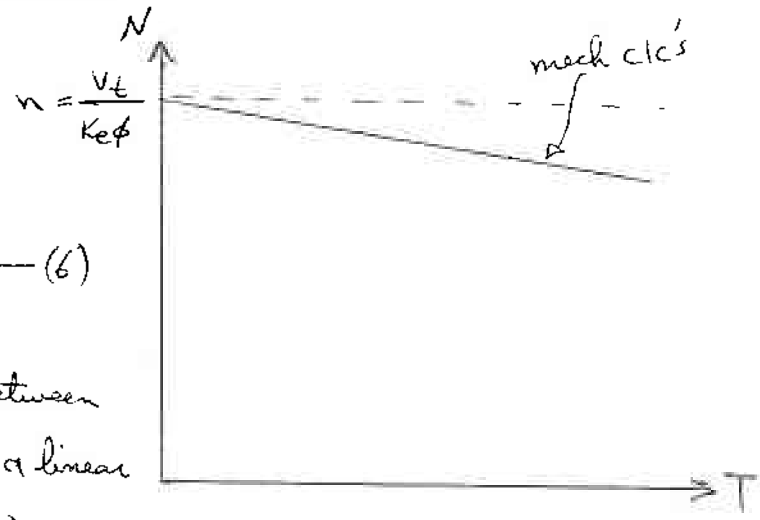


fig (4)

2. N/T Characteristics: (mechanical char.)



$$n = \frac{V_t}{K_e\phi} - \frac{R_a}{2\pi K_t^2 \phi^2} T \quad \text{———} (6)$$

Eqn (6) shows the relation between speed and torque which is a linear one as shown in fig (5)

fig (5)

3. T/Ia characteristics: (electrical char.)

$$T = K_t \phi I_a \quad \text{———} (5)$$

Eqn (5) shows the relation between torque & armature current (T versus I_a) as shown in fig (6), and it is called the electrical char..

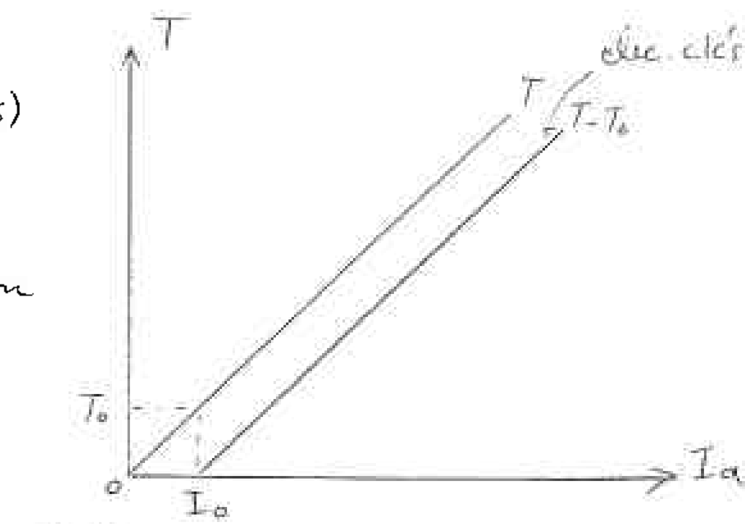


fig (6)

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2- Shunt motor:

For this motor, the same series of eq'n (from 1 to 7) can be applied to this type of motor and the same c/c's are obtained. Due to the constancy of their speed, shunt motors are suitable for driving shafting, machine tools, laths wood-working machines and for all other purposes where an approximately constant speed is required.

Equivalent circuit is shown in fig (7)

