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ELECTROMAGNETIC Induction

"Faraday Discovered that a changing magnetic field generates an electric current in a conductor. This is called as electromagnetic induction."

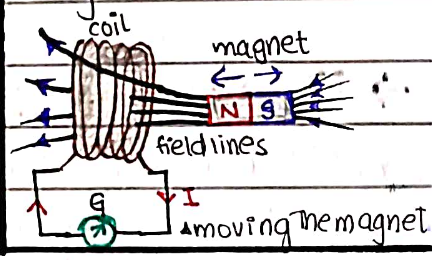
1. Induced EMF and Magnetic Flux:

"EMF is said to be induced when the magnetic flux linking with a conductor (coil) changes"

→ **Moving a bar magnetic back and forth near the coil:** Suppose a coil is connected with a galvanometer, near the coil is placed a bar magnet. Moving bar magnet back and forth will cause change in magnetic flux through the coil. This change in magnetic flux will induce current in coil.

→ **Direction of current:** when magnet is moved towards coil galvanometer will show deflection in one direction, when it's moved away, galvanometer will show deflection in other direction. This is because current reverses its direction.

Diagram:

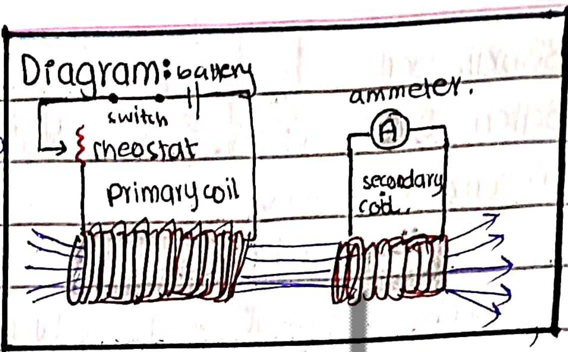


→ **What causes emf to be induced?** Changing magnetic flux pushes the free charges in conductor and forces them to flow. This way current is generated. When conductor is stationary emf induced is statically induced emf.

→ **What if magnet is not moved back and forth?** If both the coil and magnet are stationary, no change in magnetic flux will occur. No change means no push for free charges thus current will not generate.

→ **What if coil is moved instead of magnet?** Change in magnetic flux will occur either way, emf will be induced.

→ **Electromagnetic induction in secondary coil placed near primary coil:** Consider a primary coil connected to an emf source (battery) when switch is turned on, coil becomes a tempory magnet and field lines originate from it. Placed near this primary coil is a secondary coil with only an ammeter connected to it. When switch is turned on and off rapidly, ammeter will show deflection. This means emf will be induced in secondary coil due to primary coil.

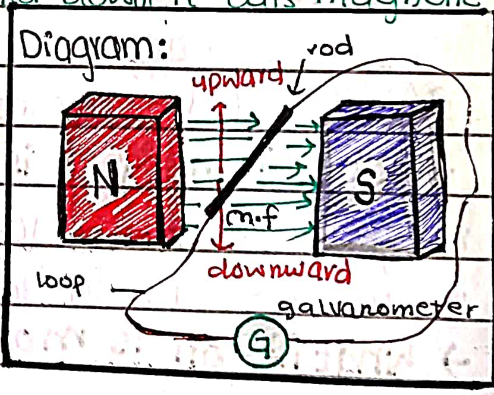


→ **What happens when the switch is turned on and off?** Basically turning the switch on and off causes the primary coil to magnetize and de-magnetise repeatedly. This will cause change in magnetic flux. This change will induce emf in the secondary coil through which field lines are passing. Ammeter will show deflection.

→ **What happens when switch is just kept turned on?** This will not cause any change in magnetic field lines. Thus no emf will be induced.

→ **Using rheostat insted of switch:** If switch is kept ON and rheostat is used to vary current, magnetic field lines will change thus emf will be induced in secondary coil.

