classmate
Date
Page

Intro to Robotics

☆ Electric Actuators for Robotics

First Quiz → Tues 5pm, Wed 11am, Fri 8am — ED 108

ESB 208B

Actuators → elements in a system to create motion - Hydraulic Actuators, Pneumatic Actuators, Electric Actuators.

Robotics -

· Examples of robots + Drones
Robotic Arm - Pick & Place
Autonomous ability — Assistive devices - Prosthesis
Remotely supervised — Mobile robots - Terrain Mapping
Medicine
Remotely operated system

· Movement
☆ Size reasonably small
· Industrial Robots - Pick & Place, Material Handling
· Underwater Robots

Electric → ☆ System should meet operational needs
→ depends on capacity of the actuator

Electronics → ☆ Ability for control

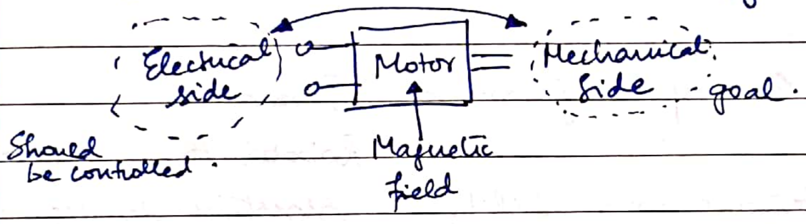
☆ Sources for energy
→ industrial robots stationary (welding robots)
Electric actuation is preferred.
→ underwater robots
Battery / Long cable.
→ Remotely Operated Armoured Vehicle
Diesel engine → generate electricity
↓

Actuators → we need high torque but low weight of the actuator. Therefore we mainly consider "torque / weight" ratio for performance

Hydraulic is best, but very hard maintanence and so we are moving away. The next best is Electric Actuators

Electric Actuators - Motor / valves
DC or AC

Motors ⟶ Electro-Mechanical energy conversion

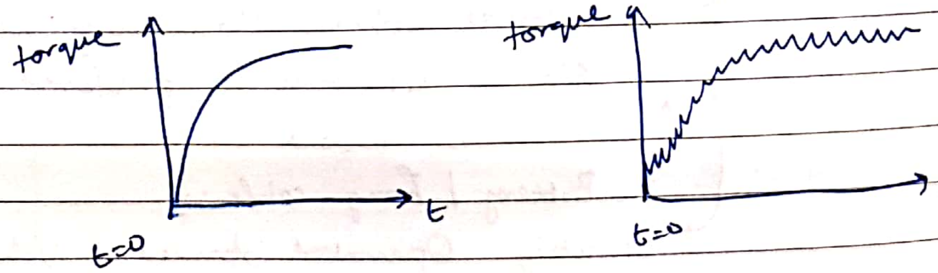


DC motors

AC motors
- Induction motor
- Synchronous motor
  - Brushless DC motor
  - Permanent Magnet Synchronous motor

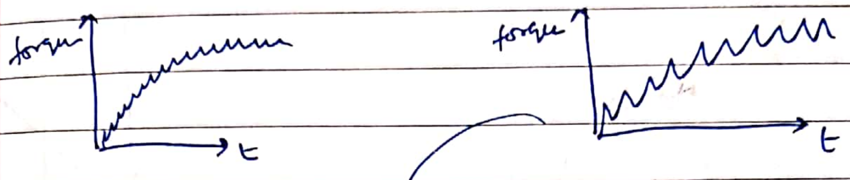
Variable Reluctance
- Stepper Motors
- Switched Reluctance Motors
- Synchronous Reluctance Motors

Operational Need → Torque capability



Actuator -1 Actuator -2

Although the torque oscillates in actuator-2, doesn't necessarily mean the robot body vibrates. Vibration depends on more factors like moment of inertia and damping. Although the actuator vibrates, the body doesn't necessarily.



Actuator-3

this has lower frequency, & more amplitudes.

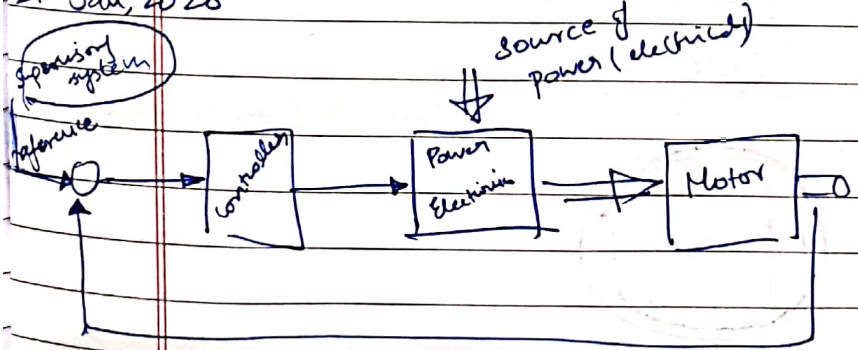
Mechanical systems have very low resonant frequency. In that case, higher frequency is better as the second case might match the resonant frequency and lead to vibrations.

∴ It is alright to have Act-2, as long as it falls in system allowance.

Speed of movement

motor speed vs load speed

21st Jan, 2020



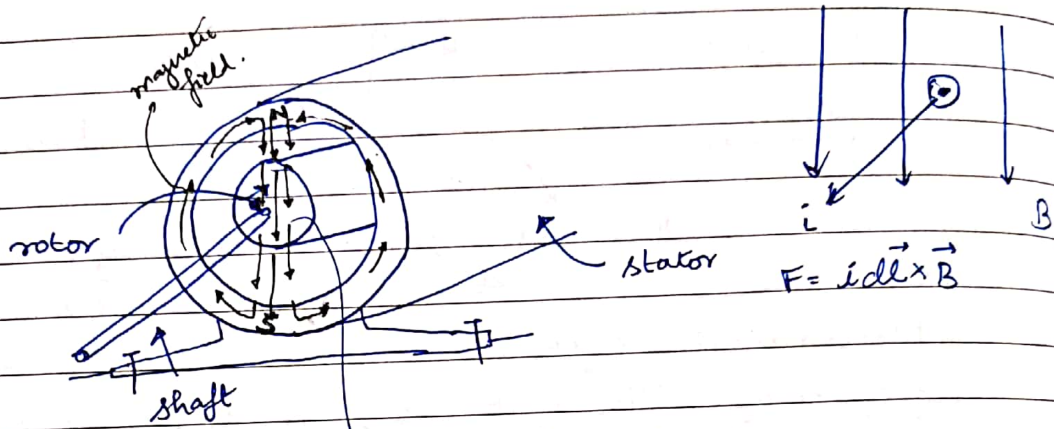
Books:

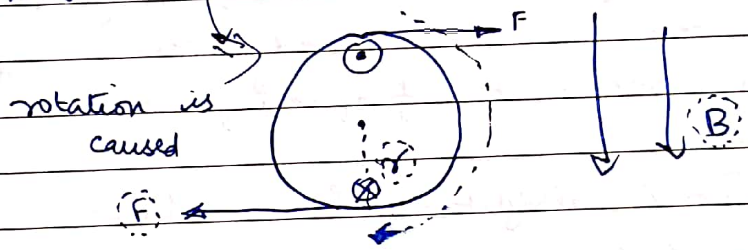
1. Modern Power Electronics & AC Drives (B. K. Bose)
2. DC drives (R. Krishnan)

Electric Motors

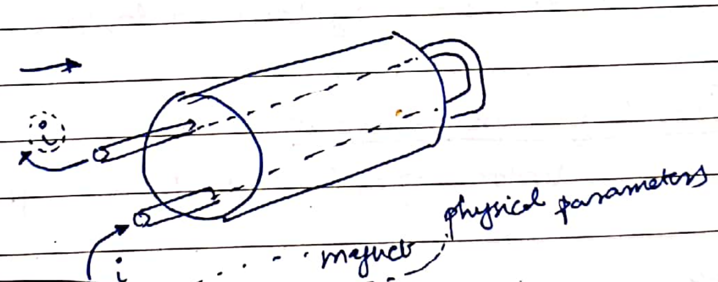
★ DC Motors → 2 basic structural parts
(rotating)

rotor, stator





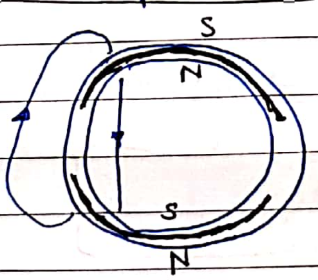
∴ rotor →



Net Torque = $Bilr * 2$

External factor (current)

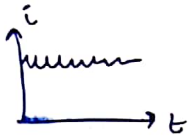
stator →



★ Farraday's law :

$$emf = Blr \cdot 2\omega$$

This is allowed if magnitude of ripple is small enough frequency is high enough.