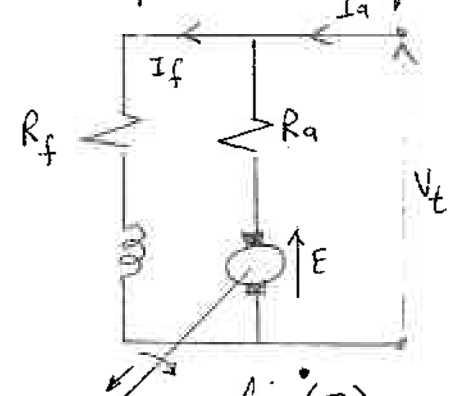


fig (7)
Equivalent circuit of shunt motor

3. Series motor

In this type $I_a = I_f$ as shown in fig (8), so

$\phi \propto I_a$ or $\phi = K' I_a$

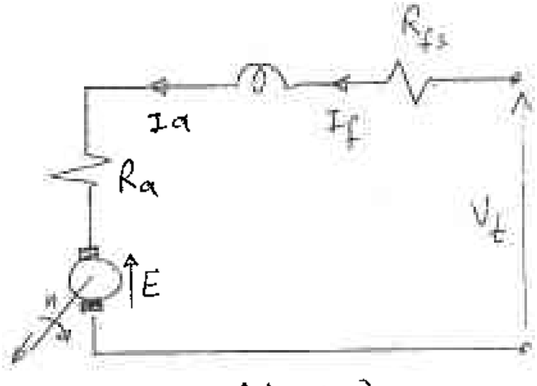


fig (8)
Equivalent circuit of a d-c series motor

1. T/Ia characteristics: (electrical c/c)

$T = K_t \phi I_a$ ——— (5)

$T = K_t K' I_a^2$

$T = K'' I_a^2$ ——— (8) (before saturation)

where $K'' = K_t K'$

$T = K_t \phi I_a$ ——— (9) (after saturation)

د. شيرين

At light loads, Ia and hence ϕ is small. But as Ia increas T increases as the square of the current. Hence T/Ia curv is a parabola as shown in fig (9). After saturation, ϕ is almost independent of Ia (ϕ is constant), hence $T \propto I_a$ only. So the characteristic becomes a straight line.

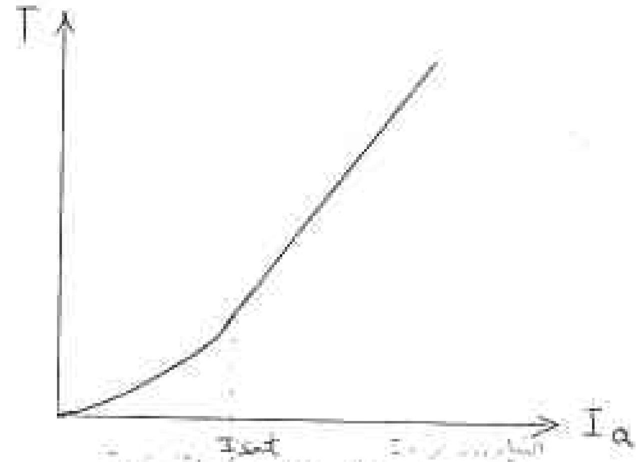


fig (9)

2. N/Ia characteristics:

$$n = \frac{V_t}{K_e \phi} - \frac{R_a}{2\pi K_t^2 \phi^2} T \quad (6)$$

It is clear that speed is inversely proportional with ϕ, so it is inversely proportional with Ia, as well then at no-load n is very high, while at heavy load n decreased gradually as shown in fig (10).

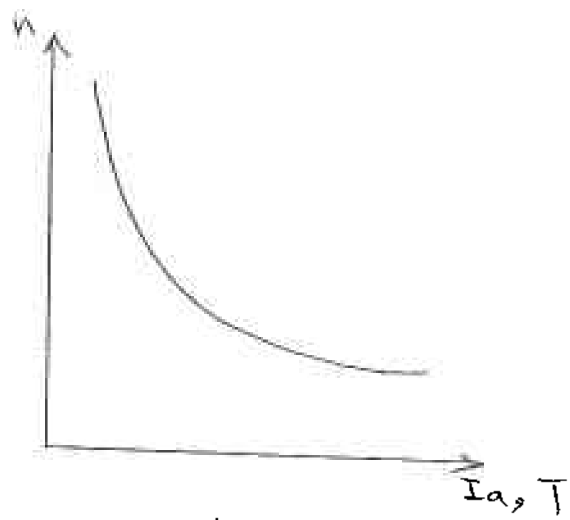


fig (10)

3. N/T characteristics: (mechanical c/c)

Since $T \propto I_a$, so the speed torque c/c will have the same shape as shown in fig (10)

These c/c leads to special usage of this type of d-c motors as in hoists and electric trains.