→ **Electromagnetic induction in a loop placed in magnetic field:**
consider a conducting rod placed horizontally in between opposite poles of magnet. Moving the rod, connected with wires with a galvanometer, will induce emf in loop. When conductor is moved up and down, it cuts magnetic field lines causing change in magnetic flux.



→ **Moving loop parallel to field lines:** Moving loop parallel to field lines will cause no change in magnetic flux thus no emf will be induced galvanometer will show zero deflection.

↳ **Conclusion:** Change in magnetic flux = Inducing emf

Faraday's Laws of Electromagnetic Induction:

1. "E.m.f is directly proportional to the rate of change of magnetic flux $\Delta\phi$ in time Δt. Greater the rate of change in magnetic flux through coil, greater is induced emf" $\mathcal{E} \propto \Delta\phi \times \frac{1}{\Delta t}$
2. "Emf is directly proportional to the number of turns in coil. greater the number of coils' turns, greater the induced emf" $\mathcal{E} \propto N$

Mathematically $\mathcal{E} = k N \frac{\Delta\phi}{\Delta t}$ (k = 1)

$$\mathcal{E} = N\frac{\Delta\phi}{\Delta t}$$ ← This equation is called as faraday's law of induction.

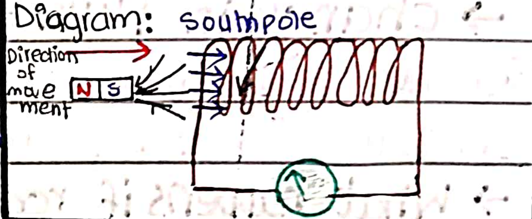
The induced emf always opposes its cause thus $\mathcal{E} = -N\frac{\Delta\phi}{\Delta t}$ ← The negative sign in equation represents Lenz's law

Lenz's Law:

"The polarity of an induced emf is such that it tends to produce a current which opposes the change in magnetic flux that produced it"

→ Moving Magnet Towards the coil:

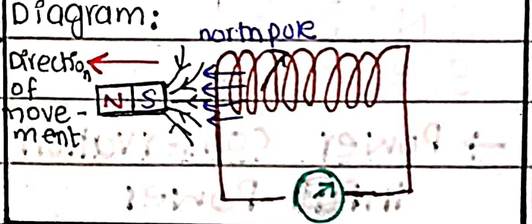
Suppose south pole of magnet is moved towards the coil. Emf will be induced in coil. This emf inturn will cause the coil to convert in a magnet.



- **Induced current's magnetic field:** Induced current's magnetic field will be such that it will repel the coil. i.e.; south pole will be generated infront of southpole of magnet.

→ Moving magnet away from coil:

Suppose south pole of magnet is now moved away from coil.



- **Induced current's magnetic field:** Induced current's magnetic field will be generate in such a way that it will oppose the magnet in moving away from it i.e. north pole will be generated in front of south pole of magnet. current will attract magnet

Conclusion:

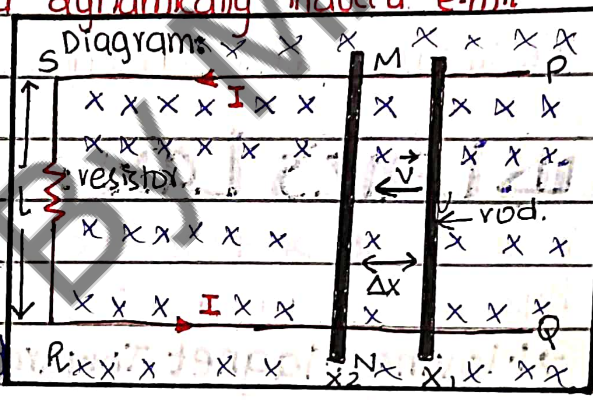
Induced current's direction is always such that the magnetic field it generates opposes the source of induction.

