SWAMI VIVEKANANDA SCHOOL OF ENGG. AND TECHNOLOGY

Sub- Energy Conversion - I

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(*). D. C. Motor :-

Operating principle of Motor :- An electric motor is a machine which converts electrical energy into mechanical energy. It is based on the principle that when a current carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's left-hand rule and whose magnitude is given by $F = BIL$ Newton.

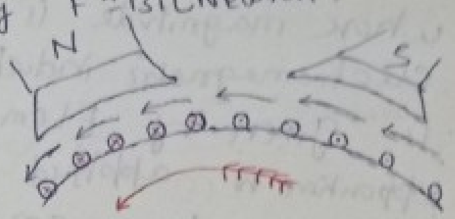

Fig. shows a part of d.c. motor. When field magnets are excited and its armature conductors are supplied with current from the supply mains, then a force is experienced which tends to rotate the armature. Armature conductors under N-poles are assumed to carry current downwards (crosses) and those under S-poles are assumed to carry current upwards (dots). By applying Fleming's left hand rule, the direction of force on each conductor is found. It is shown by small arrows placed above each ~~others~~ conductor. It will be seen that each conductor experiences a force 'F' which tends to rotate the armature in anticlockwise direction. These forces collectively produce a driving torque which set to rotate armature.

As soon as the armature starts to rotate, dynamically induced e.m.f. is produced in the armature conductors. The magnitude (whose) of induced e.m.f. is given by $E_b = (\phi Z N) \times \frac{P}{A}$ volt and the direction of induced e.m.f. is given by Fleming's Right hand rule which is in opposition to applied voltage (V). The applied voltage (V) has to force current through the armature conductors against the back emf. (E_b). The electrical work done in overcoming this opposition is converted into mechanical energy developed in the armature.

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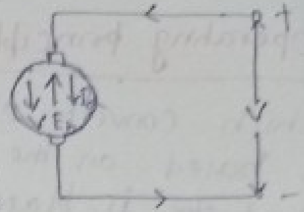
⊛ Significance of the Back e.m.f :-



- when motor armature starts to rotate the conductors also rotate and hence cut the flux. In accordance with the laws of electromagnetic induction, e.m.f. is induced in the armature conductor whose magnitude is given by according to Faraday's law of electromagnetic induction and direction of induced e.m.f is given by Fleming's right-hand rule which is in opposition to applied voltage. Due to its opposition, it is called as back e.m.f. or counter e.m.f.

⊛ Voltage equation of a motor :-

- The voltage applied motor armature has to
  (i) overcome the back-emf. (E_b)
  (ii) supply the armature ohmic drop (I_aR_a)

$$\therefore V = E_b + I_aR_a$$

This is known as voltage equation of a motor.

Multiplying by I_a on both sides,

$$VI_a = E_bI_a + I_a^2R_a$$

or $P_m = VI_a - I_a^2R_a$ is called as gross mechanical power developed by a motor.

Differentiating both sides w.r.t. I_a and equate to zero,

$$\frac{dP_m}{dI_a} = V - 2I_aR_a = 0$$

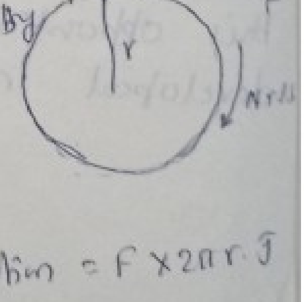
$$V = 2I_aR_a \quad \text{or} \quad I_aR_a = V/2 \quad \therefore E_b = V/2$$

As $V = E_b + I_aR_a$ or $V = E_b + V/2$ $\therefore E_b = V/2$

So the gross mechanical power developed by a motor is maximum when back e.m.f. is equal to half of applied voltage.

⊛ Torque :-

By the term torque is meant a twisting force about an axis. It is measured by the moment of force about and radius at which this force acts. product of force and radius.



Let a pulley of radius 'r' m acted upon by a circumferential force of 'F' N which causes it to rotate at N r.p.m.

Hence torque, $T = F \times r$ N-m.

work done by this force in one revolution $= F \times 2\pi r$ J

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Hence Power developed = $F \times 2\pi r \times N$ J/s or watt

$= (F \times r) \times 2\pi N$ watt.

or Power developed = $T \times \omega$ watt.

$\therefore P = T \times \frac{2\pi N}{60}$ or $P = \frac{2\pi}{60} \cdot NT = \frac{NT}{9.55}$

⊛. Armature torque of a Motor :-

Let T_a = Torque developed by armature of a motor running at N r.p.s.

power developed = $T_a \times 2\pi N$ watt ... (1)

we know that electrical power converted into mechanical power in the armature is $= E_b I_a$ ... (2)

Equating (i) and (ii), $T_a \times 2\pi N = E_b I_a$

Also $E_b = \phi Z N \times (P/A)$ volt.

$\therefore T_a = \frac{1}{2\pi} \phi Z I_a (P/A)$ N-m.

Also $T_a = \frac{E_b I_a}{2\pi N}$ m, N is r.p.s.

$= \frac{E_b I_a}{2\pi N/60}$, N in r.p.m.

$= \frac{60}{2\pi} \frac{E_b I_a}{N}$

$= 9.55 \frac{E_b I_a}{N}$ N-m.

⊛. Shaft-torque (T_{sh}) :-

Torque which is available for doing useful work is called as shaft torque.

So output $= T_{sh} \times 2\pi N$ provided T_{sh} is in N-m & N in r.p.s.

$\therefore T_{sh} = \frac{\text{output}}{2\pi N}$ N-m

$= \frac{60}{2\pi} \frac{O/P}{N}$

$= 9.55 \frac{\text{output}}{N}$ N-m.

⊛. Speed of a d.c. motor :-

we know $E_b = V - I_a R_a$

or $\frac{\phi Z N}{60}\left(\frac{P}{A}\right) = V - I_a R_a$

or $N = \frac{V - I_a R_a}{\phi} \times \left(\frac{60A}{ZP}\right)$ r.p.m.

Now $V - I_a R_a = E_b$

$\therefore N = \frac{E_b}{\phi} \times \left(\frac{60A}{ZP}\right)$ r.p.m. or $N \propto \frac{E_b}{\phi}$

Hence speed is directly proportional to E_b & inversely proportional to flux/pole.

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(*) **Speed Regulation** :- It is defined as the change in speed when load on the motor is reduced from rated value to zero value, expressed as a percentage of rated load speed.

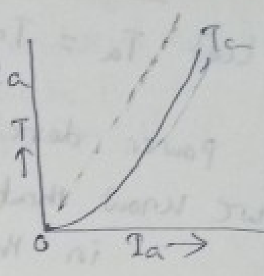
$$\therefore \% \text{speed regulation} = \frac{\text{N.L. speed} - \text{F.L. speed}}{\text{F.L. speed}} \times 100.$$

(*). Characteristics of series motor :-

(1) **T_a / I_a characteristics** :- we know $T_a \propto \phi I_a$

before the point of magnetic saturation, $\phi \propto I_a$

Hence $T \propto I_a^2$

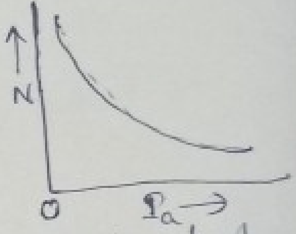


At light loads I_a and hence ϕ is small. so but as I_a increases, T_a increases as square of current. so T_a/I_a curve is a parabola.

