Mechatronics

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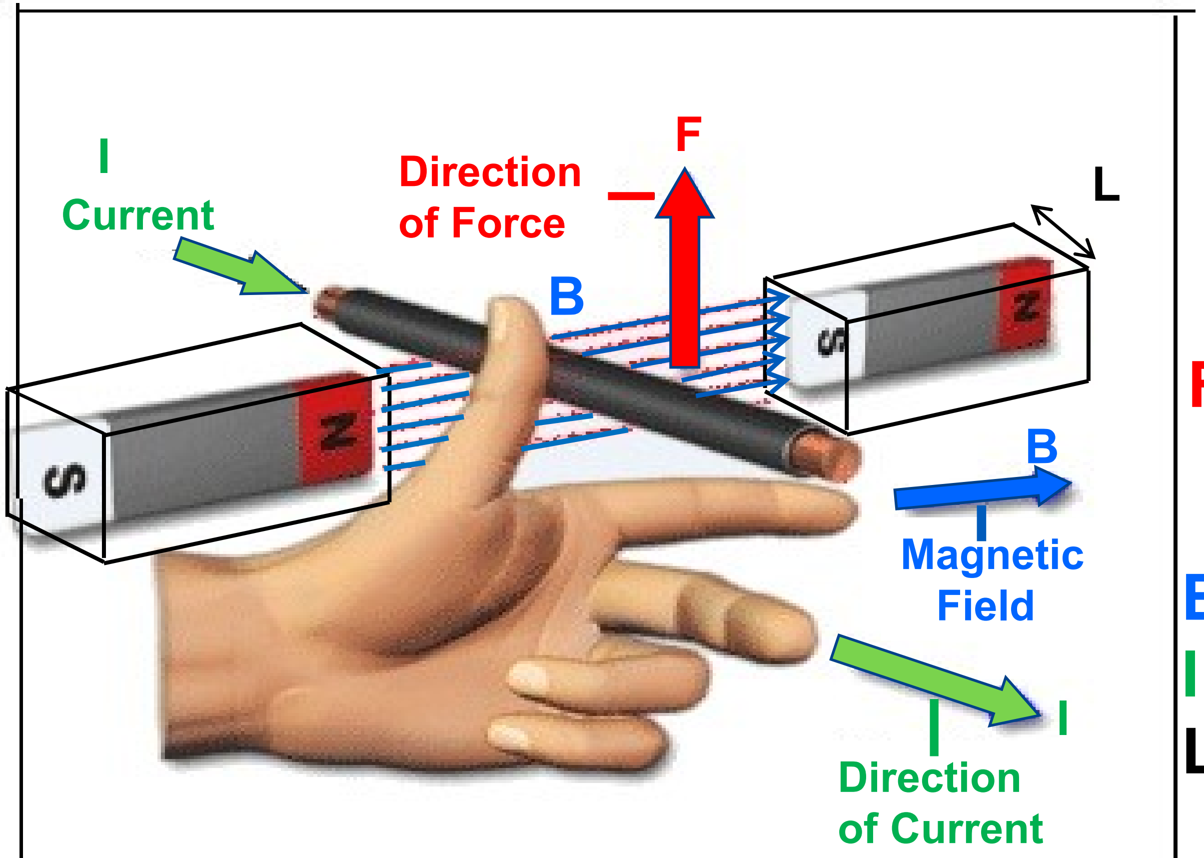
Goal of this lecture

- Understand magnetic field and magnetic circuit
- DC and AC system
- Classification of motors
- Fundamental principle of DC motor and AC motors

Force in motor



Fleming Left Hand rule (motor)

F motor (force : N)= B *I*L

B: magnetic flux density T(Tesla)

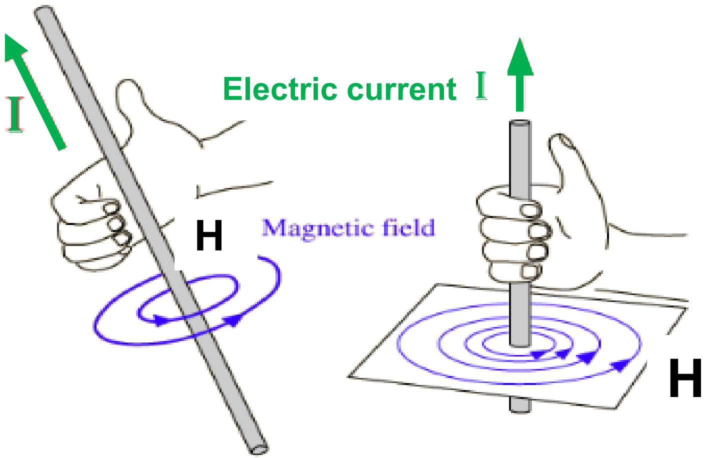
I : current A (Amper)

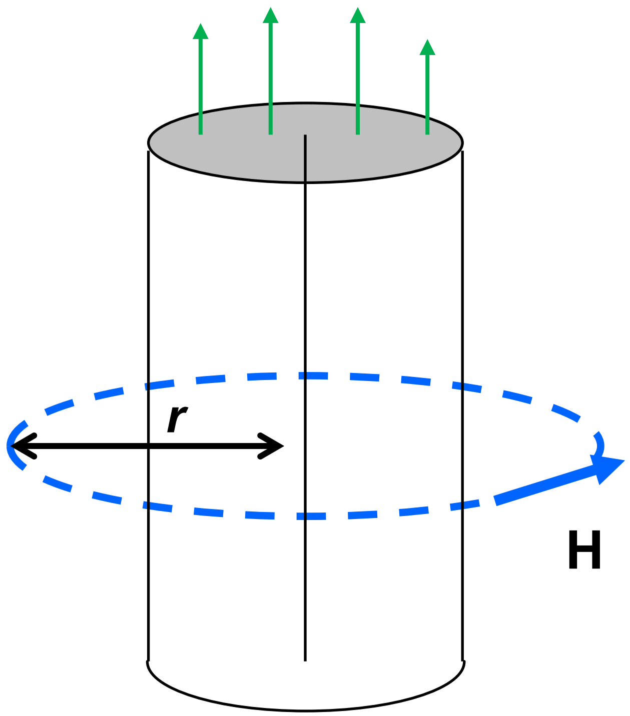
L: length of conductor (wire) in B (meter)

Magnetic field

- **Magnetic field H (A/m) has noting to do with materials**

Right-Hand Rule: Ampere's Circuital Law





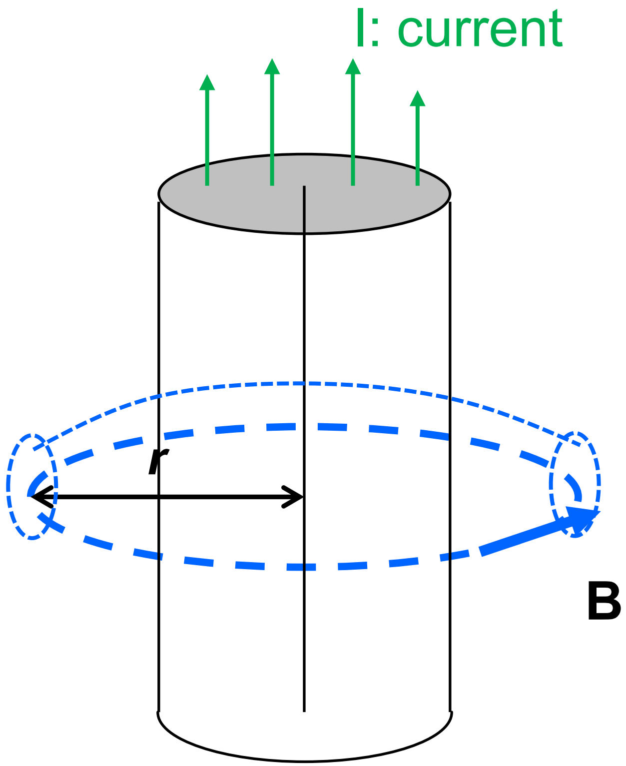
$$\oint_l \vec{H} \cdot d\vec{l} = I$$

$$2\pi r H = I$$

$$H = \frac{I}{2\pi r}$$

Magnetic flux and Magnetic flux density

- **Magnetic flux F (Wb: Weber) and Magnetic flux density B (T: Tesla Wb/m^2)**



If material in green line is air/vacuum or steel,
Magnetic flux (magnetic flux density) is changing

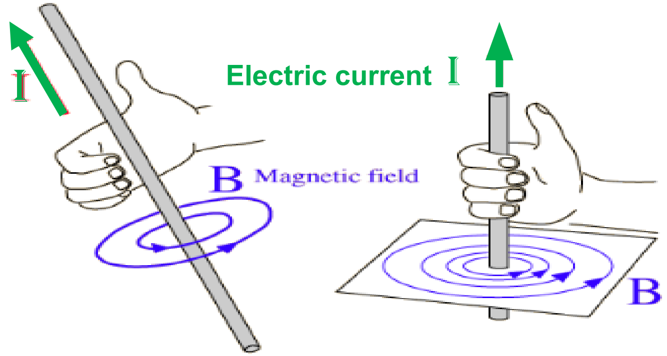
$$B = \mu_0 \text{ (air permeability)} * \mu_r \text{ (relative permeability of material)} * H$$

$$B_{\text{(in air)}} = \frac{I}{2\pi r} * \mu_0 \text{ (air permeability)}$$

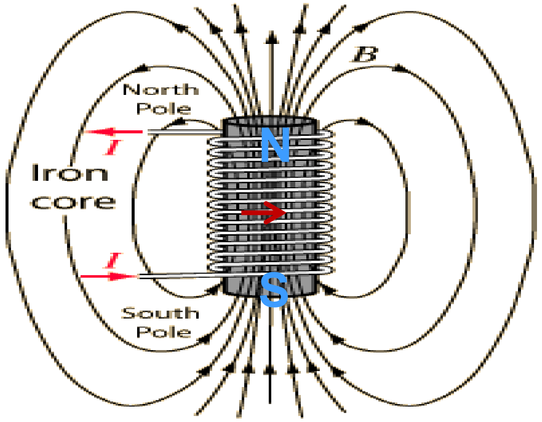
$$B_{\text{(in steel)}} = \frac{I}{2\pi r} * \mu_0 \text{ (air permeability)} * \mu_r \text{ (relative permeability of steel)}$$

Magnetic field

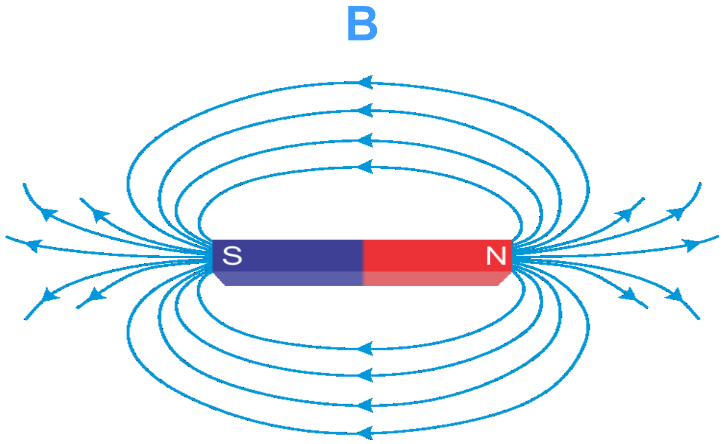
- Magnetic field H (A/m)   Magnetic flux density B (Tesla)
  - Produced by electric current or magnets
  - Direction of the magnetic field is perpendicular to the wire (Right-Hand Rule: Ampere's Circuital Law)



wire(coil)



wire(coil)+steel



permanent magnets

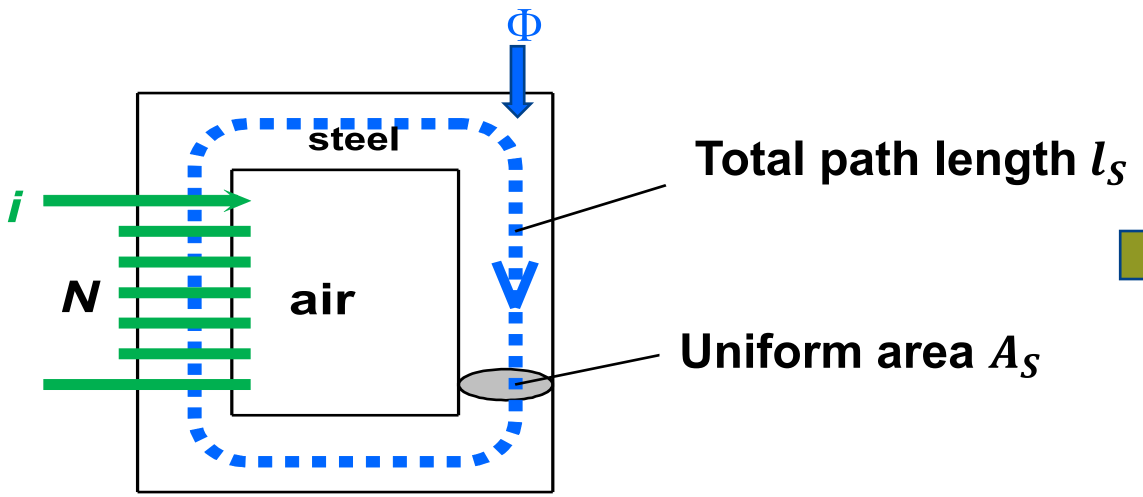
http://www.whatisamagneticfield.com/magnetic_field_generation.html

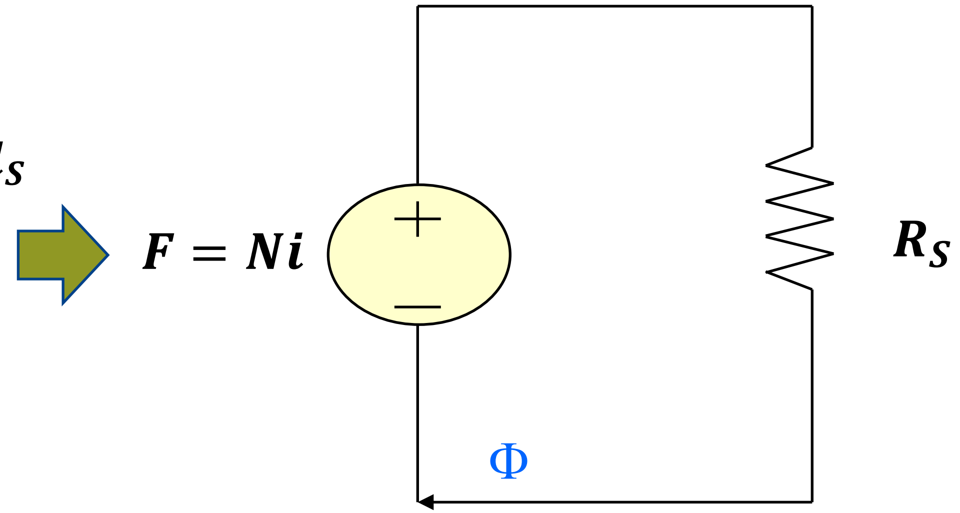
https://www.quora.com/Can-we-create-a-magnet-by-placing-a-metal-in-an-electric-field

https://www.topperlearning.com/answer/a-what-are-magnetic-field-lines-how-is-the-direction-of-a-magnetic-field-at-a-point-determined-b-draw-field-lines-around-a-bar-magnet-along-its-length/br9v335nn

Magnetic field

- **Magnetic flux density B** with iron core(steel)





R_S =(magnetic resistance in steel) = $\frac{l_s}{\mu_s A_s}$

μ_S(Magnetic permeability)

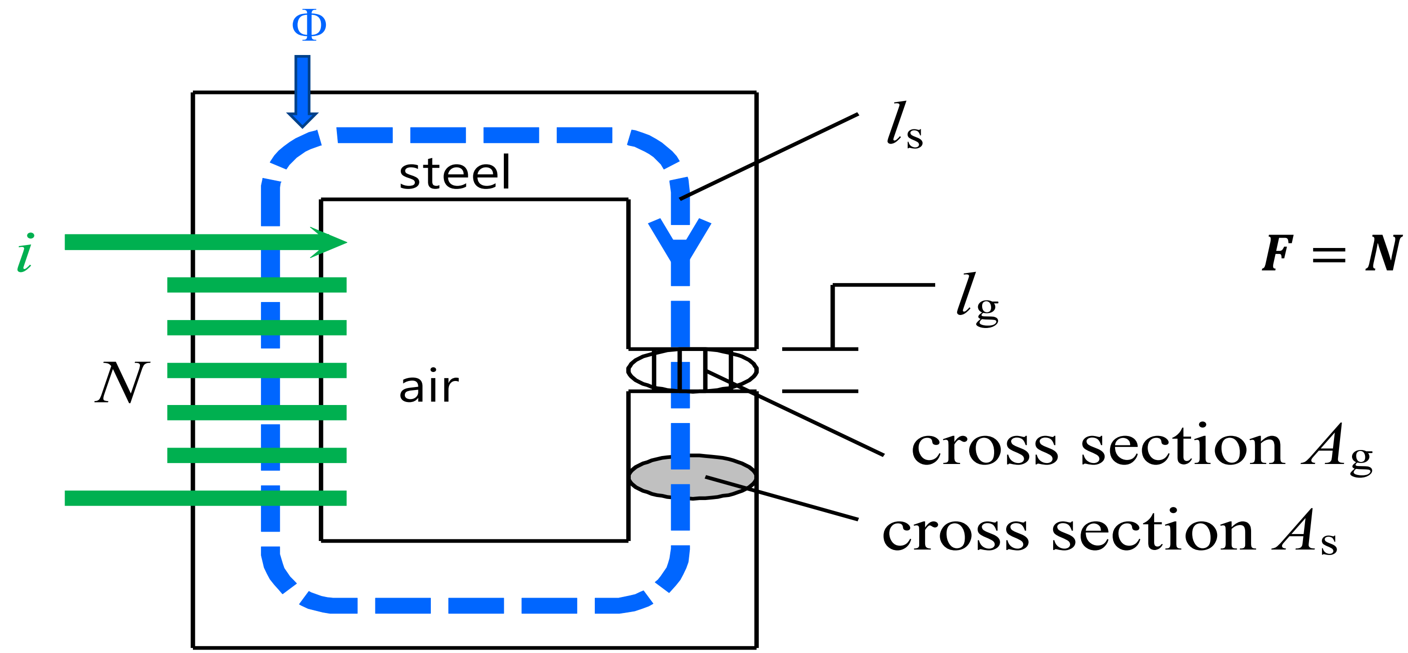
= μ_0 (air permeability) * μ_r (relative permeability)

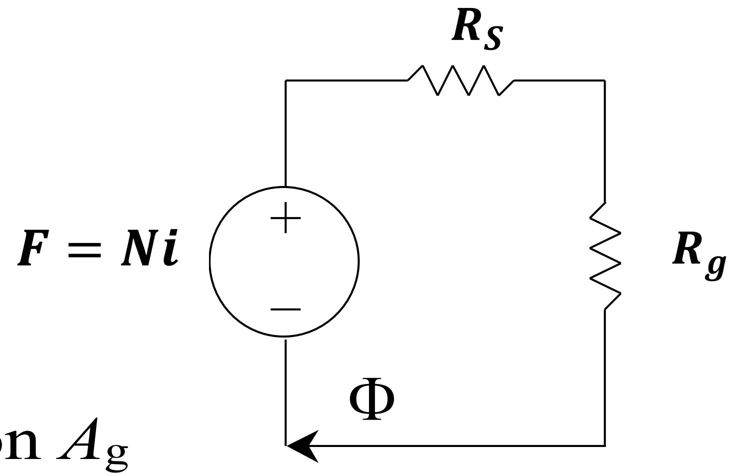
$F = Ni = R_S * \Phi$

$\Phi\ (Magnetic\ \ flux) = F\ /\ R_S$ ⇒ $\Phi = \frac{Ni}{\left[\frac{l_s}{\mu_s A_s}\right]}$ ⇒ $B = \frac{\Phi}{A_s} = \frac{\mu_s Ni}{l_s}$

Magnetic field

- **Magnetic flux density B** with iron core(steel) and air gap





R_g (magnetic resistance in air –gap)

$$F = Ni = (R_S + R_g) * \Phi$$

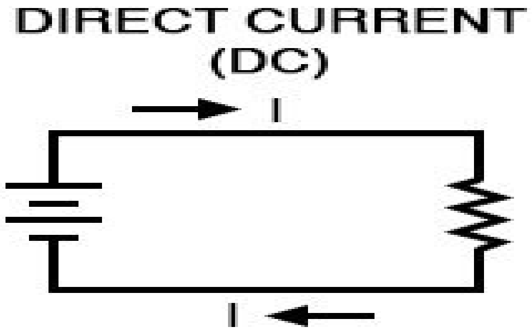
$$Ni = \Phi\left(\frac{l_s}{\mu_s A_s} + \frac{l_g}{\mu_o A_g}\right)$$

Permeability of steel is much greater than that of air in the gap

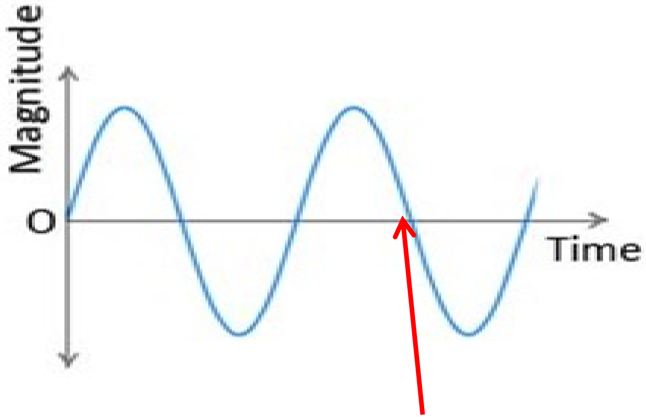
$$Ni \approx \Phi \frac{l_g}{\mu_o A_g} \qquad \Phi \approx \frac{Ni\mu_o A_g}{l_g} \qquad B = \frac{\Phi}{A_g} = \frac{\mu_o Ni}{l_g}$$

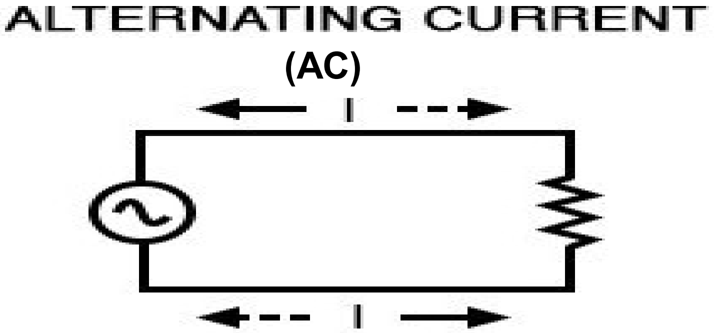
DC and AC system

- DC



- AC



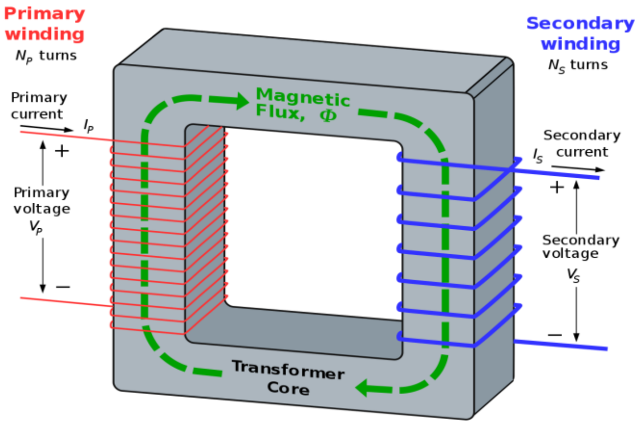


If 60 Hz, 0.0166 sec

DC and AC system

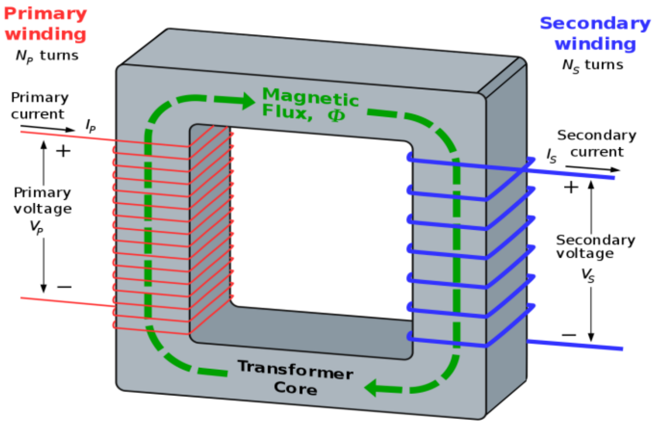
- **AC: transformer**

Np=10
100 V
10 A
1000 W



Ns=5
50 V
20 A
1000 W

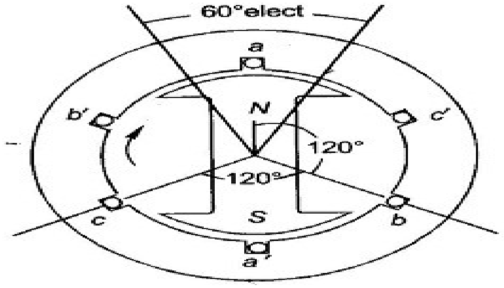
Np=10
100 V
10 A
1000 W



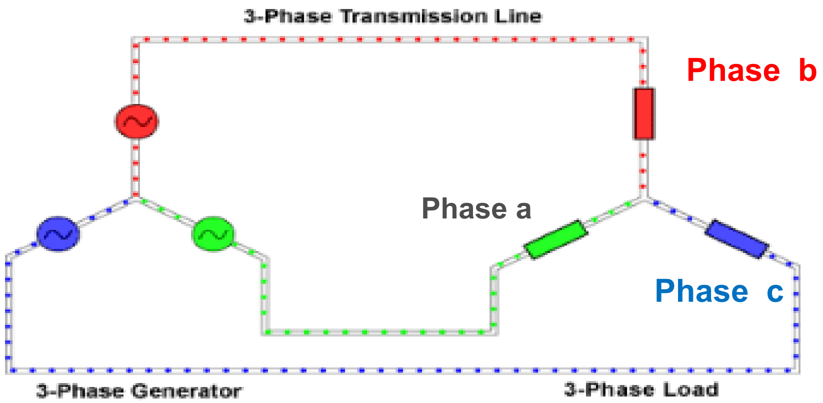
Ns=20
200 V
5 A
1000 W

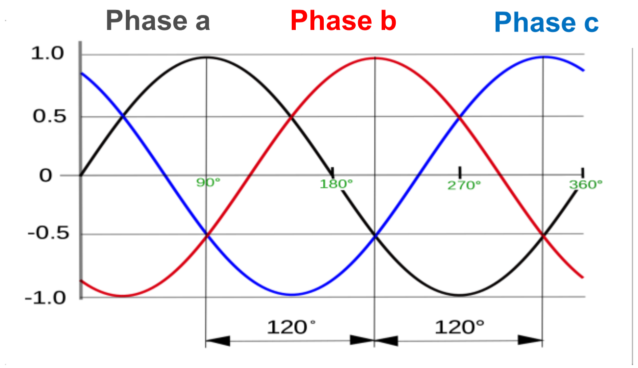
Phase 1

- **AC: three-phase electric power (page 115, 116)**



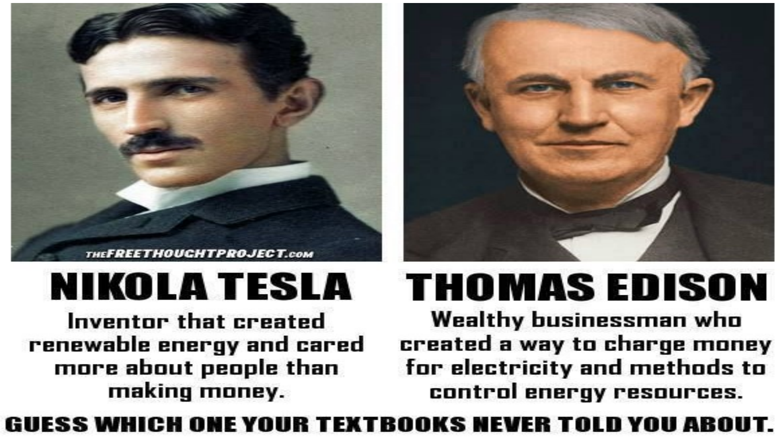
three-phase generator

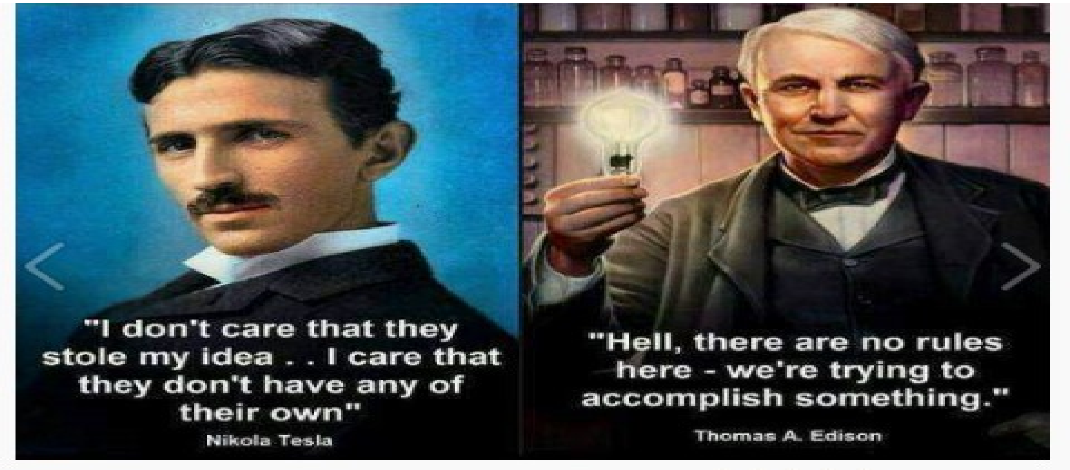


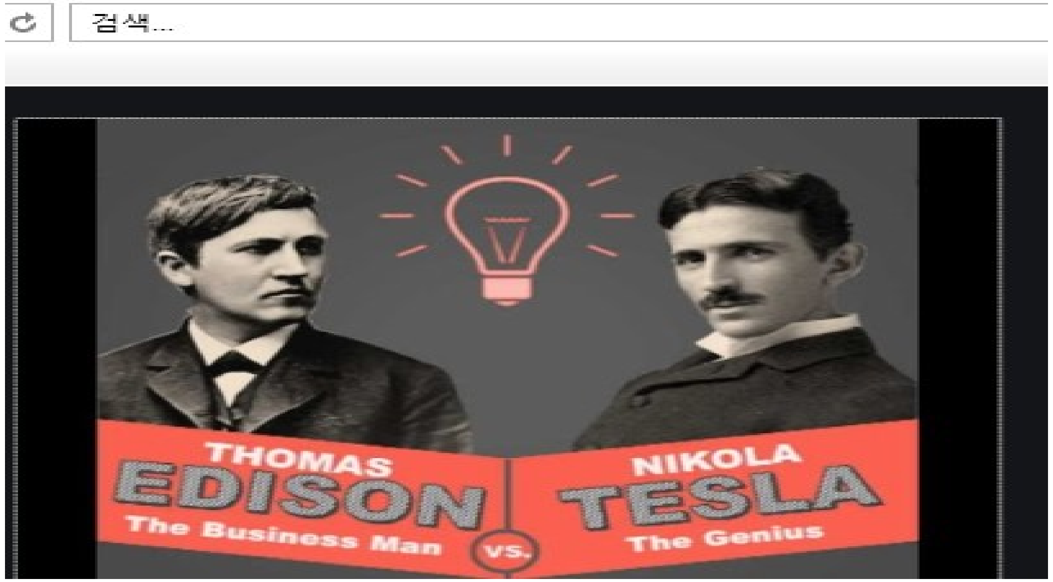


https://en.wikipedia.org/wiki/Transformer
https://en.wikipedia.org/wiki/Three-phase_electric_power

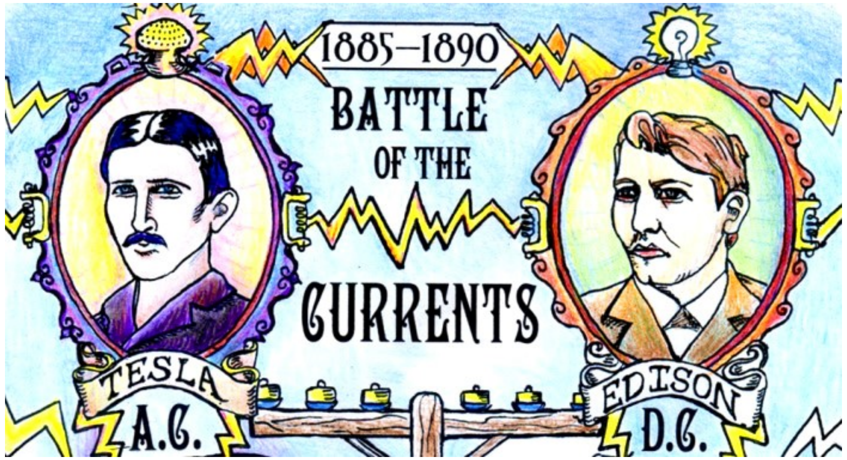
DC and AC system

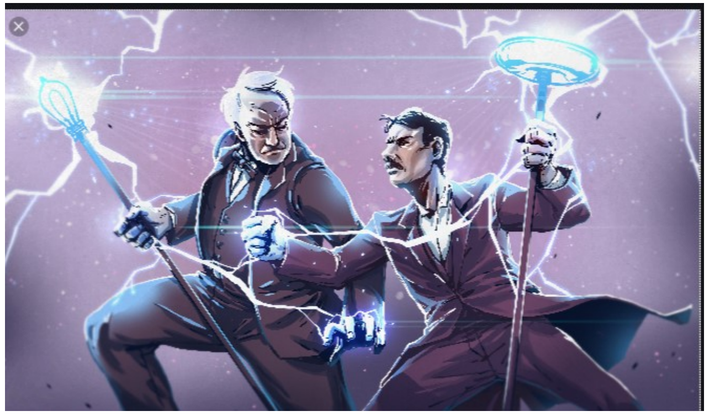






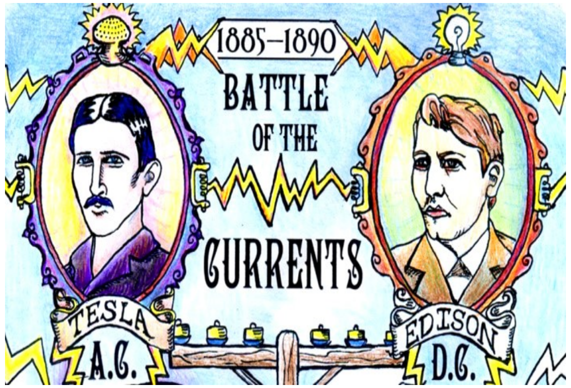
DC and AC system





https://www.youtube.com/watch?v=5UYF23C2Hew

DC and AC system



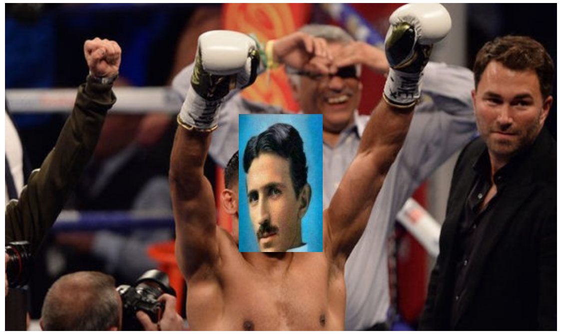
In 1888

Tesla (Westinghouse) Edison (General Electric)