Therefore for a motor,

$$\left.\begin{aligned} \text{Torque} &= ki \\ \text{Emf} &= k\omega \end{aligned}\right\} \quad k = 2Blr$$

★ Lenz's law : Induced EMF will attempt to resist change in flux.

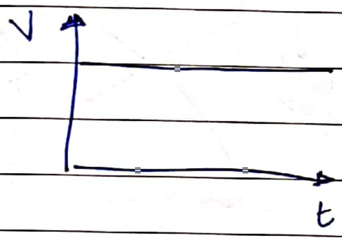
Equation :

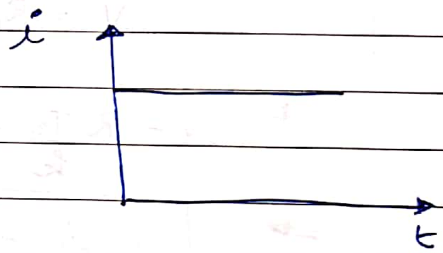
$$\boxed{V = IR + k\omega \quad \Big| \quad T = ki}$$

applied voltage

inertia, opposing forces.

For a pure DC motor,



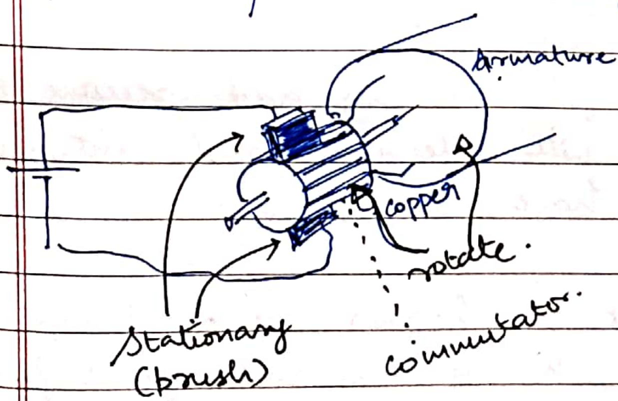


The input current, being a constant is better as it affects the torque proportionally and so will there be a constant output torque and motion. Meanwhile constant V is not mandatory.

22/1/2020 Stator → Field Assembly → magnets

Rotor → Armature Assembly → large no of conductors placed around the rotor and connected in a suitable manner

→ External voltage that is applied



$V = IR + k\omega$ | Steady state equation.

$$\left.\begin{aligned} v &= iR + L\frac{di}{dt} + k\omega \\ T_e &= ki \end{aligned}\right\} \text{Motor's equations.}$$

$$J\frac{d\omega}{dt} = ki - T_L$$

T_L → external load torque (Eg: Robotic hand lifting an object experiences torques)

$$= ki - B\omega - T_{Lo} - T_1$$

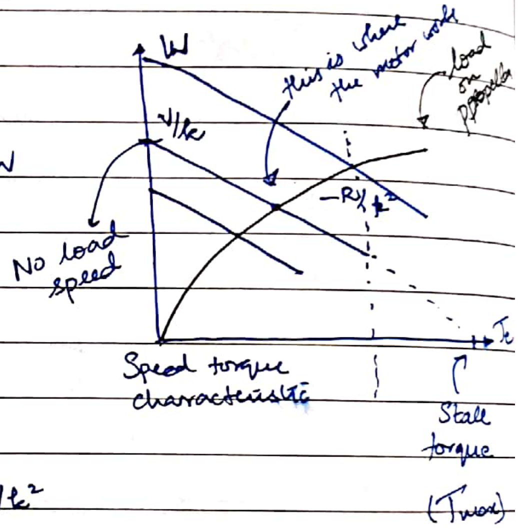
★ Torque Vs Speed

$$V = ~~IR~~\ iR + k\omega$$

$$V = R\left(\frac{T_e}{k}\right) + k\omega$$

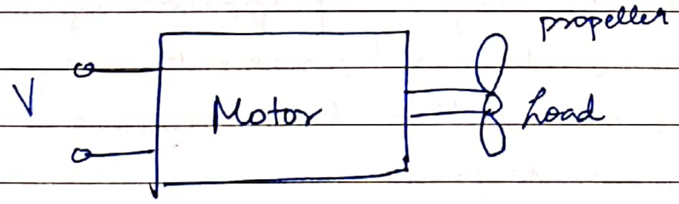
$$\Rightarrow \quad V - \frac{RT_e}{k} = k\omega$$

$$\Rightarrow \quad \boxed{\omega = \frac{V}{k} - \frac{RT_e}{k^2}}$$



Speed torque characteristic

y: V/k slope: $-R/k^2$



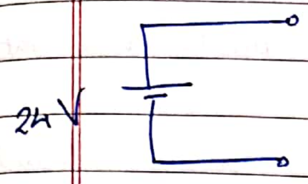
Underwater Mobile Robotic Application:

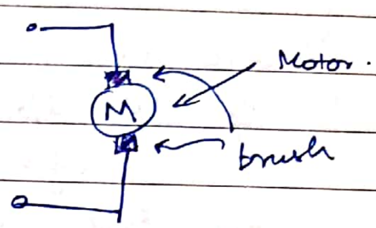
① change R (increase) Now, to have the motor intersect the load graph at a different 'ω', the resistance outside could be changed. We can add resistors outside, the slope will decrease and intersecting point will have lower 'ω'.

② change V (increase) To intersect at a higher 'ω', change V, intersection with y-axis will go higher, thereby ~~no~~ intersection happens at a higher 'ω'

Rating of the motor : Max Voltage
Max Current
Max Speed

* Armature Voltage Control desirable

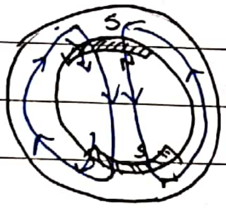


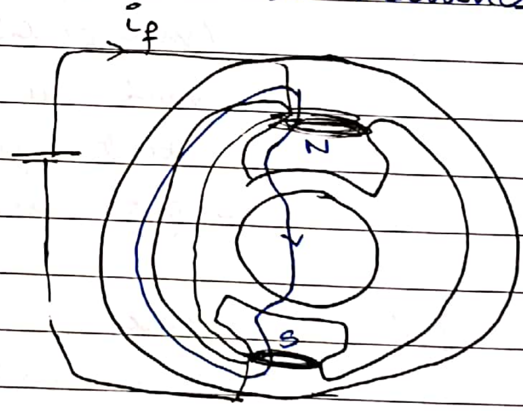


*We can add resistors to give the motor a specific voltage, but resistors eat up power supplied.

24/1/2020 Permanent Magnet Machines (PMDC)

Wound field DC machines





In the case of WFDC, we can change the magnetic field as well.

(Bigger)

Max Voltage ~~as~~ $e \propto B\omega$

Generated Electromagnetic Torque $\propto Bi$

Generated EMF $\propto B\omega$

Rating:

Max. Speed = 100 rad/s

Max. Torque = 5 Nm

$i = 5A$

$B = 1\,W/m^2$.

If I need 4Nm torque, I can choose,

$B = 2\ Wb/m^2$ $i = 2$

$B = 0.5$ $i = 8$

$B = 0.25$ $i = 16$

∴ When we can change, we choose B & i such that 'B' is taken to be the max rated and corresponding i for the case.

$B = B_{max}$, (send corresponding i_f)

⇒ i_{min} for a required torque taken

Incase we need to go to higher speed than rated.

Eg. 300 rad/s.

Emf = Bω and the machine cannot handle more Emf as the machine cannot handle the same. So, we reduce 'B' for according new 'ω'. and keep the Emf controlled.