... dangerously high speed

د. شيرين

Mechanical c/c of loads:

As it shown that there are different (Torque/speed) c/c of motors, there are different (Torque/speed) c/c of loads. So, the load torque is not constant but it is speed dependent. For example, pushing a car needs high starting torque, but when it moves the torque reduced with speed, while on contrary, the load of a fan starts with small torque and the load torque increased with speed, as shown in fig (11). So load (1) needs a high starting torque motors while load (2) needs a low starting torque motors.

Also, some kinds of loads needs a constant speed in spite of a different loading conditions like elevators.

Type of load connection with motor, is also an important factor. such as series motor should not be used when there is a possibility of load decreasing to a very small value.

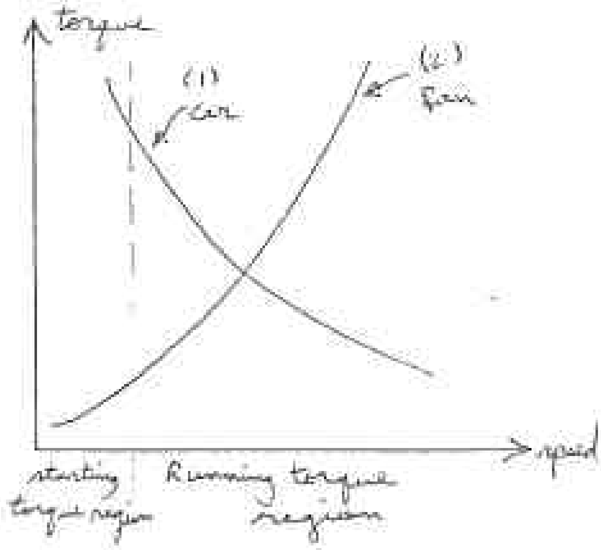


fig (11)

Another loads needs a variable speed with constant torque operation, while another loads require a soft starting torque, and soft breaking operation like elevators, cranes.

The robot needs to move, stop and revers its movement in certain time and with high accuracy.

So, the engineer have to take the load c/c into consideration in order to choose the suitable type of machine and its controller.

د. شيرين

Motor Starting : بدء حركة المحركات

The equivalent circuit of a shunt dc motor is shown in fig (12). At the instant of starting, the rotor in all dc moto is not revolving and thus the voltage generated is Zero. As a result, the terminal voltage is applied across the relatively small armature resistance. Consequently, a very large current flows through the conductors of the armature. Mathematically, the armature's starting current ($I_{a_{st}}$) is:

$$I_{ast} = \frac{V_t}{R_a}$$

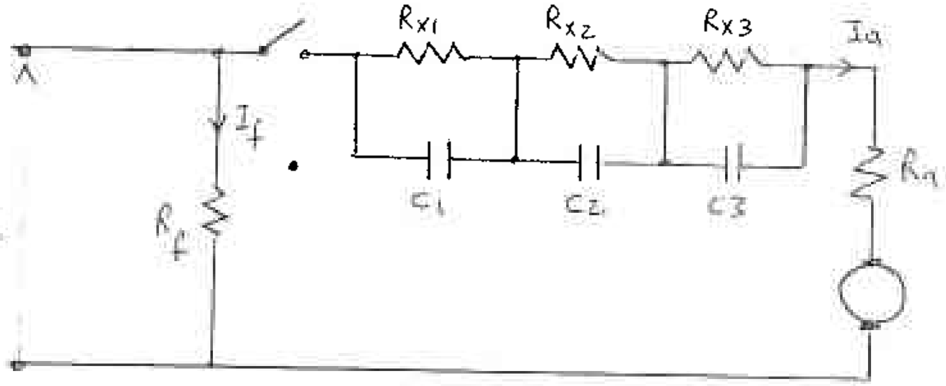


fig (12)
equivalent circuit of starting a dc shunt motor

High starting current it undesirable because it adversely effects the dc power supply, damage the commutator and the brushes.

In order to limit excessively large starting currents, dc shunt motors - like all other types of dc machines - are provide with external resistors that are connected in series with the armature circuit (fig 12). During starting, these resistors are shor in steps, by the contactors (C_1, C_2 & C_3) until the armature curr

reaches its rated value. At the same time, the speed of the motor increases from zero up to its nominal value.