After saturation, ϕ is almost independent of I_a. Hence characteristics is a straight line.

Hence $T_a \propto I_a$.

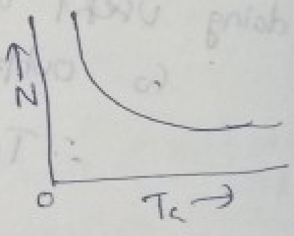
(2) **N/I_a characteristics** :- we know $N \propto \frac{E_b}{\phi}$.



when load is heavy, I_a is large and speed is low.

when load current and hence I_a falls to a small value, speed becomes dangerously high.

Hence, a series motor should never be started without some mechanical load on it. otherwise it develops excessive speed and may be damaged due to heavy centrifugal forces so produced.

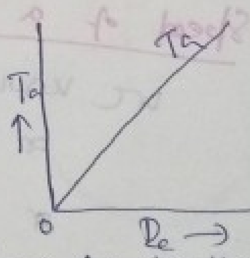


(3) **N/T_a characteristics** :-

when speed is high, torque is low and when speed is low, torque is high.

(*). Characteristics of shunt motors :-

1.1. **T_a/I_a characteristic** :-



Assuming ϕ to be constant, (practically)

$T_a \propto I_a$.

so the characteristics is a straight line practically.

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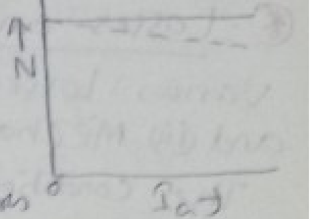
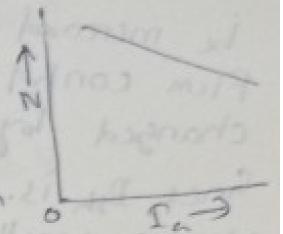
2. N/Ia Characteristics :-



If ϕ is assumed constant,
$N \propto E_b$ ~~As E_b is~~

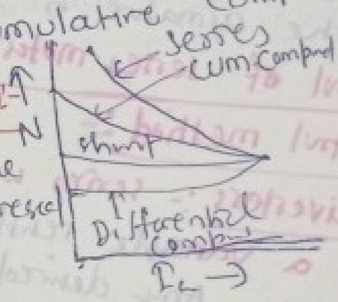
As E_b is also practically constant, speed is for most practical purposes is constant.
But strictly speaking, both E_b and ϕ decrease with increasing load. However E_b decreases more slightly than ϕ so that on the whole, there is a some decrease in speed. The drop varies from 5 to 15% of full load speed, being dependent upon saturation, armature reaction and brush position. Hence, actual speed curve is slightly drooping as shown by the dotted line. But for practical purposes, shunt motor is taken as a constant-speed motor.

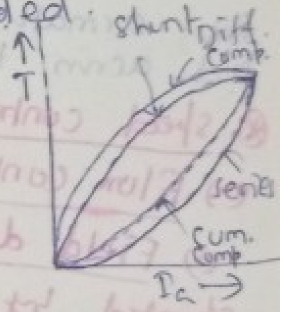


3. N/Ta Characteristic :-
when speed is high, torque and hence Ia is low.
when speed is low, torque and hence Ia is high.

(*) Compound motors :- These motors have both series and shunt windings and have cumulative compound motors and differentially compound motors.

(a) Cumulative - compound motors :- If series field helps the shunt excitation, i.e. series flux is in the same direction, then the motor is said to be cumulative compounded.





(b) Differential - compound Motors :- Since series field opposes the shunt field, the flux is decreased and motor is said to be differentially compound.

(*) Application :- ~~Series motors :- Electric locomotives, Troll~~

Series motor	Shunt motor	Compound motor
Electric locomotives, Trolley cars, cranes, hoist	Lathes, centrifugal pumps, machine tools, blowers, fans	Elevators, conveyors, Rolling mills, Printing Press, ice machines

(*) Losses and Efficiency :-

Various losses are (i) copper losses (ii) magnetic losses and (iii) Mechanical losses.

The condition for maximum power developed by motor is

$$I_a R_a = V/2 = E_b$$

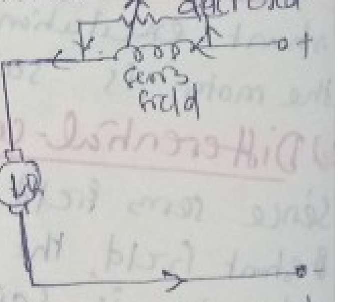
Maximum efficiency occurs when constant loss is equal to armature copper loss.

(*) Speed control of Shunt motors :-

(a) Flux control Method :- we know that $N = \frac{V - I_a R_a}{\phi} \left(\frac{A}{PZ}\right)$ $= K \cdot \frac{V - I_a R_a}{\phi}$ r.p.s.

Hence $N \propto \frac{1}{\phi}$. By decreasing flux, speed can be increased and vice versa. So the name is called as Flux control method. The flux of a d.c. motor can be changed by changing I_{sh} with the help of shunt field rheostat. Since I_{sh} is relatively small, shunt field rheostat has to carry only a small current, which means I^2R loss is small. This method is used when speed above rated speed is used.

(b). Armature or Rheostatic Control Method :- This method is used when speed below the no-load speed is required. As the supply voltage is normally constant, the voltage across armature is varied by inserting a variable resistance (called controlled resistance) in series with the armature ckt. As controlled resistance is increased, the p.d. across the armature is decreased, & hence armature speed decreased.

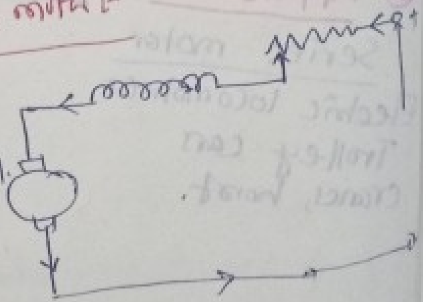


(*). Speed control of series motors :-

(a) Flux control method :-

(a) Field diverters :- series winding are shunted by a variable resistance known as field diverter. Any desired amount of current can be passed through the diverter by adjusting its resistance. Hence flux can be decreased and speed can be increased.

(b) Variable resistance in series with motor :- By increasing resistance in series with motor armature, voltage applied across the armature terminals can be decreased. With reduced voltage across armature, speed is reduced.



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(*) A d.c. motor takes an armature current of 110A at 480V. Armature resistance is 0.2Ω. The m/c has 6 poles and armature is lap-connected with 864 conductors. Flux per pole is 0.05wb. Find (i) speed (ii). gross torque developed by armature.

Ans:- $E_b = 480 - 110 \times 0.2 = 458V$, $\phi = .05wb$ $Z = 864$.

Now $E_b = \frac{\phi Z N}{60}\left(\frac{P}{A}\right)$ or $\frac{0.05 \times 864 \times N}{60} \times \left(\frac{6}{6}\right) = 458$

$\therefore N = 636 r.p.m$

& $T_a = 0.159 \times 0.05 \times 864 \times 110 \left(\frac{6}{6}\right) = 756.3 Nm.$

(*). A 25kW, 250V d.c. shunt generator has armature and field resistance of 0.06Ω and 100Ω. Find the total armature power developed when working as (i) a generator delivering 25kW output and (ii) as a motor taking 25kW I/P.