Electrical power input to machine:

V × i ← Limited by machine rating

Output power : Torque × Speed.
(mechanical)

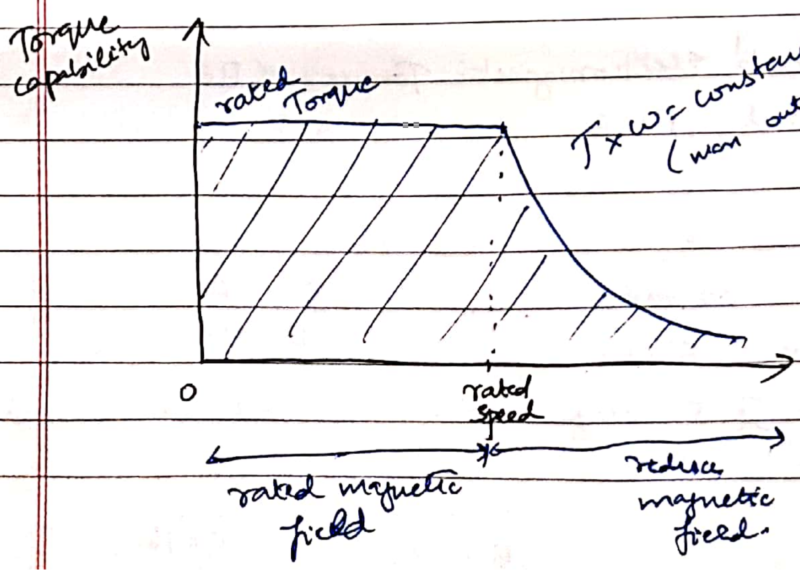
if we need an output of 5 Nm at higher speed (300),

output power = 1500 W

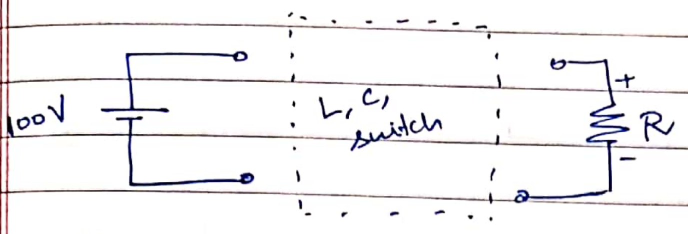
but input power is fixed ($V_{max} \times i_{max}$) = 500 W
rated

∴ ~~To increase~~

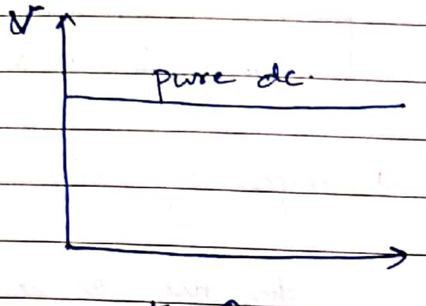
Field weakening mode: Max torque that can be allowed to be generated reduces with speed.

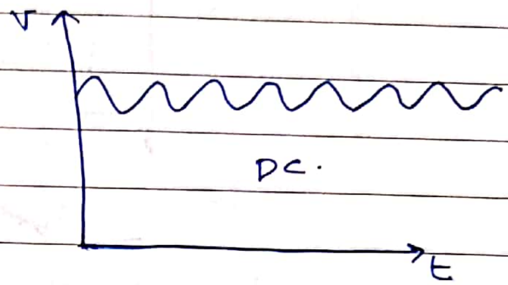


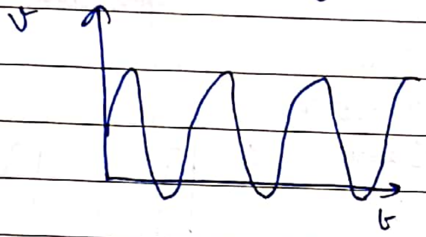
★ Power Electronics :



, Should receive 25 V DC.



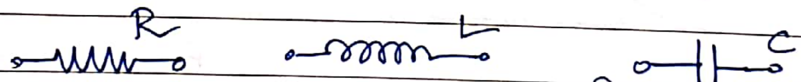




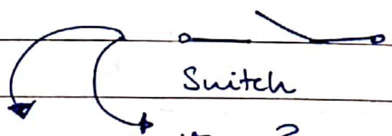
has a DC component.

dc = waveform with non-zero dc component.

A resistor only dissipates electric power, irrespective of nature of input voltage. To give ~~pure DC compt~~ component to an output, we use the following.



(energy dissipator) (energy stored as mag field) energy storers (½CV² is electric field energy stored).



$V_{ON} = 0$
$i = ?$

$V_{off} = ?$
$i_{off} = 0$

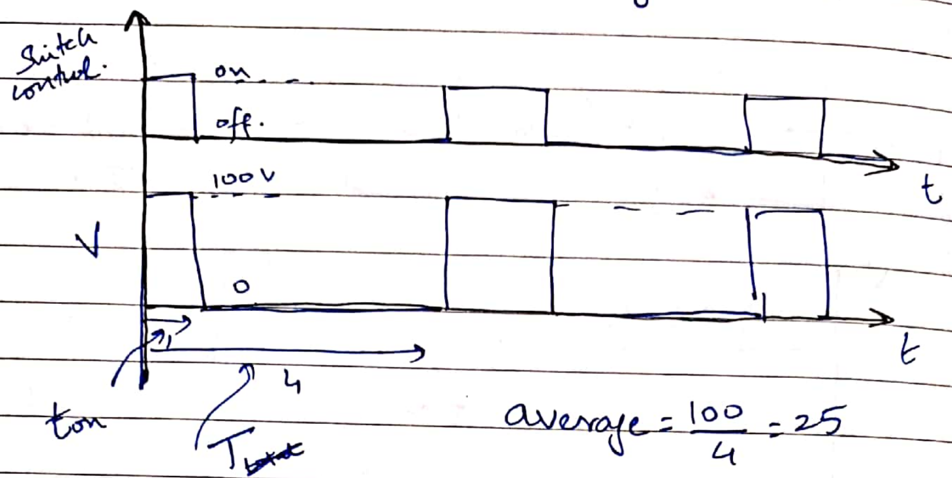
power dissipated across an element

→ $V_{across} \times i_{through}$.

∴ No power dissipation across switch = 0
(on / off)

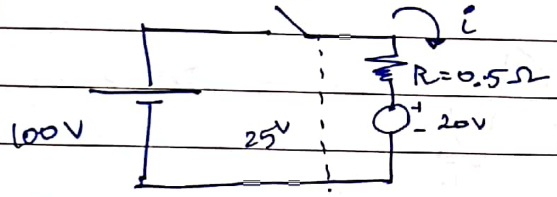
So, to give a DC component, we can use switch, inductor & capacitor.

to give a DC component of 25 V,

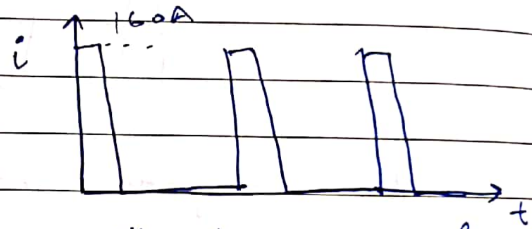


average $= \frac{100}{4} = 25$

For the case of

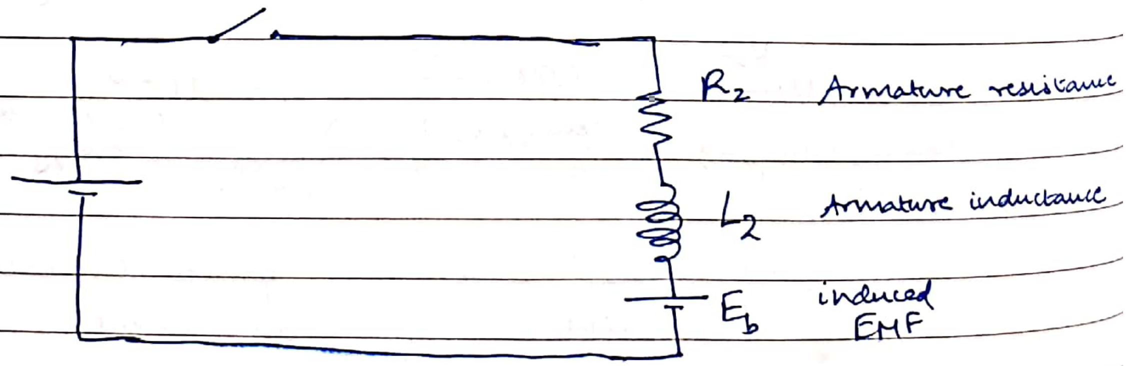


for the same switch control,



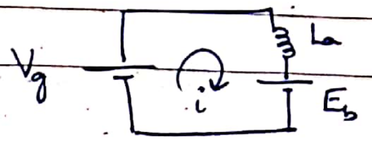
the voltage is fine,
but for a current flow with above wave form isn't suitable for the motor. As em torque generated is a function of instantaneous current.