The variations in armature current and speed, as functions of time during the step-by-step reduction in the external resistors for a particular motor, are shown in fig (13, a, b).

At starting, all the contactors are open. Therefore the armature current is limited to:

$$I_{a_{st}} = \frac{V_t}{R_a + R_{x1} + R_{x2} + R_{x3}}$$

When the armature current reaches its rated value, the resistor R_{x1} is shorted through the contactor C_1. At this instant, the speed of the motor cannot change instantaneously. Thus, the armature current must instantaneously increase in order to satisfy KVL. In fig (12) the resistors have been selected in such a way as to limit the armature current to 150% of its rated value.

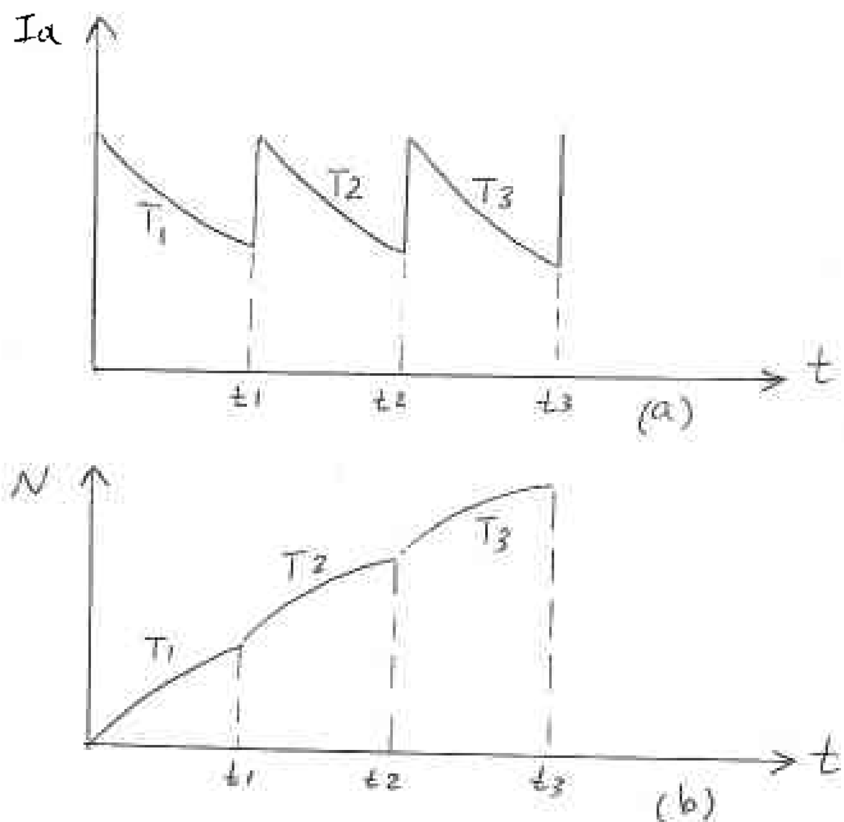


fig (13, a, b)

(a) armature current versus time. (b) speed versus time.

د. شيرين

((Speed Control of D.C Motors))

Factors controlling the speed:

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

$$N = \frac{V - I_a R_a}{Z\phi}\left(\frac{a}{p}\right) = K\,\frac{V - I_a R_a}{\phi} \quad r.p.s$$

It is obvious that the speed can be controlled by varying:

1. flux/pole ϕ (Flux Control)
2. Resistance R_a of armature current (Rheostatic control).
3. Applied voltage V (Voltage Control).

Speed Control of Shunt Motors:

1. Flux Control Method:

It is seen that $N \propto \frac{1}{\phi}$. By decreasing the flux, the speed can be increased and vice versa. The flux of a d.c motor can be changed by changing I_{sh} with the help of a shunt field rheostat (fig (14)). Since I_{sh} is relatively small, shunt field rheostat has to carry only a small current, which means I^2R loss is small, so that rheostat is small in size. This method is therefore very efficient.