1st match in 1893

Tesla : winner

2nd match in 1895
first AC power plants
at Niagara Falls



Tesla : winner

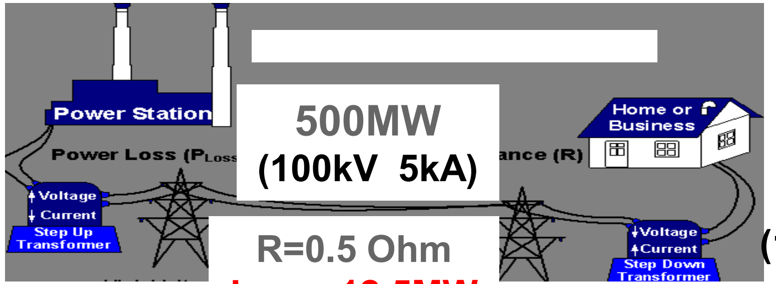
DC and AC system

- Step up transformer : higher voltage

Power line resistance: 0.5 Ohm

Power line resistance loss: 5000*5000*0.5Ohm= 12.5MW (2.5% of power: 12.5MW/500MW)

500MW
(25kV 20kA)



Loss=12.5MW

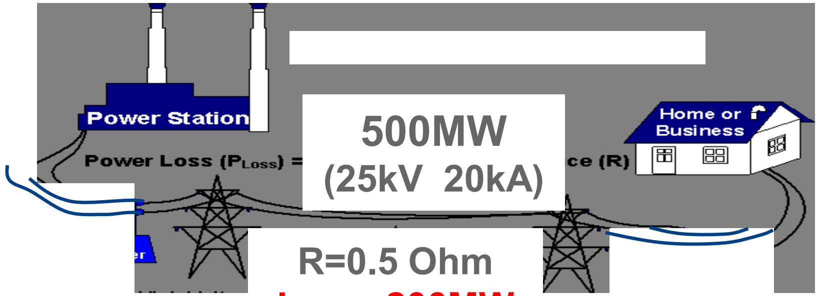
500MW
(100kV 50kA)

- Without step up transformer : lower voltage

Power line resistance: 0.5 Ohm

Power line resistance loss: 20000*20000*0.5Ohm= 200MW (40% of power: 200MW/500MW)

500MW
(25kV 20kA)



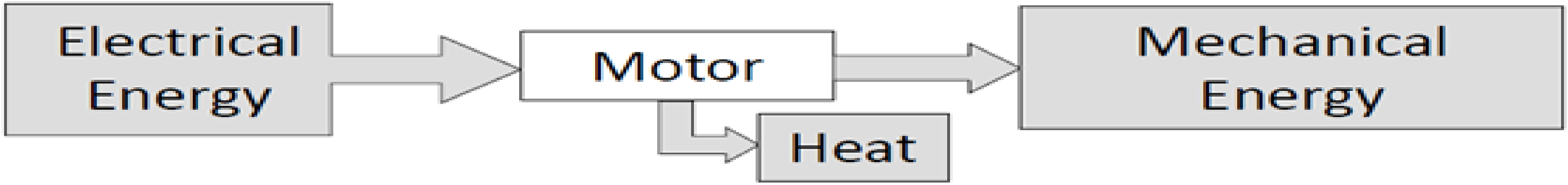
Loss=200MW

500MW
(25kV 20kA)

http://www.cmm.gov.mo/eng/exhibition/secondfloor/MoreInfo/2_4_3_HighVoltage.html

Classification of motors

- Electric Motor converts elec. energy into mechanical energy



Energy conversion in electric motors is most commonly based on ***electromagnetism***. AC motors rely on *alternating current* to establish the desired magnetic fields, while DC motors use *direct current.*

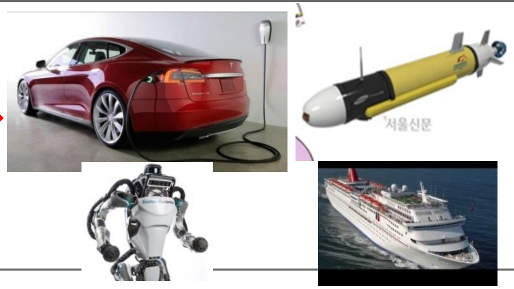
Electrical Energy In > Mechanical Energy Out

Efficiency = output mechanical energy / input electrical energy

Classification of motors

- Electrical Motor Technical Requirements

Electric Energy	Electric Motor	Mechanical Energy
Power Source	Rotary & Linear	Rotation & Translation



✓ **High Efficiency (out-put/in-put) : Loss Reduction**
-save energy and battery
-Battery for EV 30,000 US$ VS motor for EV 3,000 US$
-motor 5% efficiency up → save battery 1,500 US$

✓ **High Power Density(power/weight):Weight Reduction**
-compact system and save energy

✓ **High Accuracy(nano-micro meter accuracy) : Precision**

Classification of motors

- AC/DC Motor

Force in motor: Fleming's left hand rule

F=B*I*L

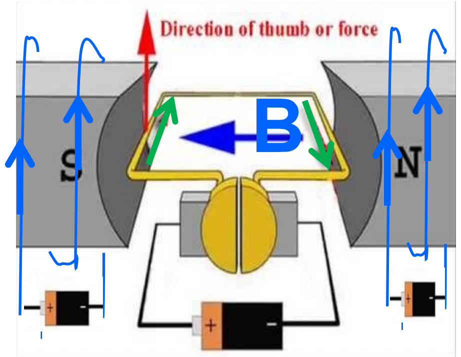
B: magnetic flux density

I: Current direction in coil

L: Coil length

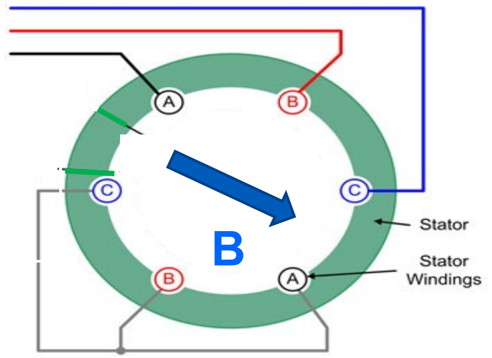
DC motor: B magnetic flux by DC current or permanent magnet

AC motor: B magnetic flux by AC current (page 117)



DC motor: B magnetic flux

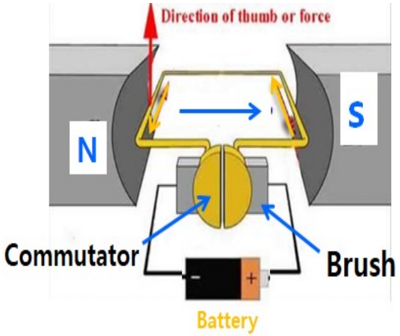
3- phase
AC current

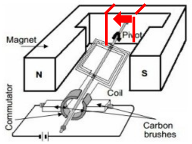


AC motor: B magnetic flux

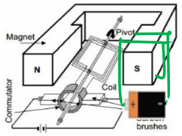
Classification of motors

- Electric Motors
  - DC Motors
    - Brushed
      - Permanent Magnet
      - Separately Excited
    - Brushless
      - Stepper
  - AC Motors
    - Synchronous
      - Reluctance
      - Permanent Magnet
    - Induction

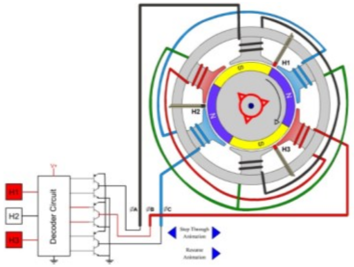


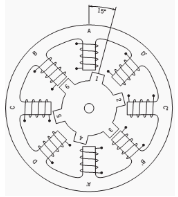


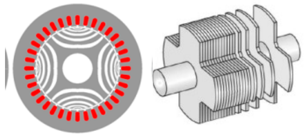
PM

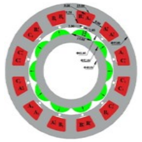


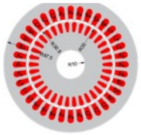
Separately Excited











Classification of motors

- Electric Motors
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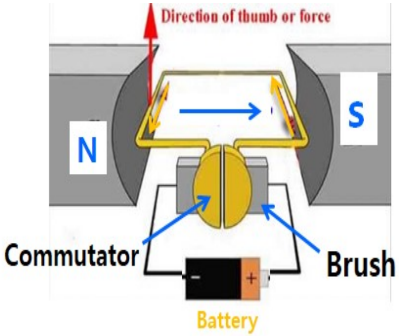
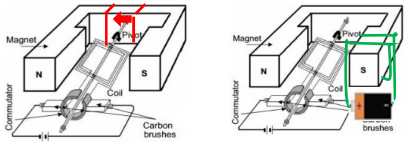
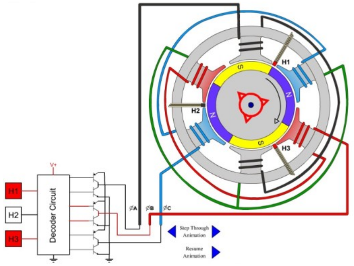
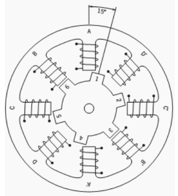


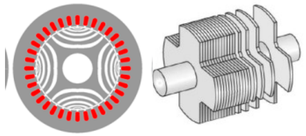


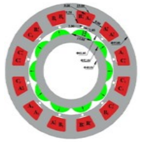
PM

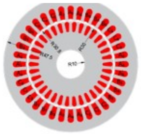
Separately Excited







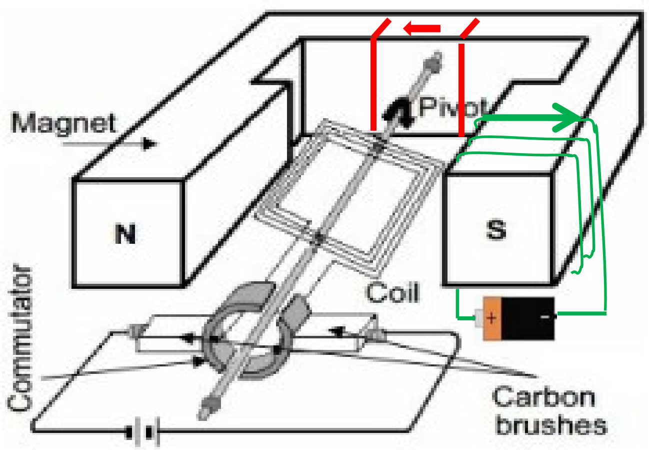




Classification of motors

-permanent magnet(no power) or

-Separately Excited: electric magnet



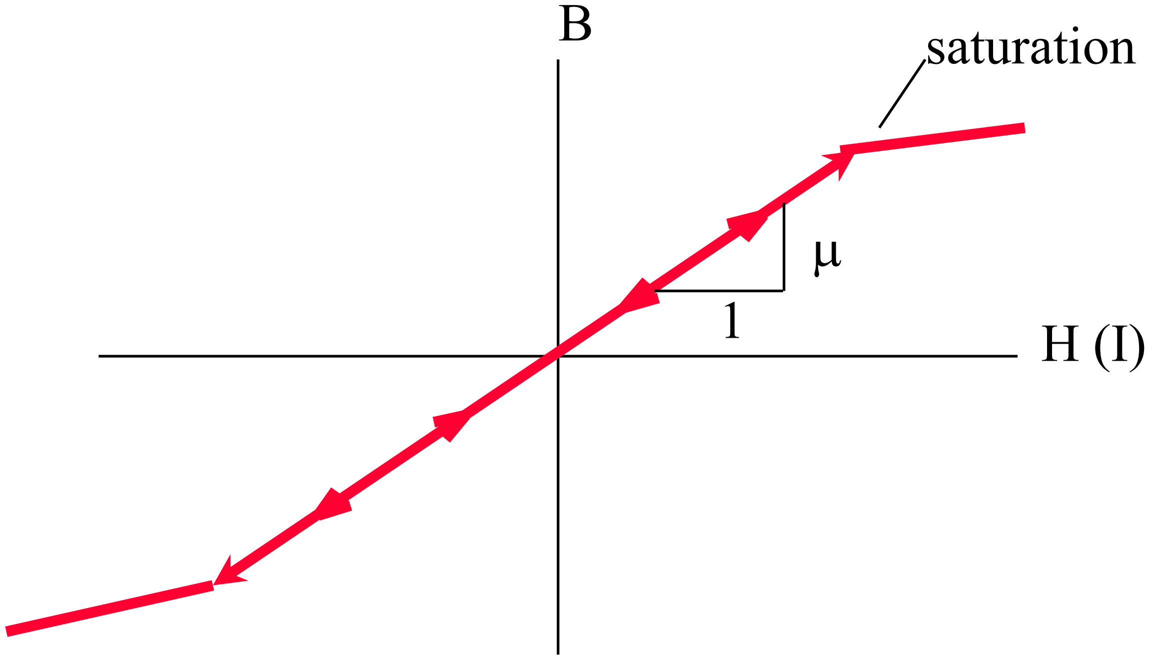
If permanent magnet is magnetized by pulse current,
PM can have magnetic flux without any thing.
But PM can be demagnetized by high temperature and high reverse magnetic flux.

https://www.google.co.kr/search?tbm=isch&q=dc+motor+principle&chips=q:dc+motor+principle,online_chips:generator,online_chips:magnetic&sa=X&ved=0ahUKEwjd-t_3gY7kAhXDJaYKHfrUACMQ4IYIMygJ&biw=2163&bih=1049&dpr=0.8#imgrc=0mLQjwqmIPudsM:&spf=1566186140824

Classification of motors

- Limit of motor force **in coil : F=B*I*L**

  - **B** magnetic flux density in motor: 1.5(Tesla) because of saturation



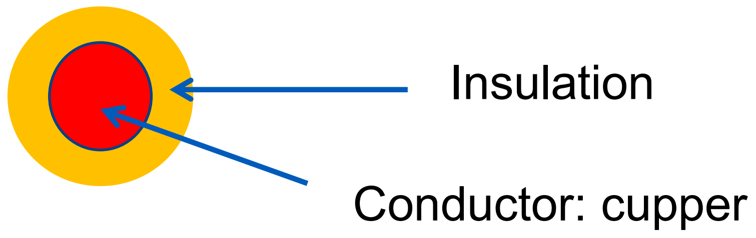
Pure iron (high μ)

Classification of motors

- Limit of motor force **in coil : F=B*I*L**

- I Current: is limited by cupper loss (heat)
  current density in coil is 4-10 A/mm ^{2}

- Max current density in coil depends on cooling system
- Water and oil cooling system up to 10-20 A/mm ^{2}
- The electric current density is measured in amperes per square meter



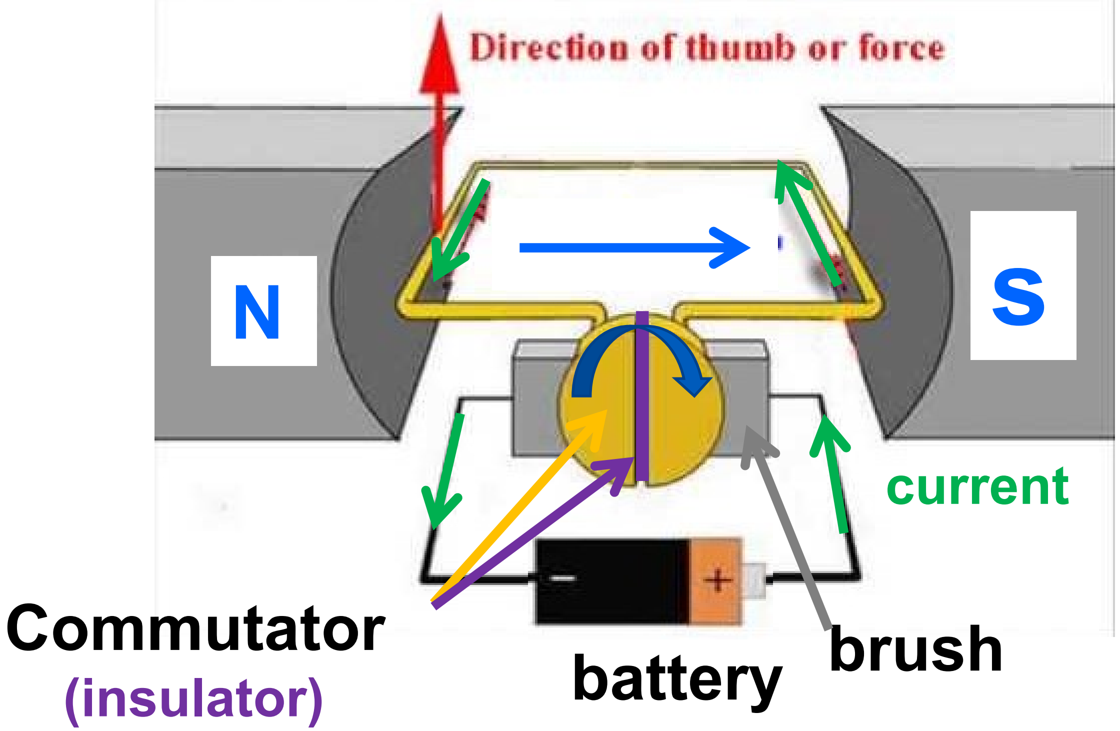
The current density = current in conductor /conductor area

DC motor working principle from Fleming's left hand rule

-B magnetic field : from N to S

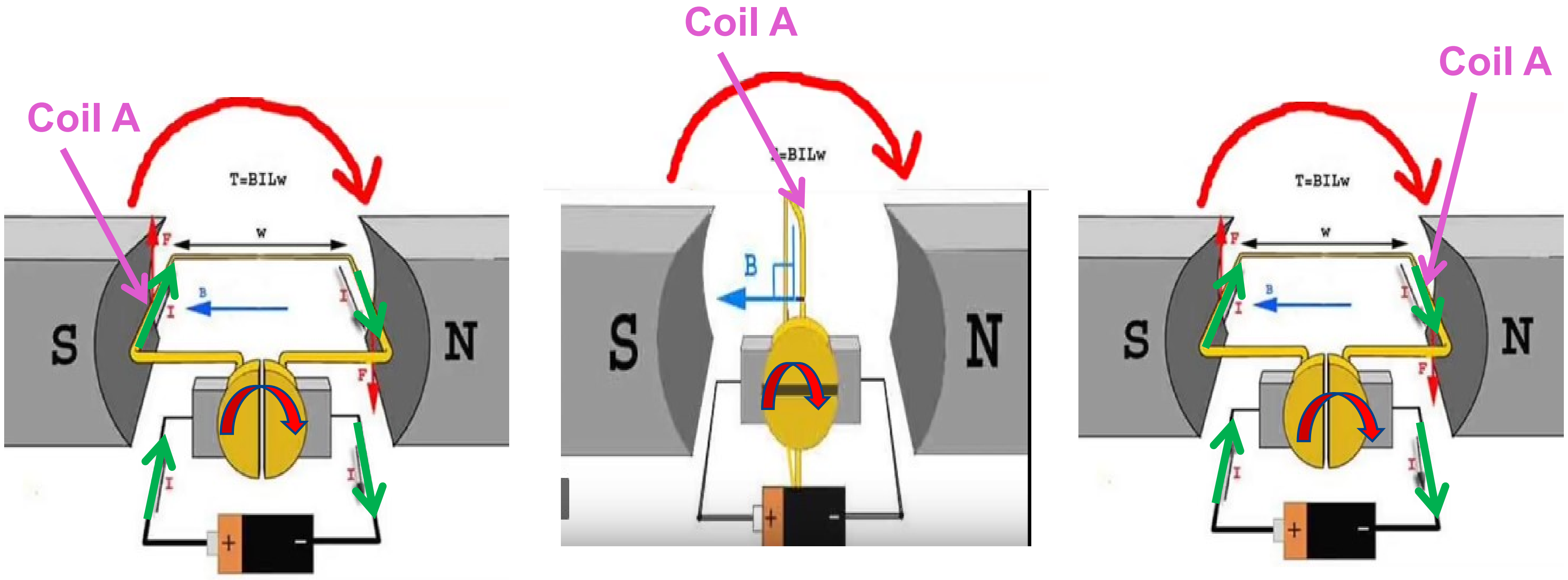
-I current direction in coil:

from battery +, brush, commutator, coil, commutator, brush to battery –



DC motor working principle from Fleming's left hand rule

- **Function of commutator and brush**



F=B*I*L

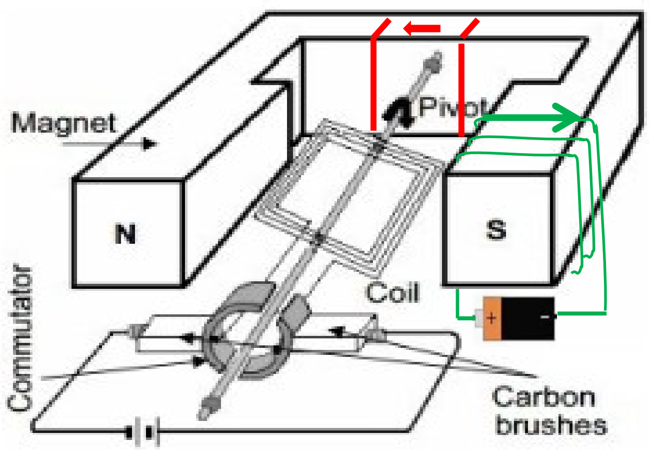
F=0

F=B*I*L

DC motor working principle from Fleming's left hand rule

- How to make B magnetic field

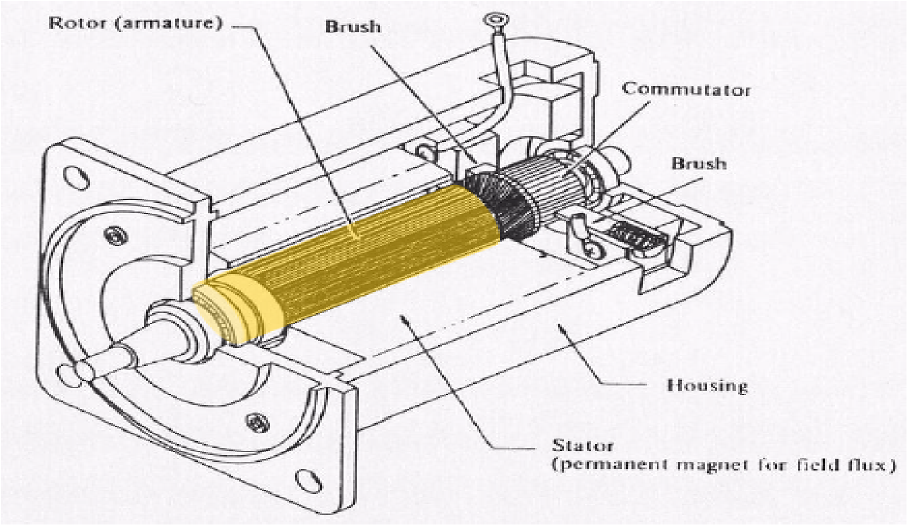
-permanent magnet or electric magnet



https://www.google.co.kr/search?tbm=isch&q=dc+motor+principle&chips=q:dc+motor+principle,online_chips:generator,online_chips:magnetic&sa=X&ved=0ahUKEwjd-t_3gY7kAhXDJaYKHfrUACMQ4IYIMygJ&biw=2163&bih=1049&dpr=0.8#imgrc=0mLQjwqmIPudsM:&spf=1566186140824

DC motor working principle from Fleming's left hand rule

● Rotor: mechanical terms



Motors are actuation devices (actuators) that generate ***torque***.

Mechanical Terms

- **Rotor**: rotating part of the motor.
- **Stator**: stationary part of the motor.
- **Commutator**: part of rotor in contact with the brushes
- **Brushes**: part of electrical circuit through which current is supplied to armature.

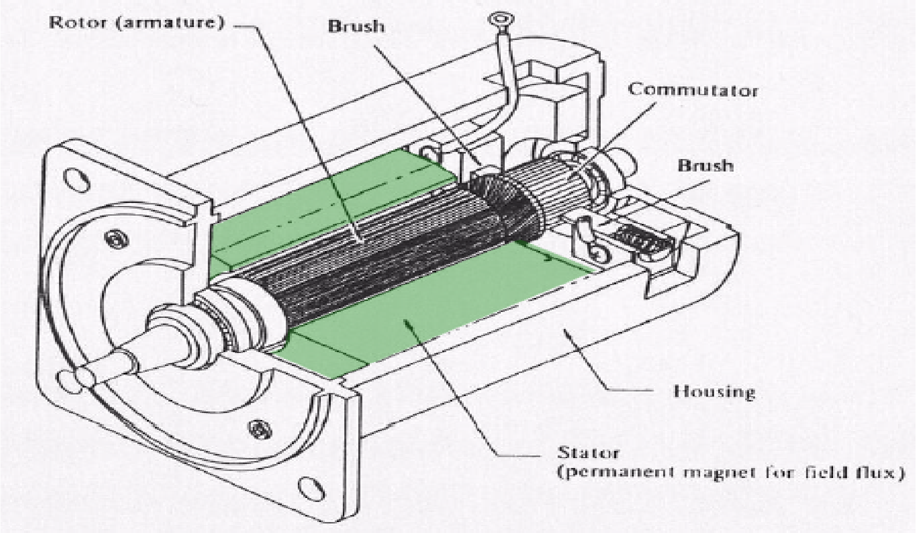
DC motor working principle from Fleming's left hand rule

- **Rotor: mechanical terms**

Image: https://en.wikipedia.org/wiki/File:Electric_Motor_Rotor.jpg
http://motorcorechina.com

DC motor working principle from Fleming's left hand rule

● **Stator : mechanical terms**



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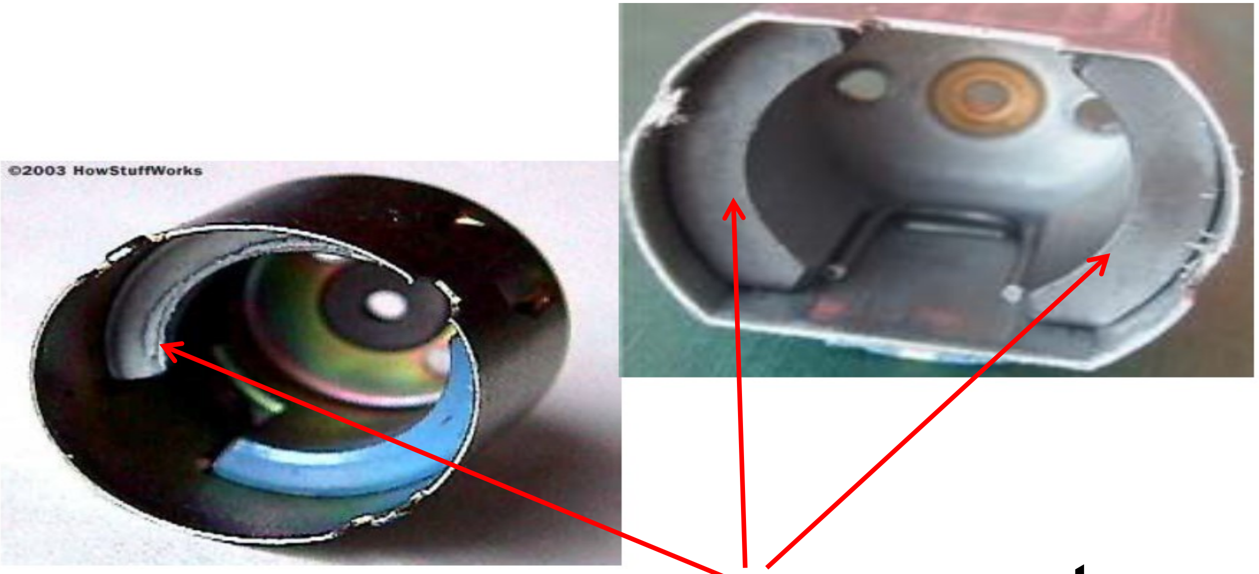
DC motor working principle from Fleming's left hand rule

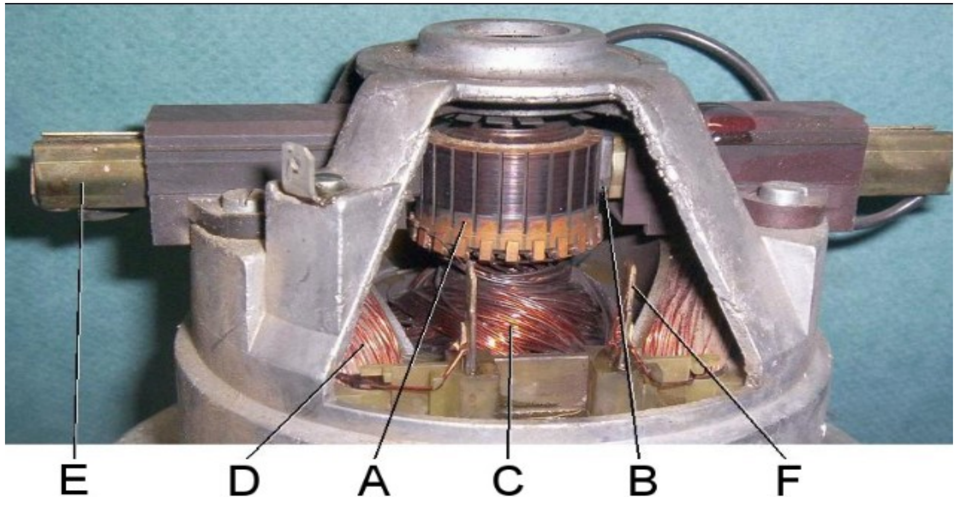
- **Stator : mechanical terms**

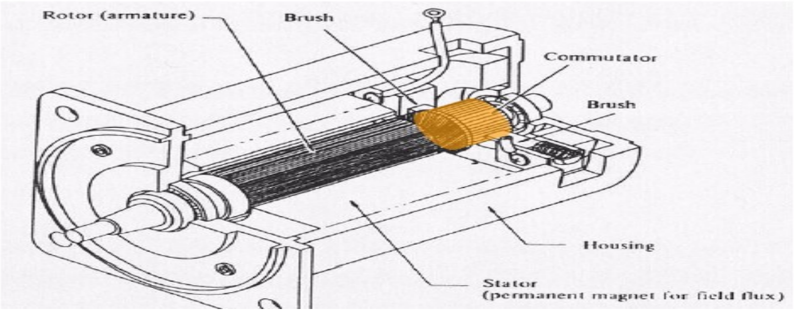


Images: http://static.howstuffworks.com/gif/
http://www.johnsonelectric.com/common/en/images/resources-for-engineers/automotive-applications/motion-technology/pmdc-motor/basic-configuration-04.jpg

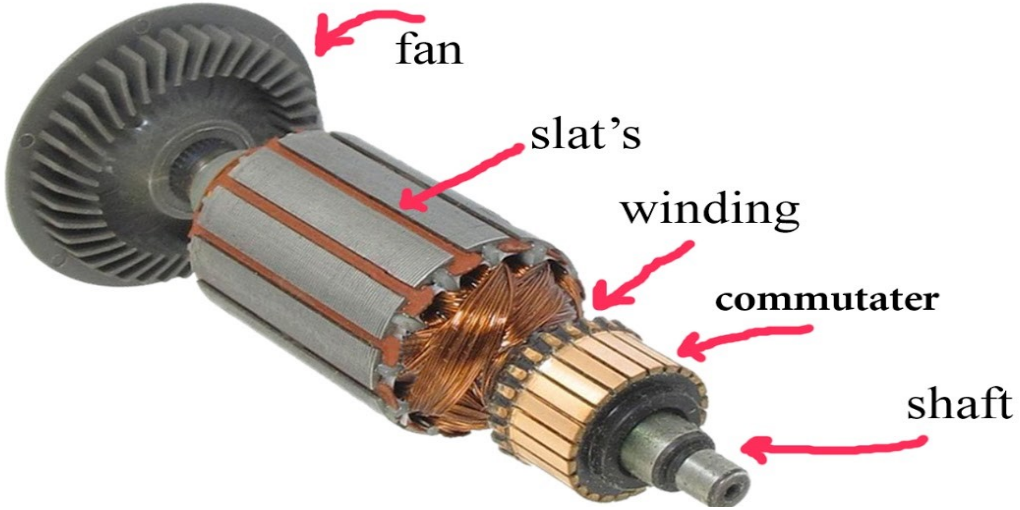
DC motor working principle from Fleming's left hand rule

- Commutator : mechanical terms





Parts: *(A)* commutator, *(B)* brush, *(C)* rotor (armature) windings, *(D)* stator *(F)* (field) windings, *(E)* brush guides

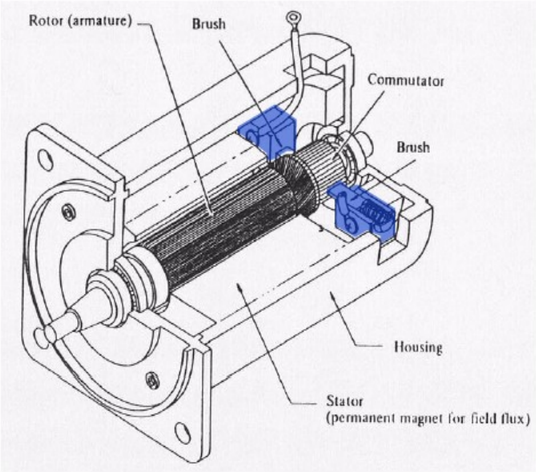


https://en.wikipedia.org/wiki/Commutator_(electric)#/media/File:Universal_motor_commutator.jpg

https://www.technicalbabajan.com/2017/11/what-is-armature-armature-kya-armature.html