28th Jan 2020



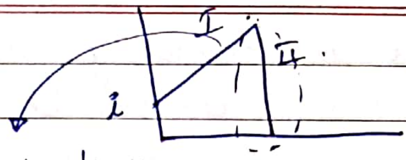
we'll neglect armature resistance as we're only considering the dynamics analysis now.

incase we had a switch, and we closed the switch for analysis



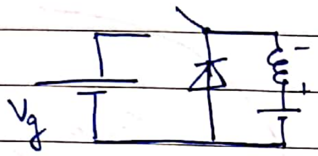
$$L_a \frac{di}{dt} = V_g - E_b$$

$$\Rightarrow \frac{di}{dt} = \frac{V_g - E_b}{L_a}$$



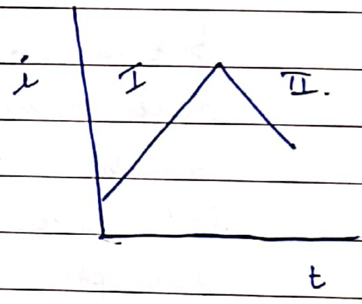
then if we turn the switch off, the current becomes 0 & then the saved energy will be dissipated as heat and would cause huge fire across switch.

Incase we had a diode,



this diode will not charge during first phase and acts as a wire in the second phase.

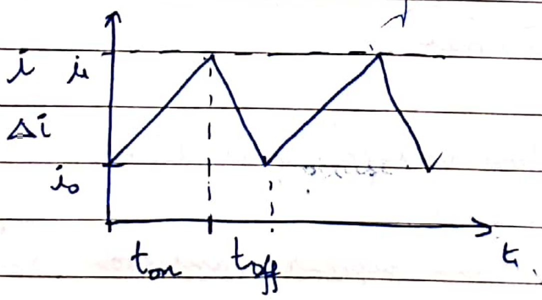
∴ The graph becomes better



$$L_a \frac{di}{dt} = 0 - E_b$$

$$\therefore \frac{di}{dt} = -E_b/L.$$

Continuing with sequential ON & OFFs we obtain



Here, the magnitude and frequency of the ripple is in control

$$\Delta i = \left(\frac{V_g - E_b}{L_a}\right) t_{on}$$

$$= \left| -\frac{E_b}{L_a} \cdot t_{off} \right|$$

$\Rightarrow$ for a given E_b ($\Rightarrow \omega$)

smaller magnitude of ripple $\Rightarrow$

We can reduce t_{on} but ~~to~~ reducing it too much would result in less avg voltage supplied (check) (V vs t graph in previous page). So T has to be reduced as well.

∴ conclusion → decrease t_{on}

decrease $T_{~~total~~}$

switching frequency made higher.

It is necessary to use switching circuits. Switches cannot be mechanical.

⇒ use electronic switch

Preferable to have higher switching frequency. (10,000 Hz to 20000 Hz)

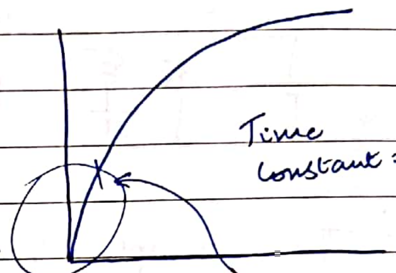
→ Low ripple current

⇒ Estimate value

actual:

$R_i + L_a \frac{di}{dt} = V_g - E_b \Rightarrow$

(first order)



Time constant = $\frac{L_a}{R}$

but usually, cases have high time constant and we will be switching off much sooner. This makes the initial case look linear and this supports our initial assumption and matches the calculation (prev page)

Electronics used,

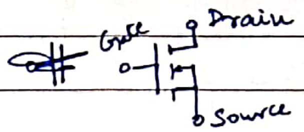
Fully Controllable Device

* MOSFET ← n-channel → ~~Enhancement mode~~ → commonly used as the switch
  - Depletion mode
  - p-channel
  - → used in low voltage applications
* IGBT - Insulate Gate Bipolar Transistor (high voltage applications)

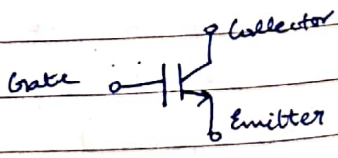
Uncontrollable device

* Diode - Circuit condns decide the working.

MOSFET



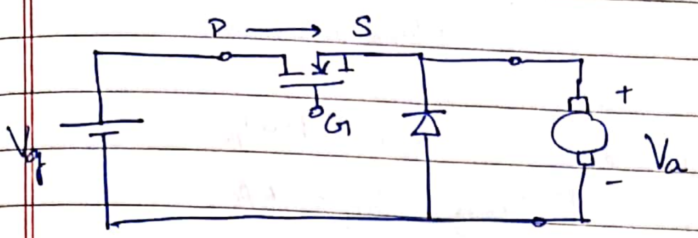
IGBT



FET: Applying a suitable across Gate - source

IGBT: Gate - emitter

In a circuit,



duty ratio

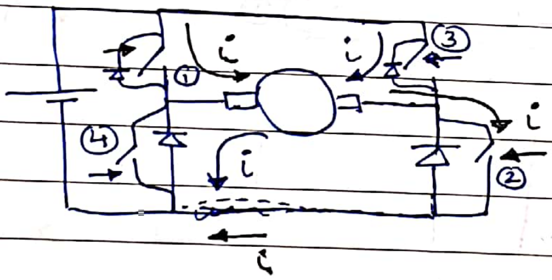
$V_a = V_g D$

$D \in (0, 1)$

→ Switching circuits need freewheeling diodes.

★ Reverse a Motor :
Apply reverse voltage
As 'D' cannot go other than (0 − 1),
the circuit above will not be able to run the motor in reverse.

∴ Modified circuit :



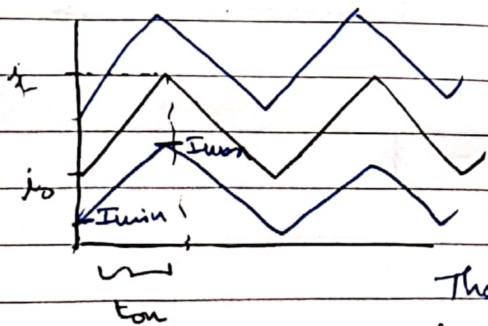
turn on ① & ② for mode of operation as seen earlier.

turn on ③ & ④ for motor to run in the opposite direction.

The above circuit is a H-bridge configuration

+ve, −ve : by that we mean the average voltage across the motor, and not the instantaneous voltage.

29/1/2020



All three, same ripple characteristics

$$\Delta i = \frac{V_g - E_b}{L_a} \cdot t_{on}$$

$$\Delta i = \left| -\frac{E_b}{L_a} \cdot t_{off} \right|$$

These equations only talk about the ripple magnitude and frequency and does not specify anything about the avg. current.