→ **Lenz's law and law of conservation of energy:** Mechanical energy is required to displace the magnet towards and away the ~~mag~~ coil against the magnetic effect due to induced current. This mechanical energy is converted into electric energy which appears in the form of induced current.

iii → Motional EMF:

"When a conductor is moved in a stationary magnetic field in such a way that the flux linking it changes in magnitude, then the emf induced in this way is called dynamically induced e.m.f"

Consider a conducting rod NM placed in uniform magnetic field $\vec{B}$ into the page. The rectangle MNRS form a closed circuit enclosing a varying area due to the motion of the rod MN.



→ **Change in flux:** When rod is displaced from x_1 to x_2 there is a change in flux linked with conductor. There fore an induced emf is produced.

→ **What happens if rod is displaced but not connected with wires to form a loop?** In this case, circuit is not close. Emf will be generated in rod but current will not flow as charges have no closed path to flow.

Mathematically Finding magnitude of induced emf using faraday's law.

$\mathcal{E} = N \Delta\phi \times \frac{1}{\Delta t}$ [here $\Delta\phi = BA\cos\theta$ but $\vec{B}$ is ∥ to $\vec{A}$ thus $\phi = BA$] $\mathcal{E} = \frac{B\Delta A}{\Delta t}$ where $\Delta A = L \times \Delta x$

$\mathcal{E} = \frac{BL\Delta x}{\Delta t}$ [here velocity of rod is $\vec{v} = \frac{\Delta x}{\Delta t}$ thus] $\boxed{\mathcal{E} = Blv}$ This equation is valid as long as B, l and v are mutually ⊥.

→ **Power conservation**

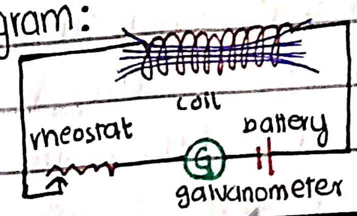
Input Power (Due to motion of MN with velocity v)	Output power (Power dissipated through resistor.)
$P = Fv$	$P = IV$
	$V = \mathcal{E} = Blv$ $\left[\begin{matrix} V = IR \\ \mathcal{E} = IR \end{matrix}, I = \frac{\mathcal{E}}{R}\right]$
	$P = IBlv$ $\left[I = \frac{Blv}{R}\right]$
	$P = Blv \times Blv \times \frac{1}{R}$
	$\boxed{P = B^2 l^2 v^2 \times 1/R}$

Input Power = Output power

$Fv = B^2 l^2 v^2 \times 1/R$

$P = B^2 l^2 v^2 \times 1/R$

↳ Self Induced E.M.F: "The emf induced in a coil due to the change of its own flux linked with it is called self induced emf."



→ **Mechanism:** Consider the circuit as shown in diagram. If the current is varried through rheostat, the magnetic flux will varry through the coil. This varrying magnetic field due to varrying circuital current will cause coil to produce its own current. This induced emf is called self induced emf.

Mathematically (finding magnitude of self induced e.m.f)

we know $\mathcal{E} = N\frac{\Delta\Phi}{\Delta t}$, $\boxed{\mathcal{E} = \frac{\Delta(N\Phi)}{\Delta t}}$ ① here $N\Phi \propto I$ [number of turns of coil and flux are $\propto$ to current induced]

thus we can also write $\mathcal{E} \propto \Delta I/\Delta t$, $\mathcal{E} = L \times \Delta I/\Delta t$ [where L is constant called inductance]

$\boxed{\mathcal{E} = \frac{\Delta \times (LI)}{\Delta t}}$ ② (comparing ① and ②) $\frac{\Delta(LI)}{\Delta t} = \frac{\Delta}{\Delta t}(N\Phi)$

$\boxed{LI = N\Phi}$ or $\boxed{L = \frac{N\Phi}{I}}$ unit of L is "Henry (H)".