DC motor working principle from Fleming's left hand rule

●Brush : mechanical terms

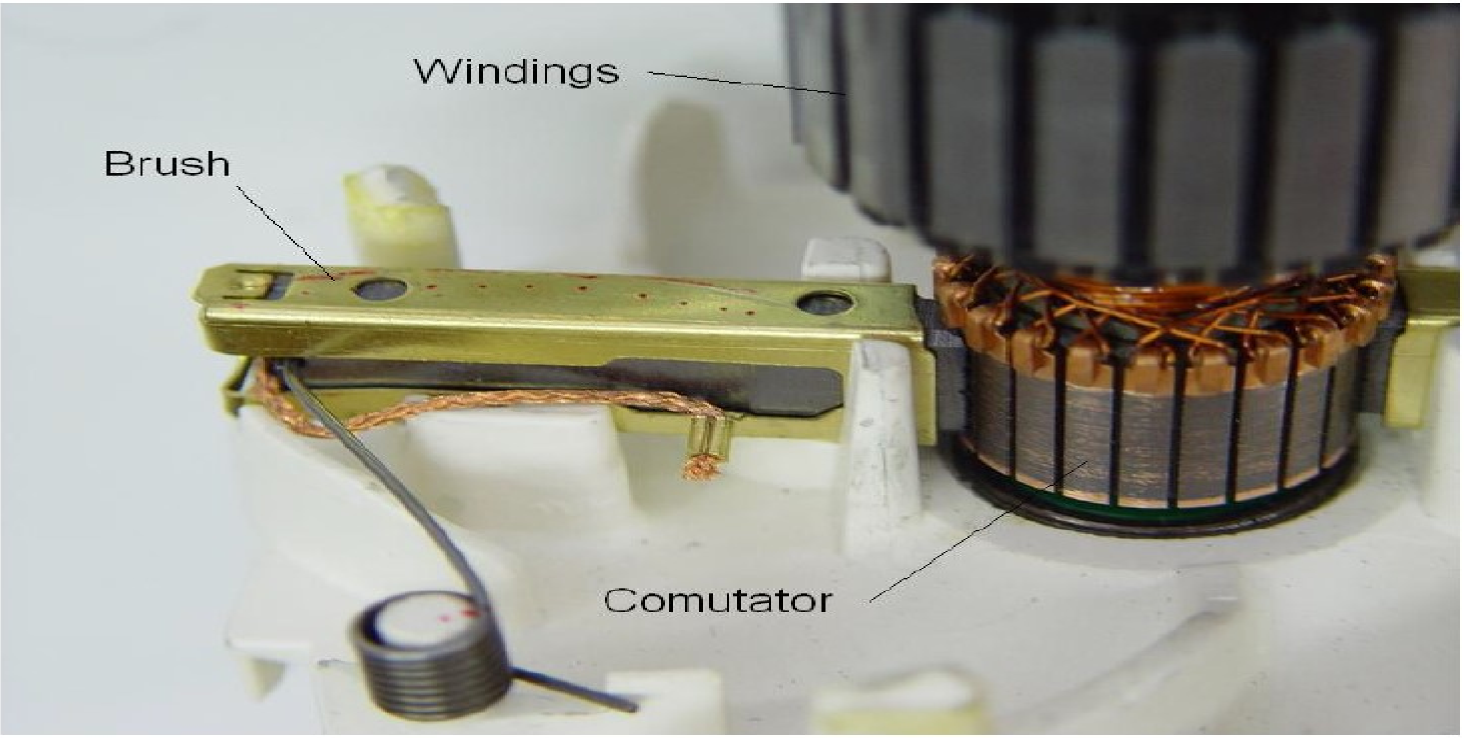


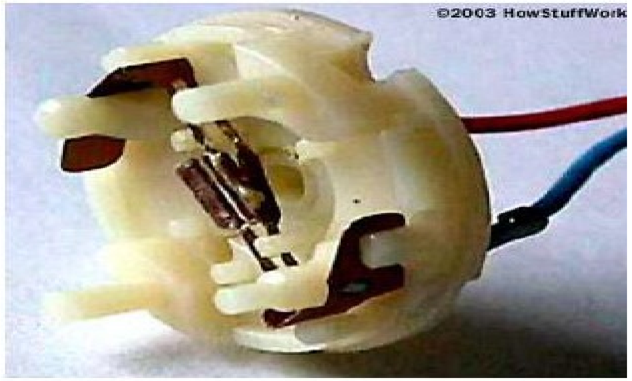
https://www.indiamart.com/proddetail/dc-motor-carbon-brushes-8580964291.html

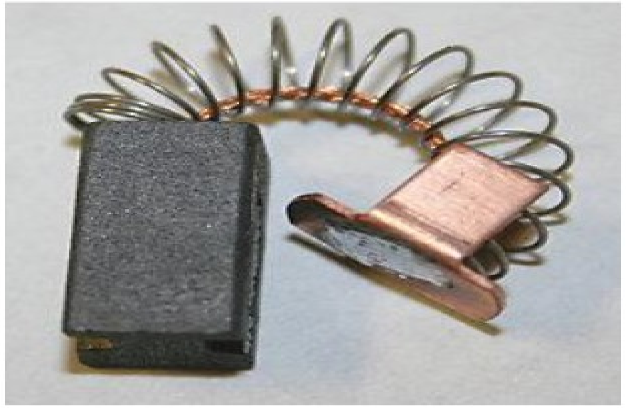
https://www.indiamart.com/proddetail/dc-motor-carbon-brush-18403148033.html

DC motor working principle from Fleming's left hand rule

- **Brush : mechanical terms**







DC motor working principle from Fleming's left hand rule

- **Commutator and brushes : mechanical terms**

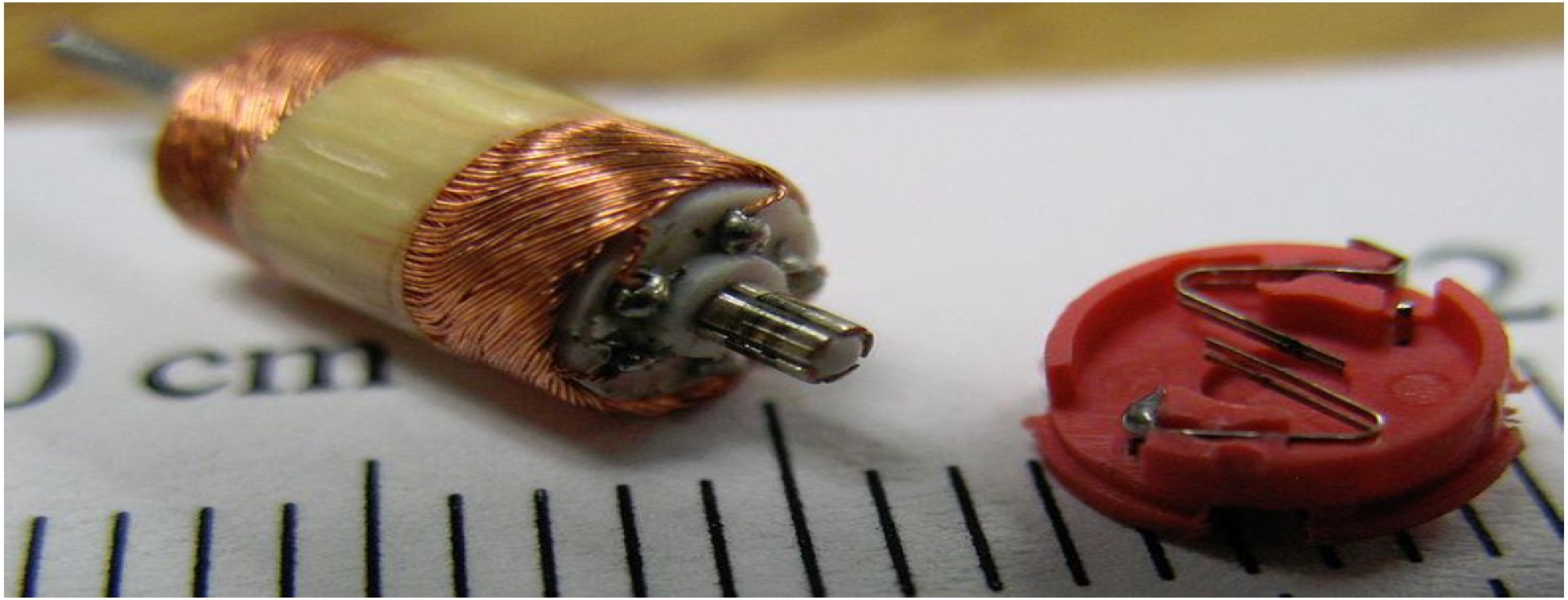


Image: https://en.wikipedia.org/wiki/File:Tiny_motor_windings_-_commutator_-_brushes_in_Zip_Zaps_toy_R-C_car.jpg

DC motor working principle from Fleming's left hand rule

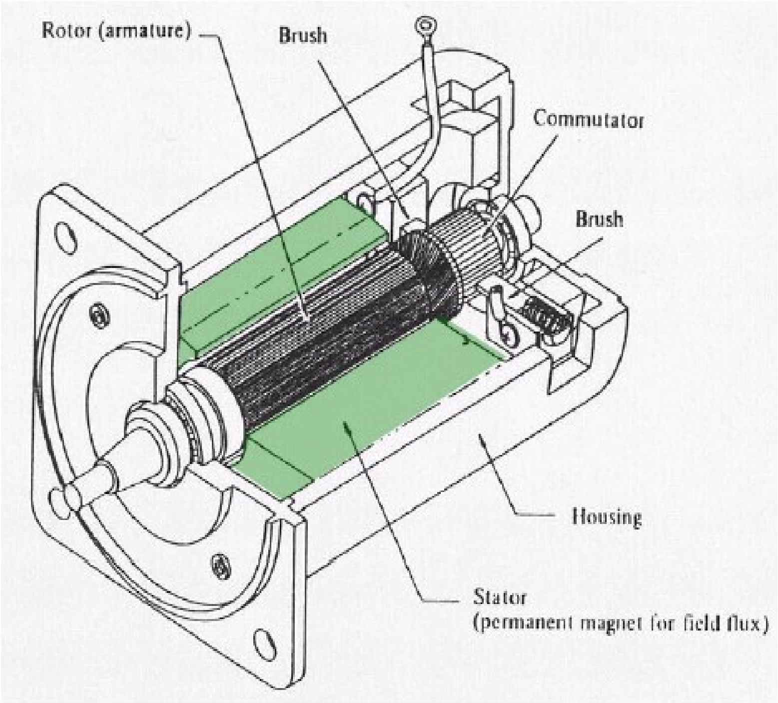
●Brush :week point for brushed DC motors

Brushes tend to:

- Wear out
- Generate electrical (and acoustic) noise
  - Copper-graphite (cheaper, more current, more noise)
  - Precious metal (more expensive, less current, less noise)
- Limit maximum voltage

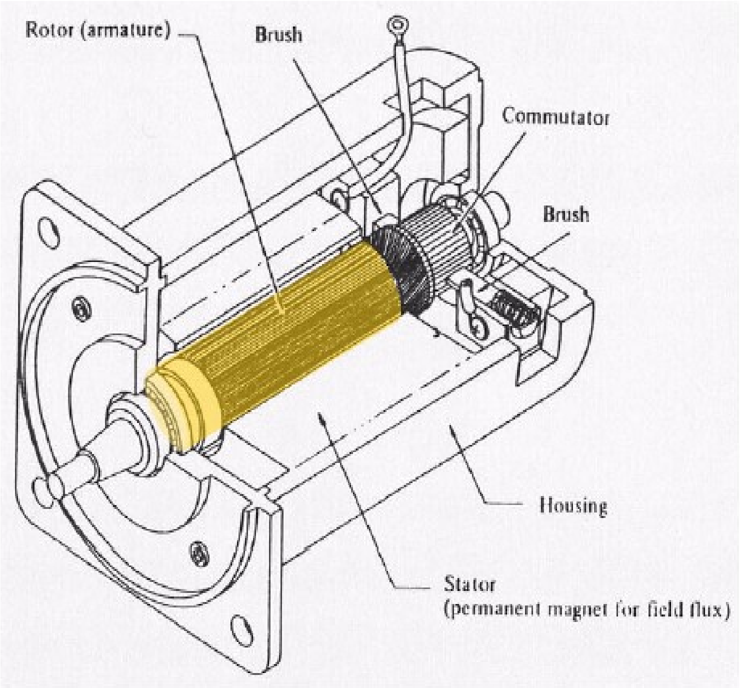
DC motor working principle from Fleming's left hand rule

- **Field system: electrical terms**



DC motor working principle from Fleming's left hand rule

- **Armature: electrical terms**



DC motor working principle from Fleming's left hand rule

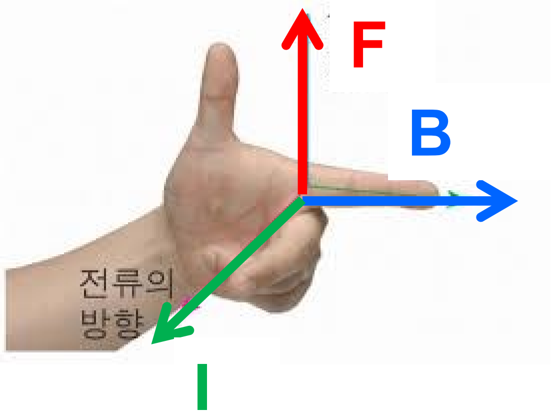
- **Force and torque**

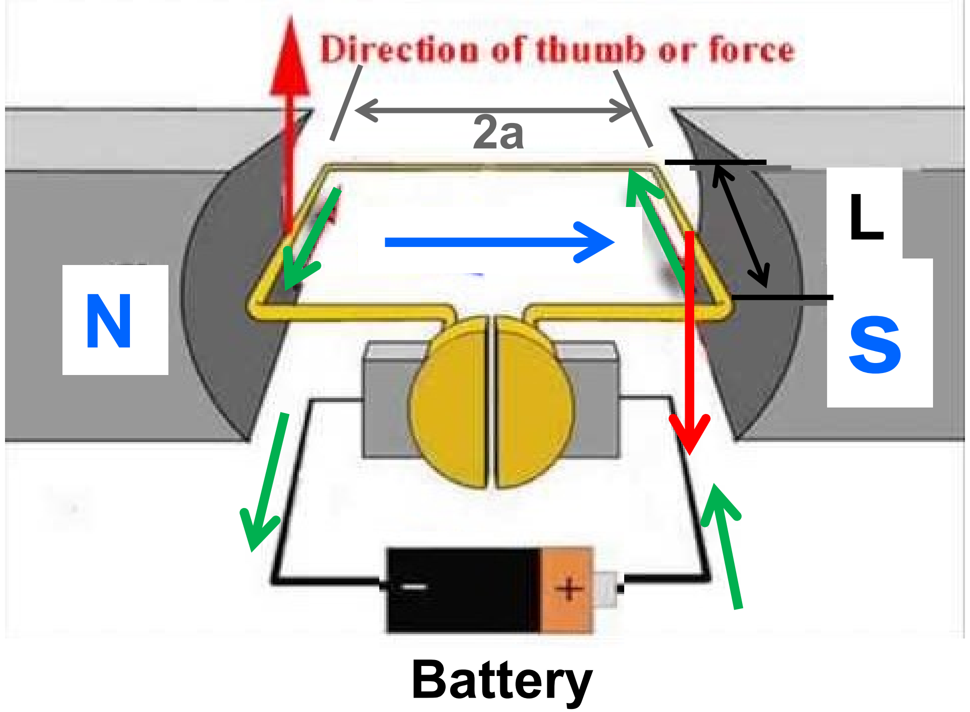
-B magnetic field : from N to S

-I current direction in coil: from battery + to battery –

-F force in coil : F=B*I*L

-T torque = 2(two coils)*F* a





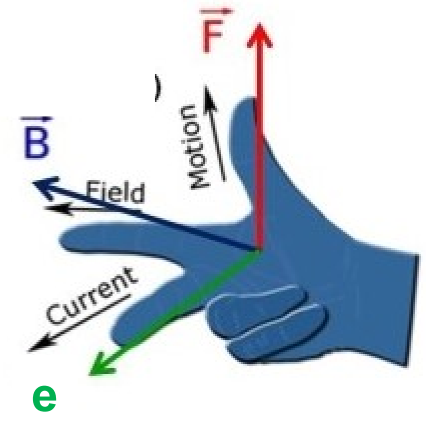
DC motor working principle from Fleming's right hand rule

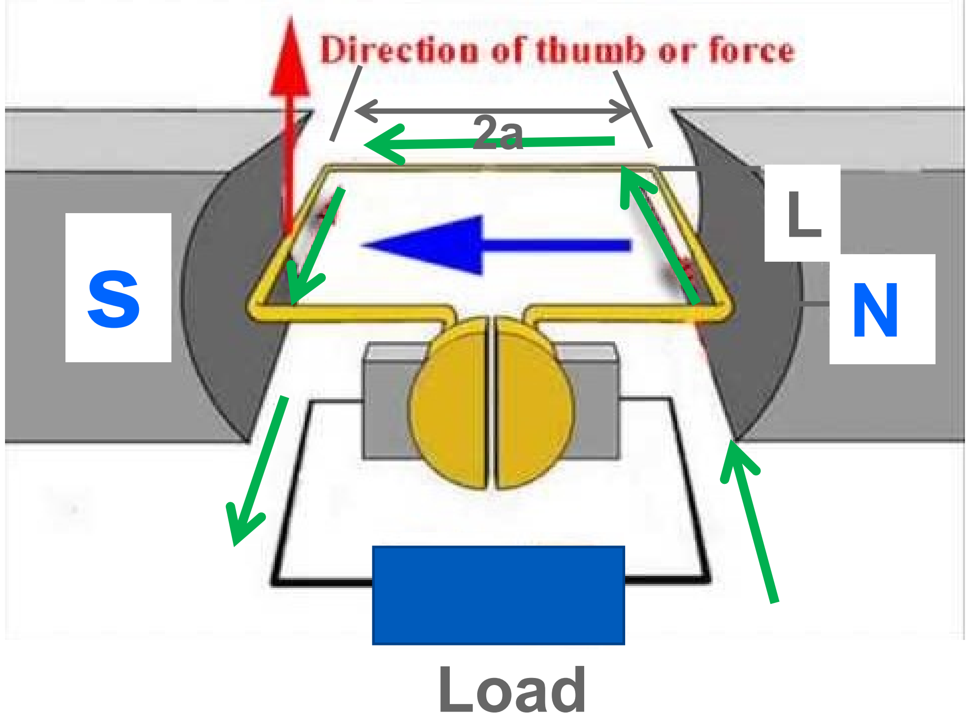
- **Fleming's right hand rule: generator**

-B magnetic field : from N to S

-F force in coil with speed v

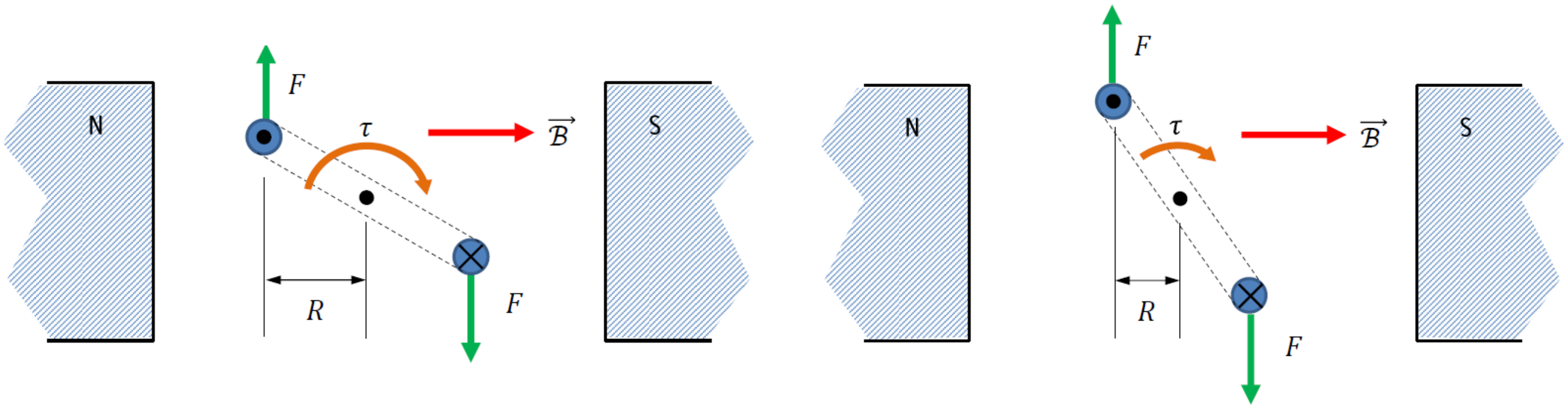
-e Induced voltage: e=B*v*L

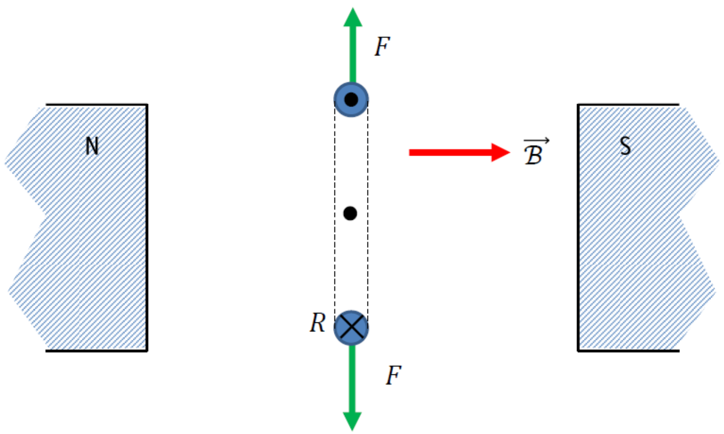


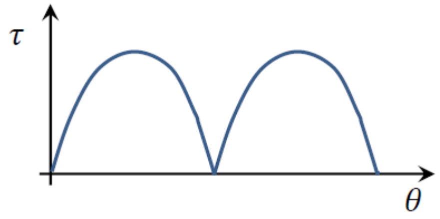


DC motor working principle from Fleming's left hand rule

- **Force and torque**





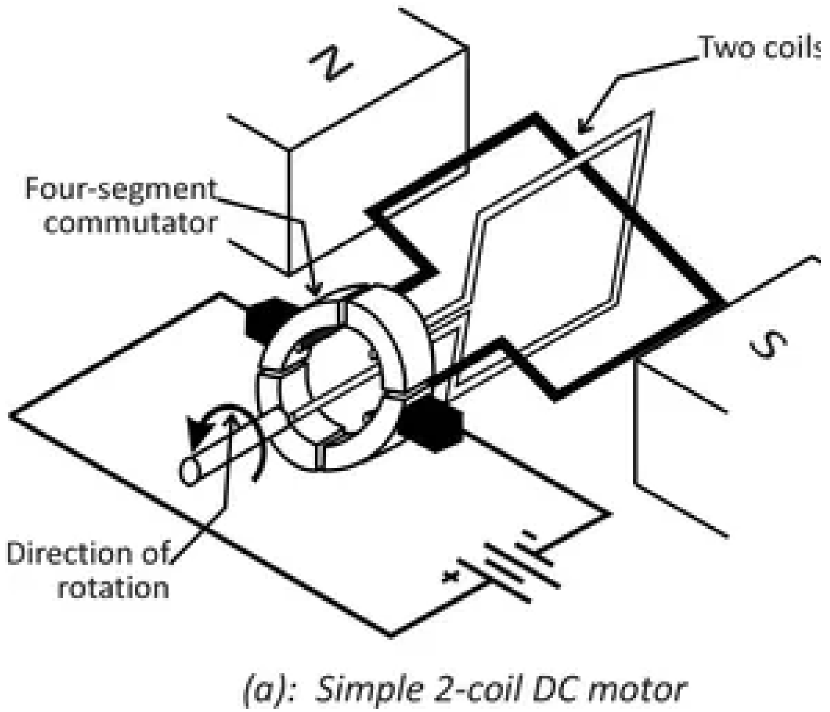


Single Phase, Two Pole

No torque at all, what shall we do ???

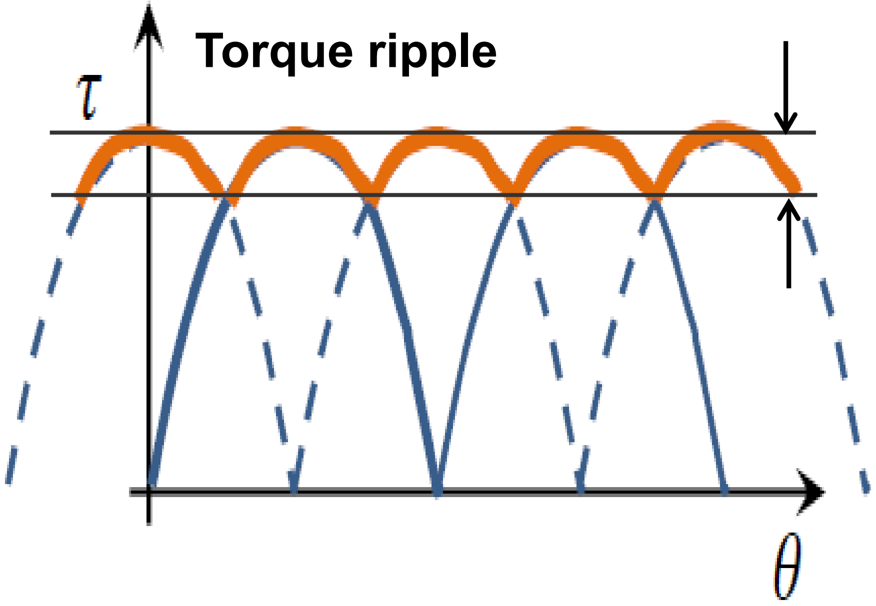
DC motor working principle from Fleming's left hand rule

- **Force and torque**



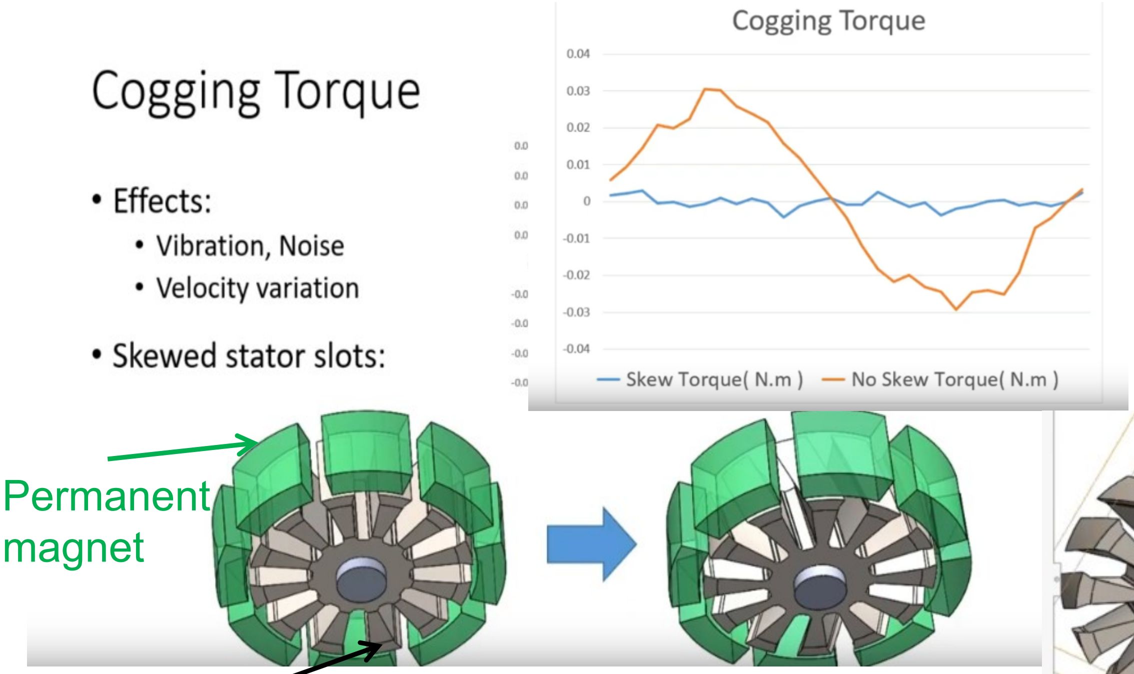
4 segment commutator and two coi

https://www.quora.com/I-could-not-understand-how-does-an-electric-motor-work-and-why-do-we-use-commutator-how-do-they-reverse-the-direction-of-the-current



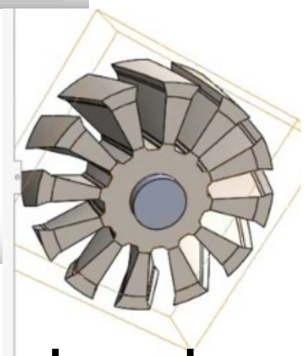
DC motor working principle from Fleming's left hand rule

- **Force and torque**

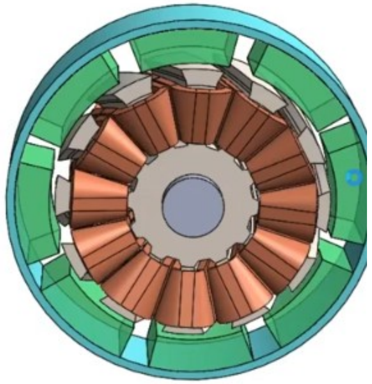


Permanent magnet

Iron core



skewed core



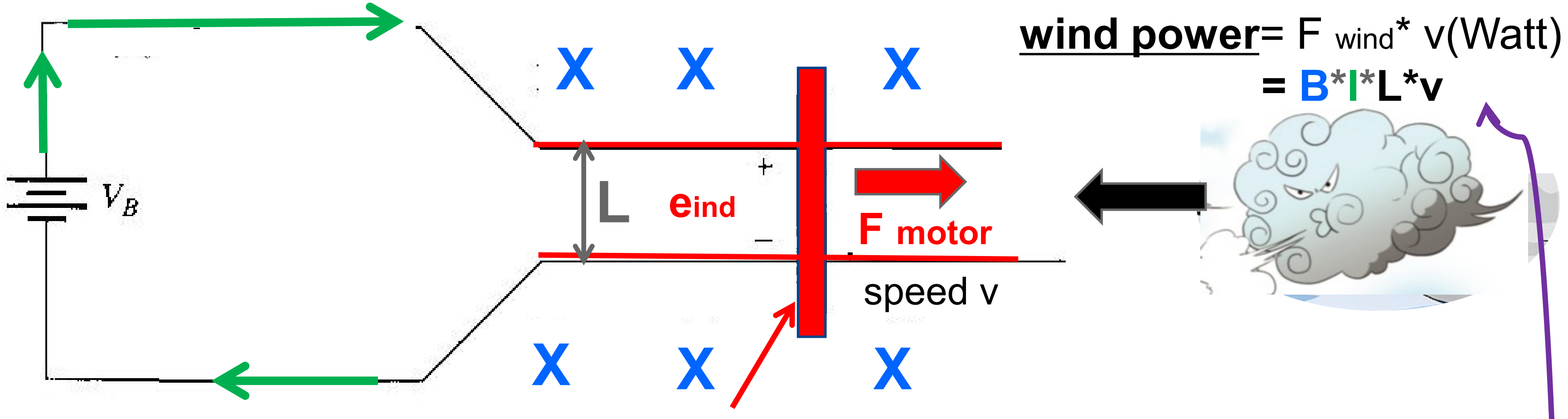
https://www.youtube.com/watch?v=O3MpiGL7CoE

DC motor working principle from Fleming's left hand rule

- Energy conversion in dc motor: without coil resistance

B: magnetic field from front to back

wind power = F $_{wind}$ * v(Watt)
= **B*I*L*v**



I current direction in coil:

Moving conductor bar: cupper

-During working with speed v, F $_{motor}$ = F $_{wind}$ means no acceleration

-Fleming's left hand rule: **F $_{motor}$ = B*I*L** ➡ **motor power** = **F $_{motor}$ *v = B*I*L*v**

-Fleming's right hand rule: **e $_{ind}$** = **B***v*L is induced at moving conductor bar

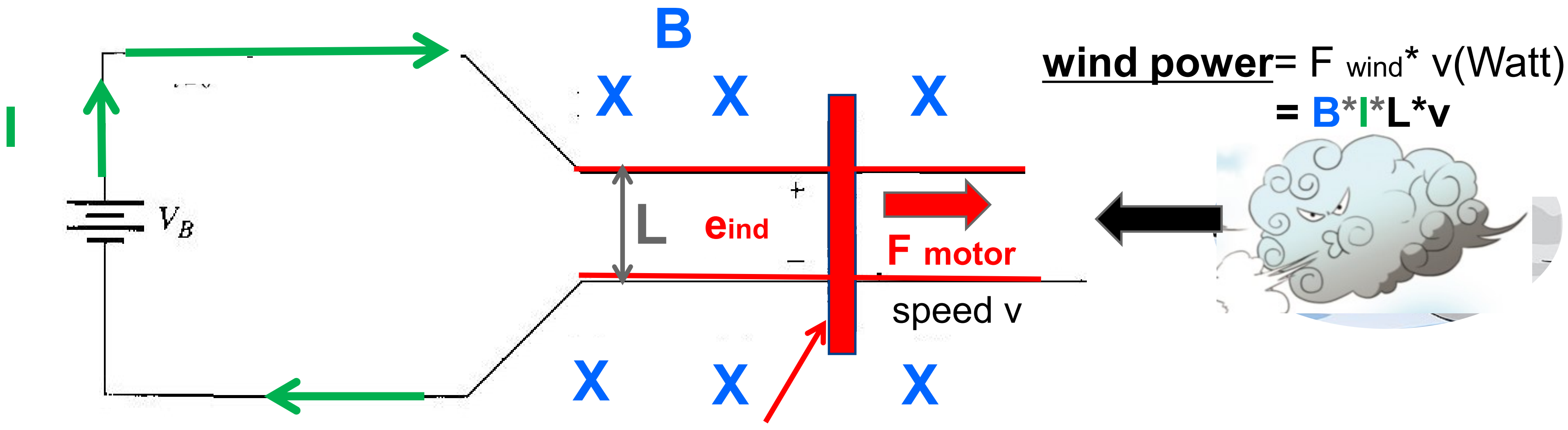
-**Battery power** V_B * **I = e $_{ind}$ * I = B***v*L* **I**

All are same!! very important

DC motor working principle from Fleming's left hand rule

- Energy conversion in dc motor: without coil resistance

wind power= F wind* v(Watt)
= **B*I*L*v**



I current direction in coil:

Moving conductor bar: cupper

-During working with speed v 4m/s, F wind = 15 N ➡ **wind power** =60W

-Fleming's left hand rule:**Fmotor=B*I*L** ➡ **F motor (15N)=B(1.5T)*I *L(0.2 m)** ➡ **I=50 A**

motor power = **F motor (15N)** * **v** (4m/s)=60W

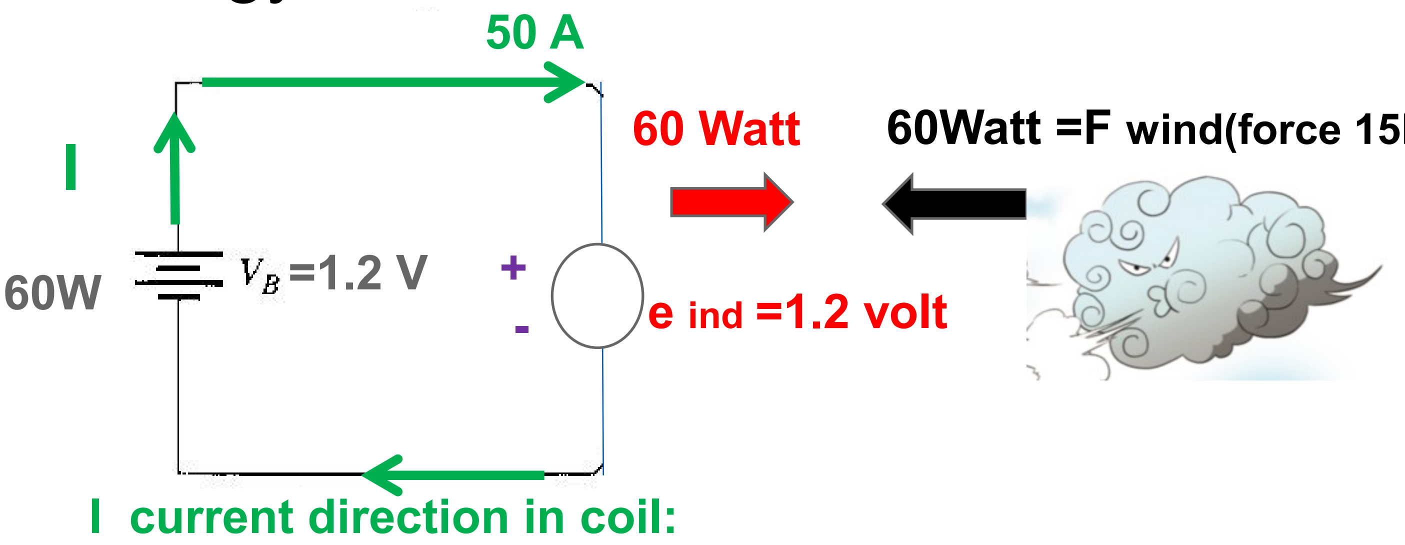
- Fleming's right hand rule: **e ind** = **B(1.5)*v(4)*L(0.2)** ➡ **e ind** = 1.2 V

-**Battery power** V_B * **I** = **e ind** * **I** = **B***v*L(1.2V)* I(50A) =60W

All are same!!