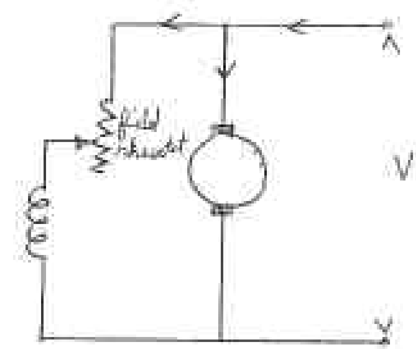


fig (14)

د. شريف

2. Rheostatic Control Method:

As the supply voltage is normally Constant, the voltage across the armature is varied by increasing a variable rheostat or resistance (Called Controller resistance) in series with the armature Circuit as shown in fig (15). As controller resistance is increased, p.d across the armature is decreased, thereby decreasing the armature speed.

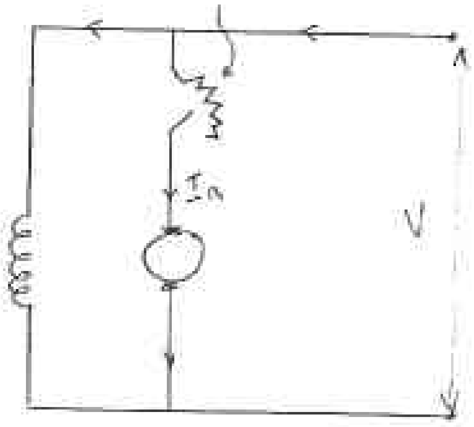


fig (15)

3. Voltage Control Method:

In this method, the shunt field of the motor is Connected permanently to a fixed exciting voltage, but the armature is supplied with different voltages by Connecting it across one of the several different voltages. The armature speed will be approximately proportional to these different voltages. as shown in fig (16)
This method is Called
(Multiple voltage Control)

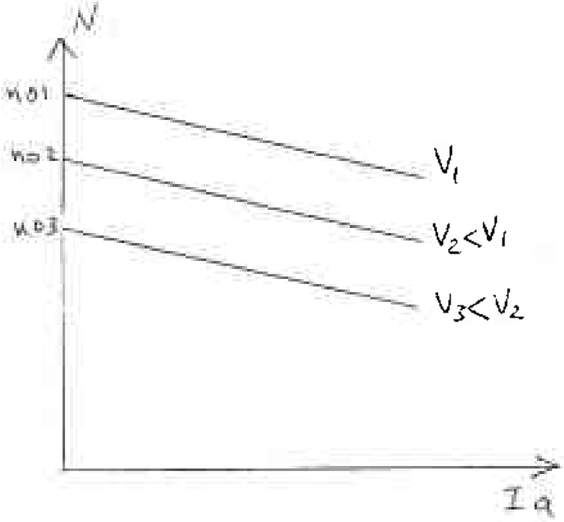


fig (16)

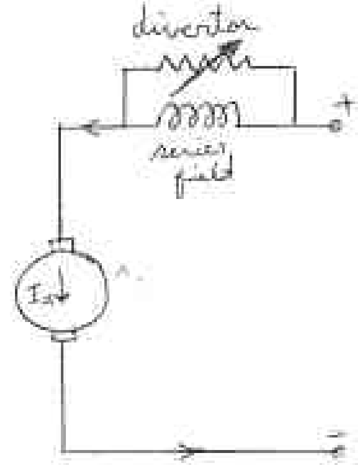
د. شريف

Speed Control of Series Motors:

1. Flux Control Method:

(a) Field Divertors:

The series winding are shunted by a variable resistance known as field divertor fig(17). Any desired amount of current can be passed through the divertor by adjusting its resistance. Hence the flux can be decreased and consequently the speed of the motor increased.



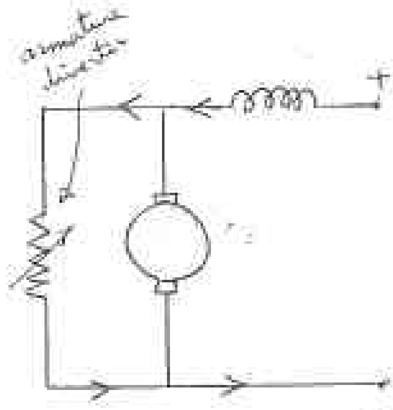
fig(17)

(b) Armature Divertor:

A divertor across the armature can be used for giving speeds lower than the normal speed (fig(18)). For a given constant load-torque, if Ia is reduced due to armature divertor, then ϕ must increase ($\because T \propto \phi I_a$).