→ **Inductance:** Self inductance of a coil may be defined as the ratio of induced emf produced to the rate of change of current in the same coil. **unit;** VsA^{-1} which is Henry **Formula;** $L = \mathcal{E} \div \frac{\Delta I}{\Delta t}$ [from eq ②]

→ Inductance may also be defined as the quality due to which one iductor opposes the cause behind emf being induced in it.

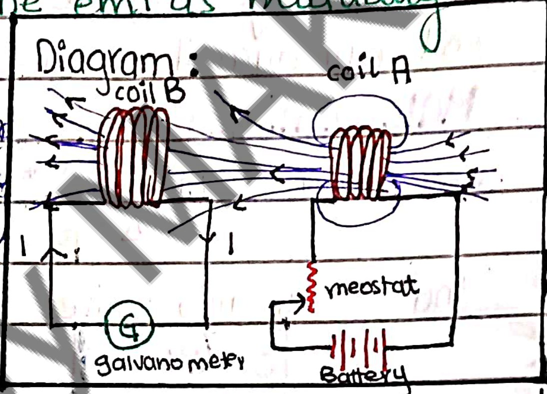
→ **Factors affecting inductance:** All factors which affect the quality of induced current, affect inductance

① shape and number of turns ② Material of the core (greater the magnetic permeability of the core, greater the inductance) ③ coil area and length.

↳ Mutual Inductance: "The property of two neighbouring coils to induce e.m.f in one coil due to the change of current in the other is called mutual inductance"

→ **Mechanism:** Consider two coils A and B placed adjacent to each other. The coil A — primary coil is connected with a battery, rheostat whereas coil B – secondary coil is connected only to a galvanometer. When varrying current passes through coil A, varrying magnetic field is produced in coil which passes through the adjacent coil B. Due to the varrying magnetic flux through coil B, an emf is induced in it. As this varrying magnetic field is mutual for both coils this process is called mutual induction and the emf as mutually induced emf. Mutual flux is represented by ϕ_m.

Diagram:



→ Opposition to the cause: The cause producing mutually induced emf in coil B is the changing mutual flux produced by coil A. Thus as per lenz's law, the direction of emf in coil B will be such that the resultant magnetic flux from it will oppose the mutual flux by coil A.

→ Trick from PKMZ to memorise: Both the self induced and mutually induced e.m.f(s) are parasites as they always oppose their cause.

Mathematically $\mathcal{E} \propto -\frac{\Delta I}{\Delta t}$ (mutually induced emf is directly proportional to rate of change of current through coil A)
(negative sign shows opposing nature)

eq(1) $\mathcal{E} = -M(\Delta I \div \Delta t)$ where 'M' is constant called mutual inductance.

eq(2) $\mathcal{E} = -N(\Delta \phi \div \Delta t)$

eq(1) tells about how induced emf depends upon rate of change of current where as **eq(2)** tells about how induced emf depends upon rate of change of magnetic flux. thus comparing both equations

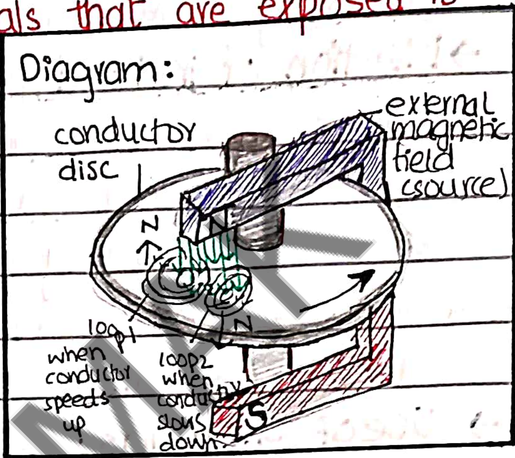
$$-\frac{\Delta}{\Delta t}(MI) = -\frac{\Delta}{\Delta t}(N\phi)$$

$$MI = N\phi \quad \text{or} \quad M = \frac{N\phi}{I}$$

ii → Statically Induced e.m.f.: "The emf induced in a coil due to change of flux linked with it is called statically induced emf."