Ans. As generator, output current $= \frac{25000}{250} = 100A$

$I_{sh} = \frac{250}{100} = 2.5A.$

$\therefore I_a = 100 + 2.5 = 102.5A.$

Generated e.m.f. $= 250 + 102.5 \times 0.06 = 256.16 V.$

Power developed in armature $= E_b I_a$

$= \frac{256.16 \times 102.5}{1000} = 26.25kW.$

As motor :- Motor input current $= 100A$, $I_{sh} = 2.5A$

$\therefore I_a = 97.5A.$

$E_b = 250 - (97.5 \times 0.06) = 244.15V$

Power developed in armature $= E_b I_a$

$= \frac{244.15 \times 97.5}{1000} = 23.8kW.$

(*).

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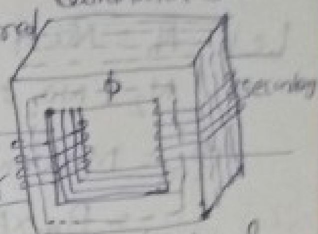
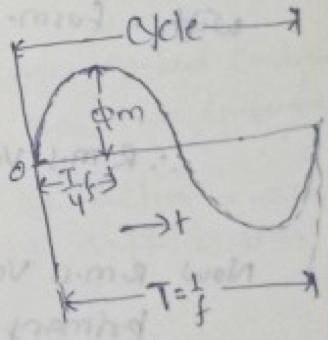
Transformer:-

Operating priciple:-

It is a static or stationary piece of apparatus by means of which electric power in one circuit is transferred into electric power of the same frequency in another circuit. It can raise or lower voltage in a circuit but with a corresponding decrease or increase in current.



The physical basic of transformer is based on mutual induction between two circuits linked by a common magnetic flux(ϕ). In other word, it consists of two inductive coils which are electrical separated but magnetically linked through a path of low reluctance. The two coils possess high mutual inductance. If one coil is connected to a source of alternative voltage, an alternative flux is set up in the laminated core, most of which is linked with other coil in which it produces mutually induced e.m.f. according to Faraday's law of electromagnetic induction $= M\frac{dI}{dt}$ If the second coil cut is closed, a current flows in it so electrical energy is tranferred (entirally magnetically) from first coil to second coil. The first coil in which electrical energy is fed from a.c. supply main is called as primary winding and the other from which electrical energy is drawn out is called as secondary winding.



Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

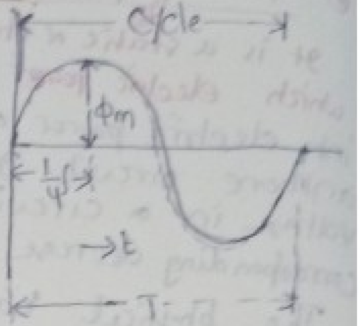
ϕ_m = Maximum flux in core in wbs.

$= B_m \times A$

f = Frequency of a.c. input in Hz.

As shown in figure, flux increases from zero

E.M.F. Equation of a transformer:-



Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

ϕ_m = Maximum flux in core in webers

$= B_m \times A$

f = Frequency of a.c input in HZ.

As shown in figure, flux increases from zero value to maximum value (ϕ_m) in one quarter of the cycle i.e. in $\frac{1}{4f}$ sec.

∴ ~~Average rate~~ of change of flux =

∴ Average rate of change of flux $= \frac{\phi_m}{\frac{1}{4f}}$

$= 4f\phi_m$ wb/sec

Now rate of change of flux per turn means induced e.m.f in volts.

∴ Average e.m.f./turn $= 4f\phi_m$ volt

If flux varies sinusoidally, then r.m.s. value of induced e.m.f. is obtained by multiplying the average value with form-factor.

∴ Form factor $= \frac{\text{r.m.s. value}}{\text{Average value}} = 1.11$

∴ R.m.s. value of induced e.m.f./turn $= 1.11 \times 4f\phi_m$

$= 4.44 f\phi_m$ volt.

Now R.m.s. value of induced e.m.f. in the whole of primary winding = (induced e.m.f./turn) × No. of primary turns

or $E_1 = 4.44 f\phi_m N_1 = 4.44 f N_1 \phi_m$ --- (1)

Similarly r.m.s. value of induced e.m.f. in the secondary

$E_2 = 4.44 f\phi_m N_2$ --- (2)

Dividing eqn.(2) by eqn.(1), $\frac{E_2}{E_1} = \frac{4.44 f\phi_m N_2}{4.44 f\phi_m N_1} = \frac{N_2}{N_1}$

Hence, e.m.f./turn is same in both primary and secondary windings.

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Voltage transformation ratio(K):-

Now $E_1 = 4.44 f \phi_m N_1$ ...(1)

and $E_2 = 4.44 f \phi_m N_2$ ...(2)

Dividing eqn(2) by eqn(1),

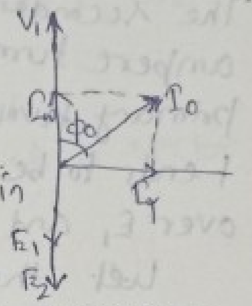
$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K (say).$$

The constant K is called as voltage transformation ratio. The transformer is called as

(i) If $N_2 > N_1$, i.e. $K > 1$, then transformer is called as step-up transformer.

(ii) If $N_2 < N_1$, i.e. $K < 1$, then transformer is called as step-down transformer.

Transformer on No-load:-



When transformer is on no-load, the primary input current has to supply (i) iron-loss in the core i.e. hysteresis loss and eddy-current loss and (ii) a very small amount of copper loss in primary and there being no copper loss in the secondary as it is open. Hence the no-load primary input current (I_0) is not at 90° behind V_1 but lags it by an angle $\phi_0 < 90°$.

No-load input power, $W_0 = V_1 I_0 \cos\phi_0$

where $\cos\phi_0$ is the primary p.f. under no-load condition

As seen in the figure, primary current I_0 has two components

(i) one in phase with V_1. This is known as active or working or iron-loss component I_w because it mainly supplies iron loss plus small quantity of primary cu loss.

so $I_w = I_0 \cos\phi_0$

(ii) The other component is in quadrature with V_1 and is known as magnetising component (I_ϕ) because its function is to sustain alternate flux in the core.

so $I_\phi = I_0 \sin\phi_0$.

Hence $I_0 = \sqrt{I_\phi^2 + I_w^2}$

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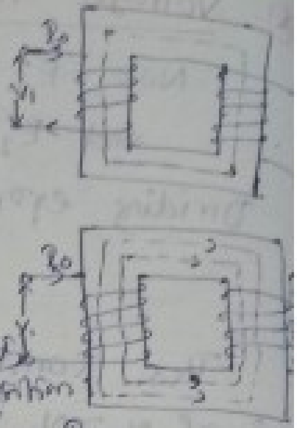
10. Transformer on Load:-



When the secondary is loaded, the secondary current I_2 is set up. The magnitude and phase of I_2 w.r.t. V_2 is determined by the characteristics of load. Current I_2 is in phase with V_2 if load is non-inductive, it lags if load is inductive and it leads if load is capacitive.