This results in an increase in current taken from the supply (which increases the flux) and a fall in speed ($N \propto 1/\phi$).

The variations in speed can be controlled by varying the divertor resistance



fig(18)

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(C) Tapped Field Control:

The number of series field turns in the Circuit Can be changed as shown in fig (19). With full field, the motor runs at its minimum speed which Can be raised in steps by cutting out some of the series turns.

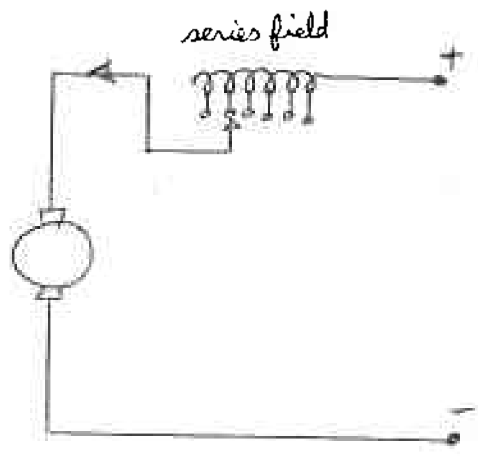


fig (19)

(d) Paralleling Field Coils:

In this method, used for fan motors, several speed Can be obtained by regrouping the field Coils as shown in fig (20).

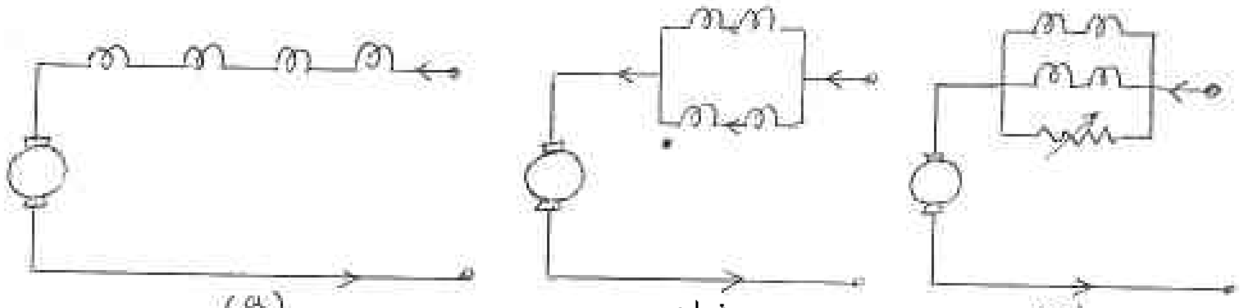
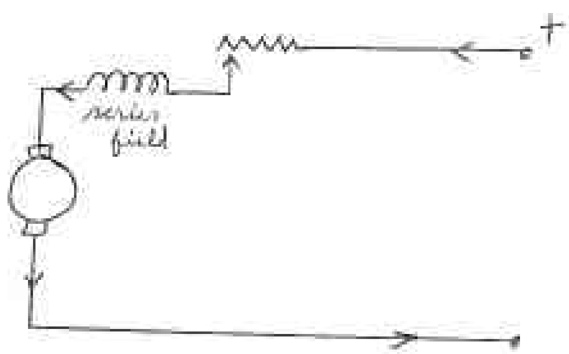


fig (20)

2. Variable Resistance in Series with Motor:

By increasing the resistance in series with armature (fig 2… the voltage applied across the armature terminals Can be decreas… With reduced voltage across the armature, the speed is redu…



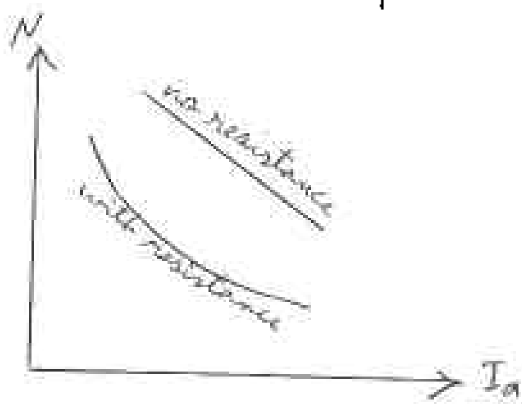


fig (21)