DC Motor : $T_e = T_{load} = kI$ → the average current

T_e → electromagnetic torque

T_{load} → load on motor

for instance,

if $T_{load} = 6\,Nm$ $\quad k = 1\,Nm/A$

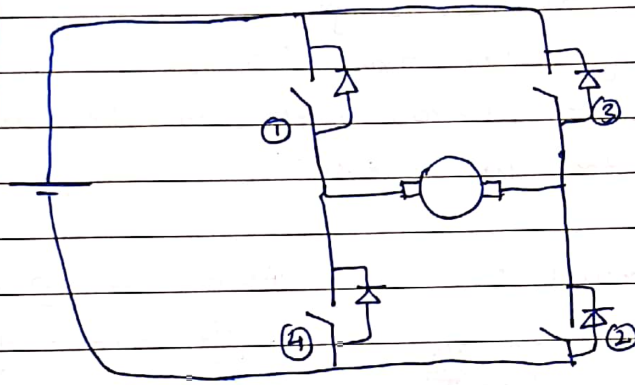
$\Rightarrow I_{avg} = 6/1 = 6A$

Equations to be used :

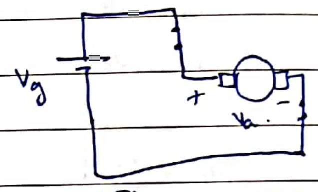
$$I_{max} - I_{min} = \Delta i$$
$$\frac{I_{max} + I_{min}}{2} = i_{avg}$$

for the circuit,

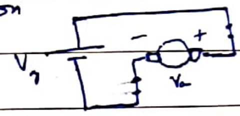
1,2,3,4 → switches

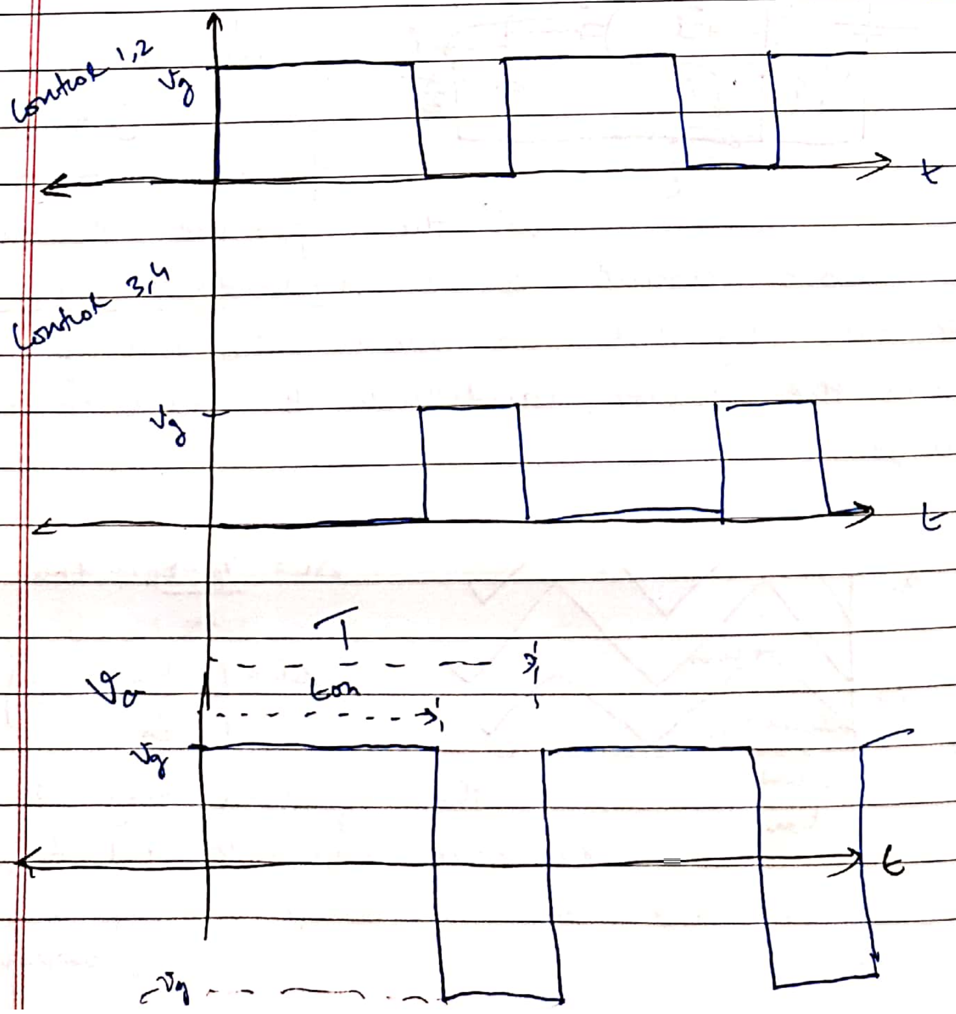


1,2 → on



3,4 → on





check conversion diagram above

∴ $\underset{(avg)}{V_a} = \frac{V_g t_{on} - V t_{off}}{T} = \frac{V_g t_{on} - V_g (T - t_{on})}{T}$

