Transformers

Module-4

A transformer is defined as a static electromagnetic device which transfers electrical energy from one circuit to another circuit at the same frequency generally with changed voltage through a media of magnetic circuit.

Working principle

A transformer operates on the principle of mutual inductance between two inductively coupled coils. It consists of two windings. The two windings are coupled by magnetic induction. One of the windings called primary is energized by a sinusoidal voltage, so similar nature of current termed as exciting current flows through it. The exciting current produces an alternating flux in the core which links with both the windings. According to Faraday's laws of electromagnetic induction, there will be self induced emf in the primary and mutually induced emf in the secondary winding. But according to Lenz's Law primary induced emf will oppose the applied voltage. In magnitude this primary induced emf is almost equal & opposite to the applied voltage. When the load is connected to the secondary side current will start flowing in the load. So voltage induced in the secondary winding is then utilized to deliver power to a load connected to it. Energy is transferd from the primary ckt to the secondary circuit through the medium of the magnetic field.

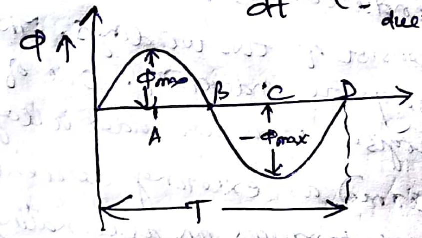
The transformer is very simple construction. It mainly consists of

1. magnetic ckt
2. Electric ckt
3. Dielectric
4. Tank & other accessories.

• The core is made up of silicon steel laminations which is either rectangular or L-shaped. A laminated high silicon sheet steel core is essential for the transformer to keep the eddy current & hystresis losses low.

EMF Equation:

When transformer is connected to alternating voltage alternating flux will be set up in the transformer. So according to Faraday's laws of electromagnetic induction emf will induce in the windings. The magnitude of the induced emf is equal to the product of number of turns & the rate of change of flux. So $e = -N\frac{d\phi}{dt}$ ($\because$ – sign due to Lenz's law)



Let us consider the average change in the flux from A to C

$= \phi_{max} - (-\phi_{max})$

$= 2\phi_{max}$ webers.

Time taken for this change $= T/2$ seconds.

There are N turns then average induced on the winding

$$E_{av} = -\frac{N \times 2\phi_{max}}{T/2} = -\frac{4\phi_{max}N}{T} \text{ volts.}$$

$T = \frac{1}{f}$

$E_{av} = -4\phi_{max} f N$ volts.

Sinusoidal wave, $\frac{E_{rms}}{E_{av}} = 1.11$

$E_{rms} = 1.11 E_{av}$

$E_{rms} = -4.44\phi_{max} f N$ volts.

If N_1 is the primary winding turns.

$E_1 = -4.44 f \phi_{max} N_1$

Emf induced is equal & opposite to the applied voltage.

$-E_1 = V_1$

$$\boxed{\begin{aligned} V_1 &= 4.44 f\phi_{max} N_1 \\ V_2 &= 4.44 f\phi_{max} N_2 \end{aligned}}$$

OR

Core flux $\phi = \phi_{max} \sin\omega t$

$$e = -N\frac{d\phi}{dt} = -N\frac{d}{dt}(\phi_{max}\sin\omega t)$$

$$= -N\phi_{max}\cos\omega t \times \omega$$

$$e = -2\pi f \phi_{max} N \cos\omega t$$

The maximum value of the induced emf will be.

$$E_{max} = -2\pi f \phi_{max} N.$$

$$\frac{E_{max}}{\sqrt{2}} = -\frac{2\pi}{\sqrt{2}}\phi_{max} f N$$

$$E_{rms} = -4.44\phi_{max} f N.$$

$$E_1 = -4.44\phi_{max} f N_1$$

$$V_1 = 4.44\phi_{max} f N_1$$

$$V_2 = 4.44\phi_{max} f N_2$$

Transformation Ratio:

The transformation ratio is defined as the ratio of the secondary voltage to primary voltage. It is denoted by 'K'.

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

- If $N_2 > N_1$ i.e. $K > 1$, then transformer is called Step-up transformer.
- If $N_2 < N_1$ i.e. $K < 1$, then transformer is called step-down transformer.

For an Ideal transformer.