→ coils are stationary and magnetic flux is changing (it could change due to alternating current).

ii → Eddy Currents: "Eddy currents are currents induced in conductor moving in a magnetic field or metals that are exposed to a changing magnetic field."



→ Procedure: When conductor disc is rotated, the magnetic flux through it will change. This change will induce a current in conductor called as eddy current

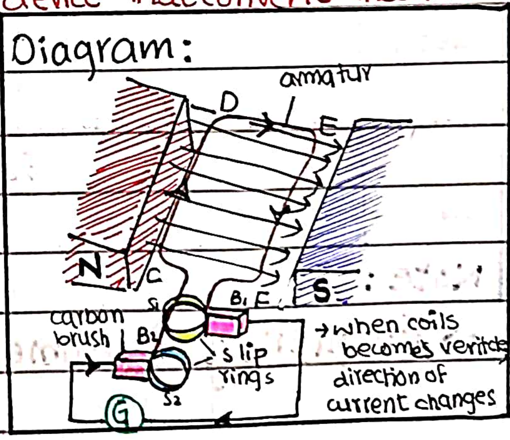
→ Antagonistic behaviour of eddy current's magnetic field: The magnetic field of eddy current will be such that eddy current will oppose its source

→ Disc speeding up: suppose disc is speeding up in counter clockwise direction, then according to right hand rule, eddy current's magnetic field will have it's North point up that is, it will oppose external magnetic field causing disc to slow down as north repels north.

→ Disc slowing down: As disc slows down, direction of eddy current becomes clockwise. In this case north pole of eddy current's magnetic field will be facing south pole of external magnetic field. This way slowing down will be opposed due to attraction between similar poles.

→ Braking system: This all is the mechanism of eddy current braking system in fast moving trains and roller coasters.

ii → AC Generator: "Generator is a device that converts mechanical energy into electrical energy."



→ Working Principle: Works on principle of electro magnetic induction

→ Construction: ① Armature (rectangular coil with many turns wound around a soft iron core) ② shaft connected to armature ③ field magnet with concave poles. ④ two slip rings S1 and S2 ⑤ Two carbon brushes B1 and B2

→ **Working:** When magnetic flux linked with armature changes continuosly, emf is induced.

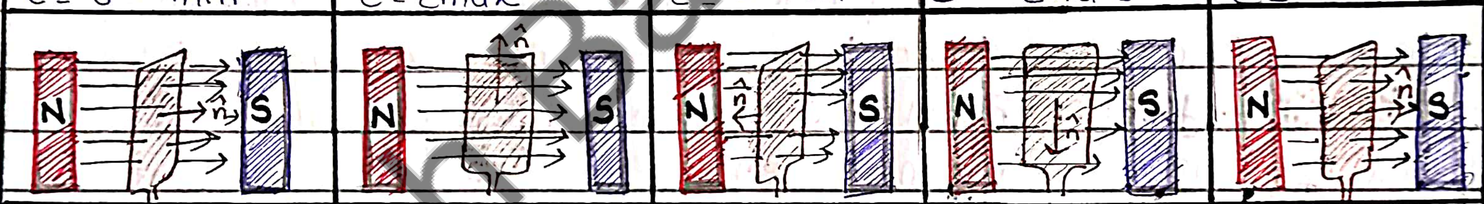
→ **Direction of induced emf:** By fleming's right hand rule, when a side of armature moves up (suppose CD) current induced is into the page when armatures side (CD) moves down, current will be out of the page. This way with every half rotation, direction of current changes or reverses. In one complete rotation direction of current reverses twice producing alternating current.