The secondary current sets up its own m.m.f ($= N_2 I_2$) and hence its own flux ϕ_2 which is in opposition to the main primary flux ϕ_0 which is due to I_0. The secondary ampere turn ($N_2 I_2$) is known as demagnetising ampere turns. The opposing secondary flux (ϕ_2) weaks the primary flux (ϕ) momentarily and hence primary back e.m.f (E_1) tends to be reduced. For a moment V_1 gains the upper hand over E_1 and hence causes more current to flow in primary.

Let the additional primary current be I_2'. It is known as load component of primary current. This current is in antiphase with I_2'. The additional primary m.m.f. $N_1 I_2'$ sets up its own flux ϕ_2' which is in opposition to ϕ_2 (but in the same direction as ϕ) and is equal to it in magnitude. Hence the two cancel each other out.

Hence, whatever the load condition, the net flux passing through the core, is approximately the same as at no-load. So due to constancy of core flux at all loads, the core loss is practically same under all load conditions.

$$\text{As } \phi_2 = \phi_2' \quad \therefore N_2 I_2 = N_1 I_2'$$

$$\therefore I_2' = \frac{N_2}{N_1} I_2 = K I_2$$

Hence, when transformer is on load, the primary winding has two currents in it, one is I_0 and other is I_2' which is antiphase with I_2 and K times its magnitude. So the total primary current is the vector sum of I_0 and I_2'.

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(7). Transformer with winding resistance but no magnetic leakage:-

In an actual transformer there is always present some resistance of the primary and secondary windings. Due to this resistance, there is always some voltage drop in the two windings. The result is that

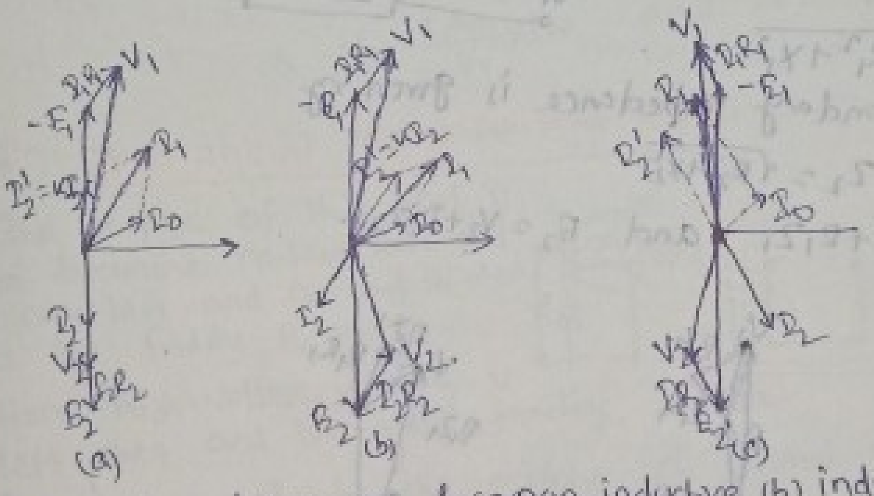
~~i) The secondary voltage drop terminal~~

(i) The secondary terminal voltage(V_2) is vectorially less than the secondary induced e.m.f(E_2) by an amount I_2R_2 where R_2 is the resistance of the secondary winding. Hence V_2 is ~~vectorially~~ equal to vector difference of E_2 and resistive voltage drop I_2R_2

$$\therefore V_2 = E_2 - I_2R_2$$

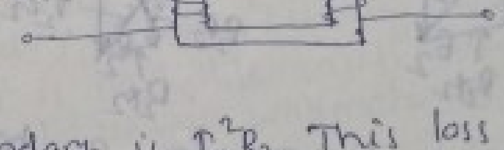
(ii) Similarly primary induced e.m.f. (E_1) is equal to vector difference of V_1 and I_1R_1

$$\therefore E_1 = V_1 - I_1R_1.$$



(a) Vector diagrams for (a) non-inductive, (b) inductive & (c) capacitive loads is shown in figure.

(8) Equivalent Resistance :-



As shown in figure, Resistances of primary and secondary having R_1 and R_2 respectively.

The copper loss in the secondary is $I_2^2R_2$. This loss is supplied by primary which takes a current of I_1. Hence if R_2' is the equivalent resistance in the primary

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Similarly leakage reactances can be transformed from one winding to other as

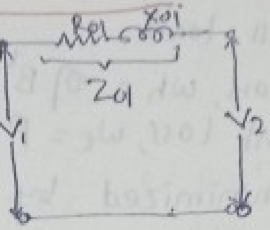
$$X_2' = X_2/K^2 \quad \text{and} \quad X_1' = K^2 X_1$$

$$\text{and } X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

$$\text{and } X_{02} = X_2 + X_1' = X_2 + K^2 X_1$$

⊛. Regulation of a transformer:-

The change in secondary terminal voltage from no-load to full-load, keeping primary voltage as constant & is divided by full-load secondary voltage is called as regulation.



$$\therefore \% \text{ regulation} = \frac{{}_0V_2 - V_2}{V_2} \times 100$$

$$= v_r \cos\phi \pm v_x \sin\phi \text{ approximately.}$$

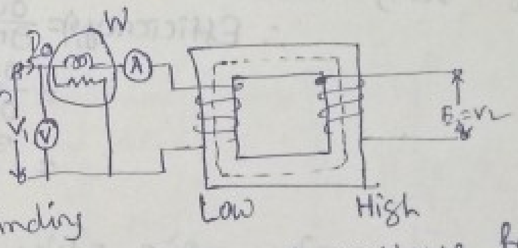
where +ve sign for lagging p.f. and −ve sign for leading p.f.

$$\& \quad v_r = \frac{I_1 R_{01}}{V_1} \times 100 \quad \text{and} \quad v_x = \frac{I_1 X_{01}}{V_1} \times 100.$$

⊛ Open-circuit test or No-load test:-

The purpose of this test is to determine no-load loss and or core loss and no-load I_0 which is for finding R_0 and X_0.

Here high voltage winding is left open and low voltage winding is connected to the supply of normal voltage, frequency. A wattmeter, voltmeter and an ammeter are connected in the low voltage (primary winding).



With normal voltage applied to primary, normal flux will be set up in the core and hence normal iron loss will occur which are recorded by the wattmeter. As primary no-load current I_0 (as measured by ammeter) is small (usually 2 to 10% of rated load current), cu loss is negligible small in primary and nil in secondary (as it open). Hence wattmeter reading represents practically core loss under no-load conditions.

$W = V_1 I_0 \cos\phi_0$ where W = wattmeter reading.

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(*). Losses in a transformer :-

Transformer being static, there being no friction or windage losses. Hence only losses occuring are

(a) Core loss or iron loss :- It includes both hysteresis loss and eddy-current loss. Due to core flux in a transformer remains constant, for all loads (its variation being 1 to 3% from no-load to full load), the core loss is practically the same at all loads.

Hysteresis loss, $W_h = \eta B^{1.6} f V$ watt

Eddy-current loss, $W_e = P B_{max}^2 f^2 t^2$ watt

These losses are minimized by using steel of high silicon content for the core and by using very thin laminations.

(b) Copper loss :- This loss is due to ohmic resistance of the transformer windings. Total Cu loss $= I_1^2 R_1 + I_2^2 R_2 = \ldots$

$= I_1^2 R_{01} + I_2^2 R_{02}$

Hence cu loss is proportional to $(\text{current})^2$ or KVA^2.