Input (VA) = output (VA)

$$V_1 I_1 = V_2 I_2$$

$$\boxed{\frac{V_2}{V_1} = \frac{I_1}{I_2} = K}$$

Q.1 A 20KVA, 1-ϕ transformer has 300 turns on the primary and 15 turns on the Secondary. The primary is connected to a 1000 volts, 50 Hz supply. Calculate (i). the secondary voltage (ii) maximum value of flux (iii) the value of currents in both windings.

Soln:

i) $\frac{V_2}{1000} = \frac{15}{300}$

$V_2 = \frac{15 \times 1000}{3000} = 50$ volts.

ii) $1000 = 4.44 \phi_{max} \times 50 \times 300$

$\phi_{max} = \frac{1000}{4.44 \times 50 \times 300} = 0.015$ wb.

iii) $20{,}000 = 50 I_2$

$I_2 = \frac{20000}{50} = 400$ A

$\frac{V_2}{V_1} = \frac{I_1}{I_2}$

$\frac{50}{1000} = \frac{I_1}{400}$

$I_1 = 20$A

P-2: find the primary numbers of turns for 440/220 V, 50 Hz, 1-ϕ transformer if the maximum value of flux at no load is 1 mwb.

Soln: $V_1 = 440$V $\quad V_2 = 220$ V. $\quad f = 50 \quad \phi_{max} = 1 \times 10^{-3}$ wb

$V_1 = 4.44 \phi_{max} f N_1$

$N_1 = \frac{440}{4.44 \times 10^{-3} \times 50} = 1982$ turns.

P-3: The emf/turn of 3300/395, 50 Hz, 1-ϕ core type transformer is 7.5V, if the maximum flux density is 1T, then find a suitable no. of primary & secondary turns & the net cross-sectional area of iron core.

Soln: $V_1 = 3300$ V, $V_2 = 395$

Voltage/turn = 7.5 $\quad B_{max} = 1$ wb/m²

$N_1 = \frac{3300}{7.5} = 440$

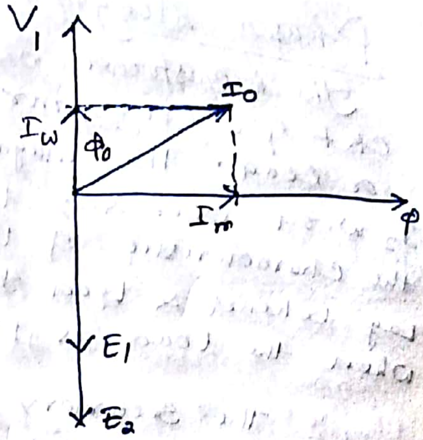
$N_2 = \frac{395}{7.5} = 52.667 \approx 53$ turns.

$N_1 = \frac{3300 \times 53}{395} = 443$ turns.

$A = \frac{7.5}{4.44 \times 1 \times 50} = 337.84$ cm²

Transformer on No Load

When sinusoidal voltage is applied to the primary of the transformer, similar nature of the flux will be set up in the core of the transformer.



$$\phi = \phi_m \sin\omega t$$

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

$$e = -\frac{N}{dt} d(\phi_m \sin\omega t)$$

$$e = -2\pi f \phi_{max} N \cos\omega t$$

$$= 2\pi f \phi_{max} N \sin(\omega t - \pi/2)$$

Where V_1 is the applied voltage to the primary & since transformer is connected to supply but secondary is open. Under such situation transformer draws a small amount of current I_0 (about 3 to 5% of full load current).

Thus I_0 is not at 90° behind V_1 but lags behind by angle $\phi_0 < 90°$.

No load power $= P_0 = V_1 I_0 \cos\phi_0$

Primary current I_0 has two components

1. Iron loss component $I_w = I_0 \cos\phi_0$ or Active or working loss component.
2. Magnetising component $I_m = I_0 \sin\phi_0$

$$I_0 = \sqrt{I_w^2 + I_m^2}$$

P-4: A 330/300V 1-ϕ transformer gives 0.6A & 60W as ammeter & wattmeter reading when supply is given to the low voltage winding & high voltage winding is kept open. Find (i) P.f on no load current (ii) Magnetising component (iii) Iron loss component.