$= \frac{2 V_g t_{on} - V_g T}{T} = V_g (2D - 1)$

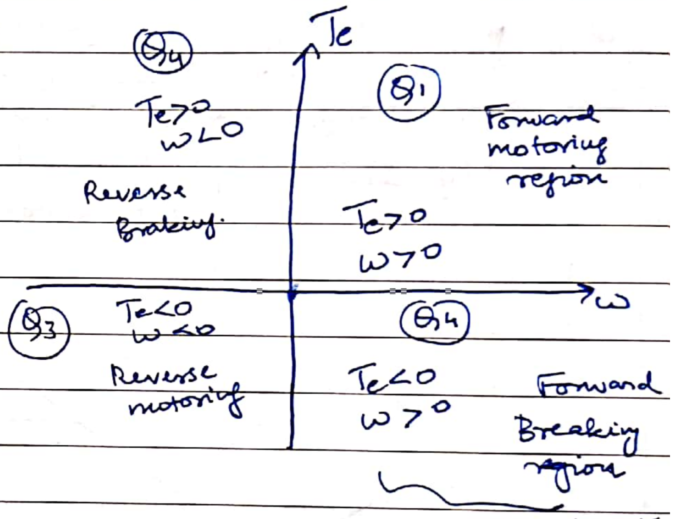
duty ratio $D = \frac{t_{on}}{T}$

∴ Now for this case, if $V_a > 0$,
then the setting must be $D > 0.5$

$V_a > 0 \mid D > 0.5$

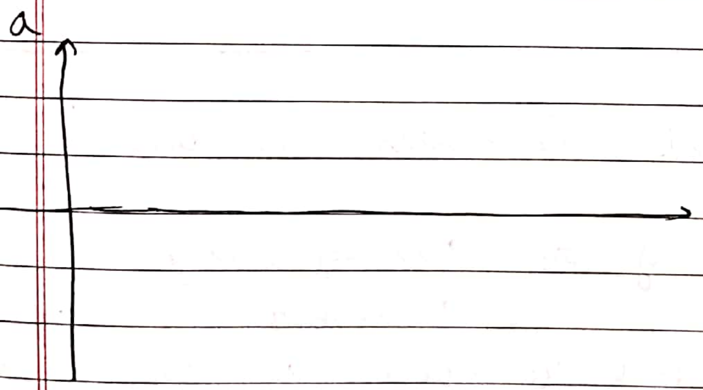
$V_a = 0 \mid D = 0.5$

$V_a < 0 \mid D < 0.5$



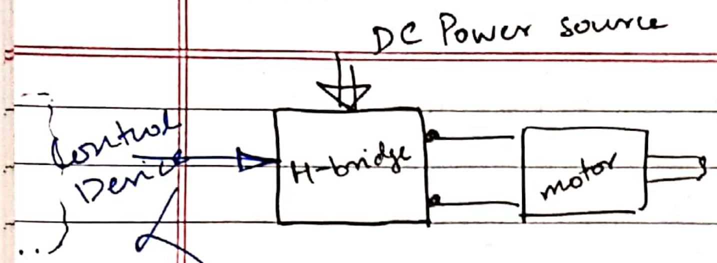
Two quadrant drive

Let us consider the case of a robotic arm



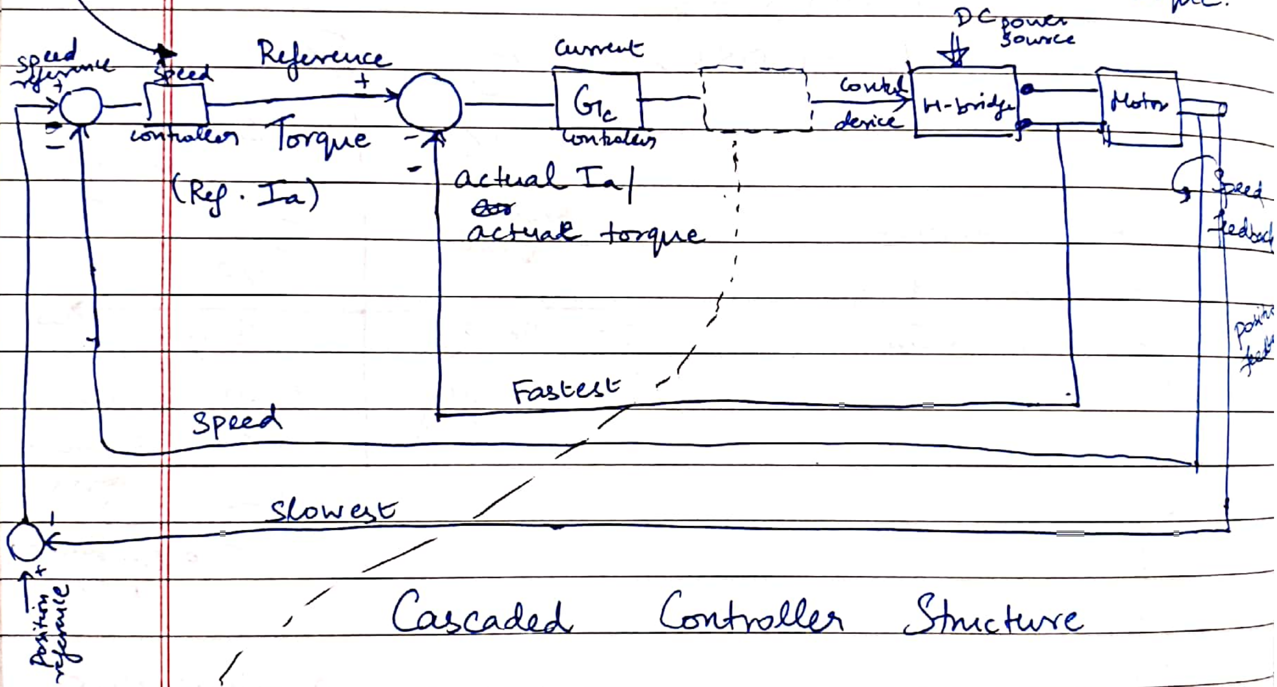
A circuit that allows a motor to operate in all 4 quadrants above is a 4-quadrant drive

Eg: H-bridge.



→ Should give instructions on when switches should be triggered

The electrical subsystem of the motor is the first thing that responds first
→ responsible to generate electromagnetic torque.

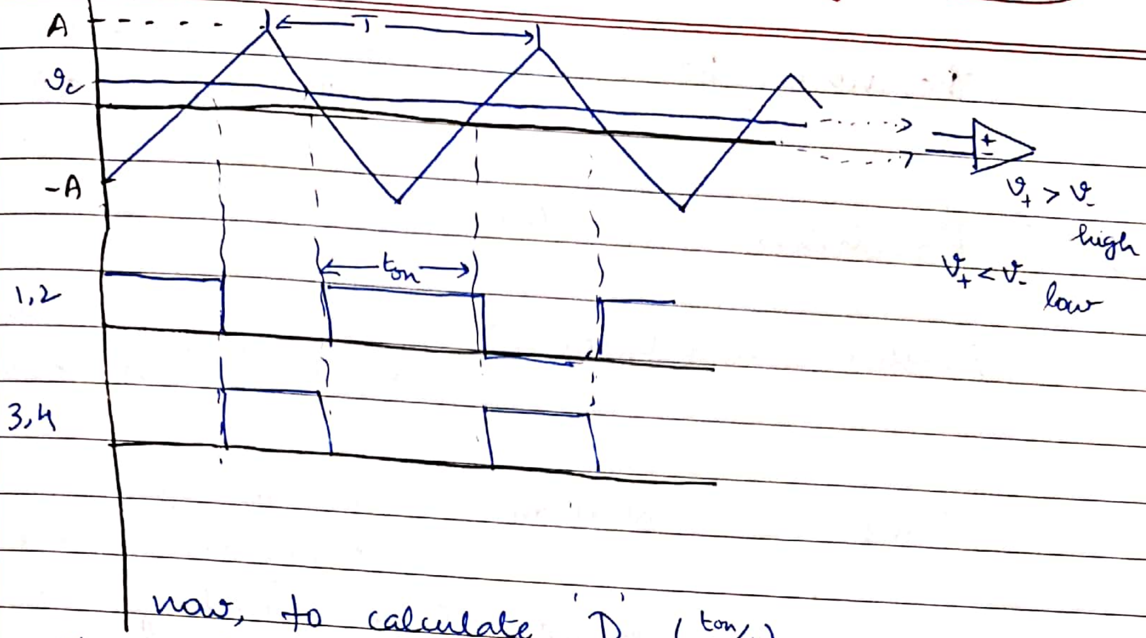


Cascaded Controller Structure

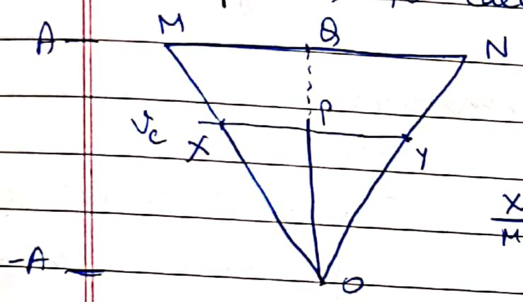
→ The output of G_c → analog voltage
→ number

The input H-bridge requires → Switching controls
This conversion is done by 'Modulator'.

★ Earlier we saw, the t_{on} to T can be changed to alter the average V. So theoretically, we modify the pulse width. So the term "Pulse Width Modulation". ~~An~~



now, to calculate 'D' (t_{on}/T)



OMN OXY Similar Triangles

$$\frac{XY}{MN} = \frac{OP}{OQ} \quad \Big| \quad \frac{t_{on}}{T} = \frac{A + v_c}{2A} = \frac{1}{2} + \frac{v_c}{2A}.$$

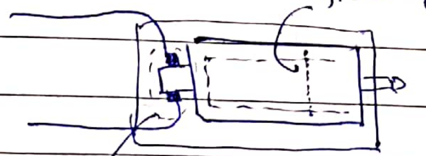
$\frac{v_c}{A} \rightarrow$ Modulation Index. m_a.

$$\cancel{V_a = V_g\left[\frac{2(m_a+1)}{2} - 1\right]} \qquad D = \frac{1}{2} + \frac{m_a}{2} = \frac{m_a+1}{2}$$

$$V_a = V_g\left[\frac{2(m_a+1)}{2} - 1\right] = m_a V_g$$

DC Motor Control Structure:

field generated at stator.



slipping brushes: rigorous to tackle sliding friction.

∴ Brushes are made of Graphite.

Graphite → soft. With use, the brushes erode. eroded material settles on the cylinder, shorts between input & output.

∴ DC Motors are not used in Robotic Applications.

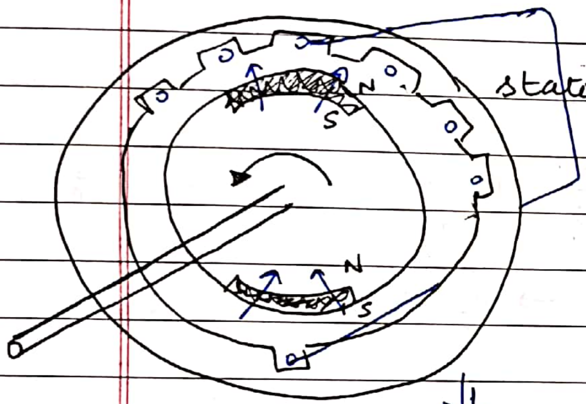
The next best alternative is a BLDC machine (brushless DC)

31/1/2020

Brushless DC Motors

Brush + commutator ⇒ stationary power source → energize the rotating member

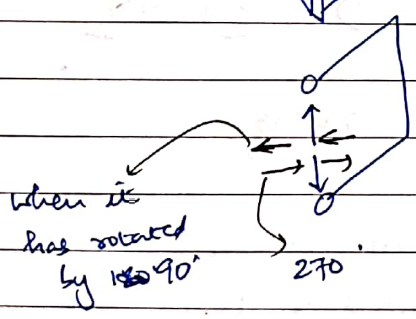
Brushless → stationary power source
→ they have to energize stator
then, the field should go on the rotor



stator → armature

emf
e proportional to rate of change of flux

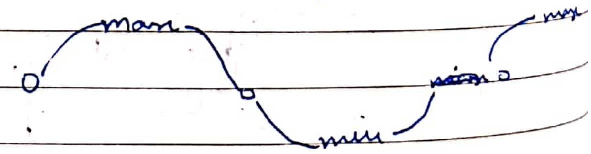
⇓



flux cutting across the plane of the loop = 0.
(for initial angle of rotor according to ~~the~~ the diagram above).