DC motor working principle from Fleming's left hand rule

- Energy conversion in dc motor: without coil resistance



Mechanical load power : **wind power= F wind*v(Watt)** **60W**

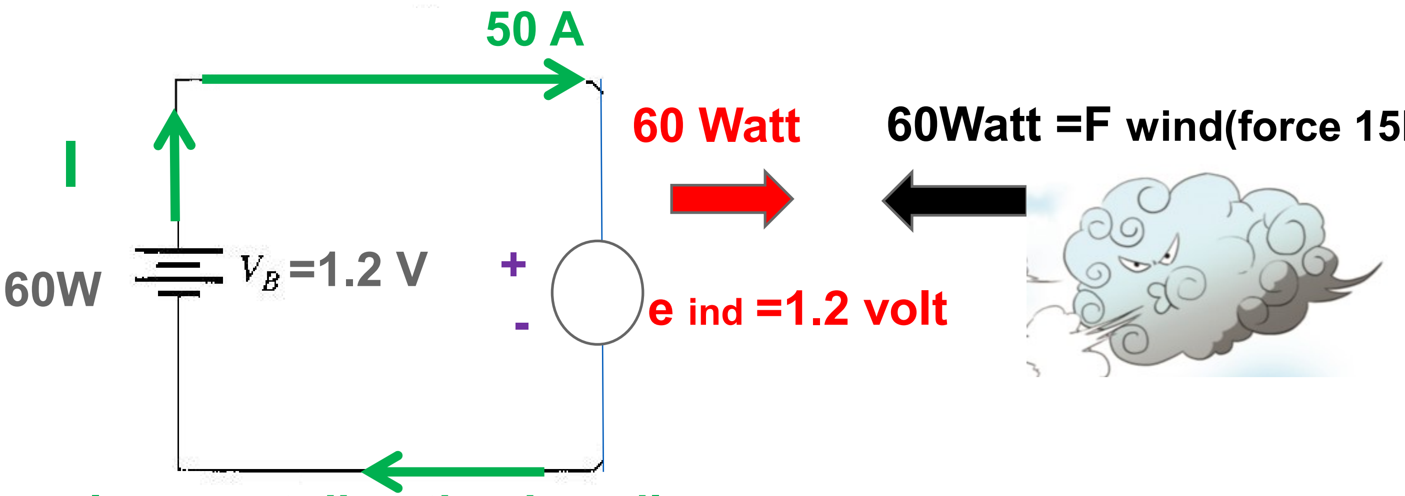
Battery power: V_B * **I,** V_B **= e ind** **60 W**

Motor power : **e ind * I** **60 W**

Efficiency=motor out- put power / motor in put power(Battery out put power)
= 60/60= 100%

DC motor working principle from Fleming's left hand rule

- Energy conversion in dc motor: without coil resistance



I current direction in coil:

Mechanical load power : wind power= F wind*v(Watt) **60W**

Battery power: V_B * I, V_B = e ind **60 W**

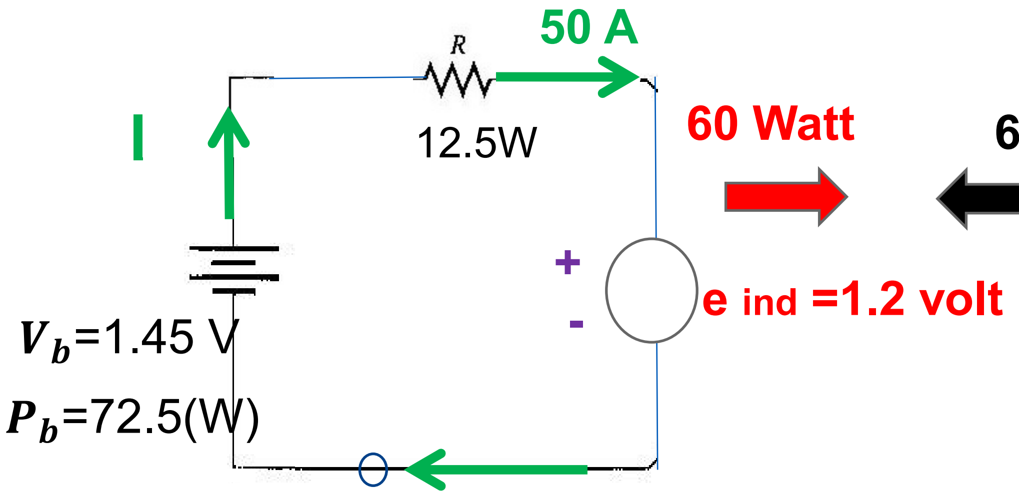
Motor power : e ind * I **60 W**

Efficiency=motor out- put power / motor in put power(Battery out put power)
= 60/60= 100%

DC motor working principle from Fleming's left hand rule

- Energy conversion in dc motor with coil resistance

If there is R=0.005 ohm, V_R = 0.005*50 =0.25 V



Battery power: V_b= e ind (1.2) +V_R (0.25) =1.45V ➡ V_b (1.45)* I(50)=72.5W

Motor output power: e ind * I = e ind (1.2)* I(50) = 60W

Motor input power: power in coil resistance (12.5) +motor output power(60) =72.5 Watt

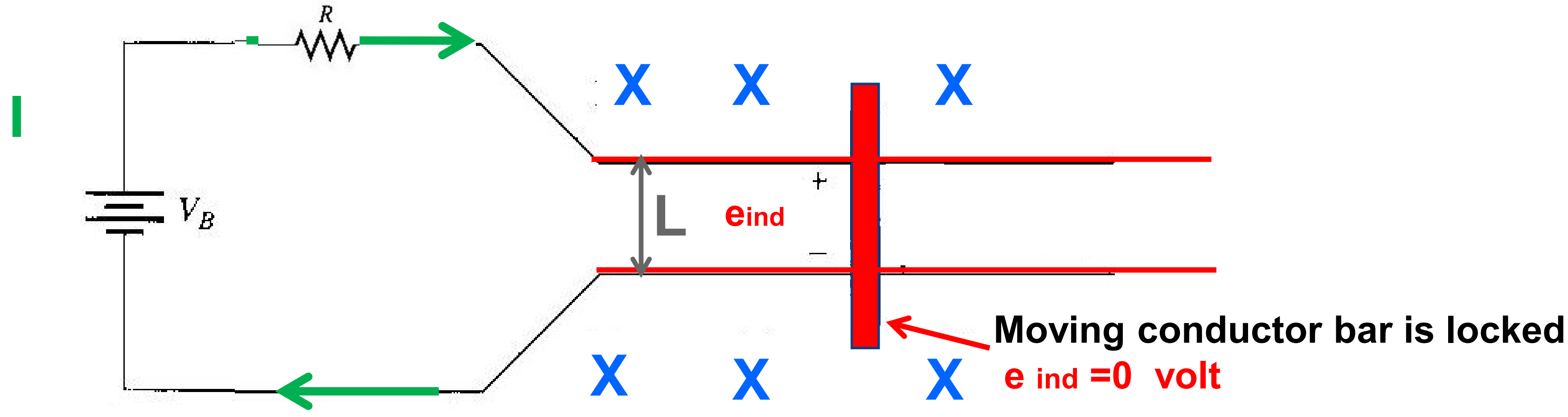
Motor efficiency = motor out put power/motor in put power = 60/72.5= 82.75%

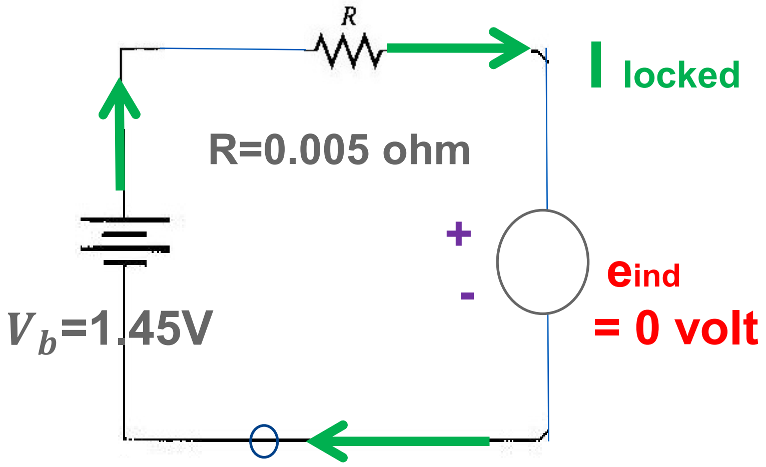
DC motor working principle from Fleming’s left hand rule

- If motor mover or rotor is locked, what will be happened

DC motor working principle from Fleming's left hand rule

- If motor mover or rotor is locked, what will be happened

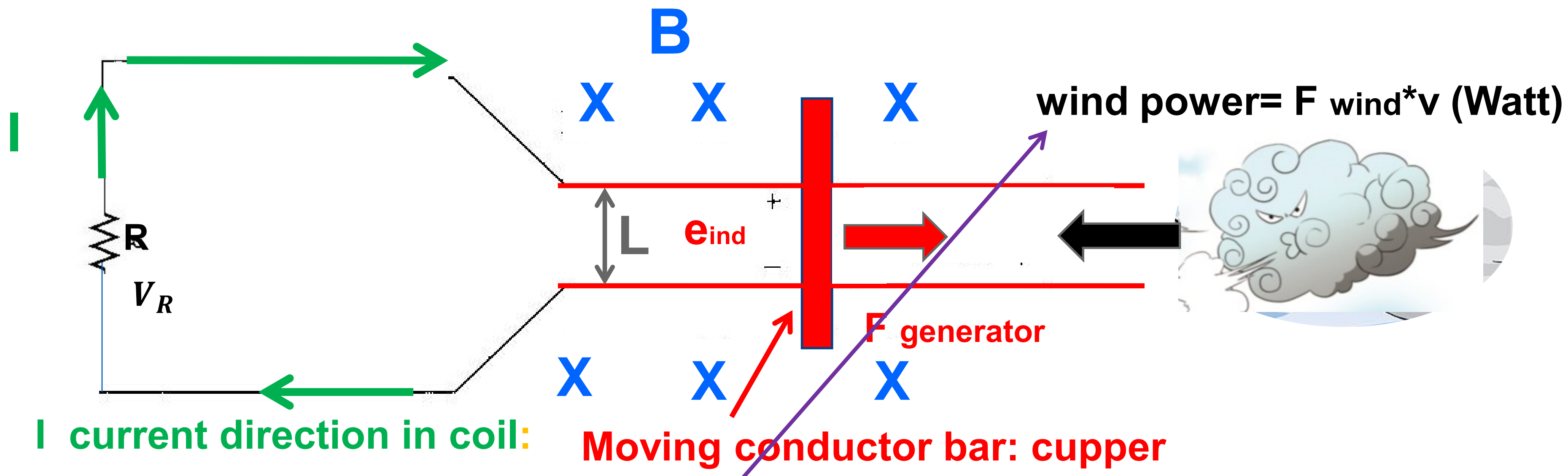




I locked = 1.45/ 0.005 = 290A
will burn motor winding
(!!!!!normal motor operation 50A)

-Immediately turn off motor
-remove the locking

DC generator working principle from Fleming's right hand rule



-During working with speed v, $F_{generator} = F_{wind}$ means no acceleration

-Fleming's right hand rule: e induced voltage: $e_{ind} = B*v*L$ in moving conductor bar

-Fleming's left hand rule: $F_{generator} = B*I*L$ ➡ $I = F_{generator} / B*L$

-Power in generator: $e_{ind} = B*v*L * I = F_{generator} * v$

-Power in load : $V_R * I = e_{ind}*(F_{generator} / B*L) = B*v*L\ (F_{generator}/B*L) = F_{generator}*v$

-Power in wind = power in generator = power in load

DC generator working principle from Fleming's right hand rule

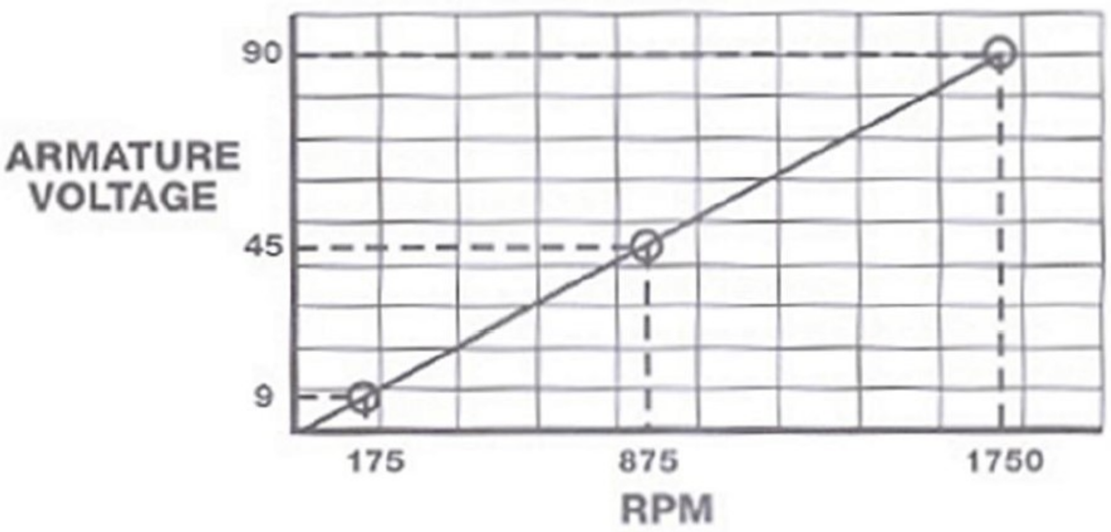
1) Fleming's left hand rule and Fleming's right hand rule are working together in energy conversion in motor or generator

2) If there is no losses in winding, efficiency=100%
-motor: electrical power (in-put)= mechanical power (out put)
-generator: mechanical power (in-put)= electrical power (out put)

3) In fact, efficiency will be 85% (depend on size and application)
-motor: electrical power (in-put) > mechanical power (out put)
-generator: mechanical power (in-put) > electrical power (out put)

DC Motor control

- Increase voltage to increase speed
- Reverse voltage to reverse direction



DC Motor control

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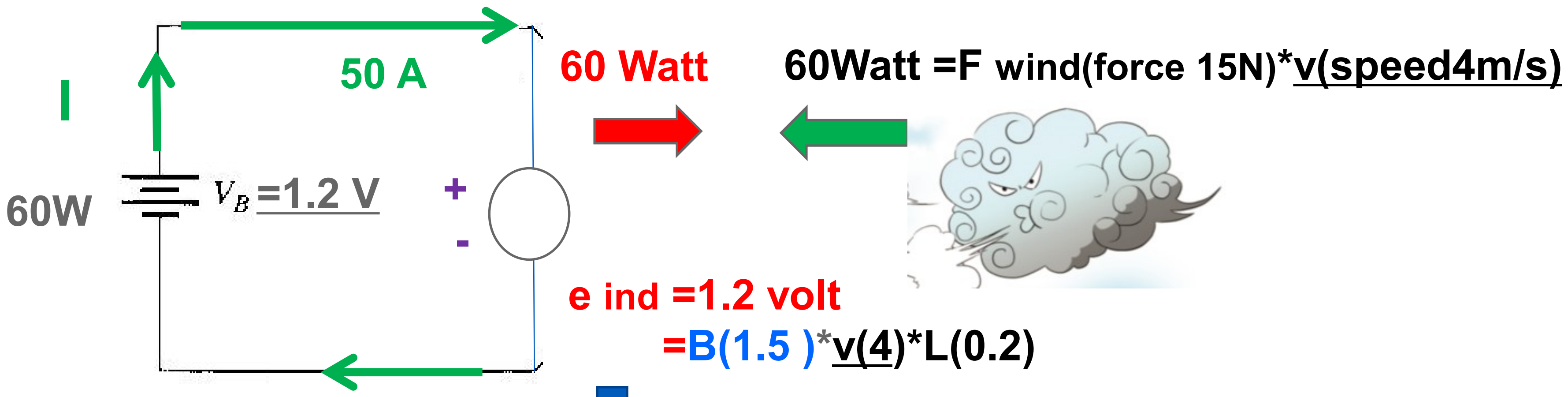

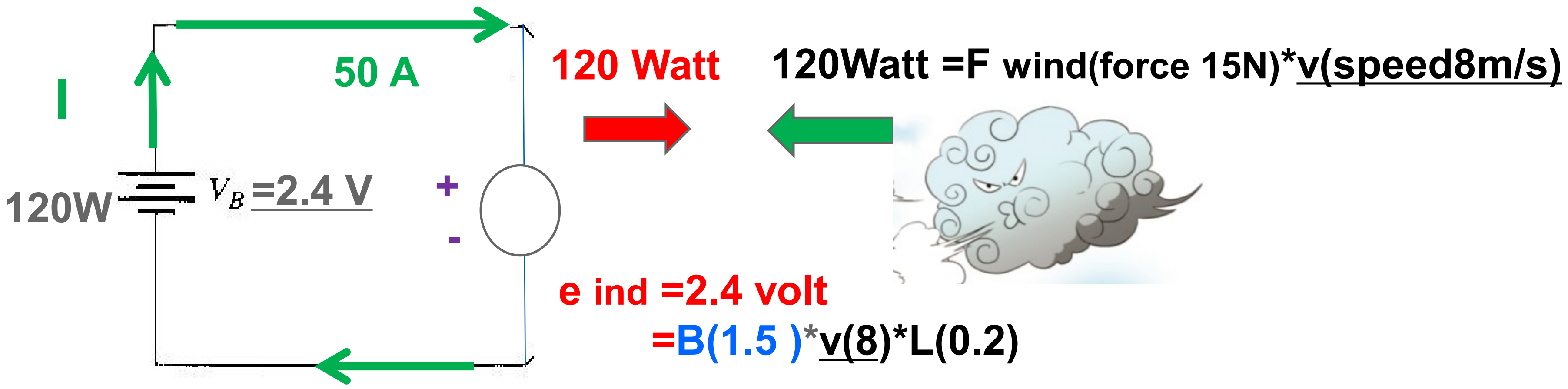

DC Motor control

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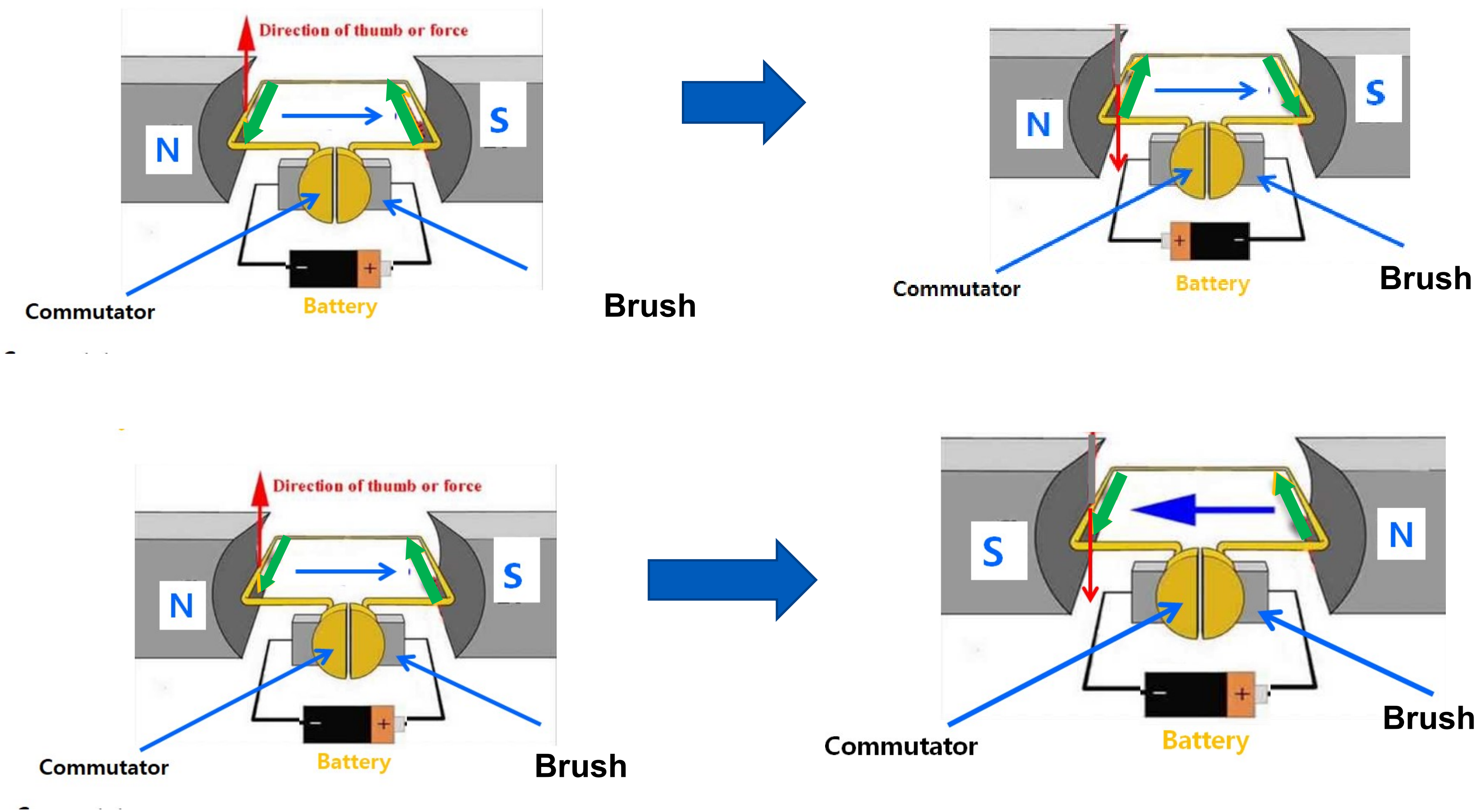

DC Motor control

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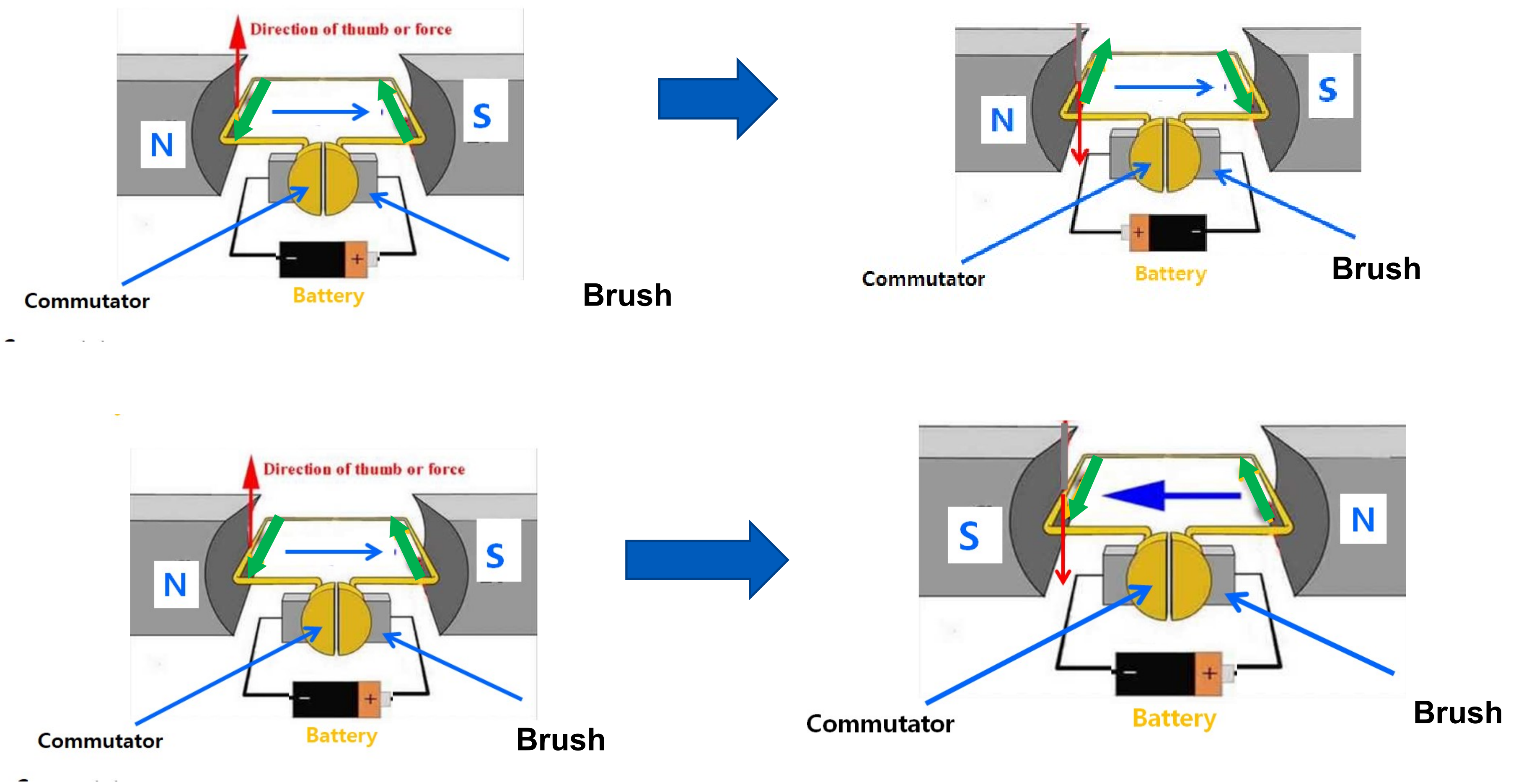
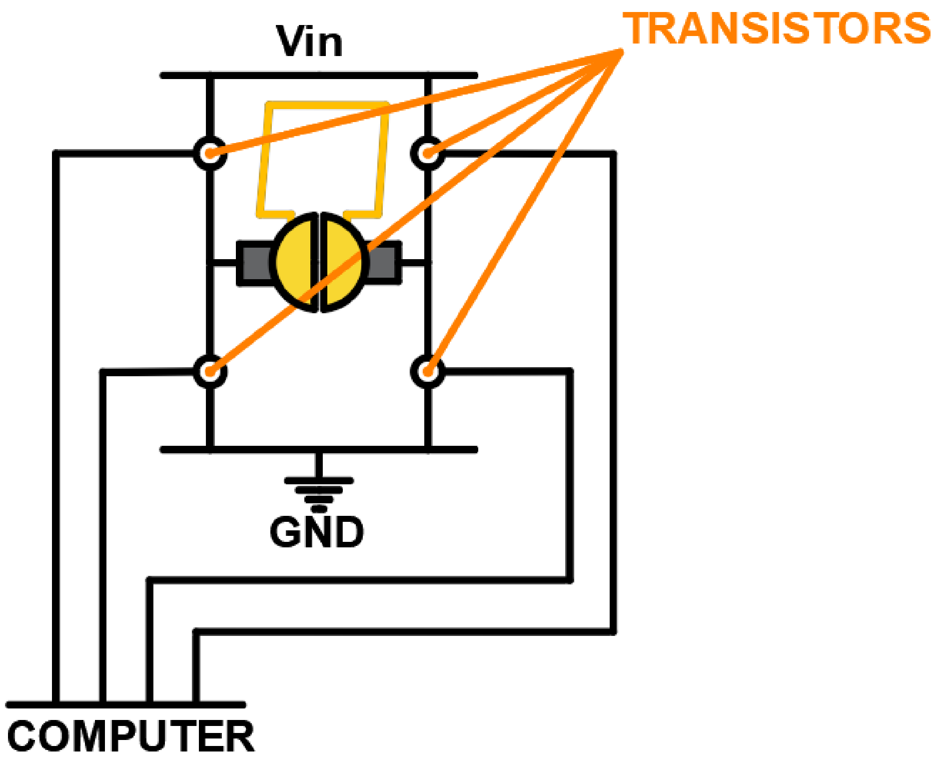
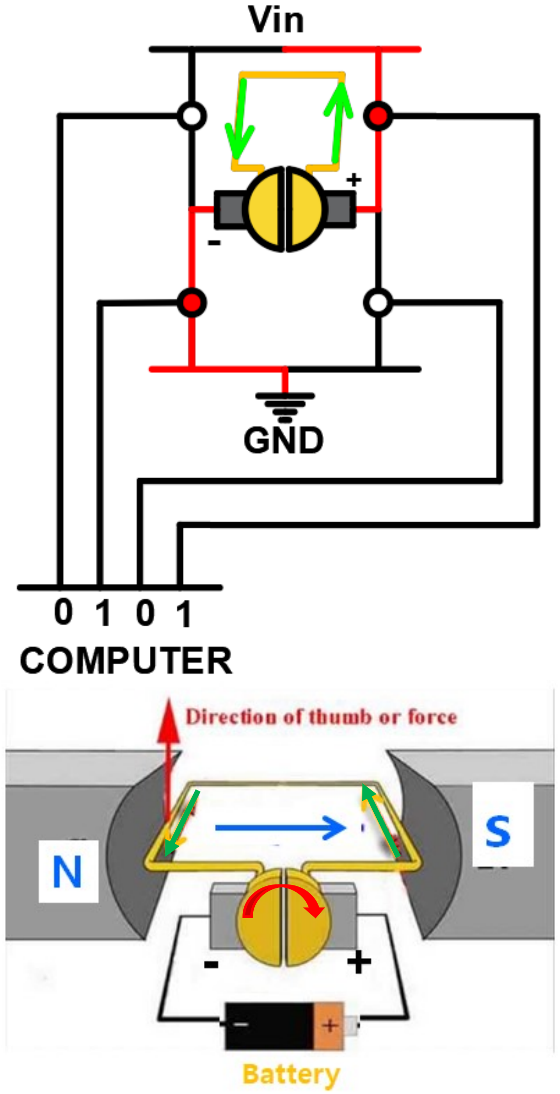


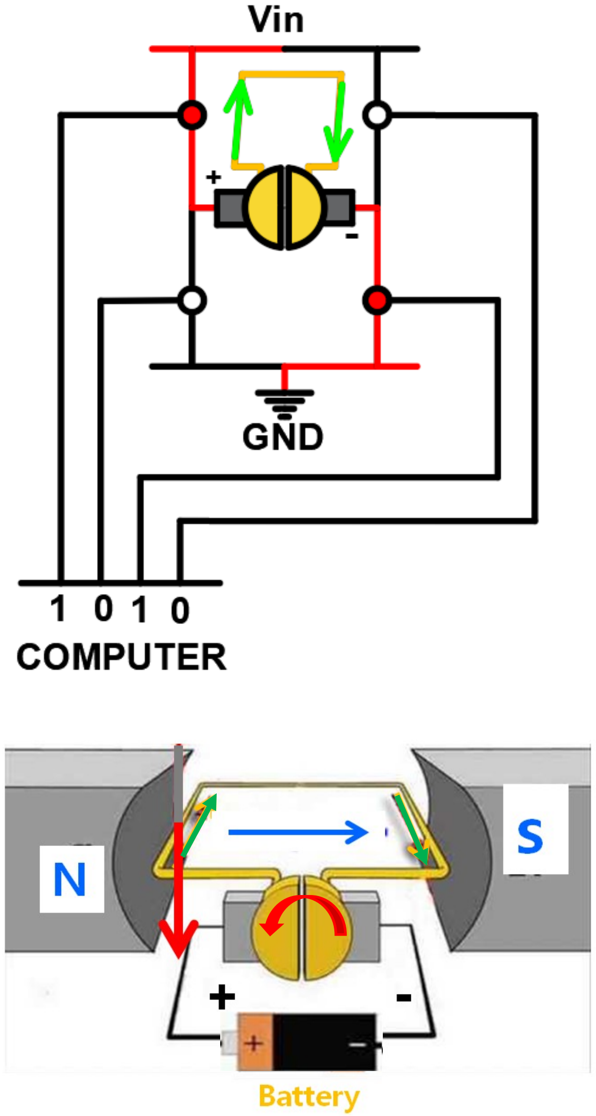
DC Motor control

- An H-bridge
  - Name derived from shape of circuit
  - Four switches (usually transistors) control circuit behavior
  - Two switches turned on at a time
  - Bipolar operation with unipolar supply voltage
  - Speed is set by input voltage



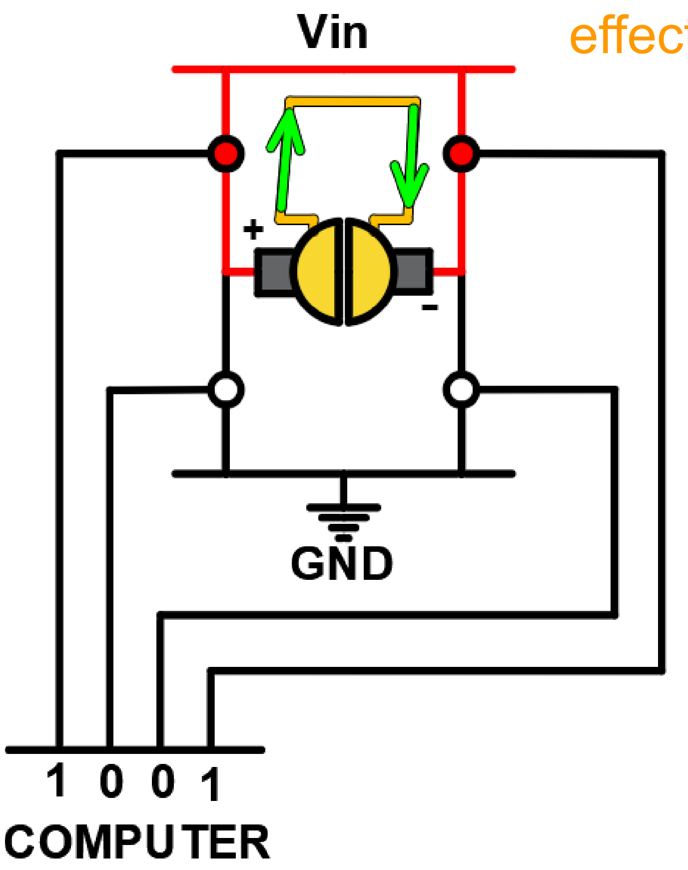
DC Motor control



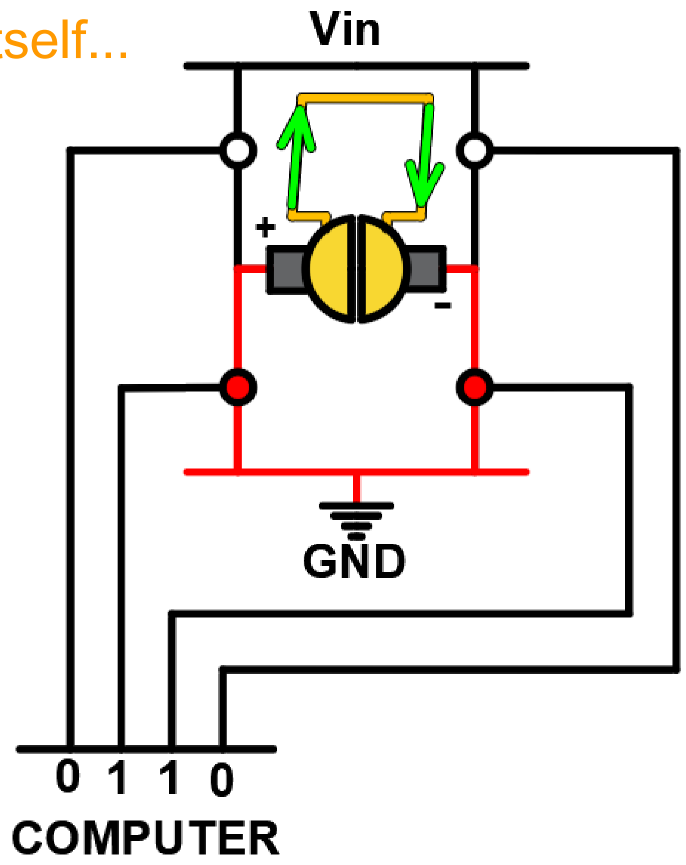


DC Motor control

Connecting motor leads causes the motor's generator effect to work against itself...