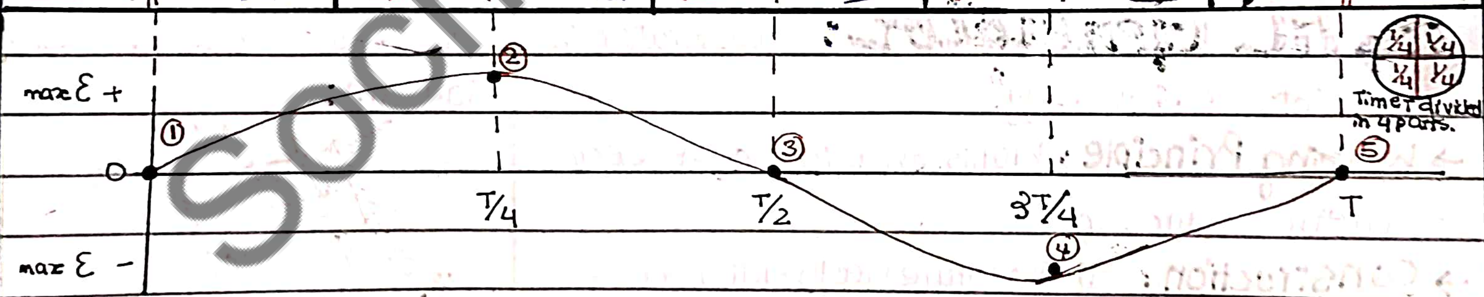
→ **Use of slip rings:** Wires attached to ends of armature will tangle if they rotate. Thus they are connected to slip rings. slip rings rotate along with wires

→ **Carbon brushes:** carbon brushes are in contact with slip rings, slip rings slip over carbon brushes

graph

Position 1 ($\theta = 0°$)	Position 2 ($\theta = 90$)	Position 3 ($\theta = 180$)	Position 4 ($\theta = 270$)	Position 5 ($\theta = 360$)
$\mathcal{E} = \mathcal{E}_{max} \sin 0°$	$\mathcal{E} = \mathcal{E}_{max} \sin 90$	$\mathcal{E} = \mathcal{E}_{max} \sin 180$	$\mathcal{E} = \mathcal{E}_{max} \sin 270$	$\mathcal{E} = \mathcal{E}_{max} \sin 360$
$\mathcal{E} = 0 = min$	$\mathcal{E} = \mathcal{E}_{max}$	$\mathcal{E} = 0 = min$	$\mathcal{E} = -\mathcal{E}_{max}$	$\mathcal{E} = 0 = min$





Note: The coil is rotating anticlockwise. Full rotation angles are 0→90→180→270→360

→ **Frequency of domestic electric supply:** Domestic electric supply has a frequency of 50 Hertz (50 revolutions per second)

Mathematically [magnetic flux is given by] $\Phi = NBA\cos\theta$ where $\theta = \omega t$.

$\Phi = NBA\cos\omega t$ ① [but induced emf is] $\mathcal{E} = -\frac{\Delta\Phi}{\Delta t}$ [putting value of Φ from ①] $\mathcal{E} = -\frac{\Delta(NBA\cos\omega t)}{\Delta t}$

for a specific instant $\mathcal{E} = -NAB \lim_{\Delta t \to 0} \frac{\Delta(\cos\omega t)}{\Delta t}$ ②

in eq ②, $\lim_{\Delta t \to 0} \frac{\Delta(\cos\omega t)}{\Delta t} = -\omega\sin\omega t$ thus putting value we get

$\mathcal{E} = N\omega AB\sin\omega t$ or $\mathcal{E} = N\omega AB\sin\theta$

maximum value of $\sin\theta$ is 1 (for sin 90) thus $\mathcal{E}_{max} = N\omega AB$ or $\mathcal{E} = \mathcal{E}_{max}\sin\theta$

we know that $\omega = \theta/t$. for 1 revolution, $\omega = 2\pi/T$ where $T = 1/f$, thus $\omega = 2\pi f$, so $\mathcal{E} = \mathcal{E}_{max}\sin 2\pi f t$