Soln

$P_0 = 60W \quad I_0 = 0.6A$

$$\cos\phi_0 = \frac{60}{300\times0.6} = 0.33 \text{ (lagging)}$$

$$I_m = I_0 \sin\phi_0 = 0.6\sqrt{1-(0.33)^2} = 0.566A$$

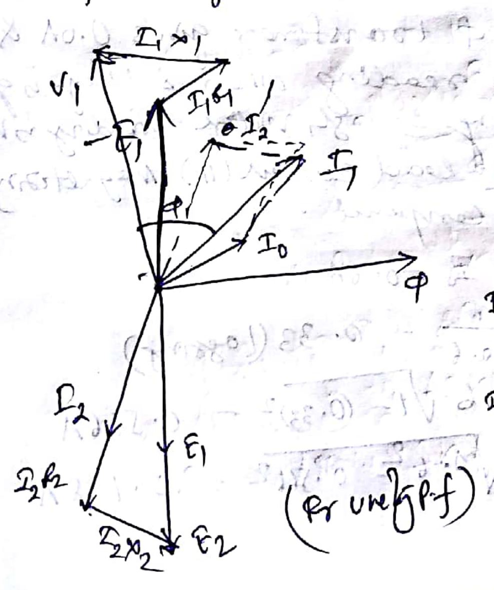
$$I_w = \sqrt{I_0^2 - I_m^2} = \sqrt{0.6^2 - 0.566^2} = 0.198A$$

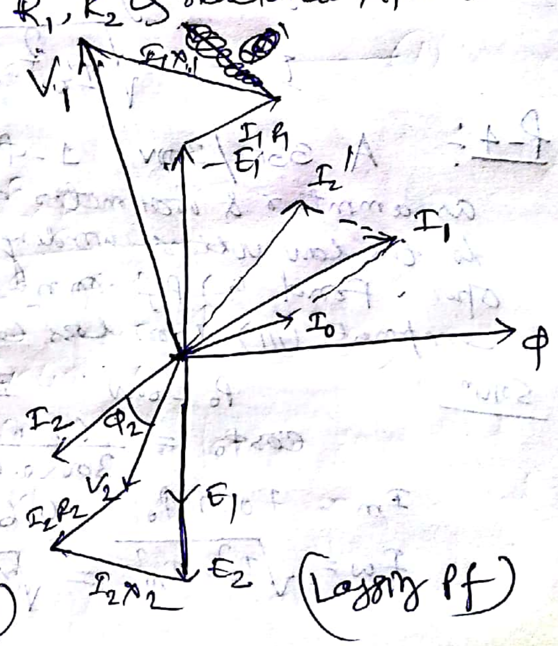
Phasor Diagram on Load :-

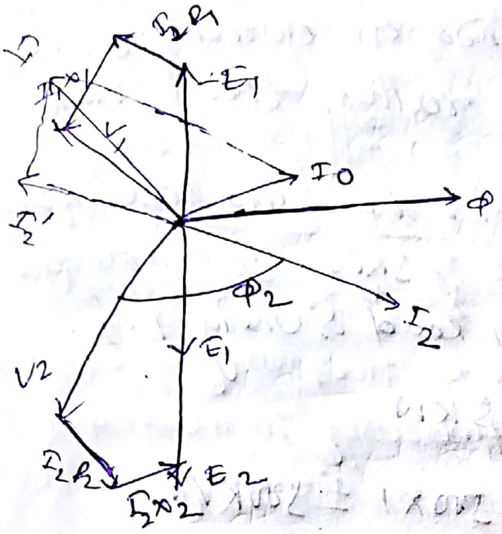
The transformer is said to be loaded when the secondary ckt of a transformer is completed through an impedance or load. The magnitude & phase of secondary current I_2 w.r.t secondary terminal voltage will depend upon the characteristic of load i.e current I_2 will be in phase, lag behind & lead the terminal voltage V_2 respectively when the load is purely resistive, inductive & capacitive.

The secondary current I_2 set up its own characteristic ampere-turns $(= N_2 I_2)$ & creates its own flux ϕ_2 opposing the main flux ϕ_0 created by no-load current I_0. The opposing secondary flux ϕ_2 weakens the primary flux ϕ_0 momentarily hence primary counter or back emf E_1 tends to be reduced. V_1 gains the upper hand over E_1 momentarily & hence causes more current to flow in primary. Let this additional primary current be I_2'. It is known as load component of primary current. 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 is in the same direction as ϕ_0) & is equal to its in magnitude. Hence they cancel each other. Thus we find that magnetic effects of secondary current I_2 are immediately neutralised by the additional primary current I_2' which is brought into existence exactly at the same instant as I_2.