(*). Efficiency of a transformer and condition for max. efficiency

Efficiency of a transformer at a particular load and power factor is defined as the output divided by the input, the two being measured in the same units.

$$\therefore \text{Efficiency}, \eta = \frac{\text{output}}{\text{input}}$$

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

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

Now cu loss $= I_1^2 R_{01}$ or $I_2^2 R_{02} = W_{cu}$

Iron loss $=$ Hysteresis loss $+$ Eddy current loss

Considering primary side,

Primary input $= V_1 I_1 \cos\phi_1$

$$\therefore \eta = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$

$$= 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

Differentiating both sides with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} + \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

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For η to be maximum, $\frac{d\eta}{dI_1} = 0$

Hence, the above equation becomes as

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

or, $W_i = I_1^2 R_{01} = I_2^2 R_{02}$

or, Iron loss = cu loss.

The output current corresponding to maximum efficiency,

$$I_2 = \sqrt{\frac{W_i}{R_{02}}}$$

⊛. All-day efficiency:-

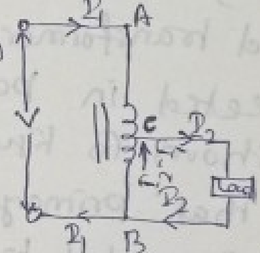
It is defined on the basic of energy consumed during a certain time period, usually a day of 24 hours.

$$\eta_{all\text{-}day} = \frac{\text{output in kwh}}{\text{Input in kwh}} \text{ (for 24 hours)}$$

This efficiency is always less than the commercial efficiency of a transformer.

⊛. Auto-transformer :-

It is a transformer with one winding, part of being common to both primary and secondary. So in this transformer, the primary and secondary are not electrically isolated from each other as in the case with a 2-winding transformer.



As shown in figure, AB is the primary winding having N_1 turns and BC is the secondary winding having N_2 turn.

Neglecting iron losses and no-load current,

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$$

The current in the section CB is the vector difference of I_2 & I_1.

The auto transformer has higher efficiency but smaller size.

Saving of cu :- volume and hence weight of cu is proportional to length and area of x-section of conductors. Now length of conductors is proportional to no. of turns and cross-section depends on current. Hence weight is proportional to the product of current and no. of turns.

so wt. of cu in section $AC \propto (N_2 - N_1) I_1$

wt. of cu in section $BC \propto N_2 (I_2 - I_1)$

$\therefore$ Total wt. of Cu in auto-transformer $\propto (N_1 - N_2)I_1 + N_2(I_2 - I_1)$

Now wt. of Cu in the primary $\propto N_1 I_1$

and wt. of Cu in the secondary $\propto N_2 I_2$

$\therefore$ Total wt. of Cu $\propto N_1 I_1 + N_2 I_2$

$$\therefore \frac{\text{wt. of Cu in autotransformer}}{\text{wt. of Cu in ordinary two-winding transformer}} = \frac{(N_1 - N_2)I_1 + N_2(I_2 - I_1)}{N_1 I_1 + N_2 I_2}$$

$$= 1 - \frac{2\frac{N_2}{N_1}}{1 + \frac{N_2}{N_1} \times \frac{I_2}{I_1}} = 1 - \frac{2K}{2} = 1 - K \quad \left(\because \frac{N_2}{N_1} = K\right)$$

$\therefore$ wt. of Cu in autotransformer $(W_{Cu}) = 1 - K$ (wt. of Cu in ordinary transformer W_0)

$\therefore$ saving $= W_0 - W_{Cu}$

$= W_0 - W_0(1 - K)$

$= K \times$ (wt. of Cu in ordinary transformer)

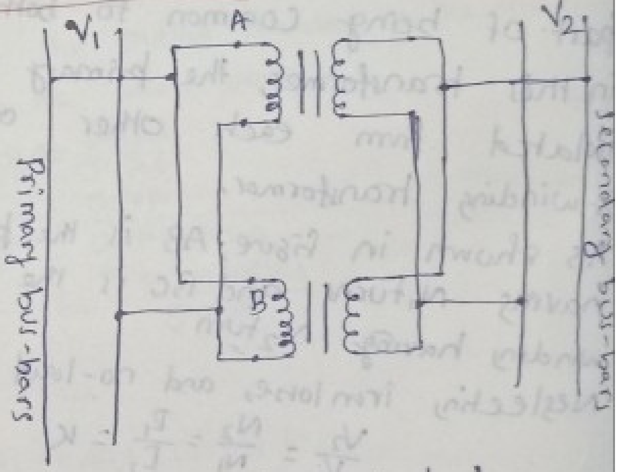
<u>Uses</u> :- (1) to give small boost to a distribution cable to correct voltage drop.

(2). an auto-transformer starter to give 50 to 60% of full voltage to an induction motor during starting.

(3). as an interconnecting transformers in 132/330kV system.

Parallel operation of transformer:

For supplying a load in excess of rating of an existing transformer, a second transformer may be connected in parallel as shown in figure. It is seen that primary windings are connected to supply bus-bars and secondary windings are connected to load bus-bars.



<u>Conditions</u>. 1. Primary windings of transformers should be suitable for supply system voltage and frequency.

2. The transformers should be properly connected with regards to polarity.

3. The voltage ratings of both primaries and secondaries should be identical. In other words, the transformers should have the same turn-ratio i.e. transformation ratio

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4. The percentage impedances should be equal in magnitude and have the same X/R ratio in order to avoid circulating currents and operating at different power factors.

5. With transformers having different KVA rating the equivalent impedances should be inversely proportional to individual KVA rating if the circulating currents are to be avoided.

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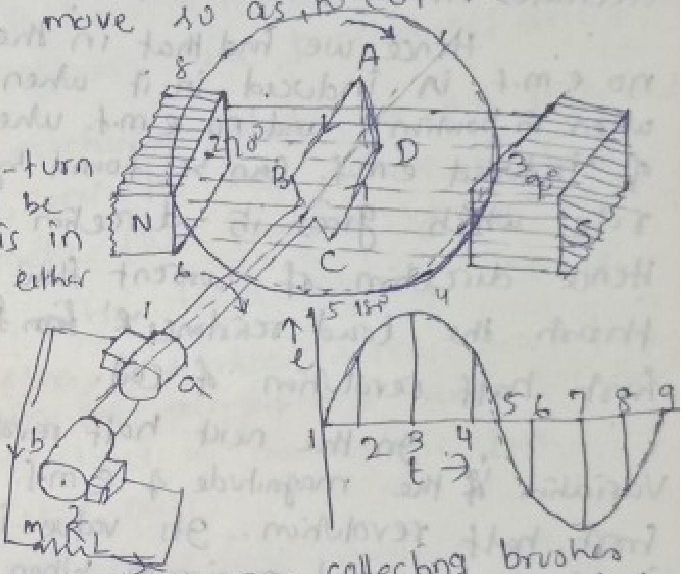
D.C. Generator :-

Operating Principle :- An electric generator (d.c.) is a machine which converts mechanical energy to electrical energy.

It is based on the principle of production of dynamically or motionally induced e.m.f. i.e. whenever a conductor cuts magnetic flux, dynamically induced e.m.f. is produced in it according to Faraday's law of electromagnetic induction. This e.m.f. causes a current to flow if the conductor cut is closed.

Hence, the two basic essential parts of an electric generators are (i) a magnetic field and (ii) a conductor or conductors which can move so as to cut the flux.