→ **Can we obtain or can we convert AC generator into DC generator?**

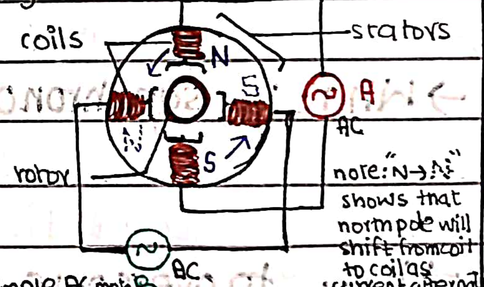
Yes, we can obtain direct current instead of alternating current if we convert AC generator into DC generator. All we have to do is to replace the slip rings with 'split' rings. Split rings will act as commutator and DC will be obtained.

↳ AC Motor:

"An electrical motor is a device that converts electrical energy into mechanical energy."

→ **Construction:** ① stator → stationary part; a group of individual electromagnets (coils) arranged to form a hollow cylinder. ② rotor → rotating part; situated inside the stator ③ A shaft on which rotor is mounted ④ AC source supplying two coils; every two coils (electromagnets) are joined to one AC source.

Diagram:



Simple AC motor

→ **Working Principle:** Current-carrying coil in a magnetic field experiences a torque.

Working

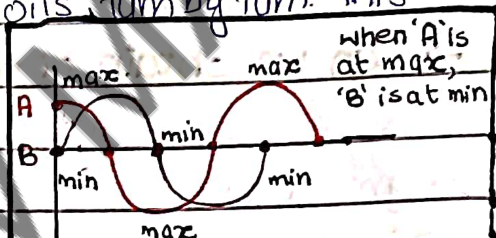
→ **Magnetic field of stators:** (for simplification let us consider 4 coils only as shown in diagram) Two coils are joined to one AC source i.e. A. This way one coil will be north pole and other will be south pole. Same goes for the two coils joined with AC source B.

• **Phase difference between AC sources A and B:** Phase difference is 90°

• **When current of 'A' is at max:** The magnetic field of stators joined to A will be at max aswell but as the phase difference b/w A and B is 90°, magnetic field of stators joined to B will be minimum.

• **When current of 'B' is at max:** Magnetic field of stators joined to B will be max while it will be minimum for those joined to A.

• **Rotating magnetic field:** This way as the current alternates the stators of 'A' and 'B' are magnetized and demagnetized in such a way that North and south pole shift to adjacent coils, turn by turn. This produces a rotating magnetic field. This rotating magnetic field will produce a rotating magnetic flux



AC graph for two sources

→ **Rotation of Rotors:** Due to the changing magnetic field, emf will be induced in the rotors. The magnetic field of induced emf will interact with external magnetic field of stators and the rotor will begin to rotate. Thus we can say electrical energy from AC is converted into mechanical energy of rotor.

→ **What happens if DC source is used?** If DC is used, there will be no alternating magnetic field thus the motor might show minute movement in the beginning but it wont proceed.

→ Though if rheostat is used along with DC, alternating magnetic field can be produced and motor will function.

→ **What is synchronous speed?** The speed which rotor attains at a steady pace due to torque produced in it by rotating magnetic flux is synchronous speed.

→ **How to overcome eddy current loss:** ① by constructing cores out of thin electrically insulated sheets of iron ② by using rotor coils wound on laminated iron armature.

→ **Uses of motors:** ① fans ② electrical vehicles ③ hybrid cars ④ washing machines ⑤ grinder machine ⑥ Juicer machines etc.

Back e.m.f:

"The emf induced in the rotating coil of motor is in such a direction that it opposes the applied emf. This is why it is called back emf."