Let us consider transformer having primary & secondary windings of resistance R_1, R_2 & reactances X_1 & X_2 respectively.







(Leading pf)

Regulation : The ratio of the drop in the voltage to the no load voltage is called regulation.

% regulation = 100 × (secondary no load voltage − secondary load voltage) / (secondary no load voltage)

$$\%R = \frac{E_2 - V_2}{E_2} \times 100.$$

Losses

There are two losses in a transformer.

1. Core loss
2. Copper loss

Core loss is two types
i) Eddy current loss (ii) hysteresis loss.

Efficiency :

efficiency = output of transformer / input of the transformer

input = output + losses

Efficiency at x % full load will be

$$\eta_x = \frac{x \times \text{full load output}}{x \times \text{full load output} + \text{Core loss} + x^2 \times \text{full load copper loss}}$$

Rating ... Iron loss is depend upon voltage and copper loss depends on current. Hence the rating is VA rather than watt.

P-5: A 500 KVA transformer has a core losses of 2KW and full load copper losses 5KW. Calculate its efficiency at 75% full load & unity p.f.

Solⁿ: $P_i = 2KW$ $P_c = 5KW$

Full load output $= 500 \times 1 = 500KW$

75% load $= 500 \times \frac{75}{100} = 375KW$

$$\eta = \frac{375}{375 + 2 + (.75)^2 \times 5} = 98.73\%$$

P-6: The efficiency of a 200 kVA, 1-ϕ was 98.5% when delivery full load at 0.8 pf & 99% at half load & unity p.f. Calculate the iron losses & full load copper losses?

Solⁿ: Full load output $= 200 \times 0.8 = 160KW$

$$0.985 = \frac{160 \times 1000}{160 \times 1000 + P_c + P_i}$$

$P_c + P_i = 2436.548$ —— (I)

Half load:

$$0.99 = \frac{20 \times 10^3 \times \frac{1}{2}}{\frac{1}{2} \times 20 \times 10^3 + P_i + \frac{P_c}{4}}$$

$P_c + 4P_i = 4040.4$ —— (II)

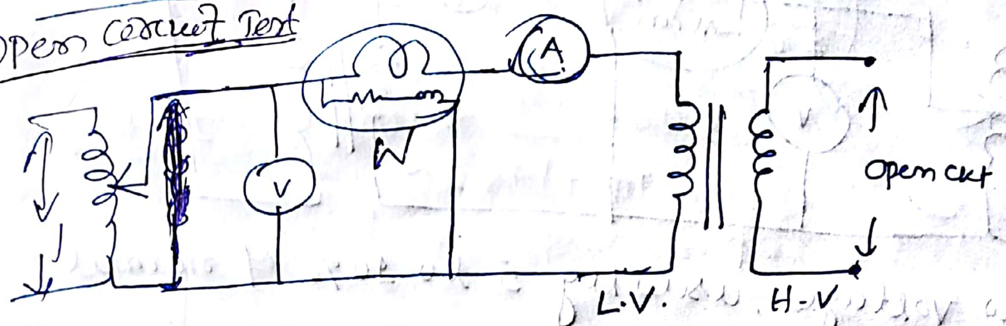
Solving eqⁿ (I) & (II):

$P_i = 534.62W$

$P_c = 1901.93W$

Open Circuit & short ckt Test

Open circuit Test



The instruments are connected on the low voltage side and high voltage side is open ckt. An open ckt or no load test is conducted to find.

(i) No load loss or Core loss

(ii) No Load current I_0 which is helpful in finding R_0 & X_0.

A wattmeter & ammeter are connected to measure no load current (I_0) & no load power (P_0) respectively. As the primary no load current I_0 is small (3 to 10% of rated load current) copper loss is negligible small.