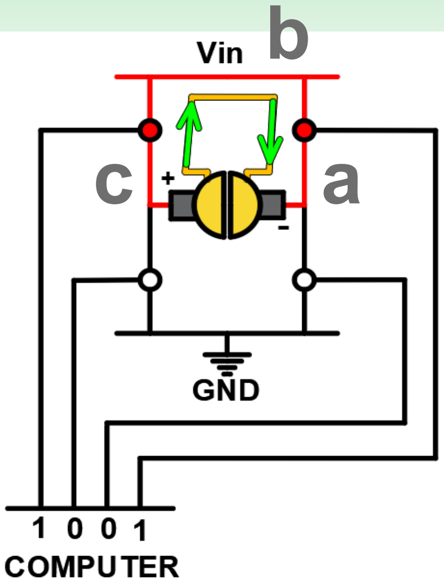


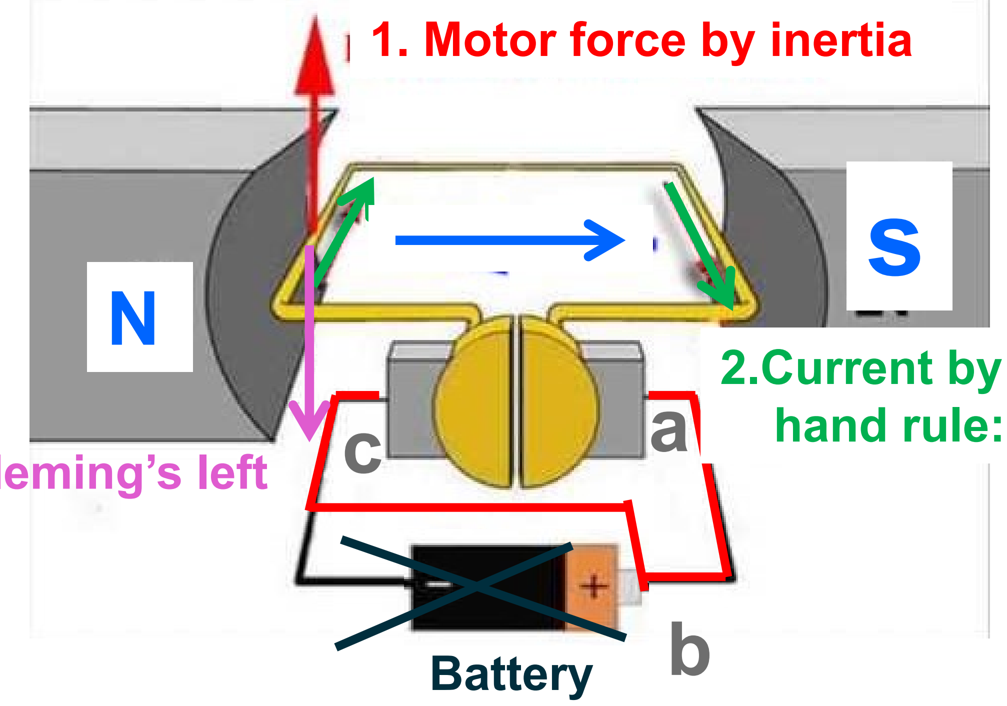
Braking Operation-1



Braking Operation-2

DC Motor control

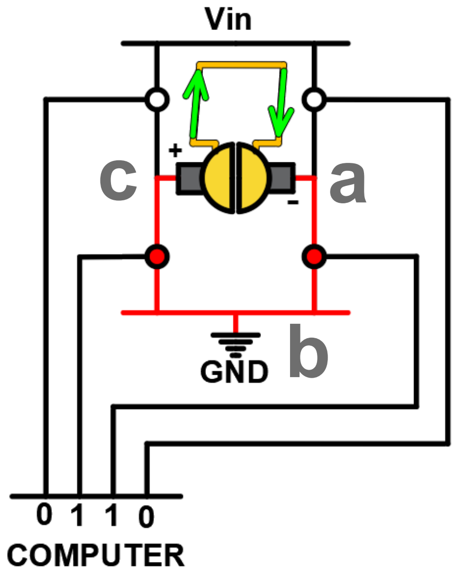


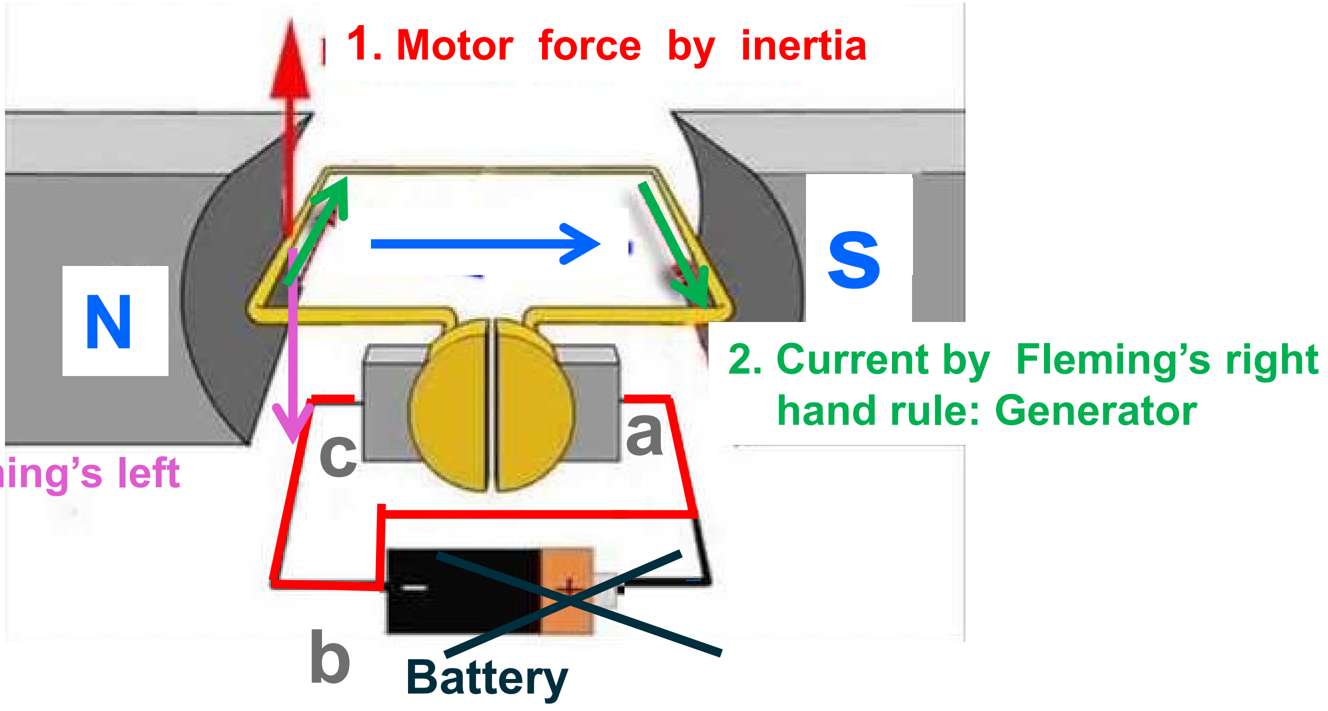


1. Motor force by inertia ⟷ 3. Force by Fleming's left hand rule in short circuit at generator

Braking force

DC Motor control





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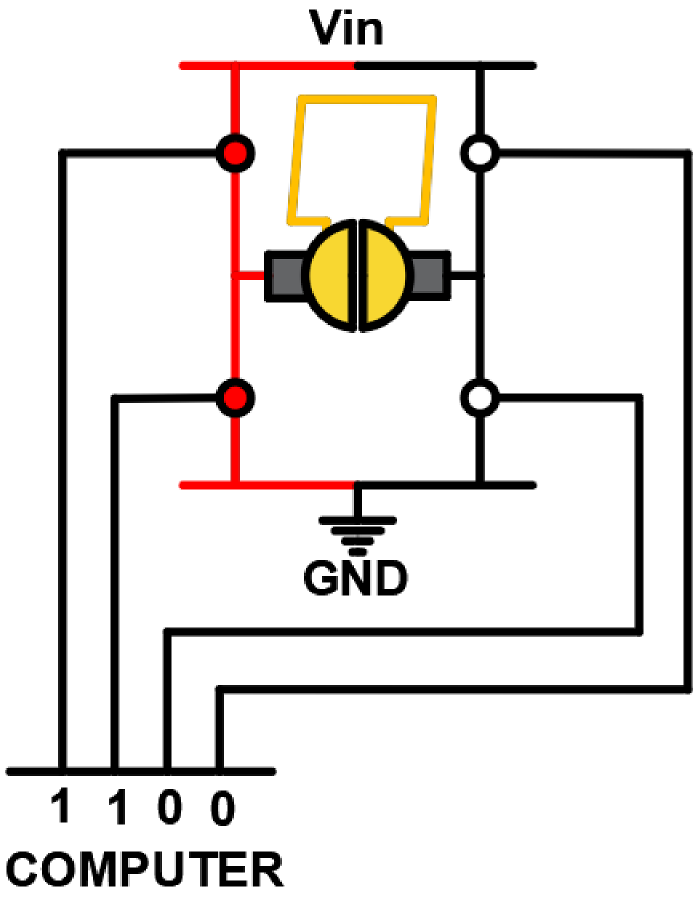
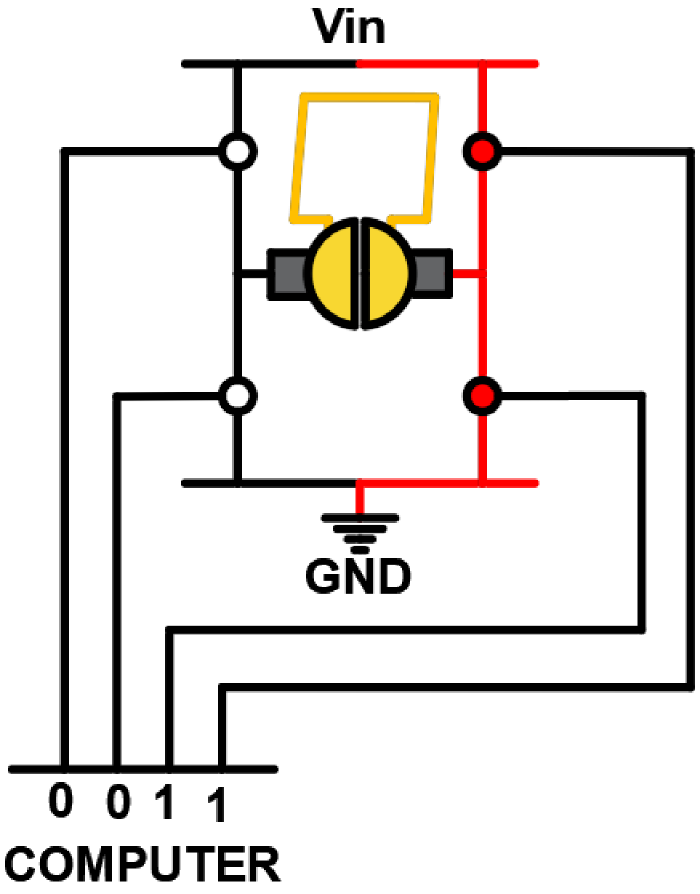
Braking force

DC Motor control

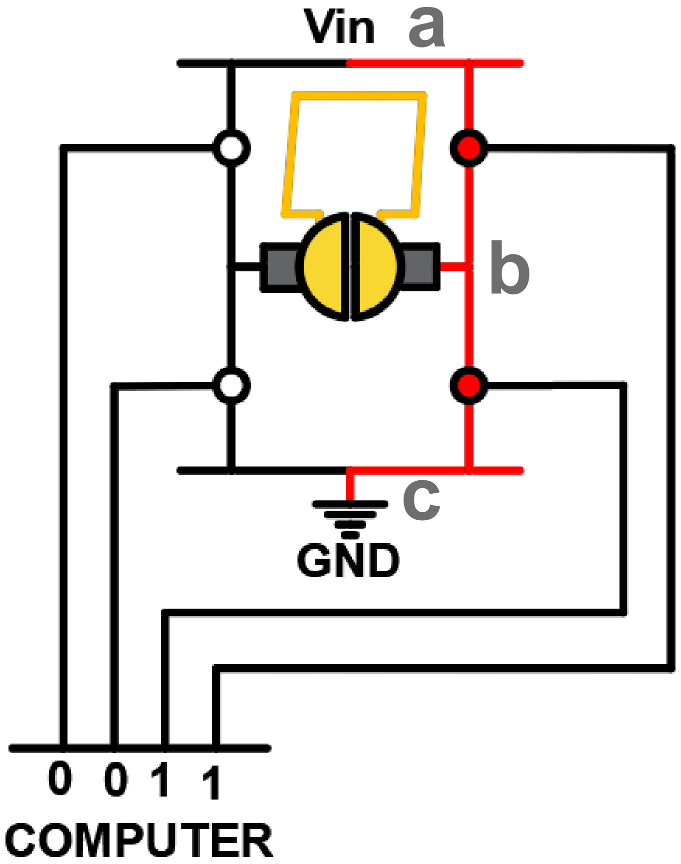


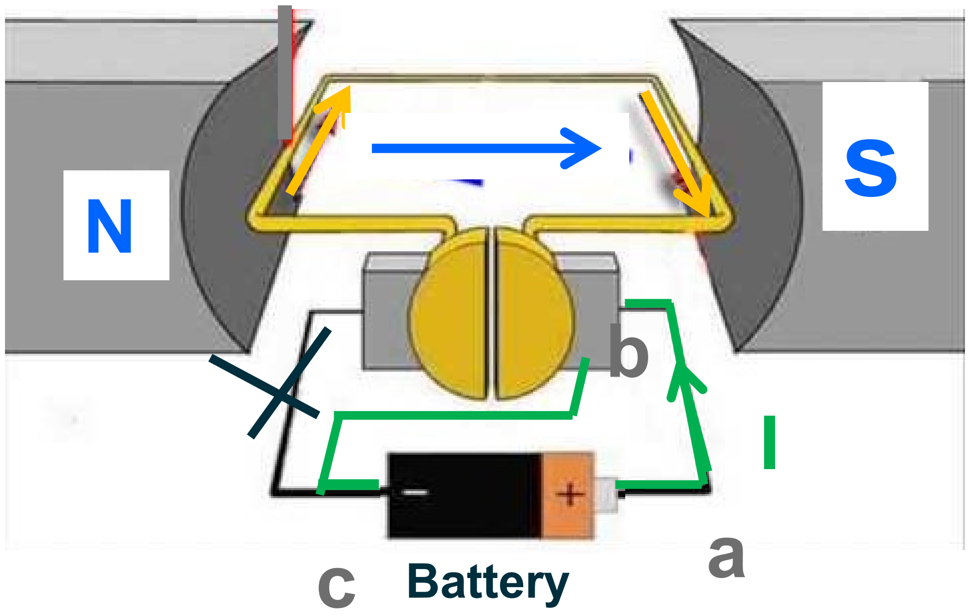
"Shoot thru" (not desirable)



"Shoot thru" (not desirable)

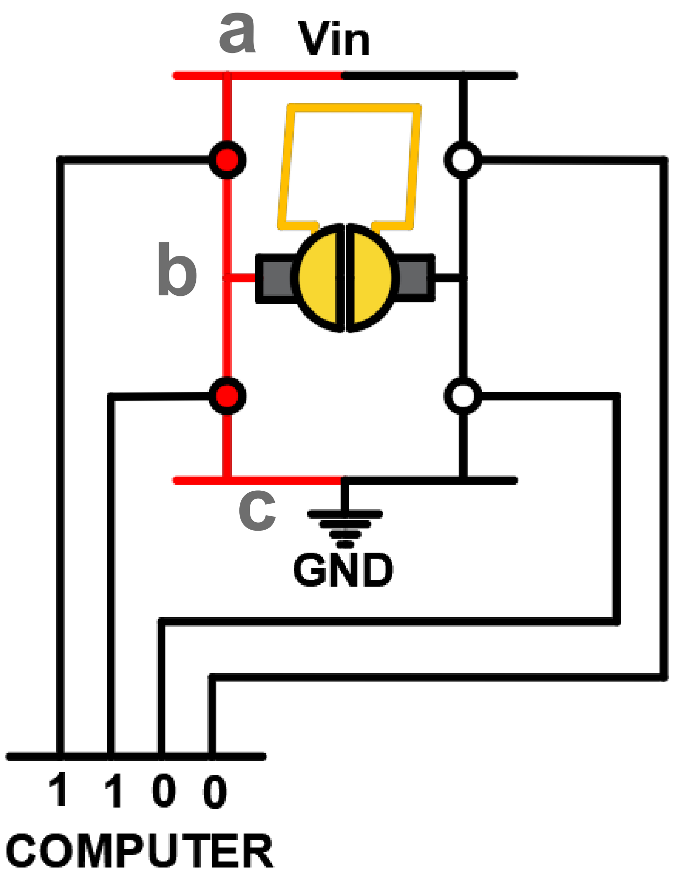
DC Motor control

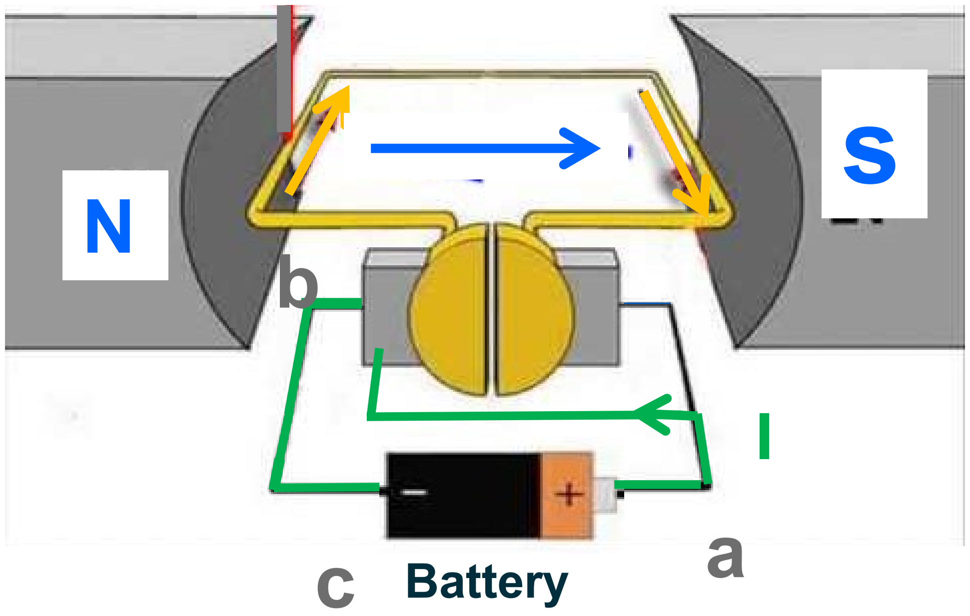




$I = V_b / R$ ➡ $R = 0$ Ohm ➡ I = infinite

DC Motor control





$I = V_b / R$ ➡ R = 0 Ohm ➡ I = infinite

DC Motor control

- **A DC motor can be driven using a PWM signal**

- Can run PWM signal through an H-bridge to drive the DC motor
- PWM behaves most linearly near 50% duty cycle; linearity drops off at the extremes.
- Arduino Uno supplies 6 PWM output pins

DC Motor specification

Nominal voltage is the input voltage used to establish published specifications. You can apply higher and lower voltages, but watch out not to exceed max. current ratings!

	Motor Data		118749	118750	118751	118752	118753	118754	118755	118756	118757
1	Assigned power rating	W				20					
2	Nominal voltage	Volt				24.0					
3	No load speed	rpm				9660					
4	Stall torque	mNm				240					
5	Speed / torque gradient	rpm / mNm				41.2					
6	No load current	mA				37					
7	Starting current	mA				10300					
8	Terminal resistance	Ohm				2.32					
9	Max. permissible speed	rpm				11000					
10	Max. continuous current	mA				1230					
11	Max. continuous torque	mNm				28.4					
12	Max. power output at nominal voltage	mW				58400					
13	Max. efficiency	%				85					
14	Torque constant	mNm / A				23.2					
15	Speed constant	rpm / V				412					
16	Mechanical time constant	ms				5					
17	Rotor inertia	gcm^2				10.3					
18	Terminal inductance	mH				0.24					
19	Thermal resistance housing-ambient	K / W				14					
20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

DC Motor specification

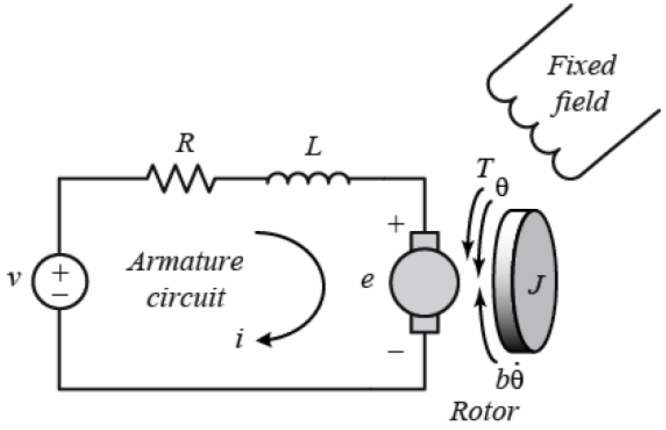
- **Factors to consider when selecting a motor**

While the nominal voltage is not an absolute definition of the operating voltage, it’s a pretty good guideline:

- If you apply a voltage far above the nominal voltage, you risk overheating the motor (due to too much current).
- If you apply a voltage far below the nominal voltage, you may not overcome the motor's internal friction (too little current and, hence, too little torque).

DC Motor specification

- **DC motors function using two fundamental principles**



- **Torque Production**: current-carrying conductor in magnetic field will induce electro-magnetic force acting on the conductor
- **Back EMF**: electric potential will be generated across moving conductor in magnetic field

DC Motor specification

Value Added Mechatronics

Torque in coil

-F force in coil : F=B*I*L

-Torque in coil

T=2F* a

=2*B*I*L*a

=2a*B*L*I

= K_T * I

K_T: Torque constant

e Induced voltage:

e= B*v*2L (2 sides)

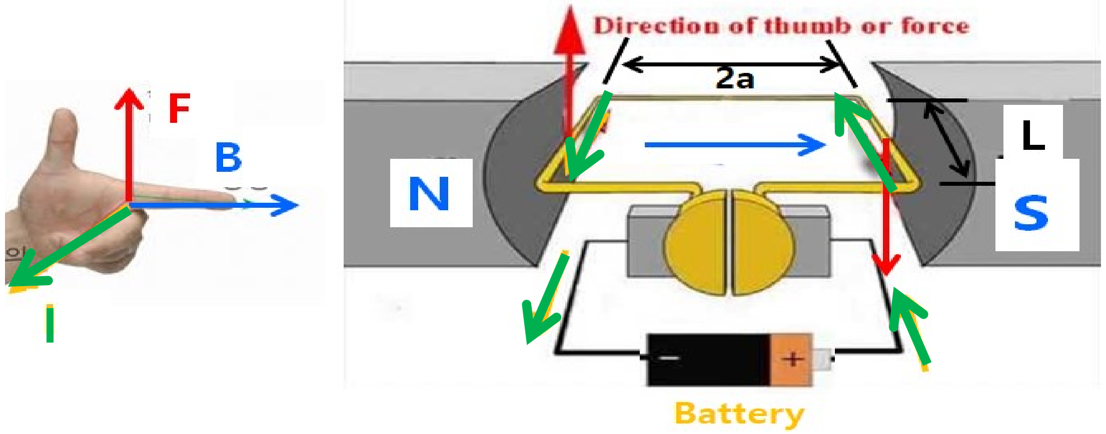
= B*2a π * rps*2L

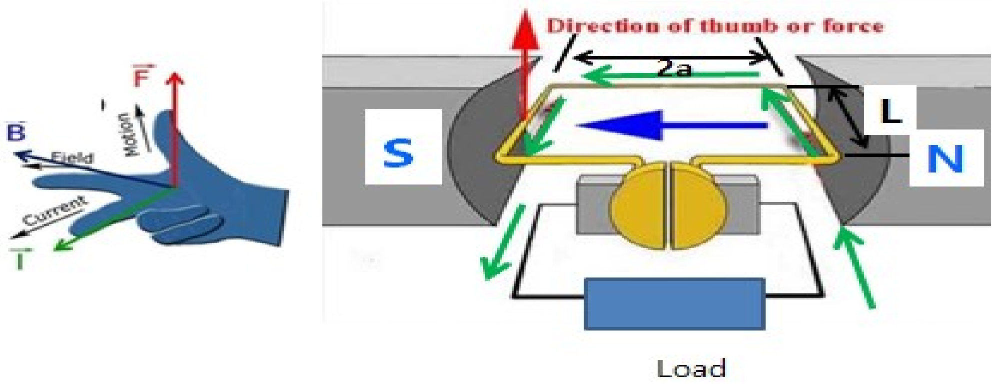
= (B* 2a* L)*2π*rps

= 2a*B*L * ω

= K_{EMF} * ω

K_{EMF}: Back-EMF constant





DC Motor specification

$$T_M = K_T \cdot i_a$$

	Motor Data		118749	118750	118751	118752	118753	118754	118755	118756	118757
1	Assigned power rating	W				20					
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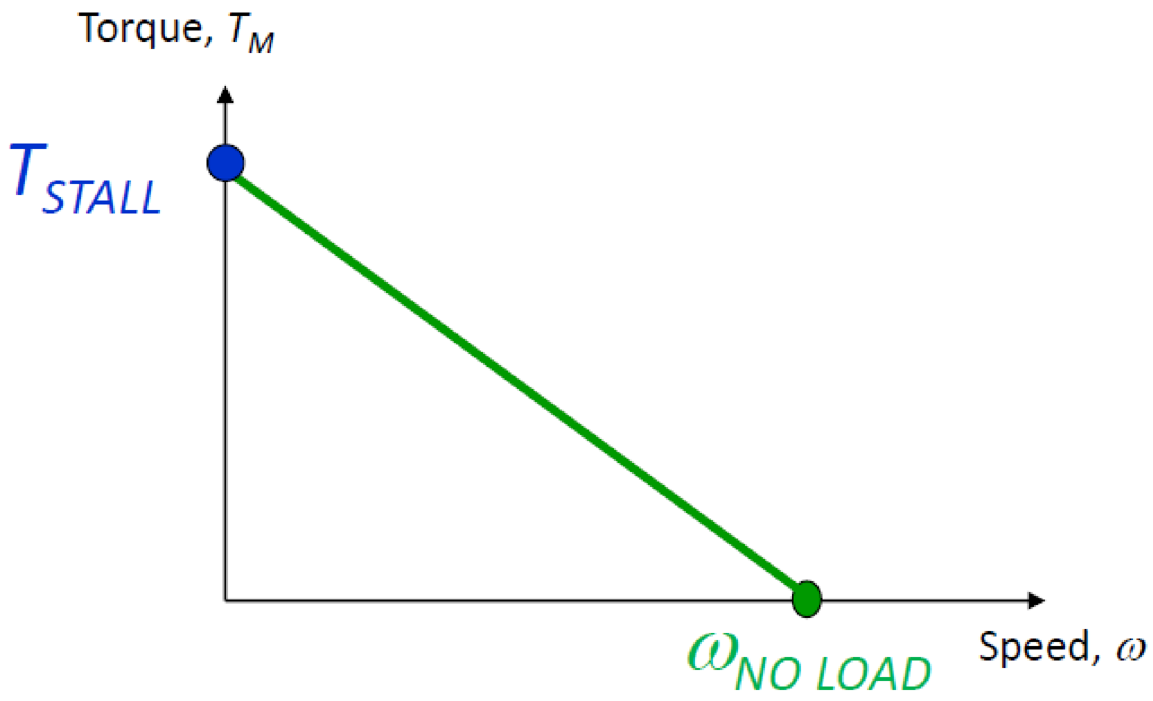
DC Motor specification

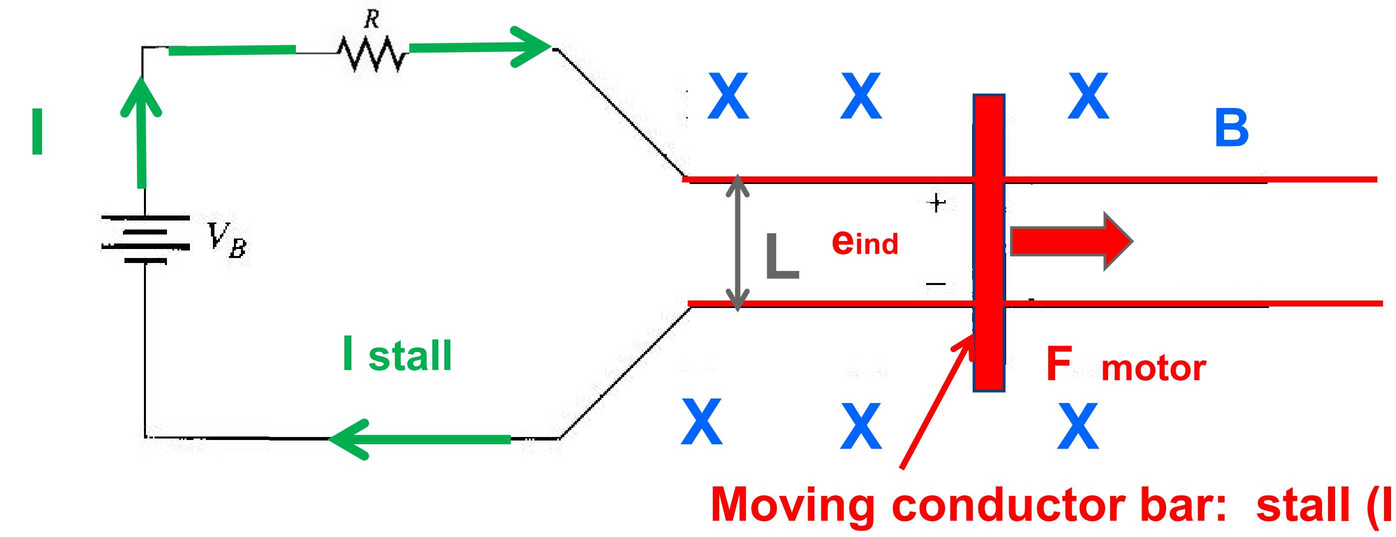
Value Added Mechatronics

- **Torque and speed are linearly related for DC motors**

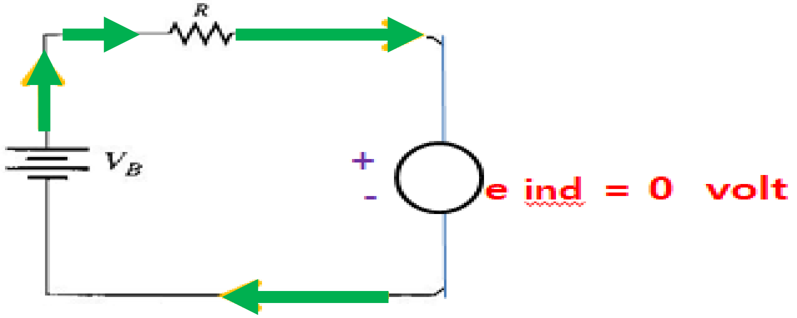


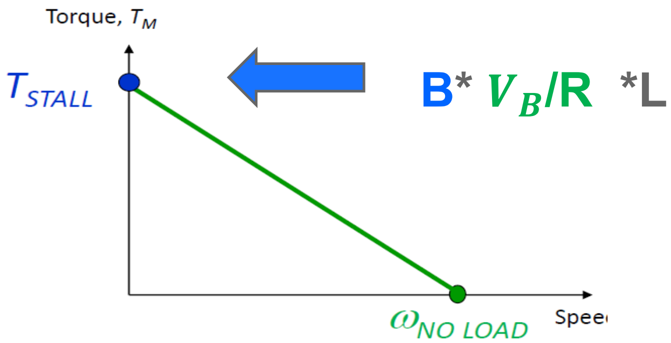
DC Motor specification

- Torque and speed are linearly related for DC motors



- Speed =0 e ind=0 I stall= V_B/R ➡ Fstall =B* I stall *L

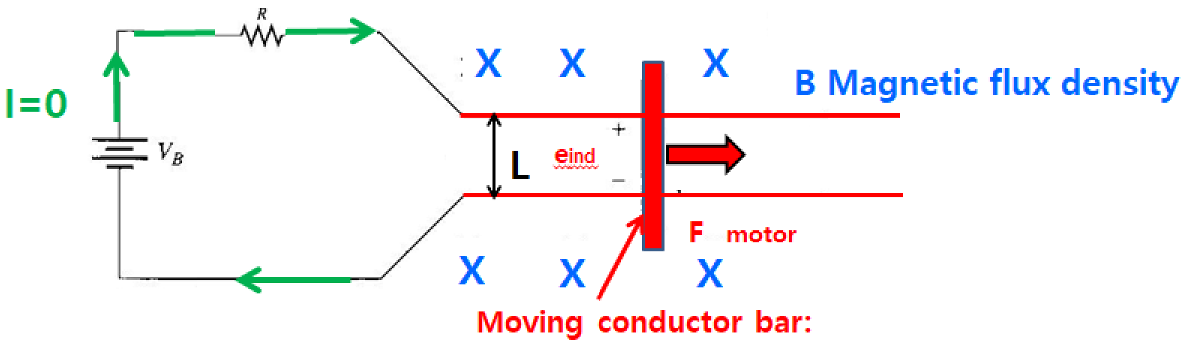




I stall current direction in coil:

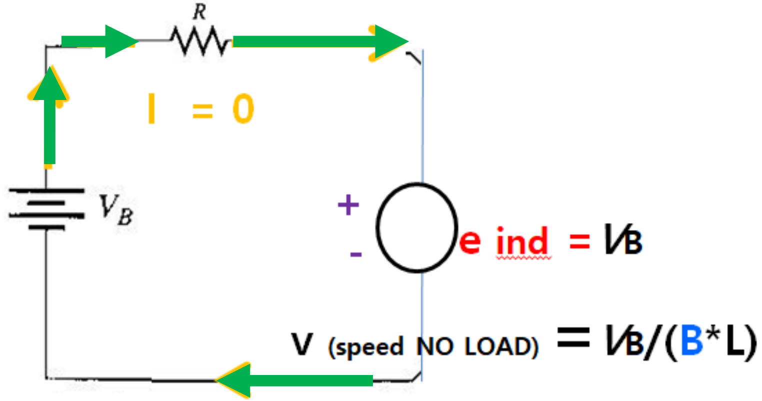
DC Motor specification

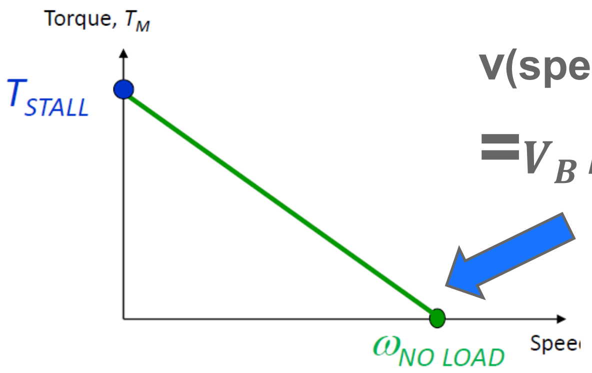
- Ω *NO LOAD* : motor speed at no load means no current



-Fmotor=0 I =0 이므로 e_{ind} = B* v (speed NO LOAD) *L= V_B

- v (speed NO LOAD) = V_B / (B *L)



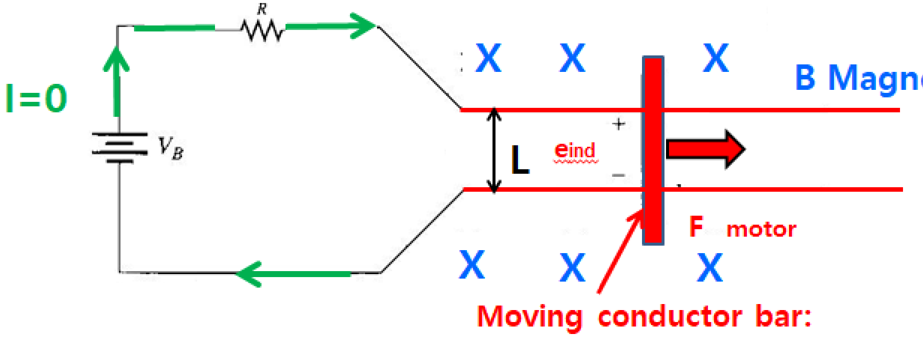


v(speed NO LOAD)

= V_B / (B*L)

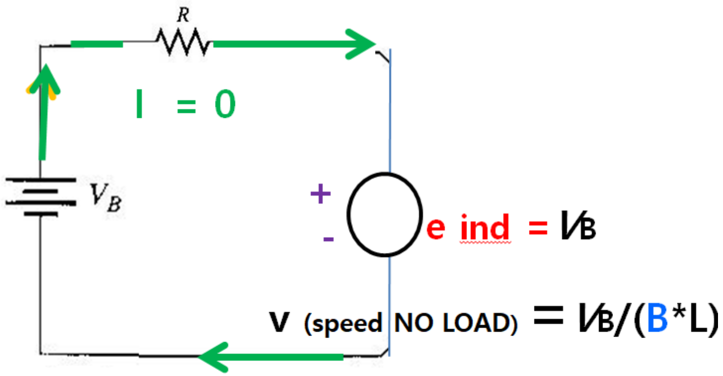
DC Motor specification

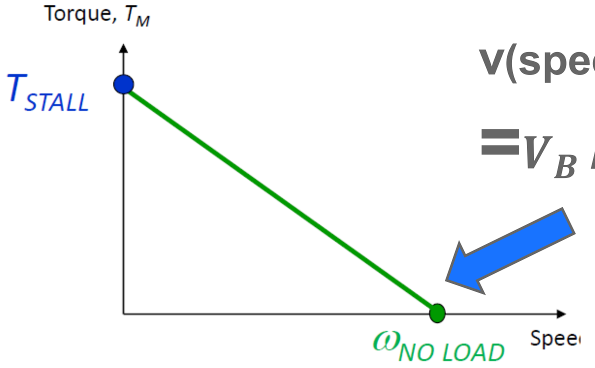
- Ω *NO LOAD* : motor speed at no load means no current



-Fmotor=0 I =0 and e_{ind} = B* v (speed NO LOAD) *L=V_B

- v (speed NO LOAD) =V_B / (B *L)



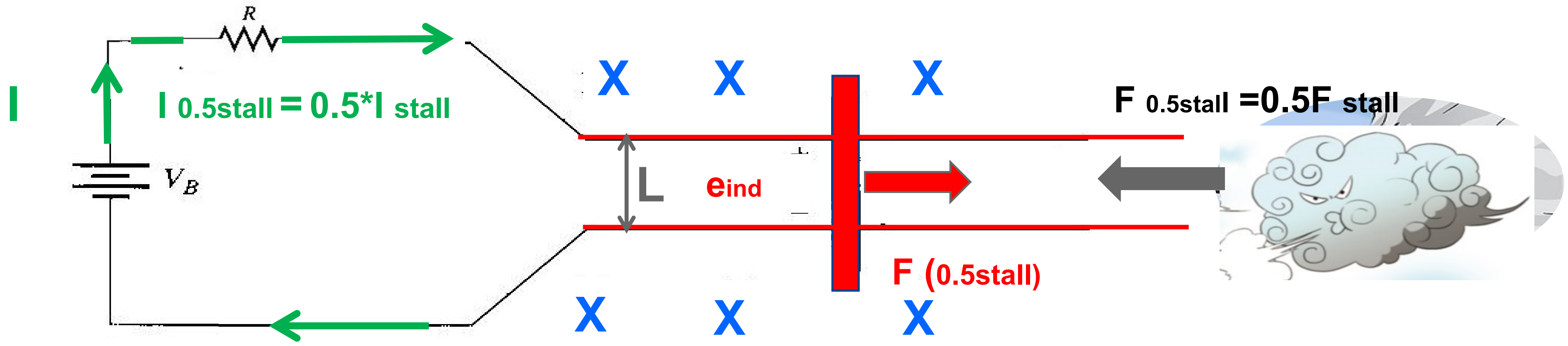


v(speed NO LOAD)

=V_B / (B*L)

DC Motor specification

- Ω *at* 0.5*T stall



1) F (0.5stall) = B* I 0.5stall *L = B* 0.5*I stall *L by Fleming's left hand rule
   F (0.5stall) = B* 0.5 V_B/R *L

2) V_B = R *I 0.5stall + e ind at F 0.5stall = R *0.5*I stall + e ind at F 0.5stall
   e ind at F 0.5stall = V_B - R *0.5*I stall = V_B - R *0.5* V_B/R = 0.5V_B

B* V (0.5stall) *L = 0.5V_B by Fleming's right hand rule

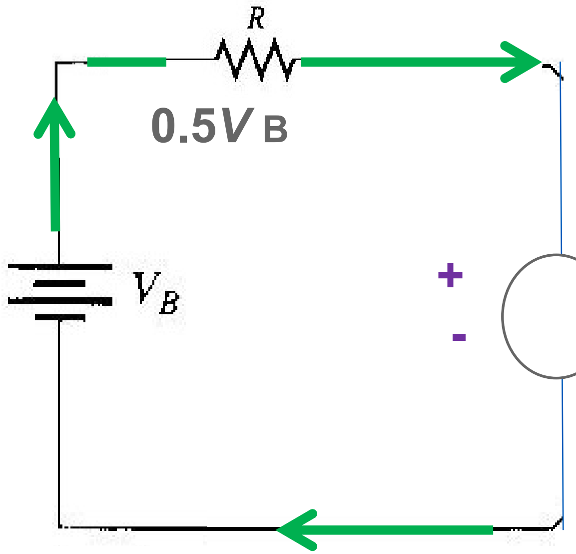
V (0.5stall) = 0.5V_B/ (B *L)

DC Motor specification

- Ω *at* 0.5*T stall

B* V_B/R *L

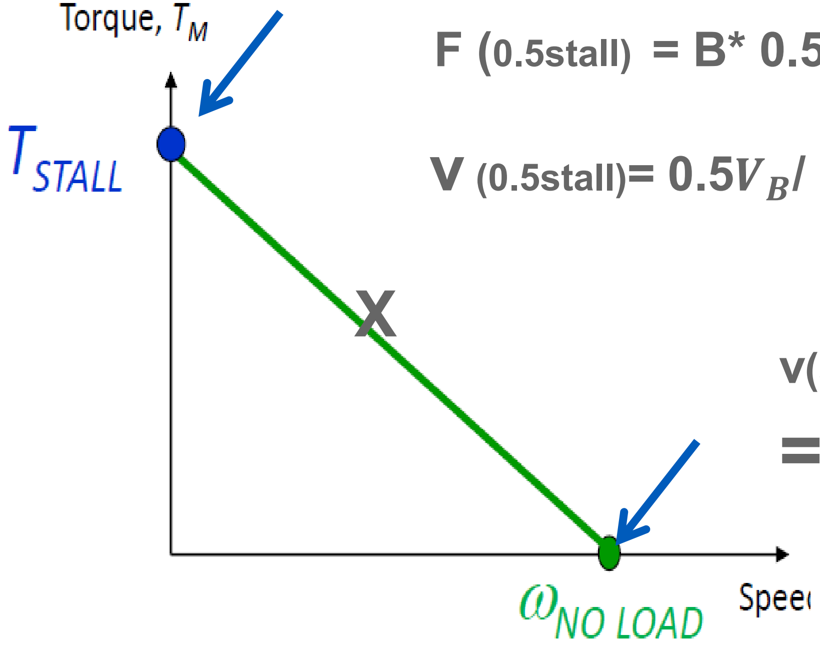
0.5*I stall



e ind = $0.5V_B$

V (speed 0.5 LOAD)

=$0.5V_B$/(B*L)



F (0.5stall) = B* 0.5 V_B/R *L

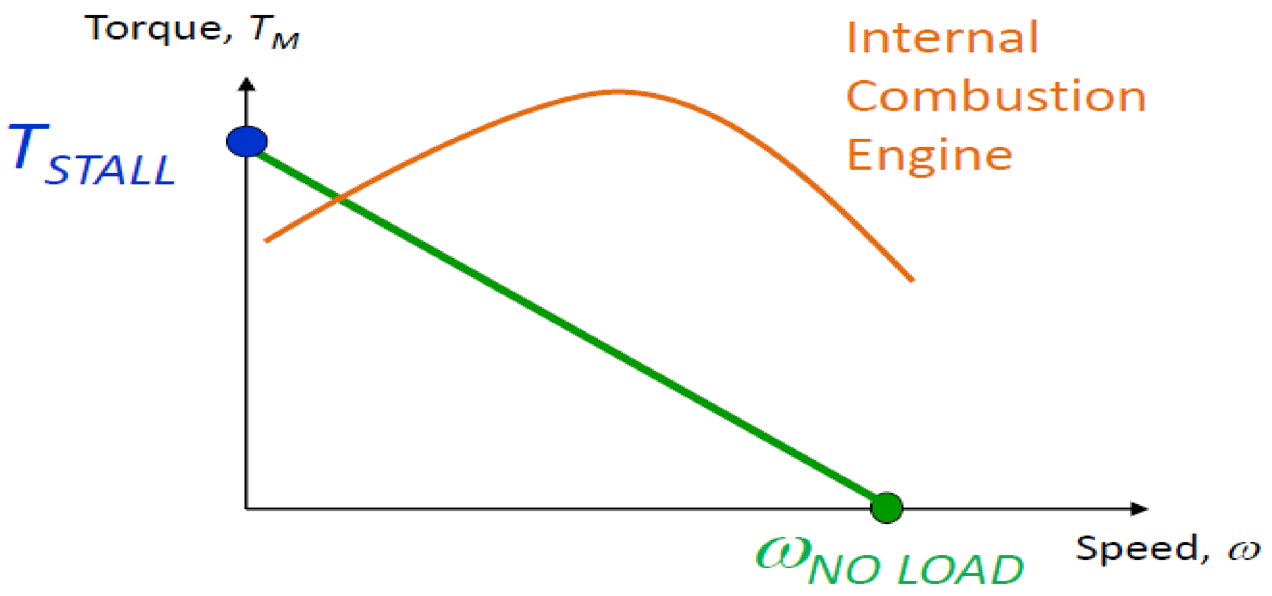
V (0.5stall)= $0.5V_B$/ (B *L)

v(speed NO LOAD)

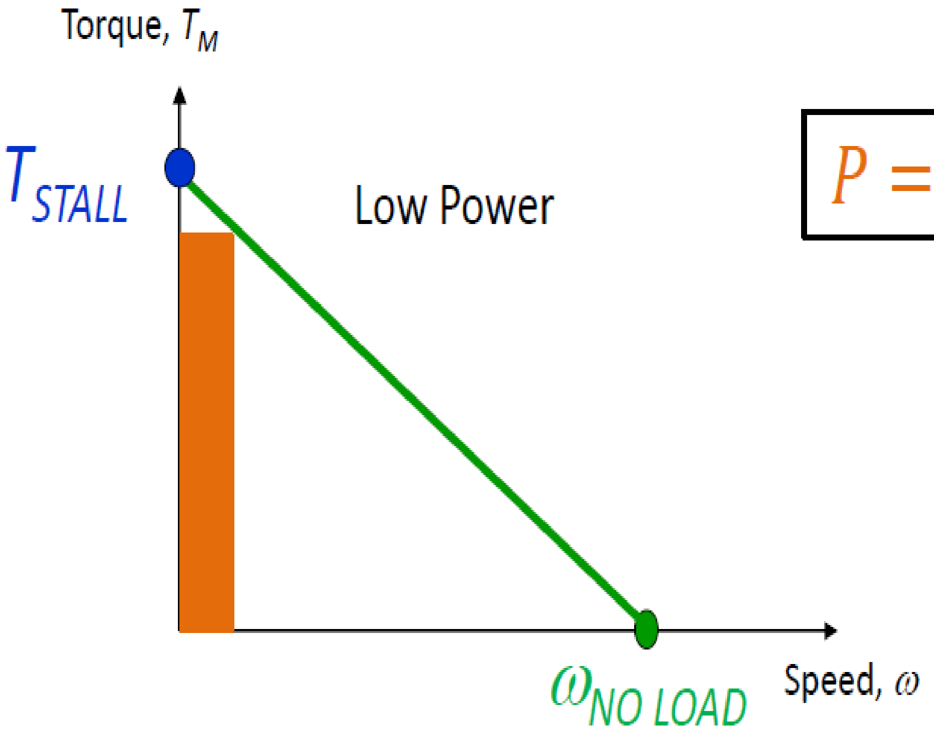
=V_B / (B*L)

DC Motor specification

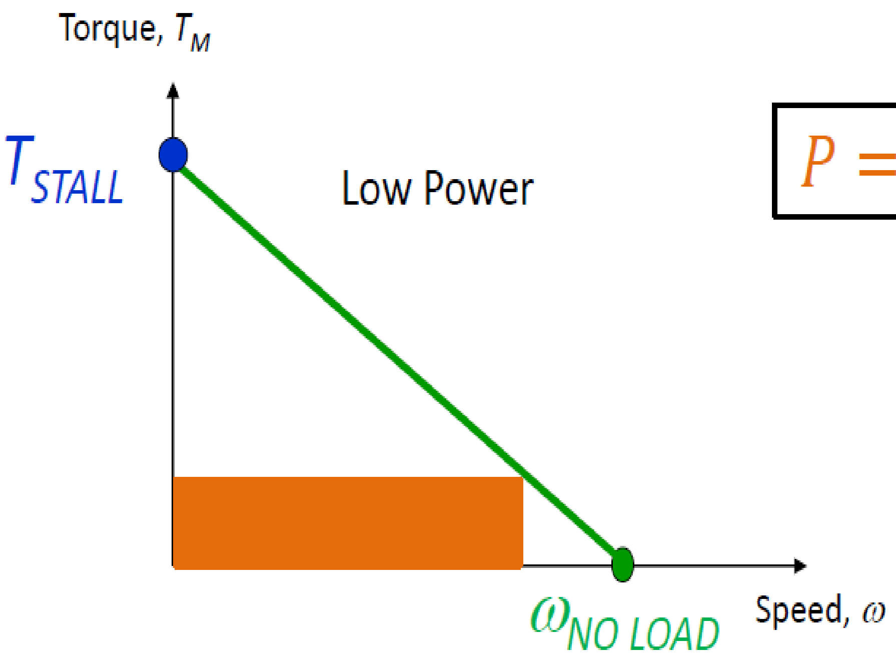
Other actuators have very different speed/torque curves



DC Motor specification

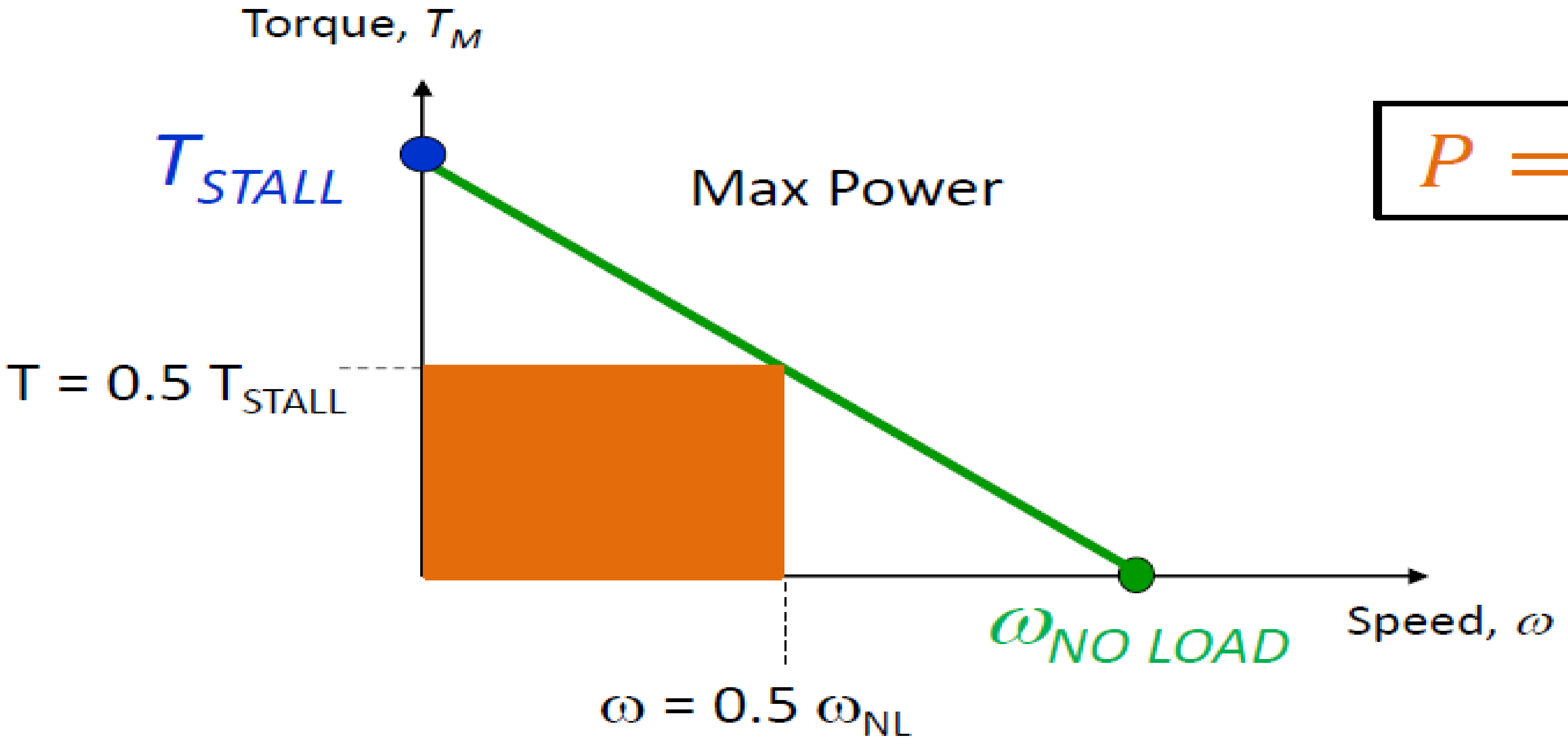


$$P = \tau \cdot \omega$$



$$P = \tau \cdot \omega$$

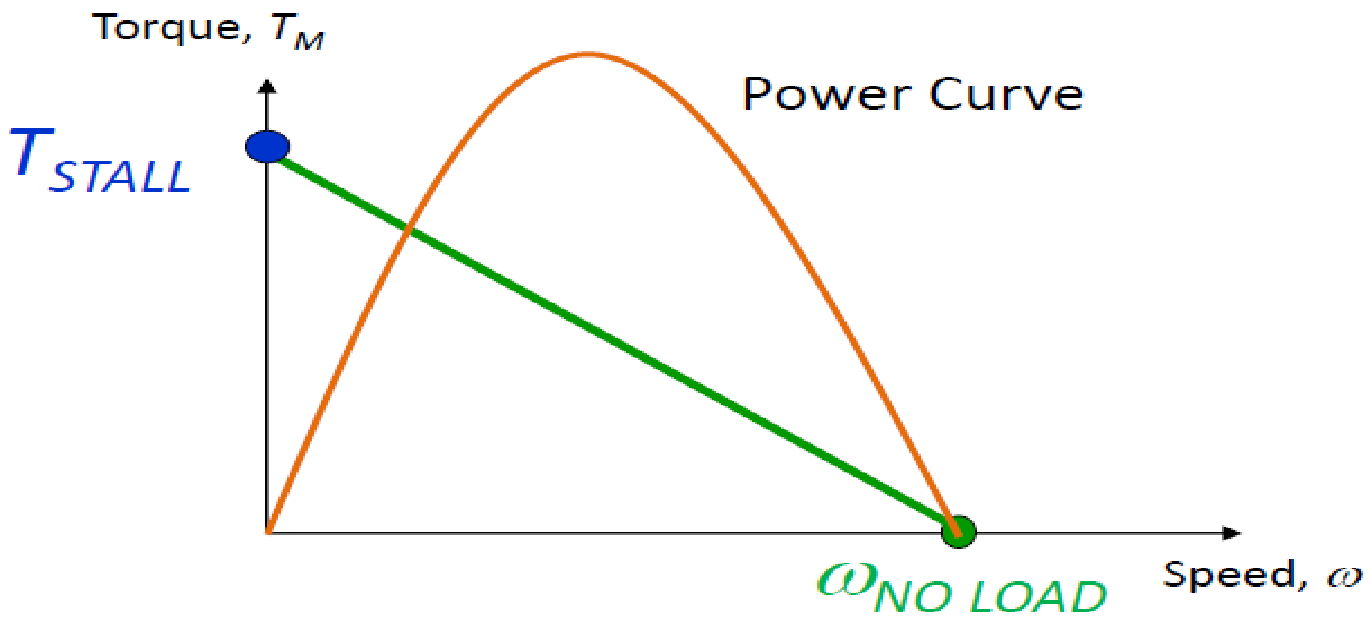
DC Motor specification



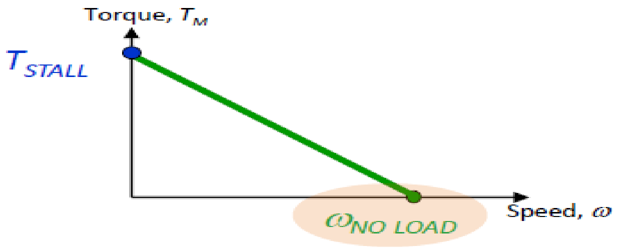
$$P = \tau \cdot \omega$$

DC Motor specification

Important to remember if you want to optimize your vehicle's acceleration!



DC Motor specification



#	Motor Data	Unit	118749	118750	118751	118752	118753	118754	118755	118756	118757
1	Assigned power rating	W				20					
2	Nominal voltage	Volt				24.0					
3	No load speed	rpm				9660					
4	Stall torque	mNm				240					
5	Speed / torque gradient	rpm / mNm				41.2					
6	No load current	mA				37					
7	Starting current	mA				10300					
8	Terminal resistance	Ohm				2.32					
9	Max. permissible speed	rpm				11000					
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19	Thermal resistance housing-ambient	K / W				14					
20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

The difference from 9660rpm is mechanical friction and wind load

412*24(volt)=9888 rpm

DC Motor specification

Value Added Mechatronics

$$T_M = K_T \cdot i_a$$

Stall torque is a test parameter, not a upper bound on the torque you should expect from your DC motor during continuous operation!

Motor Data			118749	118750	118751	118752	118753	118754	118755	118756	118757
1	Assigned power rating	W				20					
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21	Thermal time constant winding	s				12					

Istall= *V* B/R = 24/2.32 = 10.3 A

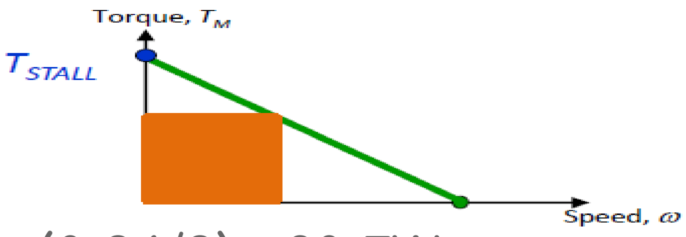
How long can you run with a stalled out motor?

Not long if you're running applying a high load torque!

10.3 A * 23.2 = 239 mNm

DC Motor specification

Value Added Mechatronics



Our theoretical peak power output is:

$$P=\omega T=2\pi * rps*T = 2\pi * ((9660/2)* 1/60)*(0.24/2)= 60.7W$$

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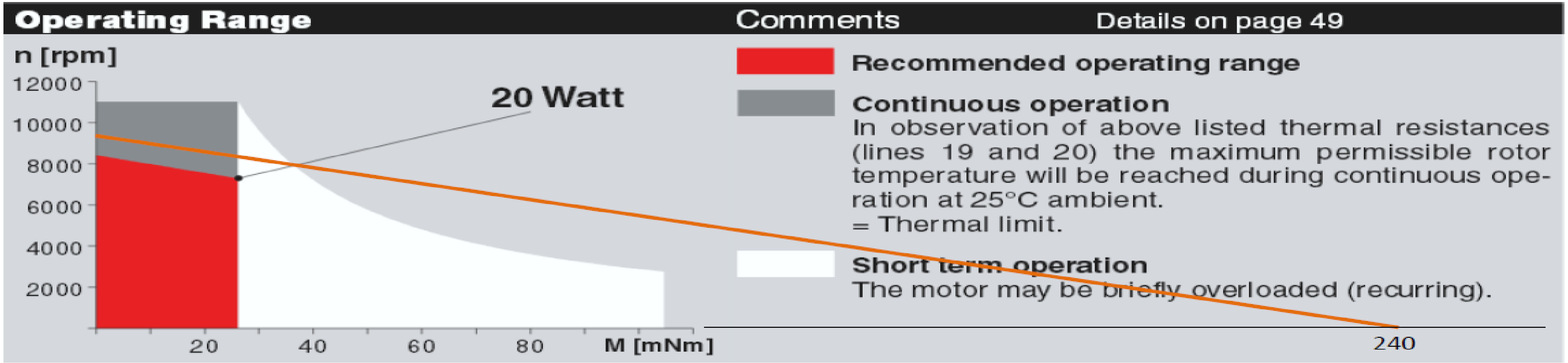
12	Max. power output at nominal voltage	mW				58400					
13	Max. efficiency	%				85					

The manufacturer is being conservative in assigning a power level for ***continuous*** operation.

Note that the max. power output listed here is closer to our theoretical calculation

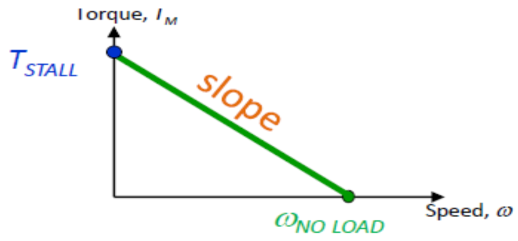
DC Motor specification

This manufacturer is conservative in its recommendations...



This manufacturer recommends keeping the torque at about 1/8th of stall torque for continuous operation! A more common rule of thumb is limiting continuous torque from 1/3 to 1/2 the stall torque. The higher the continuous torque, the closer you need to watch the motor temperature!

DC Motor specification



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Slope=9660/240
=40.25

DC Motor specification

Value Added Mechatronics

How can the motor speed be greater than no load speed?

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20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

If the input voltage is greater than 24V, the speed can be greater than no load speed.

But, do not exceed Max. permissible speed
because the commutator and brushes wear more rapidly

DC Motor specification

Torque in coil

- F force in coil : $F = B*I*L$
- Torque in coil

$T = 2F*a$

$= 2*B*I*L*a$

$= \underline{2a*B*L}*I$

$= K_T * I$

K_T: Torque constant

e Induced voltage:

$e = B*v*2L$ (2 sides)

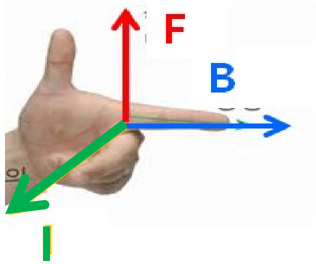
$= B*2a\pi*rps*2L$

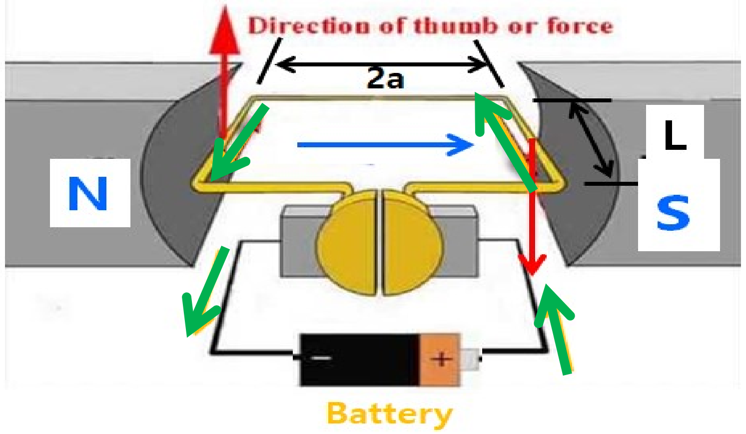
$= (B*2a*L)*2\pi*rps$

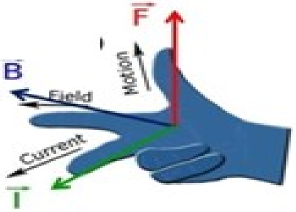
$= \underline{2a*B*L} * \omega$

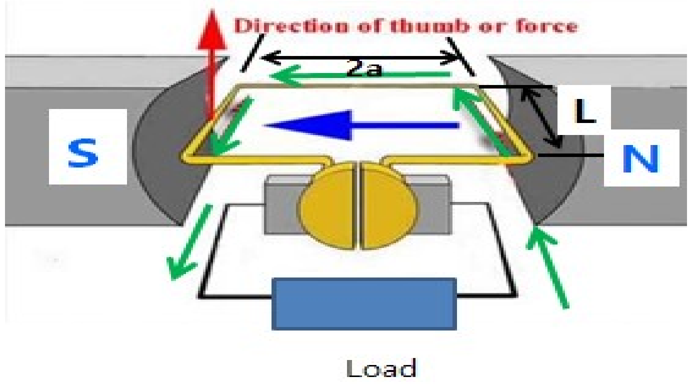
$= K_{EMF} * \omega$

K_{EMF}: Back-EMF constant









DC Motor specification

This spec sheet gives the inverse of K_{EMF}

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18	Terminal inductance	mH				0.24					
19	Thermal resistance housing-ambient	K / W				14					
20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

Speed constant

-412 = rpm/V

-412/60 = rps/V (1rpm =1/60 rps)

Back-EMF constant

60/412=V/rps

(60/412)/ 2 π =V/(rad/s) **(1rps=2π** rad/s **)**

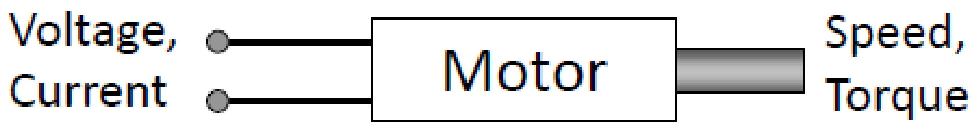
23(mV/ω)

Torque constant = Back-EMF constant

DC Motor operating characteristics

From a ***control*** view of a DC motor

- We treat the "motor" as a box that is lossless and stores no energy. In reality, power losses exist due to internal resistance and friction.