∴ The induced emf keep alternating

flux linkage



e → alternating
⇒ cannot connect a DC source to this.

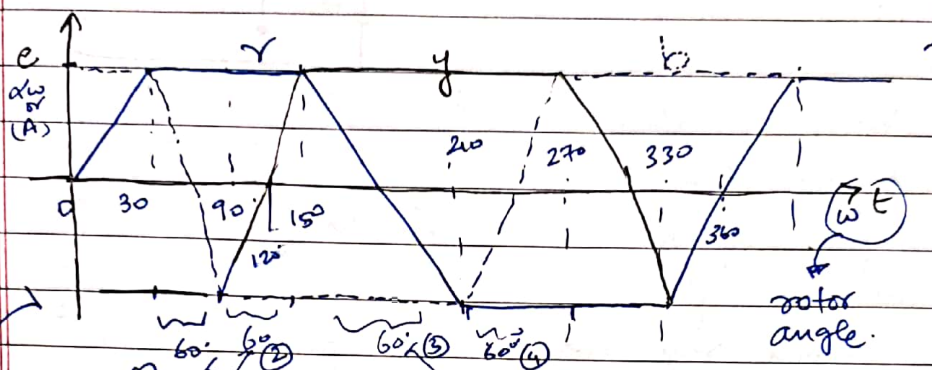
∴ e = AC waveform
↳ frequency depends on speed amplitude, also depends on speed.

∴ An AC source where magnitude + frequency can be controlled should be synchronous with the 'e'.

3-phase machines (3 groups = phases)

Diagram

(for future reference)



Trapezoid. (3 different)

frequency ∝ speed.

waveforms of induced emf (depends on rotor current)

① r, y constant, b varying

② y varying, r, b constant

③ r varying, b, y fixed.

④

∴ in any 60°, one varies and other two remain constant.

60 60 60 60

$e_r > 0$, $e_y < 0$ | $e_r < 0$, $e_y > 0$

$e_{ry} > 0$ (2A) | $e_{ry} < 0$ (-2A)

→ if current i flows into the machine, then,

$i \cdot B \cdot l \cdot r = T_e$

electromagnetic torque.

We want a fixed torque (T_e) and not oscillating.

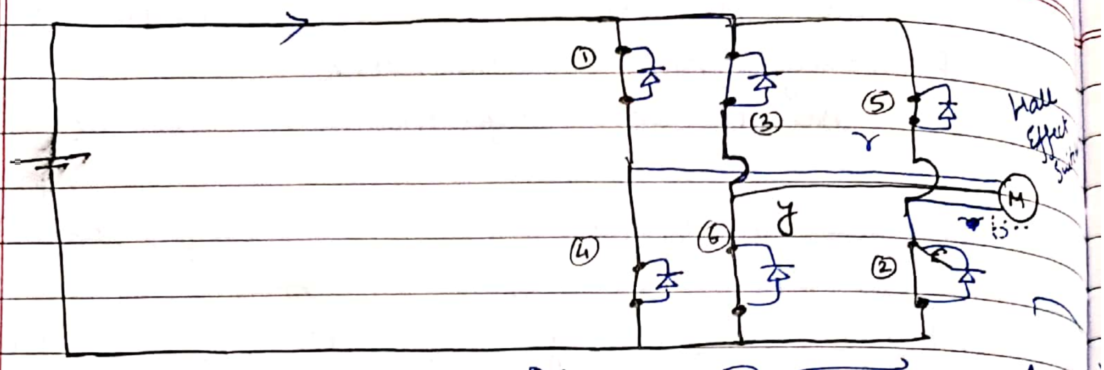
① In the first 60° mentioned above, energize r & y, keep b open
(what is fixed) (what is fluctuating)

② energize r, b, keep y open

③ energize b, y, keep r open

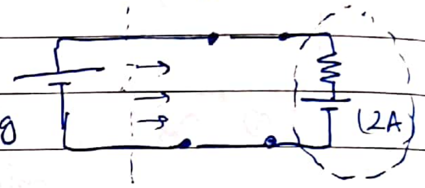
④ energize r, y, keep b open
but in the opposite sense of ①
(check signs of e_{ry} in both cases)

Scanned by CamScanner



Vary switches accordingly depending on the kind of output required

∴ In every 60°,



From the point of the source, at every instant it looks like a DC load only.

Now, if we feel like reducing voltage of the BLDC, switches must be operated within 60°, at some rate, by making them go on & off, thereby varying duty ratio, and so the average voltage on the motor, reducing its speed.

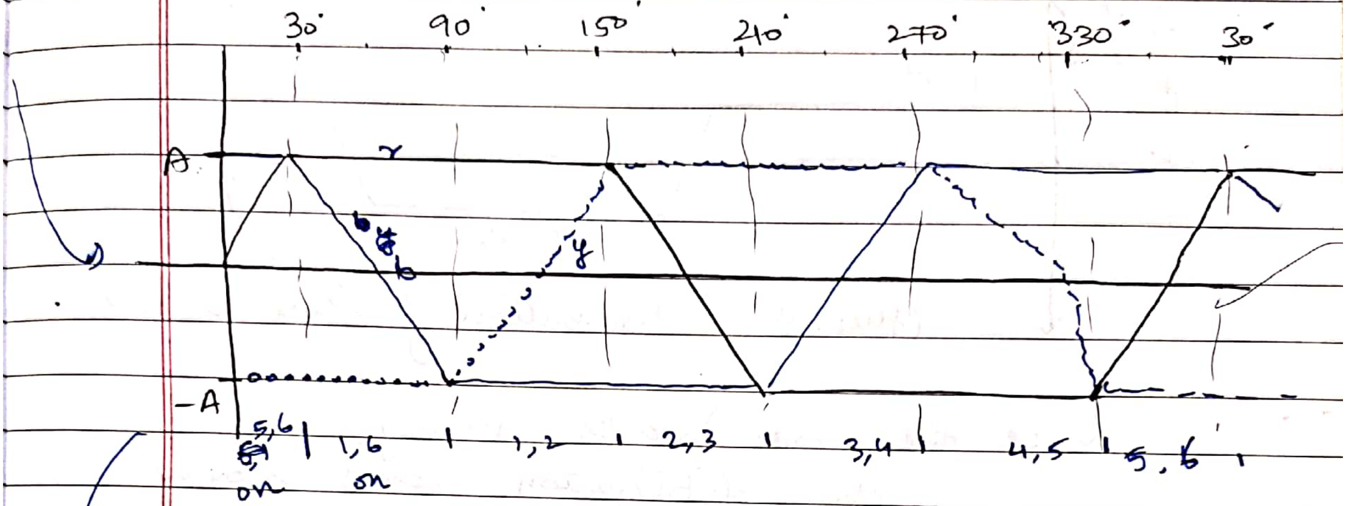
Eg: In first 60°, switch (1) & (6).

For every 60° interval, one pair of switches are ON.

Once in 60°, ~~the~~ one switch is turned off & another is turned ON.