P_0 = input power on no-load

$$P_0 = V_1 I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{P_0}{V_1 I_0}$$

$$I_W = I_0 \cos\phi_0$$

$$I_m = I_0 \sin\phi_0$$

$$R_0 = \frac{V_1}{I_W} = \frac{V_1^2}{P_0}$$

$$X_0 = \frac{V_1}{I_m}$$

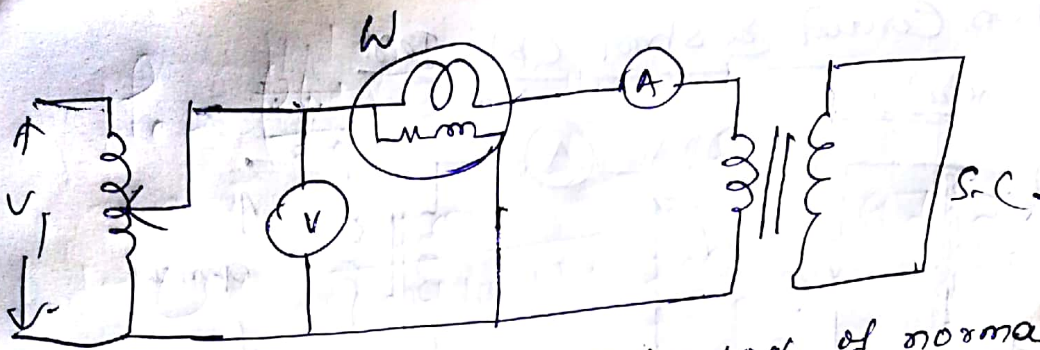
Short circuit Test

This test is conducted to determine the following

(i) Full load copper loss

(ii) Equivalent resistance reffered to metering side.

The instruments are connected high voltage side & low voltage side is short ckt.



A low voltage, usually 5 to 10% of normal primary voltage, at correct frequency is applied to the primary and is continuously increased till full-load currents flow in the primary as well as secondary windings.

Since applied voltage is very low so flux linking with the core is very small and therefore, iron losses are so small that these can be neglected, the reading of the wattmeter gives total copper losses at full-load.

V_{SC} = voltage required to circulate rated load currents.

I_1 = reading of the ammeter on the primary side.

Z_{01} = total impedance as referred to primary side.

R_{01} = total resistance as referred to primary side.

X_{01} = total reactance as referred to primary side.

Then, equivalent impedance as referred to primary side

$$Z_{01} = \frac{V_{SC}}{I_1}$$

$$P = I_1^2 R_{01}$$

$$R_{01} = \frac{P}{I_1^2}$$

$$\boxed{X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}}$$

P-7

A 100KVA, 1-phase transformer gave the following test results, open circuit test - power consumed = 700 watts. Short circuit test - power consumed = 400 watts. Calculate the efficiency of the transformer on

i) half load
ii) full load
Assume average power factor 0.8 lagging in both cases.

Solution

i) $\eta = \frac{output}{input}$

where, input = output + losses.

total losses = iron losses + copper losses

output at half load.

$= \frac{1}{2} \times 100 \times 0.8 = (50 \times 0.8) kW$

$$\eta = \frac{50 \times 0.8}{50 \times 0.8 + P_i + P_c}$$

$$\eta = \frac{50 \times 0.8}{50 \times 0.8 + \frac{700}{1000} + \frac{100}{1000}} = 98.04\%$$

ii) Full load

output $= 100 \times 0.8 = 80 kW$

$$\eta = \frac{80 \times 1}{80 \times 1 + 0.7 + 0.4} \times 100 = 98.64\%$$

P-8 A 10kVA, 415 V/230 V, 50 Hz, single phase transformer gave the following results, when tested, No load test, 415 V, 2A, 100W.
Short circuit test, 15V, 20A, 100W.
Calculate the efficiency at full load at 0.85 power factor lagging.

Solution

output $= 10 \times 1000 \times 0.85 = 8500 W$

Iron loss $= 100 W$

Full load current $I_1 = \frac{10 \times 10^3}{415} = 24.1 A$

$$P_c = \left(\frac{24.1}{20}\right)^2 \times 100 = 145.2\,W$$

$$\eta = \frac{8500}{8500 + 100 + 145.2} \times 100 = 97.2\%$$

DC Machine

Basics of DC Machine

Basic type of D.C machine is that of commutator type. This is actually an alternating current (A.C) machine, but furnished with a special device, a commutator, which under certain conditions converts alternating current into direct current.

* The conditions under which the machine operates are greatly complicated by the commutator and for this reason at the beginning of the present century an attempt was made to develop the homopolar direct current machine. Practice has since proved, however, that the homopolar machine has no advantages over the commutator machine, moreover as during the first decade of the present century a D.C commutator machine was developed, which could meet the stringent demands of the heavy duty performance. Now-a-days, therefore the basic type of D.C machine is the commutator one, the homopolar machine being used only in cases of special nature.