Construction & working :-



As shown in figure, a single-turn rectangular copper coil ABCD be rotating about its own axis in a magnetic field provided either by permanent magnet or electromagnets. Two ends of coils are joined to two slip rings 'a' and 'b' which are insulated from each other and from central shaft. Two collecting brushes (carbon or copper) press against slip rings. Their function is to collect induced in the coil and to convey it to the external load resistance 'R'.

Let the coil to be rotating in the clockwise direction. As the coil assumes successive positions in the field, flux linked with it changes. Hence, an e.m.f. is induced in it which is proportional to the rate of change of flux linkages ($e = N\frac{d\phi}{dt}$). When the plane of coil is at right angles to the lines of flux i.e. when it is in position 1, the flux linked with the coil is maximum but rate of change of flux of flux linkages is minimum.

It is so called because in this position the coil sides AB and CD do not cut or shear the flux, rather they slide along them, i.e. they move parallel to them. Hence there is no induced e.m.f in the coil. Let this no e.m.f. or vertical position of coil as the starting position. The angle of rotation or time will be measured from this position. As the coil assumes continues rotating further, rate of change of flux linkages increases till position 3 is reached where θ = 90°. Here the coil plane is horizontal i.e. parallel to the lines of flux. Here flux linked with the coil is minimum but rate of change of flux linkages is maximum. Hence maximum e.m.f. is induced in the coil when in this position.

In the next quarter revolution i.e. from 90° to 180°, the flux linked with the coil gradually increases but rate of change of flux linkages decreases. Hence the induced e.m.f. gradually decreases till in position 5 of the coil, it is reduced to zero value.

Hence, we find that in the first half revolution of coil no e.m.f. is induced in it when it is in position 1, maximum when in position 3 and no e.m.f. when in position 5. The direction of induced e.m.f. can be found by applying Fleming's right hand rule which gives its direction from A to B and C to D. Hence direction of current flow is ABMLCD. The current through the load resistance 'R' flows from M to L during first half revolution of coil.

In the next half revolution i.e. from 180° to 360°, the variation of the magnitude of e.m.f. are similar to those in the first half revolution. Its value is maximum when coil is in position 7 and minimum when in position 1. But the direction of induced current is from D to C and B to A. Hence the path of current flow is along DCLMBA which is just reverse of the previous direction of current flow. Such a current undergoing ~~per previous direction of~~ periodic reversals is known as alternating current.

For making flow of current unidirectional in the external circuit, the slip rings are replaced by split rings. The split rings are made out of a conducting cylinder which is cut into two halves or segments insulated from each other by a thin sheet of mica.

It is seen that in the first half revolution, current flows along ABMLCD i.e. brush no. 1 comes in segment 'a' acts as a positive end of supply and 'b' as the negative end. In the next half revolution, the direction of induced current

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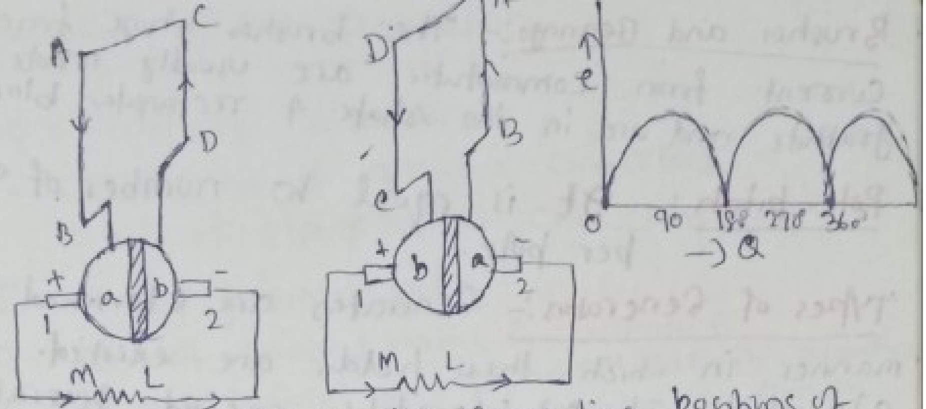

in the coil is reversed. But at the same time positions of segments 'a' and 'b' has also reversed with the result that brush no. 1 comes in touch with the segment which is positive i.e. segment 'b' in this case. Hence current in the load resistance is at again from M to L. The waveform of the load current through the external ckt is shown in figure. The current is unidirectional but not continuous like pure direct current.

⊛ Yoke :- (i) It provides mechanical support for the poles and as acts as a protecting cover for the whole machine.
(ii). It carries the magnetic flux produced by the pole.

Pole cores and Pole Shoes :- The field magnets consists of pole cores and pole shoes. Pole shoes serves two purposes.
(i) they spread out flux in the air-gap and being of larger cross-section reduces the reluctance of the magnetic path.
(ii) They support the excited coils.

Pole coils :- The field coils or pole coils which consists of copper wires or strip are former wound. then former is removed. when current is passed, they electromagnetic & hence produce necessary flux.

Armature core :- It houses the armature conductors & causes them to rotate & hence cut the magnetic flux of field magnet. It provides a path of very low reluctance to the flux through the armature from N-pole to a S-pole.

Commutator :- The function of commutator is to facilitate the collection of current from the armature conductors. It rectifies i.e. converts alternating current induced in the armature conductors into unidirectional current in the external circuit. It is cylindrical structure and is built up wedge-shaped segment of high conductivity hard-drawn copper. These segments are insulated from each other by thin sheet of mica.

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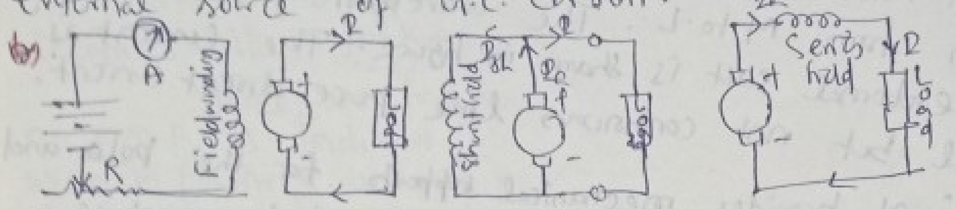
Brushes and Bearings:- The brushes whose function is collect current from commutator are usually made of carbon or graphite and are in the shape of rectangular block.

Pole-pitch:- It is equal to number of armature conductors per pole.

Types of Generators:- Generators are classified according to the manner in which their fields are excited. Generators are classified into (a) separately excited generators and (b) self excited generators.

(a) Separately excited Generators:- These generators are those whose field magnets are energised from an independent external source of d.c. current.



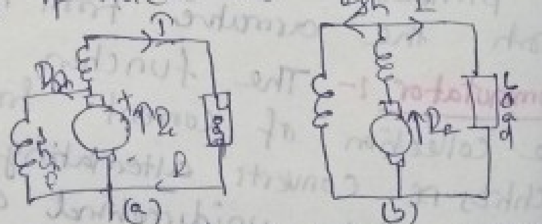
(b) Self-excited generators:- Self excited generators are those whose field magnets are energised by current produced by generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated some e.m.f. and hence some current is induced which is partly or fully passed through the field coils and hence strengthens the residual pole flux.

There are three types of self-excited generators according to the manner in which field coils are connected to the armature.