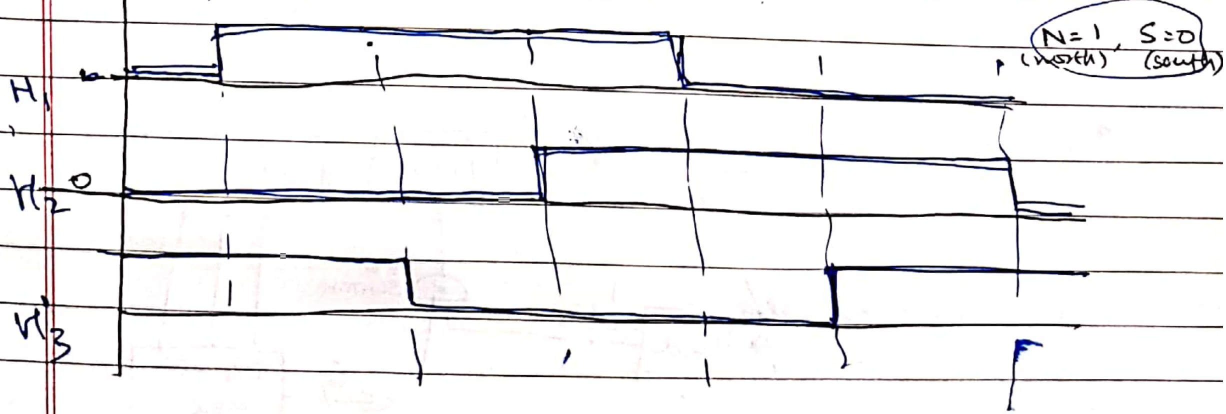
Switches in each 60° interval can be operated in high for PWM to control rotor voltage & speed

4/2/20



At a particular interval, if a phase is changing sign, don't use it.
if it is steady, use that phase.

→ the patterns used is different from previous diagram. Please do not follow it.
Refer to 'r', 'y', 'b' notation used.

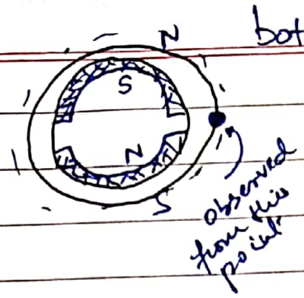


∴ now, writing algorithm for switches switching,

Switch ①: $(H_1 \cdot \overline{H_2})$
when H_1 is on & H_2 is off.

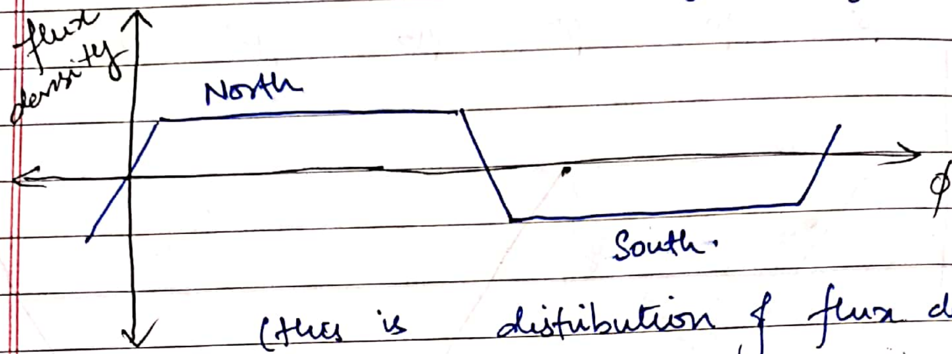
Switch ②: $(H_1 \cdot \overline{H_3})$ — boolean expression

similarly, for all switches. logic gate.



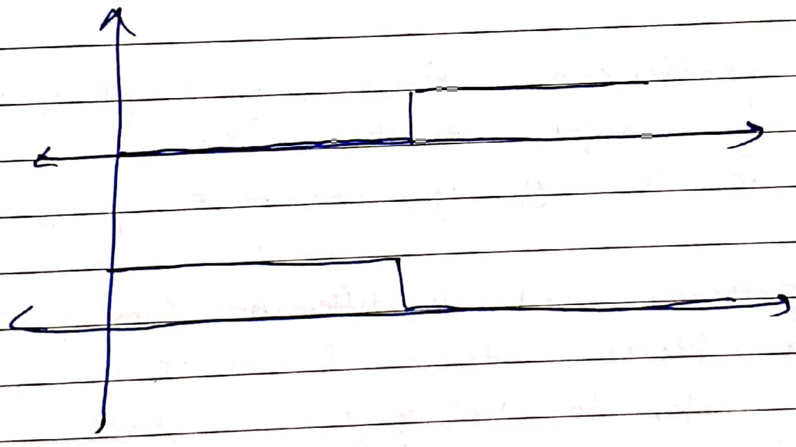
both magnets are uniformly magnetized
⇒ flux density is uniform

Magnetic field ⇒ flux
B – flux density
H – Magnetic field intensity

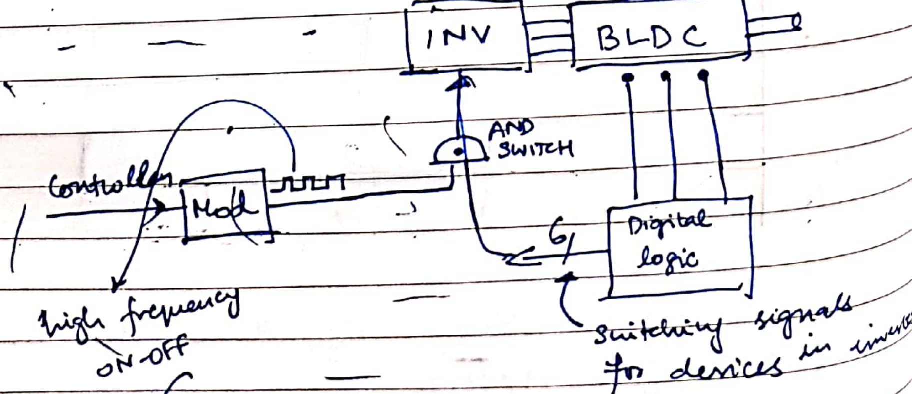


(this is distribution of flux density.

Once the rotor starts moving,
the distribution starts moving.

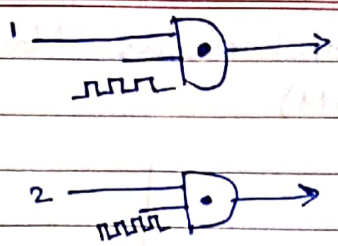


★



→ the rest is similar to closed loop structure seen before

Digital logic



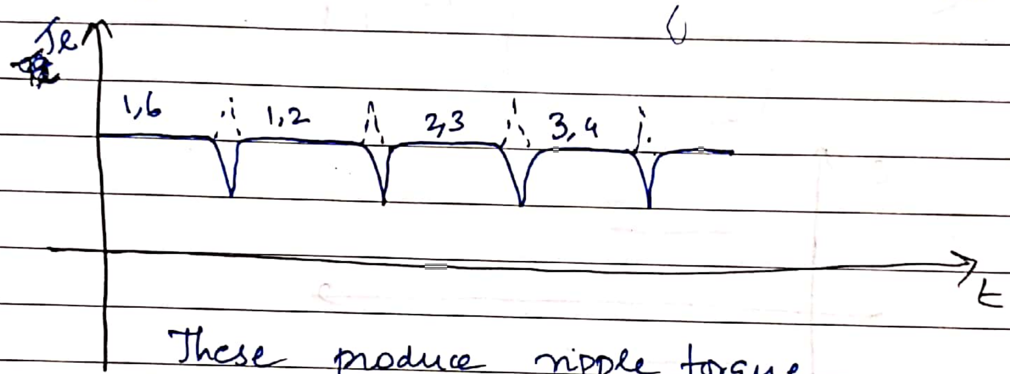
Switching control for ①

②

These kinds of motors are used for, drones
simple robotic devices
unmanned vehicles.

Limitations :

* During the & 60° intervals rotor angle information is unavailable, we have the info only at the ends of the 60° intervals (when the switches switch)



These produce ripple torque (because one phase goes out and new one comes in) which is unavoidable. and the frequency depends on speed.

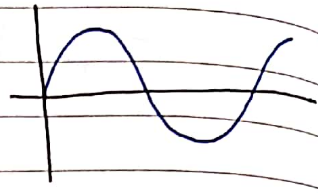
This ripple torque might ~~a~~ result in the ~~chang~~ compromise in the accuracy of the rotor angle.

∴ A low precision application would still be fine. Or if the rotating part has high moment of inertia, a dip in load torque won't be felt.

But for cases which ~~of~~ requires higher precision, we use some thing else.

Permanent Magnet Synchronous Machines (PMSM)

- Sinusoidal EMF



BLDC 1, 6 are ON