* As the field of industrial application of direct current is very wide D.C machines are produced both as generators and motors, for a large range of outputs, voltages, speeds, etc.

But closer acquaintance with the various types of D.C machines reveals that the main design elements and processes taking place in them have much in common.

Principle of a generator

An electrical generator is a machine which converts mechanical energy into electrical energy. A motor is a machine which converts electrical energy to mechanical energy.

EMF Equation of DC machine

ϕ = Flux / pole in wb.

Z = Total no. of armature conductors.

P = No. of poles.

A = No. of parallel paths in armature.

N = speed in rpm of the armature.

E = emf induced in armature conductors, volts.

emf generated by armature = emf generated by one of the parallel paths.

emf generated = Flux cut per second, volts.

Flux cut by one conductor = No. of poles $\times \phi$ = $P\phi$ webers.

Flux cut by one conductor per second

$$= P\phi \times \frac{N}{60}$$

Hence emf generated by conductor of the armature $= \frac{\phi P N}{60}$ volts.

Emf generated / path, E = emf generated in one conductor $\times$ no. of conductors in each parallel paths.

$$= \frac{\phi PN}{60} \times \frac{Z}{A}$$

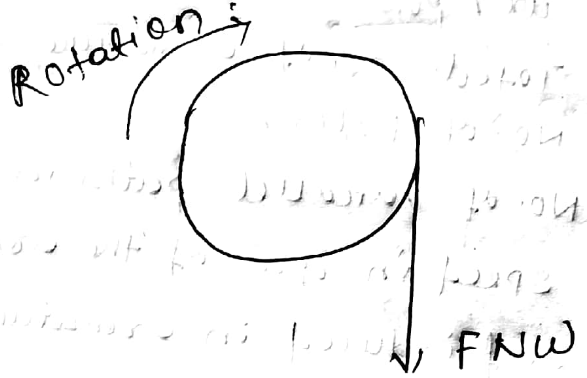
$$E = \frac{\phi ZN}{60} \times \frac{P}{A} \text{ volt}$$

For wave winding, $A = 2$

and for Lap winding, $A = P$.

TORQUE:-

"Torque means the turning or twisting moment of a force about an axis". Torque is measured by the product of force and the radius at which this force acts.



Torque, $T = F \times r$ Newton-meters.

Work done per revolution = Force × distance moved

$= F \times 2\pi r$ Joules

Work done per second $= F \times 2\pi r \times N$

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

$= T \times 2\pi N$ Joules.

ARMATURE TORQUE:-

Let T_a be the torque developed in Newton-meters by the motor armature running at N rps

power developed = Work done per second.

$= T_a \times 2\pi N$ watts —— (1)

armature $= E_b I_a$ watts —— (2)

Comparing expression (1) and (2)

$$T_a \times 2\pi N = E_b I_a$$

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

$$= \frac{\phi Z N \times (P/A) \cdot I_a}{2\pi N} \qquad \therefore E_b = \phi Z N \cdot \left(\frac{P}{A}\right)$$

$$= \frac{1}{2\pi} \cdot \phi Z I_a \cdot \left(\frac{P}{A}\right) \; N\text{-}m$$

$$\therefore T_a = 0.159\, \phi Z I_a \left(\frac{P}{A}\right) N\text{-}m.$$

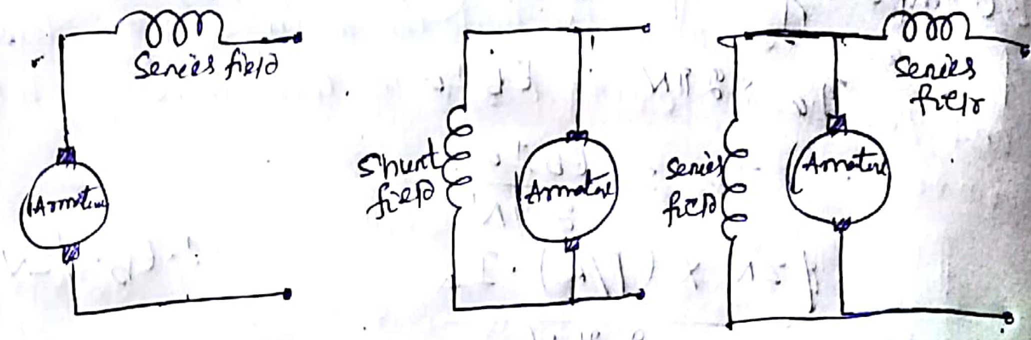
Since Z, P and A are constant for a particular machine,