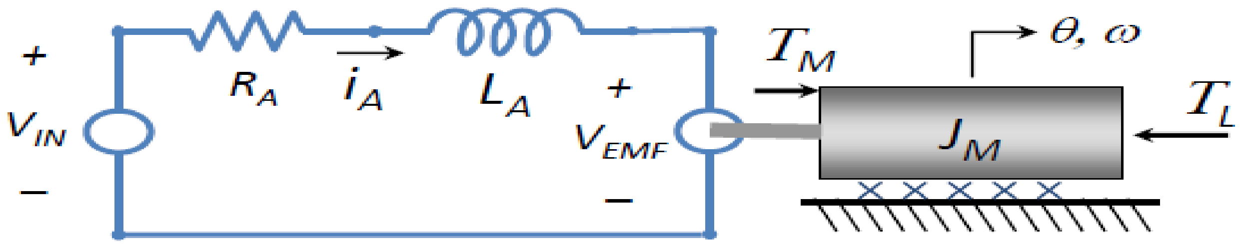
DC Motor operating characteristics

Value Added Mechatronics

- At steady state, power flow on the mechanical and electrical sides instantaneously match (why?)

$$P = \underbrace{V_{IN} \cdot i}_{\text{Electrical power}} = \underbrace{T \cdot \omega}_{\text{Mechanical power}}$$

$$P = K_{EMF} \cdot \omega \cdot \frac{T}{K_T} = T \cdot \omega$$

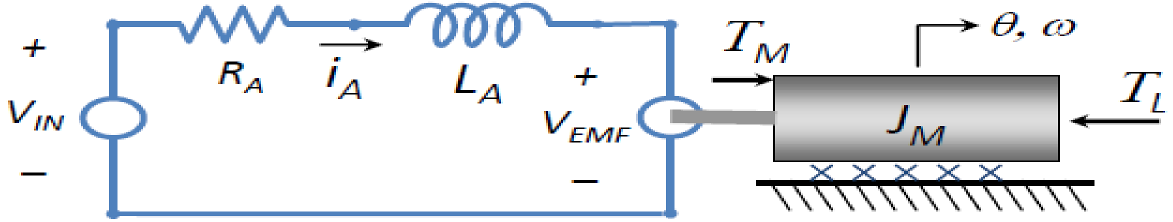


During constant speed operation, the input voltage is equal to the back-EMF generated by the motor, since $T = K_T \cdot i$ and $K_{EMF} = K_T$. Hence, by maintaining a constant supply voltage of $V_{IN} = K_{EMF} \cdot \omega$, we achieve a constant output speed

DC Motor operating characteristics

Equivalent circuit:

$$V_{IN} = i_A \cdot R_A + V_{EMF} + \cancel{L_A \frac{d}{dt} i_A}$$



At steady-state:

$$V_{IN} = i_A \cdot R_A + V_{EMF} = \frac{T_M}{K_T} \cdot R_A + K_{EMF} \cdot \omega$$

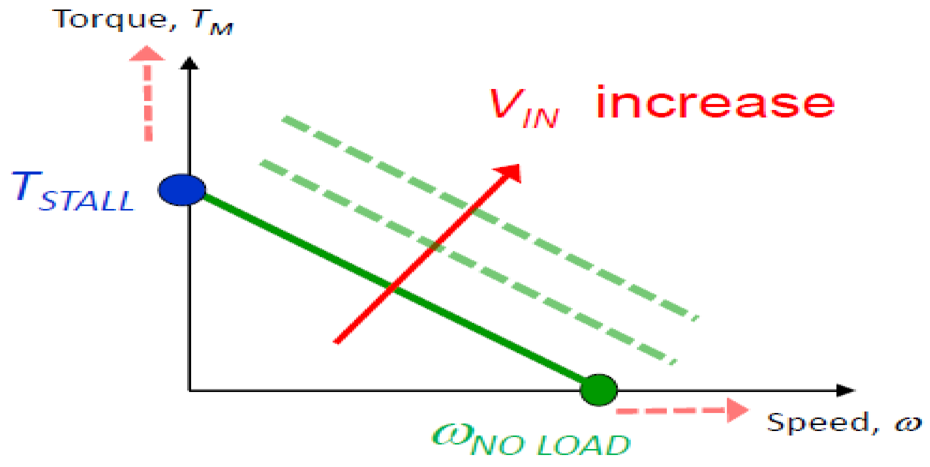
$$\Rightarrow T_M = \frac{K_T}{R_A}(V_{IN} - K_{EMF}\,\omega)$$

- Stall Torque (ω = 0):

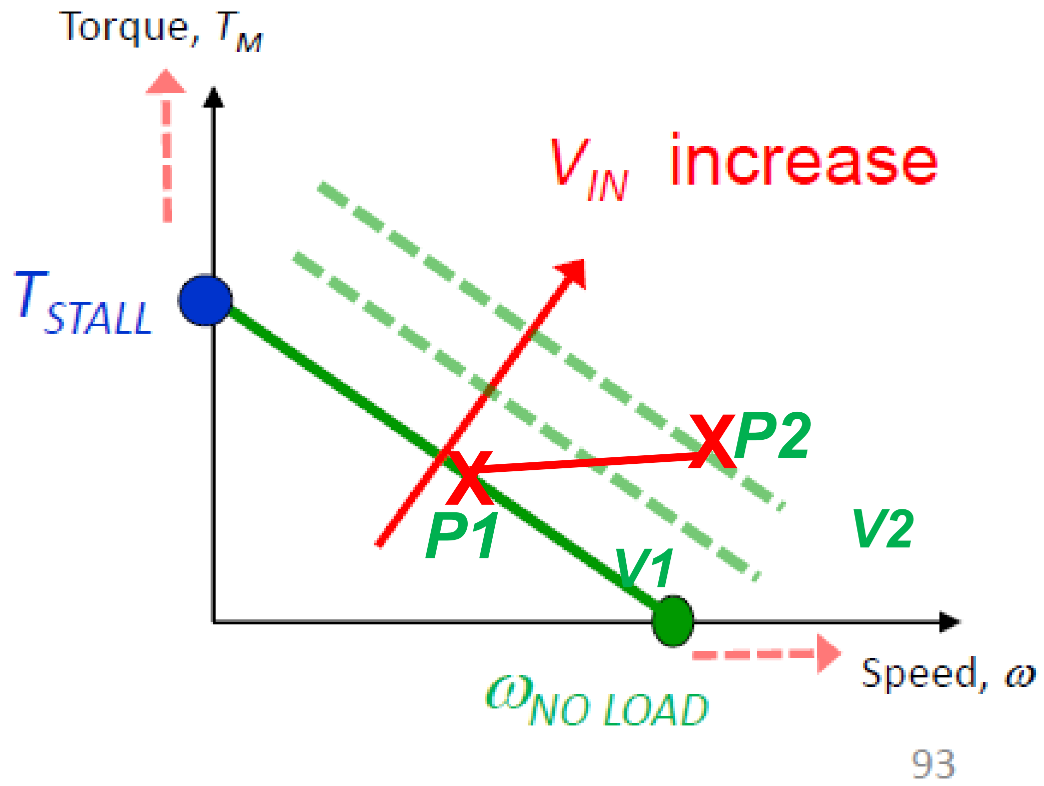
$$T_{STALL} = \frac{K_T}{R_A} \cdot V_{IN}$$

- No-Load Speed (T_M = 0):

$$\omega_{NO\ LOAD} = \frac{V_{IN}}{K_{EMF}}$$



DC Motor operating characteristics



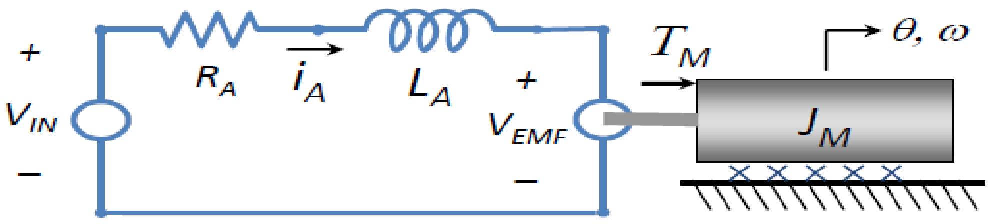
V1 → V2 ⇒ P1 → P2

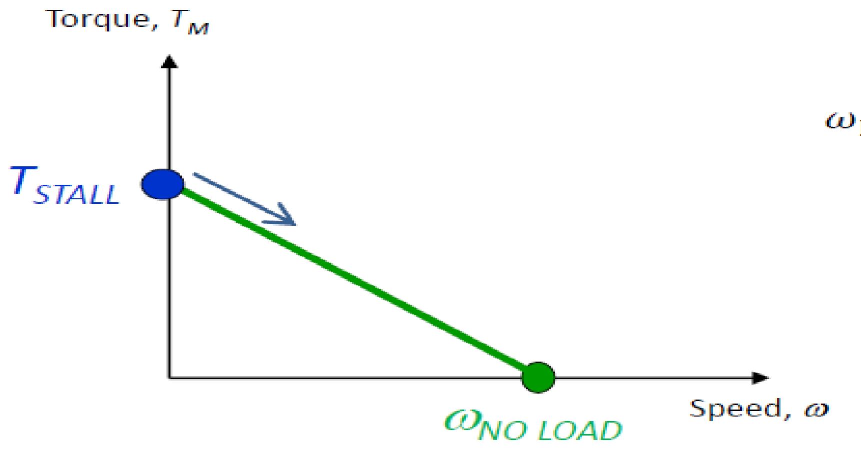
means same torque (same current/same winging loss) with higher speed (more power with same current)

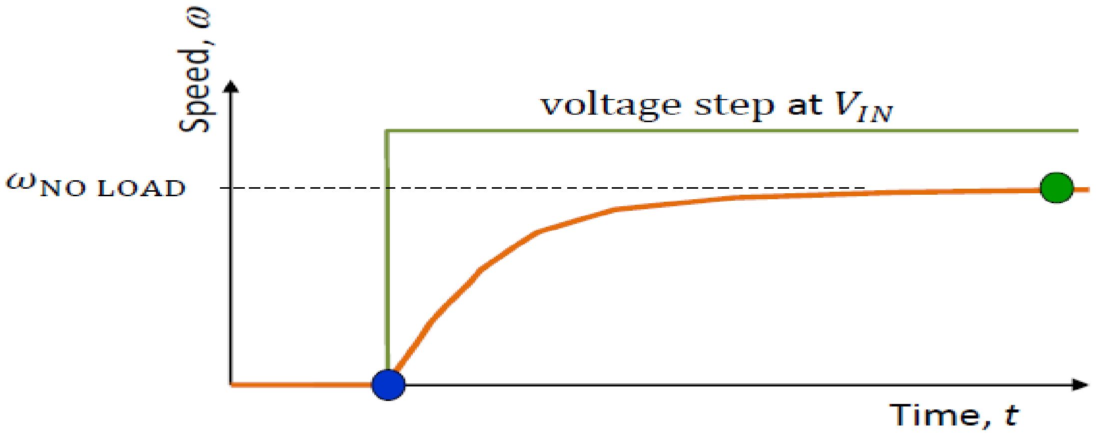
DC Motor operating characteristics

- **No load**

- For a step voltage input, rapid acceleration occurs as motor starts from a standstill. As more and more back EMF is generated, the motor torque decreases, and acceleration slows, with the speed eventually settling at $\omega_{\text{NO LOAD}}$.



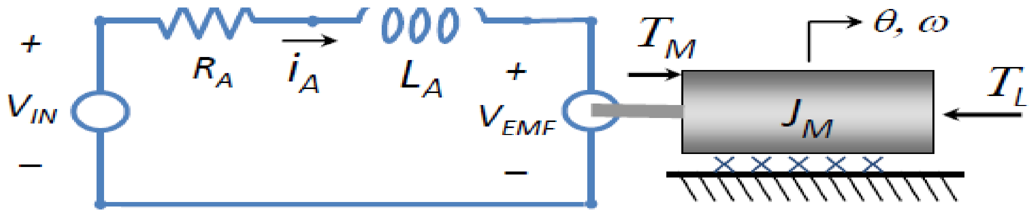




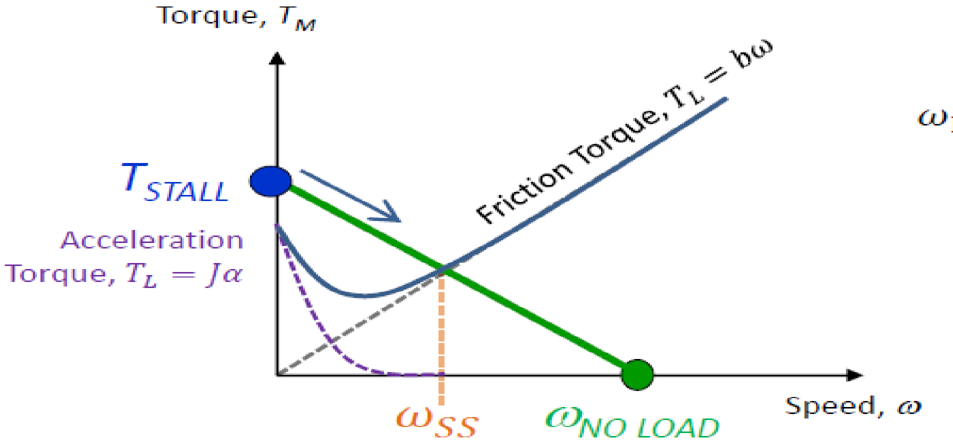
DC Motor operating characteristics

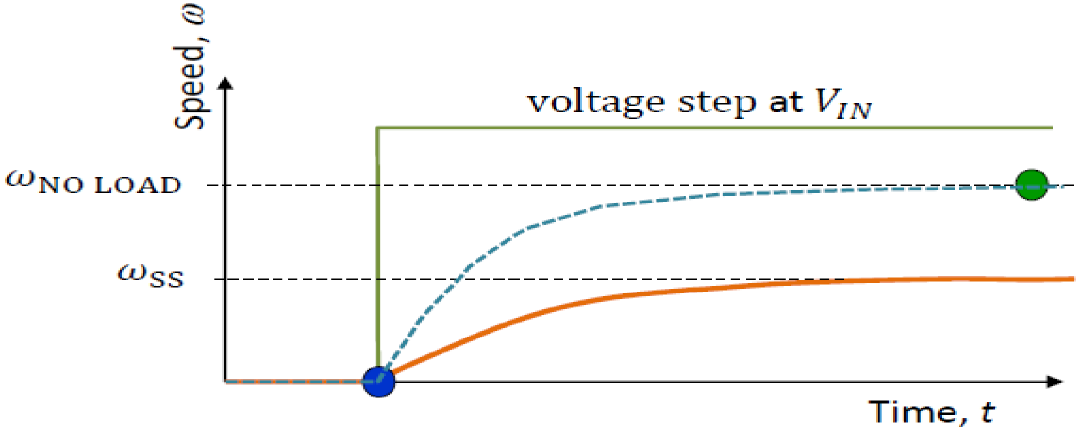
- **With load**

Q: Does the load on the mechanical side affect the steady-state speed?



$$T_L = J\alpha + b\omega$$





DC Motor operating characteristics

The mechanical time constant tells us the time it takes an <u>unloaded</u> motor to reach 63% of its no-load speed under a constant voltage, when starting from rest

Motor Data			118749	118750	118751	118752	118753	118754	118755	118756	118757
1	Assigned power rating	W				20					
2	Nominal voltage	Volt				24.0					
3	No load speed	rpm				9660					
4	Stall torque	mNm				240					
5	Speed / torque gradient	rpm / mNm				41.2					
6	No load current	mA				37					
7	Starting current	mA				10300					
8	Terminal resistance	Ohm				2.32					
9	Max. permissible speed	rpm				11000					
10	Max. continuous current	mA				1230					
11	Max. continuous torque	mNm				28.4					
12	Max. power output at nominal voltage	mW				58400					
13	Max. efficiency	%				85					
14	Torque constant	mNm / A				23.2					
15	Speed constant	rpm / V				412					
16	Mechanical time constant	ms				5					
17	Rotor inertia	gcm²				10.3					
18	Terminal inductance	mH				0.24					
19	Thermal resistance housing-ambient	K / W				14					
20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

DC Motor operating characteristics

Value Added Mechatronics

Why doesn't the no load current go to zero?

	Motor Data		118749	118750	118751	118752	11
1	Assigned power rating	W				20	
2	Nominal voltage	Volt				24.0	
3	No load speed	rpm				9660	
4	Stall torque	mNm				240	
5	Speed / torque gradient	rpm / mNm				41.2	
6	No load current	mA				37	
7	Starting current	mA				10300	
8	Terminal resistance	Ohm				2.32	
9	Max. permissible speed	rpm				11000	
10	Max. continuous current	mA				1230	
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19	Thermal resistance housing-ambient	K / W				14	
20	Thermal resistance rotor-housing	K / W				3.1	
21	Thermal time constant winding	s				12	

Because of mechanical friction loss and wind loss load

DC Motor operating characteristics

Maximum efficiency in converting electrical power to mechanical power usually occurs at high speeds and low torques

	Motor Data		118749	118750	118751	118752	118
1	Assigned power rating	W				20	
2	Nominal voltage	Volt				24.0	
3	No load speed	rpm				9660	
4	Stall torque	mNm				240	
5	Speed / torque gradient	rpm / mNm				41.2	
6	No load current	mA				37	
7	Starting current	mA				10300	
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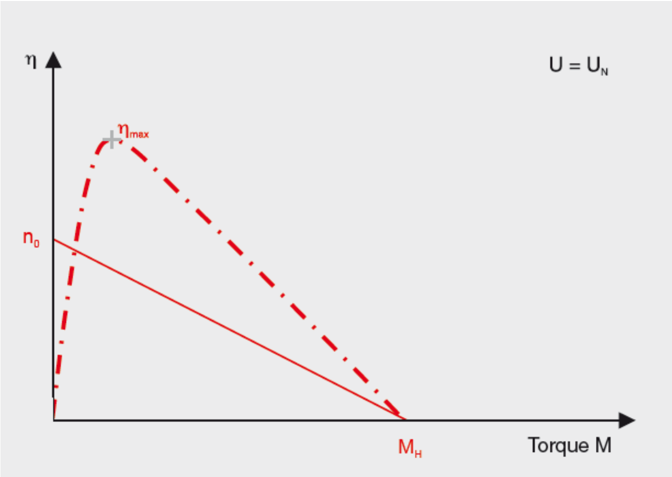
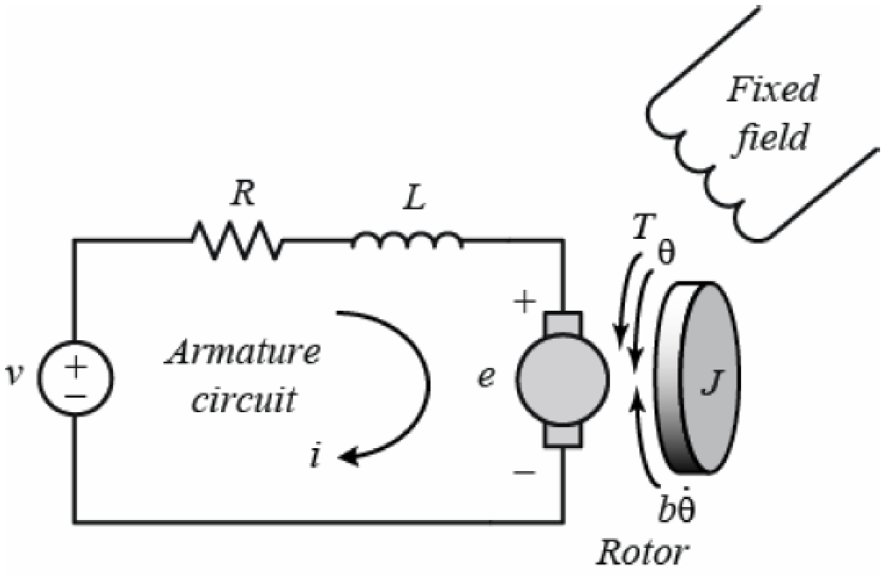
16	Mechanical time constant	ms				5	



Because major losses of motor is copper winding loss by current
Less torque → less current

But mechanical loss will be increase by higher higher speed

DC Motor operating characteristics



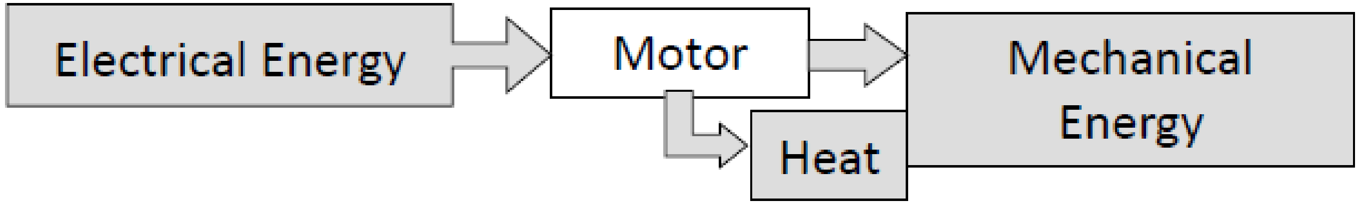
$$V_{EMF} = K_{EMF} \cdot \omega$$

$$T_M = K_T \cdot i_A$$

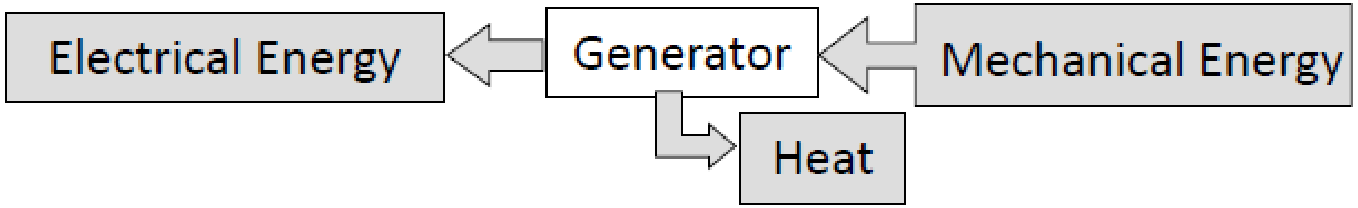
- **Voltage (velocity) mode:** control voltage across winding
- **Current (torque) mode:** control current through winding

DC Motor operating characteristics

- Motor – Electrical power in → mechanical power out.



- Generator – Mechanical power in → electrical power out.
  - When operated for its output power, it is called a generator.



DC Motor operating characteristics

- **Factors to consider when selecting a motor**

We often want more torque, but we can't increase torque without increasing current. However, ***too much current will destroy the motor windings***! Thus, we must take a look at the following constraints when selecting a DC motor:

- Torque limits
- Current limits
- Rotational speed limits

DC Motor operating characteristics

- **Factors to consider when selecting a motor**

Even if we don't burn out the windings, we can overheat the motor:

- Heat is primary performance limitation for DC motors
- Sources:
  - Electrical losses in windings
  - Eddy current
  - Hysteresis
  - Friction
  - Brush contact resistance
- Transient temperature limit is very different from steady-state limits (what is on the specifications)

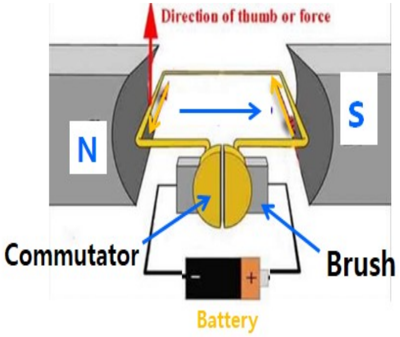
DC Motor operating characteristics

- **Factors to consider when selecting a motor**

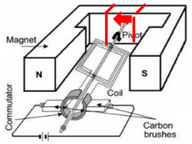
If you need more torque, however, do not fear...

As we will see shortly, you can trade speed for torque using a gearbox!

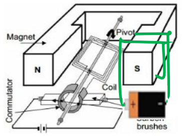
Classification of motors



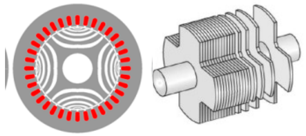
- Electric Motors
  - DC Motors
    - Brushed
      - Permanent Magnet
      - Separately Excited
    - Brushless
      - Stepper
  - AC Motors
    - Synchronous
      - Reluctance
      - Permanent Magnet
    - Induction

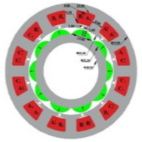


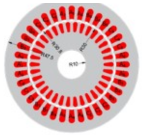
PM

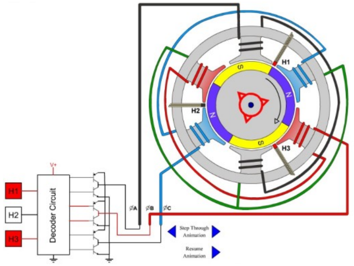


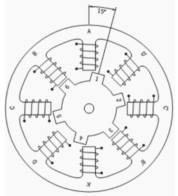
Separately Excited







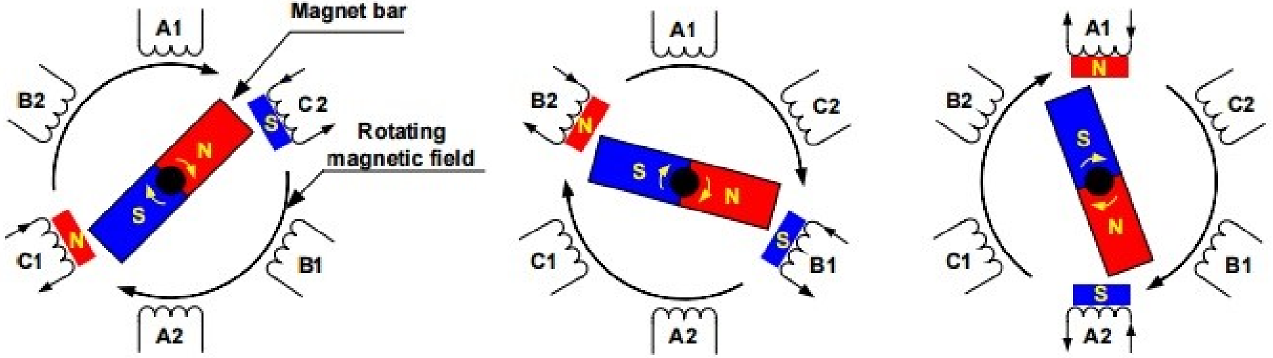




https://electricalbaba.com/brushless-dc-bldc-motor/

Classification of motors

- BLDC(brushless DC) motor

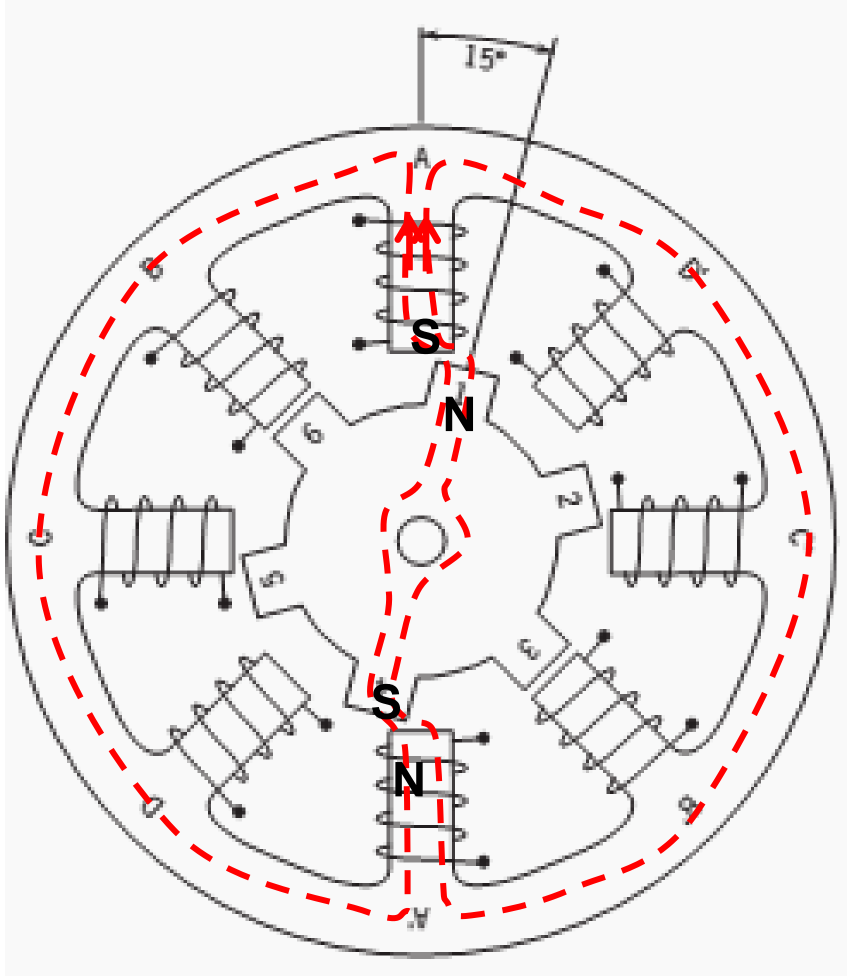


http://4.bp.blogspot.com/-9q50-d2NK_M/VztxoGsaBbl/AAAAAAAAA4o/vG_S193LnB0YFYt3OgUijUons63QD-0oACK4B/s1600/BLDC-brushless-dc-motor-animation.gif

Compared with a brushed DC motor, the has many advantages:
Higher efficiency and reliability
Lower acoustic noise
Smaller and lighter
Greater dynamic response
Better speed versus torque characteristics
Higher speed range
Longer life

Classification of motors

- Stepper motor



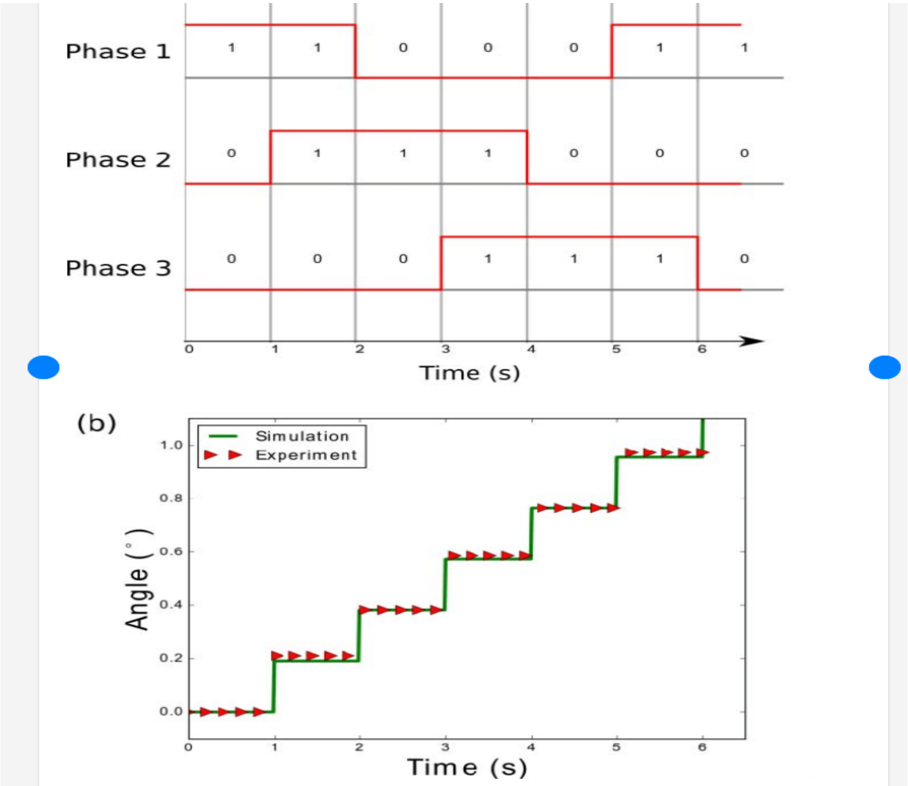
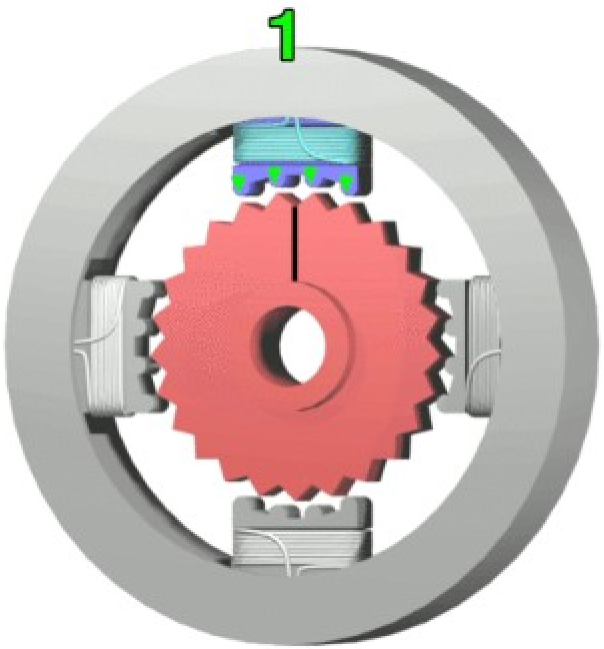


Illustration of stepper motor driving principle: (a) Driving half-stepping voltage waveform for driving rotary actuator, and (b) experimental plots showing the rotational stepping motion of the motor with an angle of 0.2° per step