Shunt wound:- The field windings are connected across or in parallel with armature conductors and have full voltage of generator applied across them.

Series wound:- Here field windings are joined in series with armature conductors. As they carry full load current they consist of few turns of thick wire.

Compound wound:- It is a combination of a few series and few shunt windings and can be either short shunt or long shunt as in fig (a) & fig (b).



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(8). E.M.F Equation of a generator:-

Let ϕ = Flux/pole in weber.

Z = Total no. of armature conductors.

= No. of slots × No. of conductors/slots

P = No. of generator poles.

A = No. of parallel paths in armature.

E = E.m.f. induced in any parallel path in armature.

N = Armature rotation in revolution per minute.

Generated e.m.f. E_g = E.M.F. generated in any one of the parallel path, i.e. E

Average e.m.f. generated/conductor $= \frac{d\phi}{dt}$ ($\because n=1$)

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

No. of revolution/second $= \frac{N}{60}$

$\therefore$ Time for one revolution, $dt = \frac{60}{N}$ second

Hence, according to Faraday's law of Electromagnetic induction,

E.M.F. generated/conductor $= \frac{d\phi}{dt}$

$= \frac{\phi P}{60/N} = \frac{\phi PN}{60}$ volt.

For a simplex wave-wound generator:-

No. of parallel paths = 2

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

$\therefore$ E.M.F. generated/path $= \frac{\phi PN}{60} \times \frac{Z}{2}$

$= \frac{\phi PNZ}{120}$ volt.

For a simplex lap-wound generator:-

No. of parallel paths = P

No. of conductors in one path = Z/P

$\therefore$ E.M.F. generated (i.e.) one path $= \frac{\phi PN}{60} \times \frac{Z}{P} = \frac{\phi ZN}{60}$ volt.

In general, E.m.f. generated, $E_g = \frac{\phi ZN}{60}\left(\frac{P}{A}\right)$ volt.

where A = 2 - for simplex wave-wound

A = P - for simplex lap wound

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(*) Losses in armature:- (Iron loss):-

Due to rotation of iron core of armature in the magnetic flux of field poles, there are some losses taking place in core continuously and is known as iron loss or core loss. Iron loss consists of

(i) Hysteresis loss (W_h) & (ii). Eddy current loss (W_e) :-

Hysteresis loss (W_h) :- This loss is due to the reversal of magnetisation of the armature core. Every portion of rotating core passes under N and S pole alternately and hence attain S & N polarity respectively. The core undergoes one complete cycle of magnetic reversal after passing under one pair of poles

If f = frequency of magnetic reversal
N = Armature speed in r.p.m.
P = No. of poles

then $f = \frac{PN}{120}$ Hz

This loss depends upon volume, and grade of iron, maximum value of flux density, B_{max} and frequency of magnetic reversal. For a normal flux density (i.e. upto 1.5 wb/m²),

$$W_h = \eta B_{max}^{1.6} f V \text{ watt}$$

where V = volume of core in m^3
η = steinmetz hysteresis coefficient

Eddy current loss (W_e) :- when armature core rotates, it cuts the magnetic flux. Hence an e.m.f. is induced in the body of core according to Faraday's law of electromagnetic induction. This e.m.f. though small, sets up large current in the body of core due to its small resistance. This current is known as eddy-current. The power loss due to flow of eddy-current is known as eddy-current loss. This loss is considerable if solid iron core were used. In order to reduce this loss and consequently heating of core to a small value, the core is build up of thin lamination which are stacked and the core is build up thin lamination. The path of eddy currents then riveted at right angles to the path. These core laminations are insulated from each other by thin coating of varnish.

Eddy-current loss is given by $W_e = K B_{max}^2 f^2 t^2 V^2$ watt

B_{max} = Max. flux density
f = frequency of magnetic reversal
t = thickness of each lamination
V = volume of armature core.

For reducing hysteresis loss, the metals are choosen for armature core which are low hysteresis coefficient. such as silicon steels.

* Total loss in D.C. Generator:-

various losses in a generator are

(a) Copper losses such as (i) Armature copper loss = $I_a^2 R_a$

(ii) Field copper loss. In case of shunt generators, it is practically constant. In case of series generator, it is $I_{se}^2 R_{se}$

(iii). This loss is due to brush contact resistance. It is usually included in the armature copper loss.

(b) Magnetic losses such as hysteresis loss and eddy-current loss.

(c) Mechanical losses. It consists of (i) Friction loss at bearings and commutator.

(ii) Air-friction or windage loss of rotating armature.

* . **Stray losses**:- usually magnetic and mechanical losses are collectively known as stray losses.

* . **Constant or Standing losses**:-

Field cu loss is constant for shunt and compound generators. Hence stray losses and shunt cu loss are constant in their case. These losses are together called as standing or constant loss W_C.

Hence total loss = Armature copper loss + W_C = $(I+I_{sh})^2 R_a + W_C$

* Condition for Maximum efficiency:-

Generator output = VI

Generator input = output + losses

$= VI + I_a^2 R_a + W_C$ $\quad (\because I_a = I + I_{sh})$

$= VI + (I+I_{sh})^2 R_a + W_C$

If I_{sh} is negligible as compared to load current, then $I_a = I$ (approx)

$\therefore \eta = \frac{\text{output}}{\text{Input}} = \frac{VI}{VI + I_a^2 R_a + W_C} = \frac{VI}{VI + I_a^2 R_a + W_C}$

$= \frac{1}{1 + \left(\frac{I_a R_a}{V} + \frac{W_C}{VI}\right)}$

Now efficiency is maximum when denominator is minimum

Hence $\frac{d}{dI}\left(\frac{I R_a}{V} + \frac{W_C}{VI}\right) = 0$ or $\frac{R_a}{V} - \frac{W_C}{VI^2} = 0$ or $I^2 R_a = W_C$.

So Generator efficiency is maximum when

variable loss = Constant loss.

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1. Mechanical Efficiency, $\eta_m = \frac{\text{Total watt generated in armature}}{\text{Mechanical power supplied}}$

2. Electrical Efficiency, $\eta_e = \frac{\text{watt available in load circuit}}{\text{Total watt generated}}$

3. overall efficiency, $\eta_c = \frac{\text{watt available in load circuit}}{\text{Mechanical power supplied}}$

so $\eta_c = \eta_m \times \eta_e$

(*). **Armature reaction**:- By armature reaction is meant the effect of magnetic field set up by armature current on the distribution of flux under main poles of a generator. The armature magnetic field has two effects

The armature magnetic field has two effects the main flux

(i) It demagnetises or weakens the main flux

(ii) It cross-magnetise or distorts it

The first leads to reduce generated volume whereas second leads to sparking at brushes.

It is seen that (a) flux is distributed symmetrical with respect to polar axis which is line joining the centre of NS poles.

(b) Magnetic neutral axis coincides with the geometrical neutral axis.

Magnetic neutral axis is defined as the axis along which armature conductor no e.m.f. is produced in the armature because they move parallel to the lines of flux.

Demagnetising AT per pole:- Since armature demagnetizing ampere-turns are neutralizing by adding extra ampere-turns to the main field winding, it is essential to calculate the number of armature conductors.

let Z = Total no. of armature conductor.

I = Current in each armature conductor.