Mathematically: Applied potential difference = V, emf induced in coil = $\mathcal{E}$, Resistance in coil = R, current drawn by motor = I

since V and $\mathcal{E}$ are opposite in polarity thus net emf in the circuit

net emf in circuit = $V - \mathcal{E}$ By Ohm's law, $I = \frac{V-\mathcal{E}}{R}$

or $IR = V - \mathcal{E}$ or $V = \mathcal{E} + IR$

→ **When motor is just started:** Back emf is zero and current drawn is max

→ **When motor attains steady speed:** Back emf is max and current is minimum

→ **When motor is over loaded:** Load will oppose the rotation, as back emf is such that it opposes its cause, it will decrease so that the opposition to rotation is lessened. As a result, maximum current starts flowing which causes motor to burn out as there is no back emf due to no rotation.

Transformers:

"A transformer is a device which is used to transform electrical power from one voltage and current level to another."

→ **Construction:** ① Primary coil connected to input AC supply. ② secondary coil ③ laminated iron core of high magnetic permeability which connects the two coils.

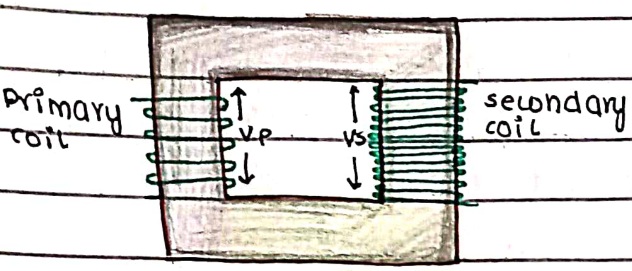
→ **Working principle:** AC current through primary coil creates a changing magnetic field which passes through secondary coil to induce emf V_s in secondary coil.

→ **Types:** Transformers are of following two types

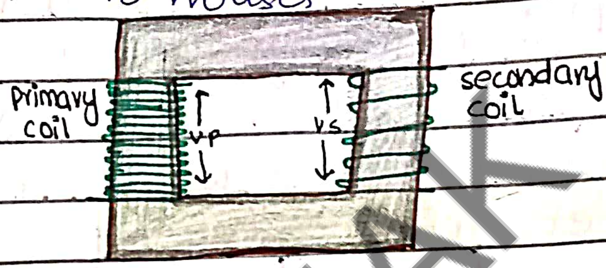
Step-Up	Step-Down
• Number of turns of secondary coil greater than primary coil $N_S > N_P$	• Number of turns of secondary coil are smaller than primary coil. $N_S < N_P$
• Increases voltage, decreases current	• Increases current, decreases voltage

- To supply voltage in factories, industries etc step up transformer is used.

- Step down transformer is used for voltage transmission to houses.



step-up



step-Down

Mathematically, voltage induced in secondary coil by Lenz's law:

$V_S = N_S \frac{\Delta\phi}{\Delta t}$ ① [but magnetic flux is common for both coils thus] $V_P = N_P \frac{\Delta\phi}{\Delta t}$ ②

taking ratio of ① and ②

$V_S : V_P = N_S : N_P$ or $\frac{V_S}{V_P} = \frac{N_S}{N_P}$ we can conclude $V_S \propto \frac{1}{N_P}$ and $V_P \propto \frac{1}{N_S}$

Power transfered: 100% power can't be tranfered from coil 'P' to coil 'S' but in ideal transformers it can take place. thus

$V_S I_S = V_P I_P$ (for ideal) This equation gives us a relation b/w V and I for all transformers regardless of them being ideal. The relation is: $V_S \propto \frac{1}{I_S}$ and $V_P \propto \frac{1}{I_P}$ or $\frac{V_S}{V_P} = \frac{I_P}{I_S}$.

Thus current and voltage are in inverse relation for a transformer.

→ **Why are step down transformers used in housing colonies if they increase current?** It is true that large current can be destructive for electrical appliances but the connection present in houses is parallel connection which causes the current to divide and thus it reaches a safe magnitude. and all points receive high voltage along with required current.

→ **Ways to decrease power loss in transformers:** ① use of laminated cores to decrease eddy current ② Decreasing distance b/w primary and secondary coil to decrease hysterisis loss.