$$T_a \propto \phi I_a$$

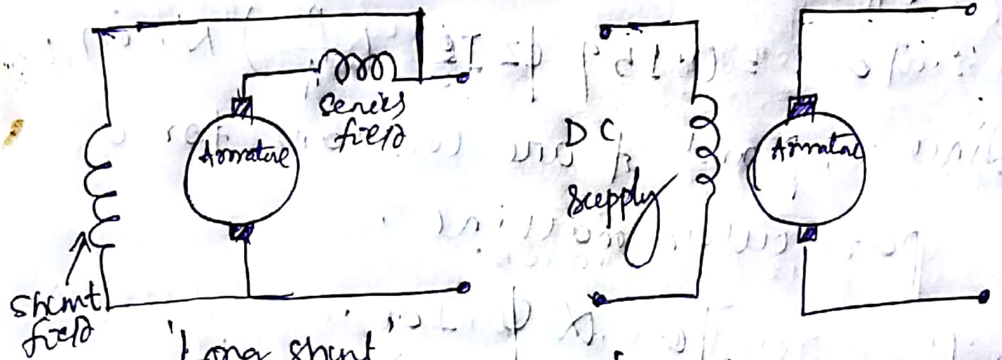
Different types of exciation :-

The manner in which field system is connected to armature or supply is termed as "method of exiation". The field winding may be connected in series, parallel or in series-parallel with the armature. In some generators field system is not at all connected with the armature but directly connected to the supply system. Hence, based on these connections, there are mainly four types of exciation,

1) series method of exication
2) Shunt method of exciation.
3) compound method of exciation
4) separately exciation method.



(a) Series method (b) shunt method (c) short shunt



'Long shunt' 'Seperately excitation method'

P-1 A dc machine when driven at 1200 rpm with a flux per pole of 0.03 wb, generates an emf of 220 volts. Now if flux per pole is reduced to 0.02 wb and speed is increased to 1500 rpm, what is then the induced emf?

Solution:-

$N_1 = 1200$ rpm, $N_2 = 1500$ rpm

$\phi_1 = 0.03$ wb, $\phi_2 = 0.02$ wb

$E_{g1} = 220$ V, $E_{g2} = ?$

$$220 = \frac{0.03 \times Z \times 1200 \times P}{60 \times A}$$

$$220 = \frac{0.03 \times 1200}{60} \times \frac{ZP}{A}$$

$$\frac{ZP}{A} = \frac{220 \times 60}{0.03 \times 1200} = \frac{1100}{3}$$

$$E_{g2} = \frac{0.02 \times 1500}{60} \times \frac{ZP}{A}$$

$$E_{g2} = \frac{0.02 \times 1500}{60} \times \frac{1100}{3} = 183.333 \text{ volts},$$

P-2 A 6-pole lap wound dc shunt generator has 1200 conductors on its armature. The flux per pole is 10m wb. Calculate the speed at which the generator should be driven to generate 250 volts. What would be the speed of the generator if it is, wave wound?

Solution: $P = 6 \quad A = 6 =$ Lap winding.

$Z = 1200, \quad \phi = 10 \times 10^{-3}$ wb $\quad E_g = 250V$

$$E_g = \frac{\phi Z N P}{60 A}$$

$$N = \frac{250 \times 60 \times 6}{10 \times 10^{-3} \times 1200 \times 6} = 1250 \text{ rpm}.$$

$A = 2. =$ wave winding.

$$N = \frac{250 \times 60 \times 2}{10 \times 10^{-3} \times 1200 \times 6} = 416.67 \simeq 417 \text{ rpm}$$

P-3 A 4 pole dc shunt generator runs at 900 rpm. Its armature is 2 layer lap wound having 32 slots & one conductor per layer. Calculate the emf generated if the useful flux per pole is 200 m wb.

Sol^n

$P = 4, \quad N = 900$ rpm.

$Z = 2 \times 1 \times 32 = 64 \quad A = 4$

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

$$E_g = \frac{200 \times 10^{-3} \times 64 \times 900 \times 4}{60 \times 4} = 192V.$$