$= I_a/2$ -- for simplex wave winding

$= I_a/P$ -- for simplex lap winding

θ_m = Forward lead in mechanical or geometric or angular degrees

Total no. of armature conductors in AOC or BOD $= \frac{4\theta_m}{360} \times Z$

As two conductors having one turn.

∴ Total no of turns in these angles $= \frac{2\theta_m}{360} \times ZI$

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Demagnetizing amp-turns per pair of poles $= \frac{2\theta_m}{360} \times Z I$

$\therefore$ Demagnetizing amp-turns/pole $= \frac{\theta_m}{360} \times Z I$

Cross-magnetizing AT per pole :-

~~Total ampere~~

Total armature conductors/pole both cross and demagnetizing $= Z/P$

Demagnetising conductors/pole $= Z \cdot \frac{2\theta_m}{360}$

Cross-magnetizing conductors/pole $= \frac{Z}{P} - Z \cdot \frac{2\theta_m}{360}$

$= Z\left(\frac{1}{P} - \frac{2\theta_m}{360}\right)$

Cross-magnetizing amp-conductors/pole $= ZI\left(\frac{1}{P} - \frac{2\theta_m}{360}\right)$

Cross-magnetizing amp-turns/pole $= ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$

(Since two conductors make one turn)

⊗ Commutation :- (Methods of improving) :-

There are two practical ways of improving commutation i.e. making current reversal in the short-circuited coil as sparkless as possible. These methods are known as (i) Resistance commutation and (ii) e.m.f. commutation. In resistance commutation, it consists of replacing low-resistance Cu brushes by ~~replacing~~ comparatively high-resistance carbon brushes whereas in e.m.f. commutation, arrangement is made to neutralise the reactance voltage by producing a reversing e.m.f. in the short-circuited coil under commutation. This reversing e.m.f. as the name shows ~~that~~ is an e.m.f. in opposition to reactance voltage and if its value is made equal to the latter, it will completely wipe it off, thereby producing quick reversal of current in the short-circuited coil which will result in sparkless commutation. The reversing e.m.f. may be produced by two ways (i) either by giving brushes a forward lead sufficient enough to bring the short-circuited coil under the influence of next pole of opposite polarity or (ii) by using interpoles.

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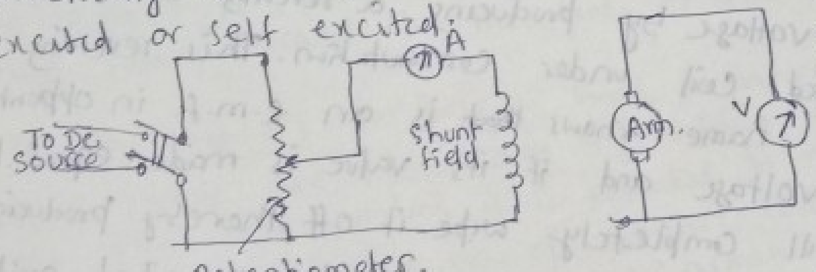
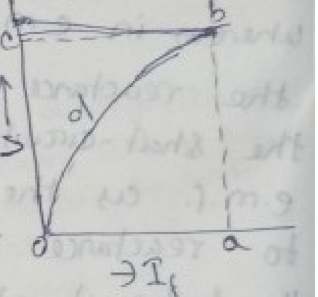
* **Interpoles :-** The function of interpoles is two folds
(i) As their polarity is same as that of main pole ahead they induce e.m.f. in the coil which help the reversal of current. The e.m.f. induced by compoles is known as commutating or reversing e.m.f. The commutating e.m.f. neutralises the reactance e.m.f. and hence making commutation sparkless. With interpoles, sparkless commutation can be obtained up to 20 to 30% overload with fixed brush position. Hence for a given output, an interpole m/c can be made smaller and thereby cheaper than a non-polar m/c.
As interpoles carry armature current, their commutating e.m.f. is proportional to the armature current.

* **Voltage regulation :-** Voltage regulation of a d.c. generator is the change in voltage when load is reduced from rated value to zero value, expressed as percentage of rated load voltage.

* **Characteristics of D.C. Generator :-**
(i) No-load saturation characteristics (E_0/I_f) :- It is known as magnetising characteristic or open circuit characteristic. It shows the relation between the no-load generated e.m.f. in the armature, E_0 and field or exciting current (I_f) at a given fixed speed. It is just the magnetising curve for the material of the electromagnets. Its shape is practically same for all generators whether separately excited or self excited.





The exciting or field current (I_f) is obtained from an external independent d.c. source. It can be varied from zero upwards by a potentiometer and its value read by an ammeter (A) connected in the field circuit as shown.

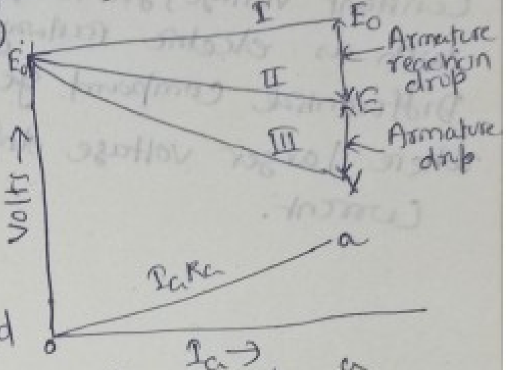
Now voltage equation of a d.c. generator is given by

$$E_g = \frac{\phi Z N}{60} \times \left(\frac{P}{A}\right) \text{ volt}$$

Hence, if speed is constant, the above equation becomes as $E_g = K\phi$

Now when I_f is increased from its initial small value, the flux(ϕ) and hence generated e.m.f.(E_g) increases directly as current so long as poles are unsaturated. This is represented by straight portion od. But as the flux density increases, poles becomes saturated, so a greater increase in I_f is required to produce a given increase in voltage than on the lower part of the curve. This is why the upper portion db of the curve odb bends over.

(2) Internal or Total characteristics (E/I_a):- It gives the relation between the e.m.f.(E) actually induced in the armature (after allowing for demagnetising effect of armature reaction) and armature current(I_a).



Let us consider a separately excited generator giving its rated no-load voltage of E_0 for a certain constant field current. If there were no armature reaction and armature voltage drop, then this voltage would have remained constant as shown in figure by a horizontal line I. But when generator is loaded, the voltage falls due to these ~~causes~~ two causes, hence giving slightly drooping characteristics. If we subtract from E_0 the values of voltage drops due to armature reaction for different loads, then we get the value of E - the actually induced em.f E in the armature under load conditions. curve II is plotted in this way and is known as internal characteristics. The straight line oa represents the I_aR_a drops corresponding to different armature currents. If we subtract from E the armature drop I_aR_a, we get terminal voltage V. curve III represents the external characteristic and is obtained by subtracting ordinates the line oa from those of curve II. Hence external characteristics (V/I) is called as voltage regulating curve. which is the relation between terminal voltage(V) and armature current(I).

⊛ Uses of D.C. generators :-

1. Shunt generators :- Shunt generators with field regulators are used for ordinary lighting and power supply purposes. They are also used for charging batteries.

2. Series generators :- They are used as boosters in certain types of distribution systems in railway service.

3. Compound generators :- Cumulative compound generators are used for motor driving which requires d.c. supply at constant voltage, for lamp loads and for heavy power service such as electric railways.
Differential compound generators are used in arc welding where larger voltage drop is desirable with increase in current.

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