Classification of motors

- Stepper motor

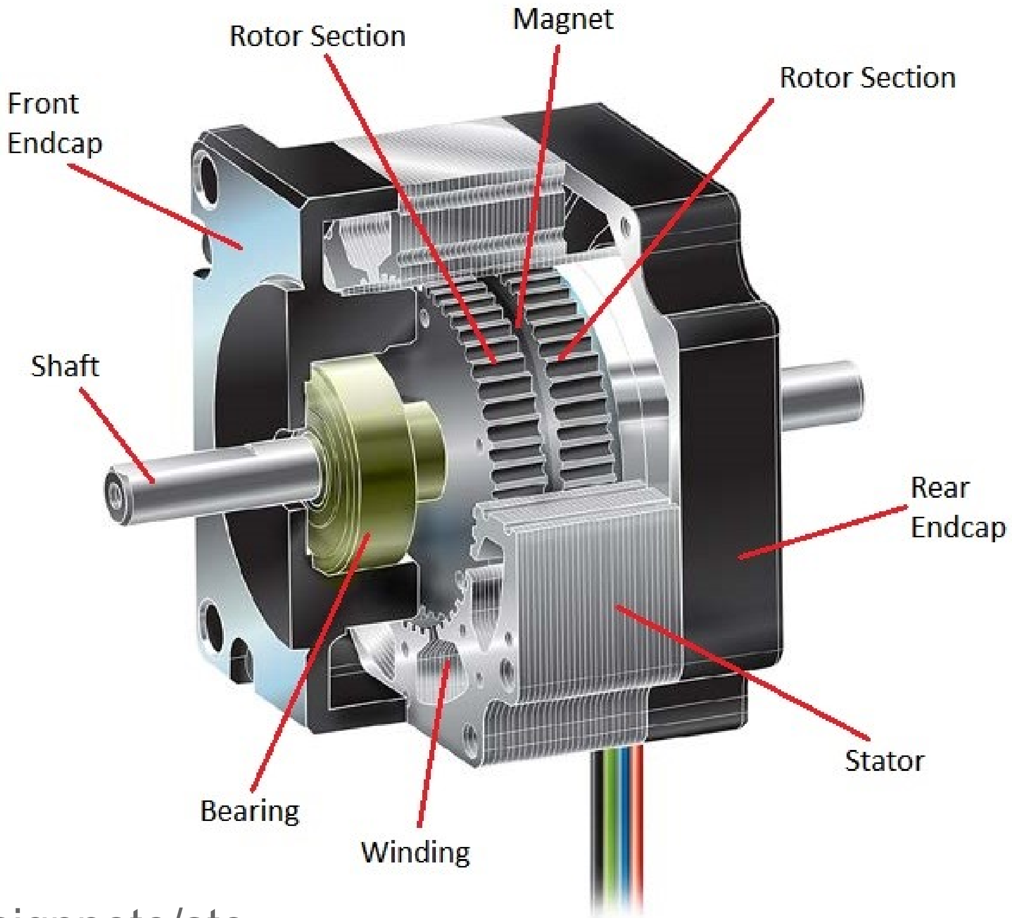
A stepper motor, also known as step motor or stepping motor, is a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor's position can then be commanded to move and hold at one of these steps without any position sensor for feedback (an open-loop controller), as long as the motor is carefully sized to the application in respect to torque and speed.
Switched reluctance motors are very large stepping motors with a reduced pole count, and generally are closed-loop commutated.



https://en.wikipedia.org/wiki/Stepper_motor#/media/File:StepperMotor.gif

Classification of motors

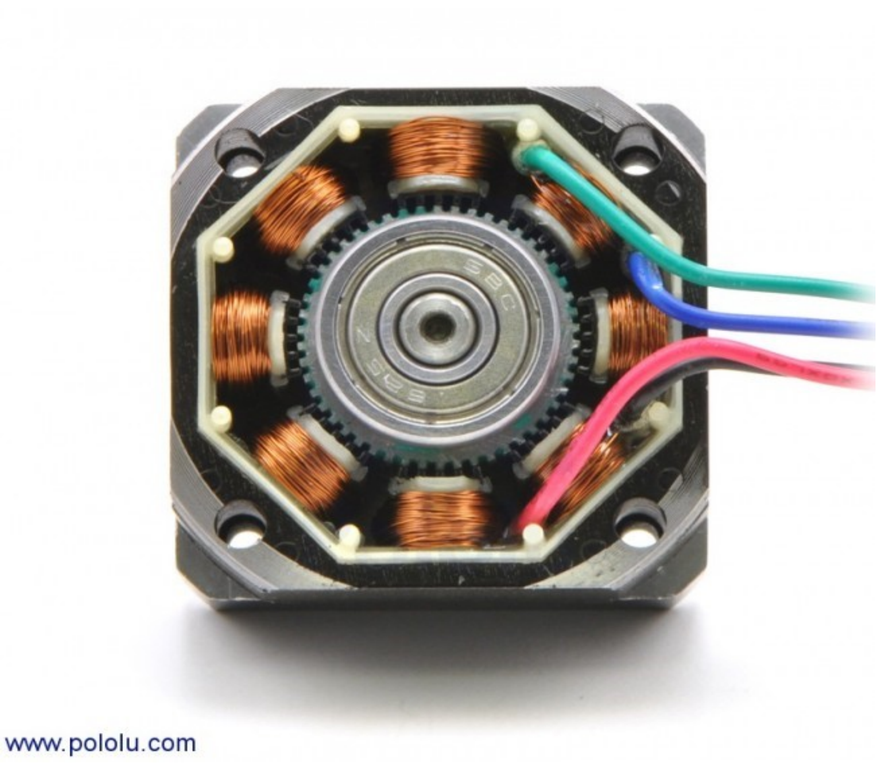
- Stepper motor



https://www.islproducts.com/designnote/stepper-motor-fundamentals/

Classification of motors

- Stepper motor

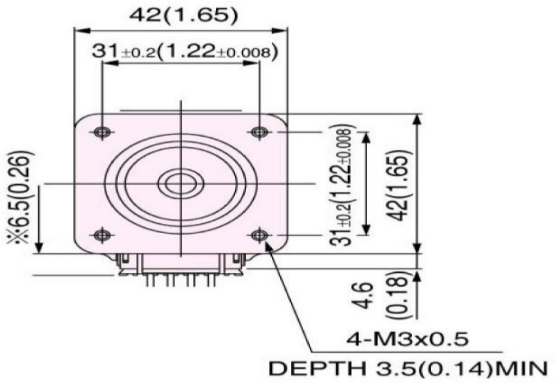


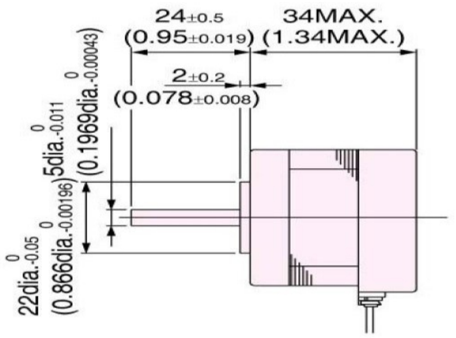
https://www.youtube.com/watch?v=eyqwLiowZiU
https://www.youtube.com/watch?v=bkqoKWP4Oy4

Classification of motors

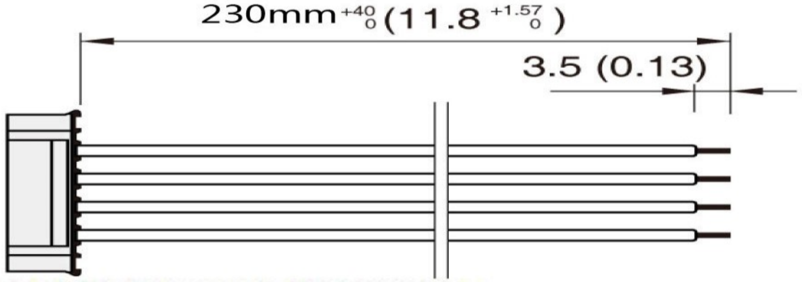
- Stepper motor : specification

M O D E L	SINGLE SHAFT	-951
DRIVE METHOD		BI-POLAR
NUMBER OF PHASES	————	2
STEP ANGLE	deg./step	1.8
VOLTAGE	V	12
CURRENT	A/PHASE	0.35
WINDING RESISTANCE	Ω/PHASE	34
INDUCTANCE	mH/PHASE	4.3
HOLDING TORQUE	mN • m	200
	oz • in	28
DETENT TORQUE	mN • m	11.8
	oz • in	2.1
ROTOR INERTIA	g • cm²	38
	oz • in²	0.21
WEIGHTS	g	200
	lb	0.57
INSULATION CLASS	————	JIS Class E (120°C 248°F) (UL VALUE : CLASS B-130°C 266°F)
INSULATION RESISTANCE	————	500VDC 100MΩmin.
DIELECTRIC STRENGTH	————	500VAC 50HZ 1min.
OPERATING TEMP. RANGE	°C	0 to 50
ALLOWABLE TEMP.RISE	deg.	70





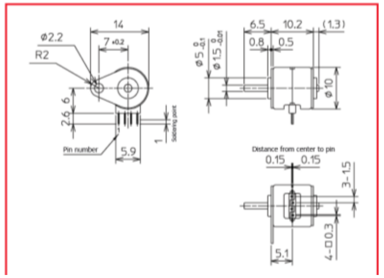
BI-POLAR



https://www.google.co.kr/search?q=stepper+motor+specification&source=lnms&tbm=isch&sa=X&ved=0ahUKEwirrMqvzZXkAhXtyosBHURHDtsQ_AUIESgB&biw=2163&bih=1049#imgrc=QwbnLWhrO2T2JM:&spf=1566446882665

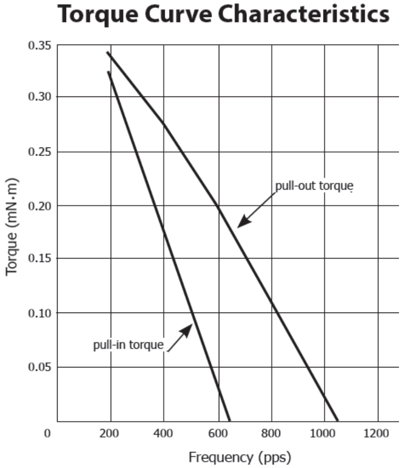
DC Motor operating characteristics

- Stepper motor : specification

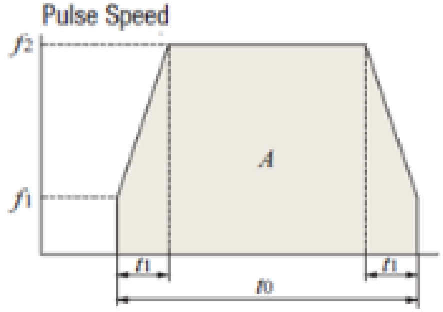


Specifications

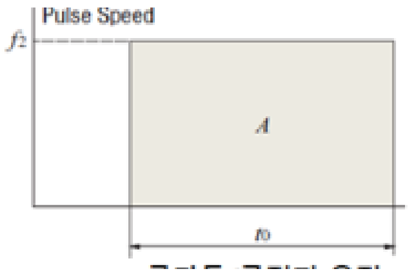
Specification	Unit	PFC10-20R6
Type of Winding		Bipolar
Excitation Mode*		Full step (2-2)
Steps/Revolution		20
Step Angle	°	18
Holding Torque	mN·m	1.0
Rated Voltage	V	2.7
Rated Current	mA/phase	135
Resistance	Ω / ϕ	20
Inductance	mH / ϕ	3.2
Coil		R
Starting Pulse Rate	pps	960
Slewing Pulse Rate	pps	1600
Rotor Inertia	kg·m²	0.03×10^{-7}
Operating Temp. Range	°C	-10 to +50
Storage Temp. Range	°C	-30 to +80
Insulation Class		E
Temperature Rise	K	70
RoHS Compliant		Yes
Weight	g	5



Pin	Coil Phase
1	4ϕ $\overline{B}$
2	1ϕ A



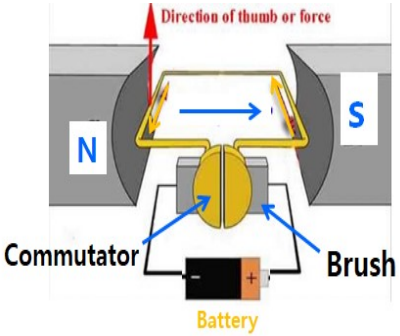
Operation for pull-out torque

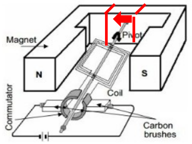


Operation for pull-in torque

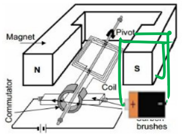
Classification of motors

- Electric Motors
  - DC Motors
    - Brushed
      - Permanent Magnet
      - Separately Excited
    - Brushless
      - Stepper
  - AC Motors
    - Synchronous
      - Reluctance
      - Permanent Magnet
    - Induction





PM



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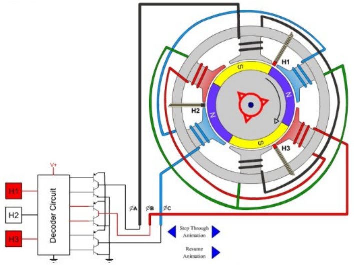
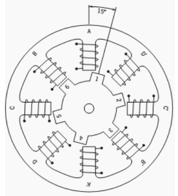
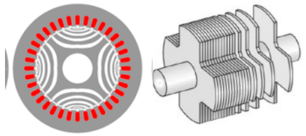
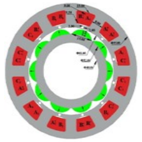
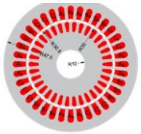










https://electricalbaba.com/brushless-dc-bldc-motor/

Classification of motors

Value Added Mechatronics

- **AC motors: Generation of 3 phase AC current**

When these windings are kept stationary, and the magnetic field is rotated as shown in the figure A below or when the windings are kept stationary, and the magnetic field is rotated as shown below in figure B, an emf is induced in each winding. The magnitude and frequency of these EMFs are same but are displaced apart from one another by an angle of 120 degrees.
In a 3 phase system, there are three equal voltages or EMFs of the same frequency having a phase difference of 120 degrees.
These voltages can be produced by a three-phase AC generator having three identical windings displaced apart from each other by 120 degrees electrical.

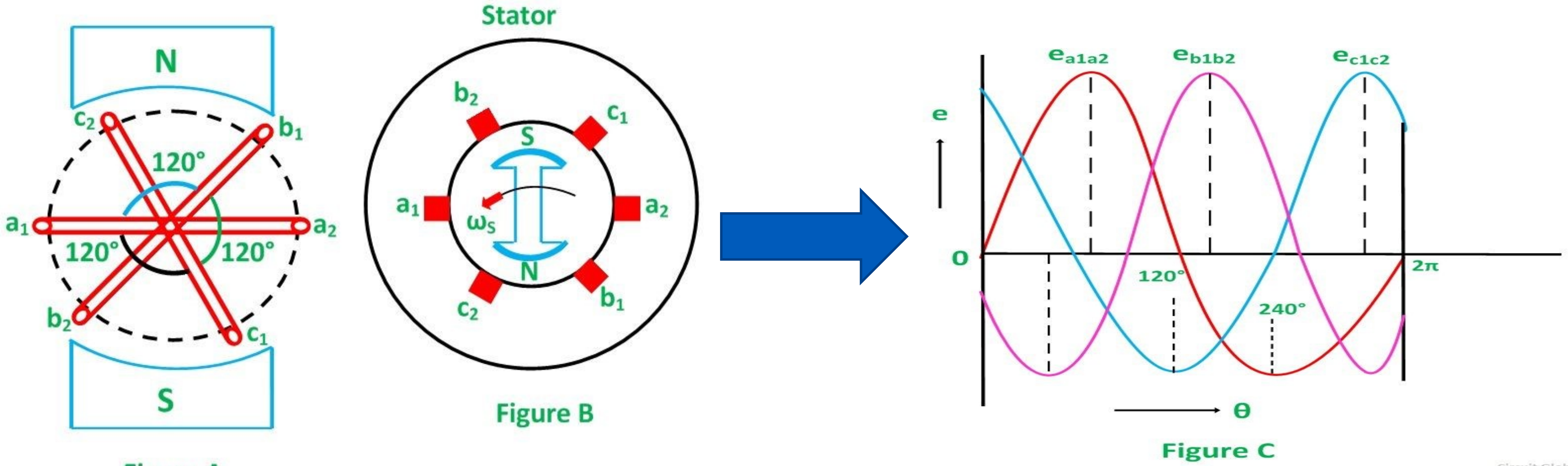


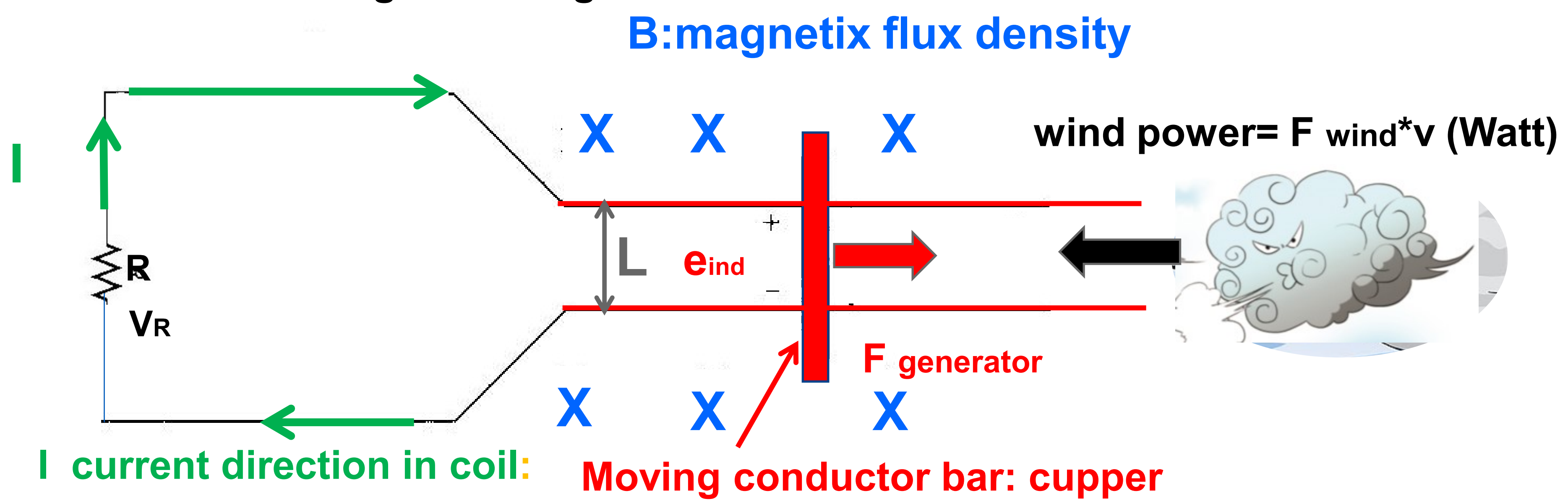
Figure A   Figure B   Figure C

Circuit Globe

https://circuitglobe.com/generation-of-3-phase-power-in-3-phase-circuits.html

Classification of motors

- Induced voltage and magnetic flux



-Fleming's right hand rule: e induced voltage: e_{ind} =B*v*L in moving conductor bar

-v(speed)=dx / dt e_{ind} =B* (dx / dt) *L = B* (dx) *L / dt = d Φ / dt

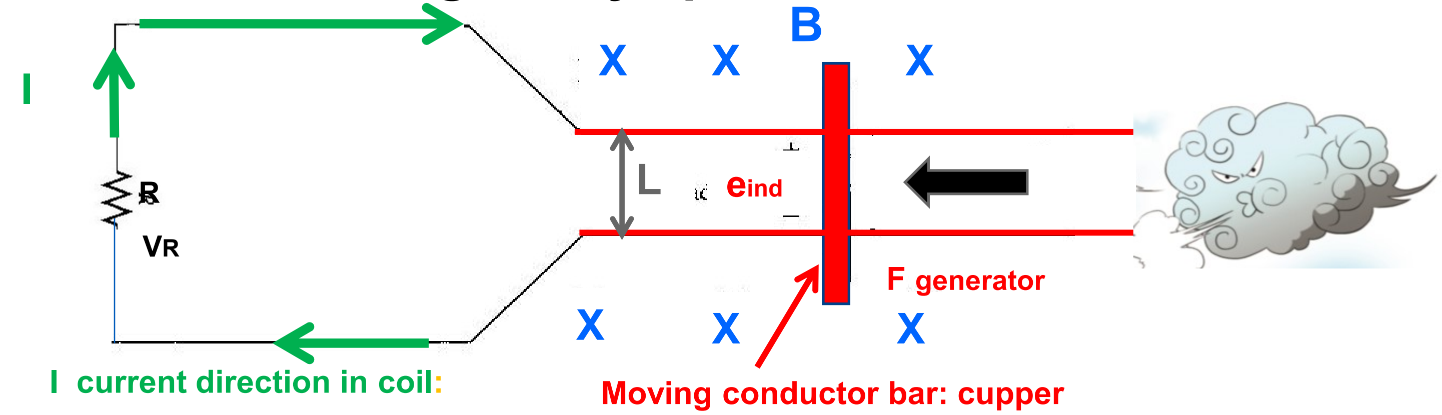
- Here Φ is magnetic flux in coil loop

!!! Remember e_{ind} = B* v *L (Fleming's right hand rule) = dΦ / dt

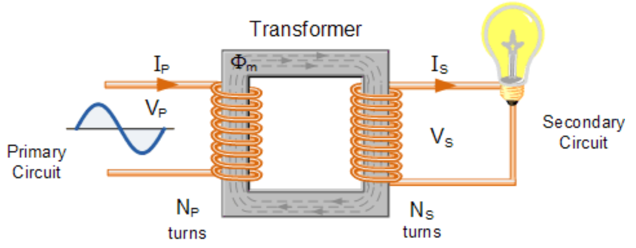
Classification of motors

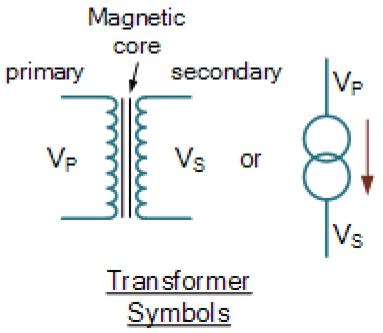
- **Induced voltage by magnetic flux change**

- Induced voltage 1: by speed

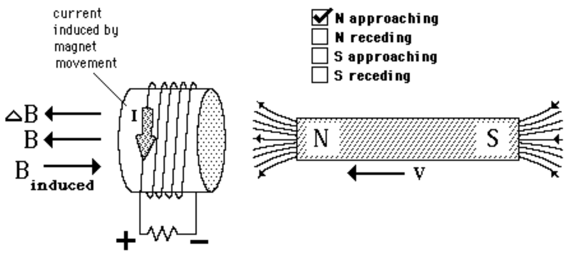


- Induced voltage 2: by AC





- Induced voltage 3:by speed

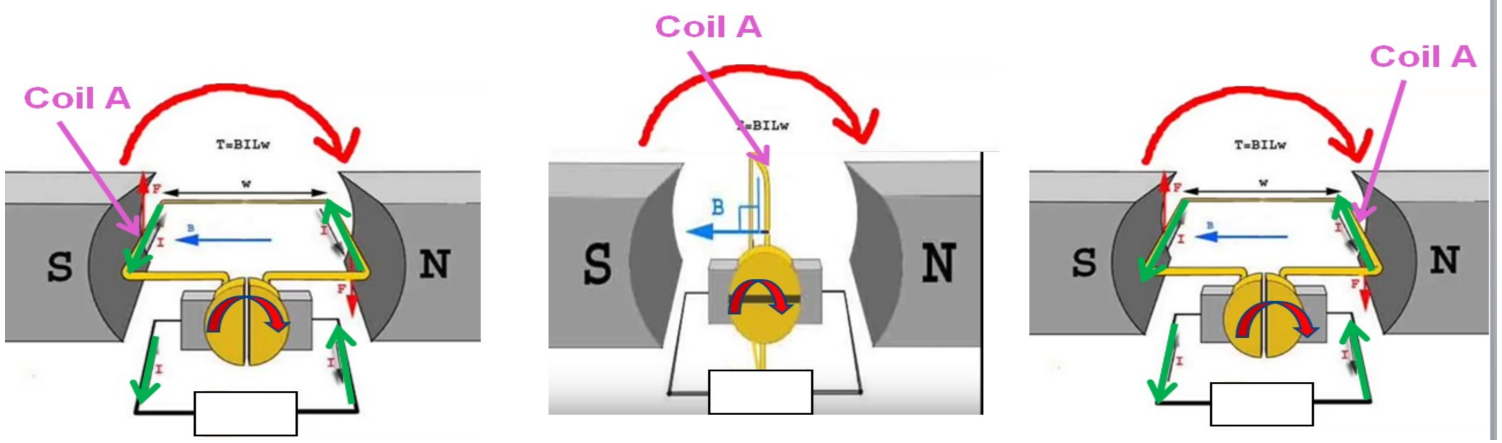


https://www.electronics-tutorials.ws/transformer/transformer-basics.html

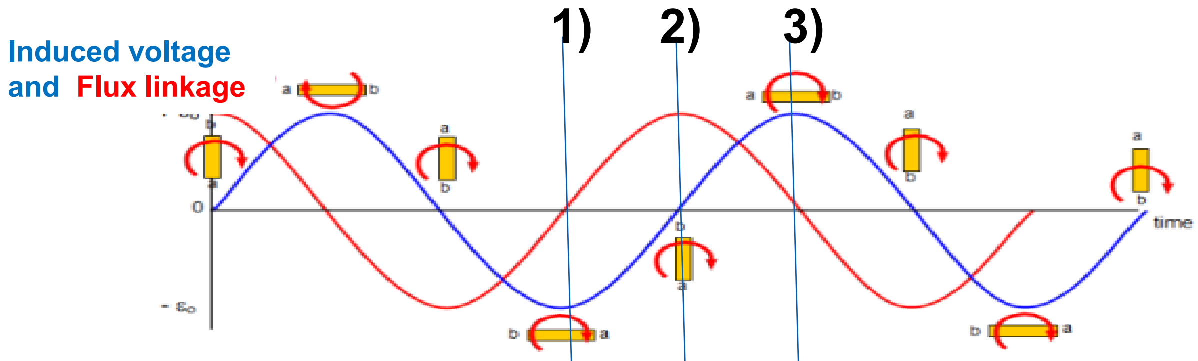
Classification of motors

Value Added Mechatronics

- **Induced voltage by magnetic flux change**
  - Induced voltage 4: by speed

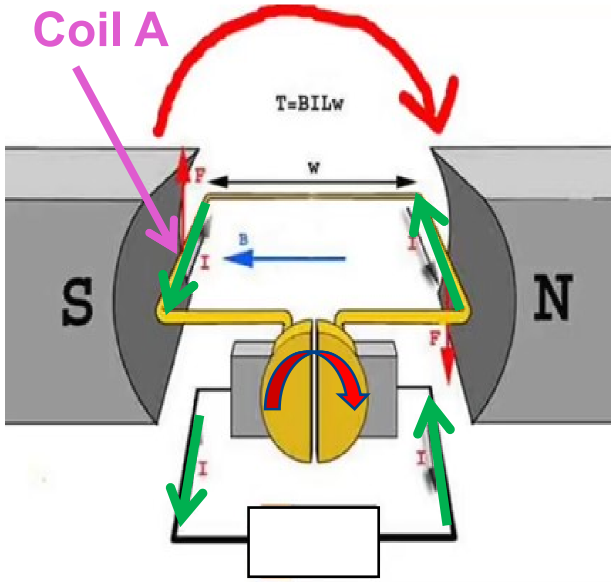


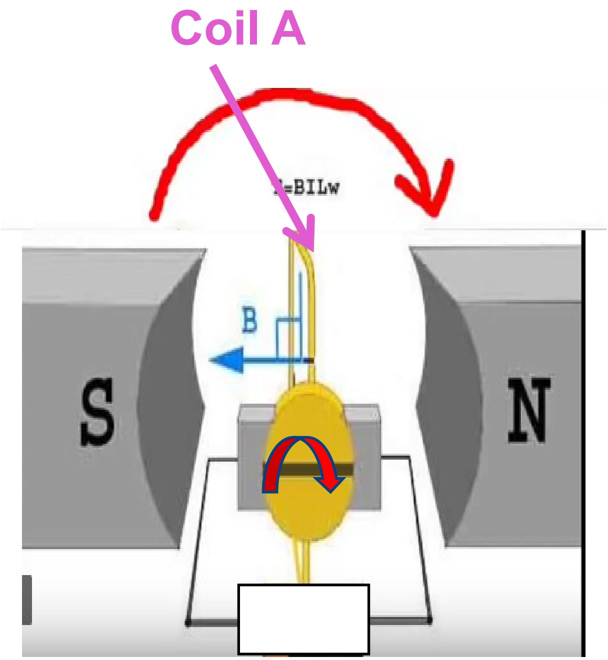
1) F=max   2) F= 0   3) F=max

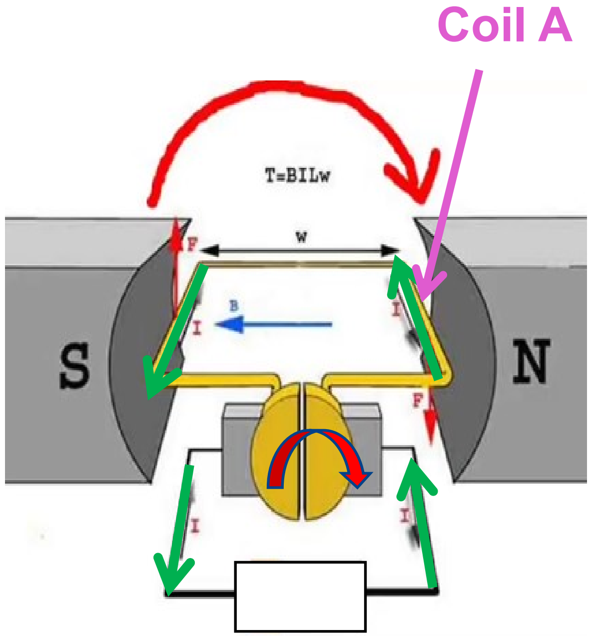


http://www.schoolphysics.co.uk/age16-19/Electricity%20and%20magnetism/Electromagnetic%20induction/text/Induced_emf_in_a_rotating_coil/index.html

Classification of motors



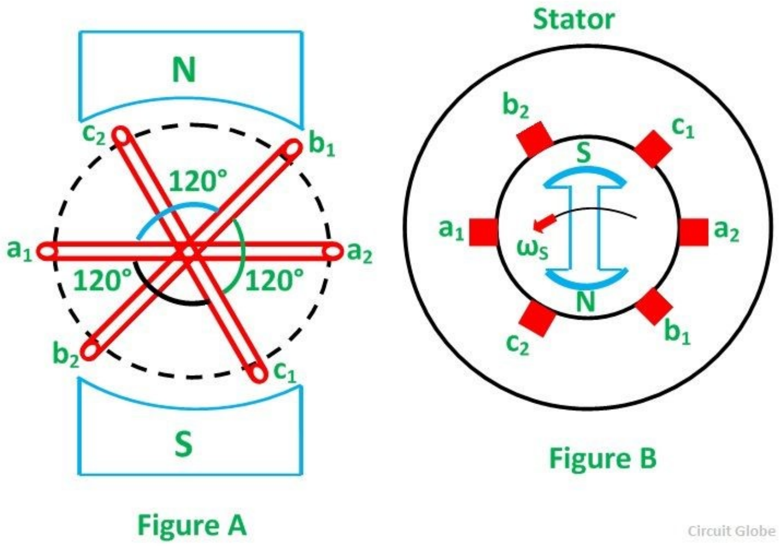


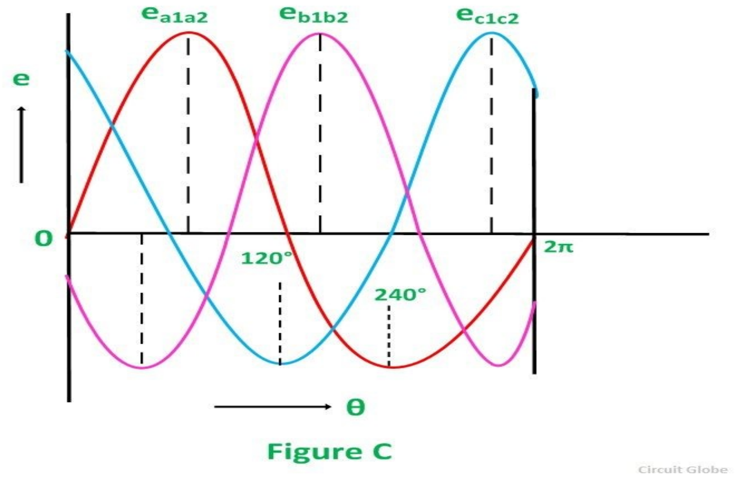


Classification of motors

- **AC motors: Generation of 3 phase AC current**

- 3 phase voltage is generated by $d\Phi / dt$ in the coil loop

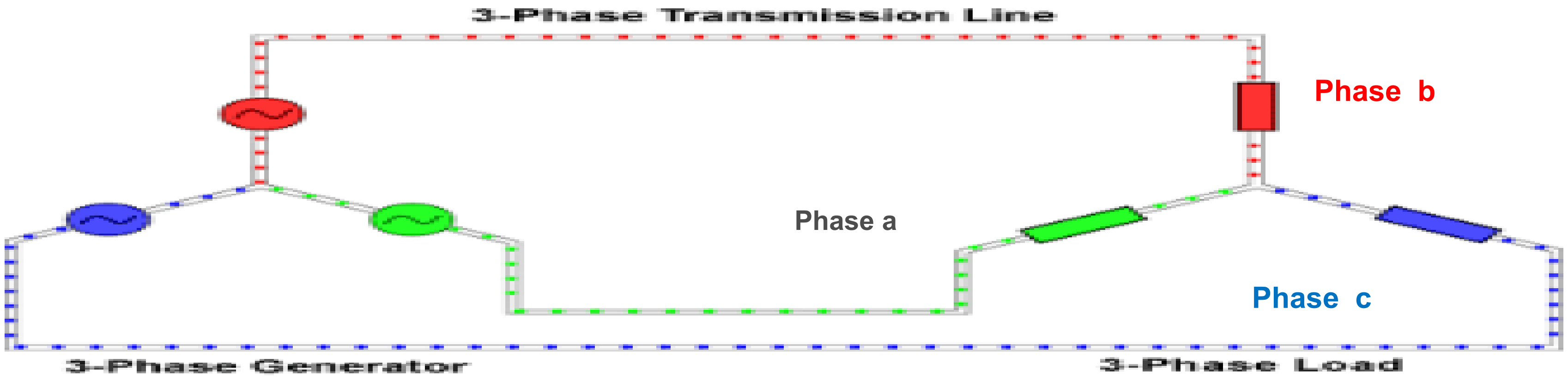


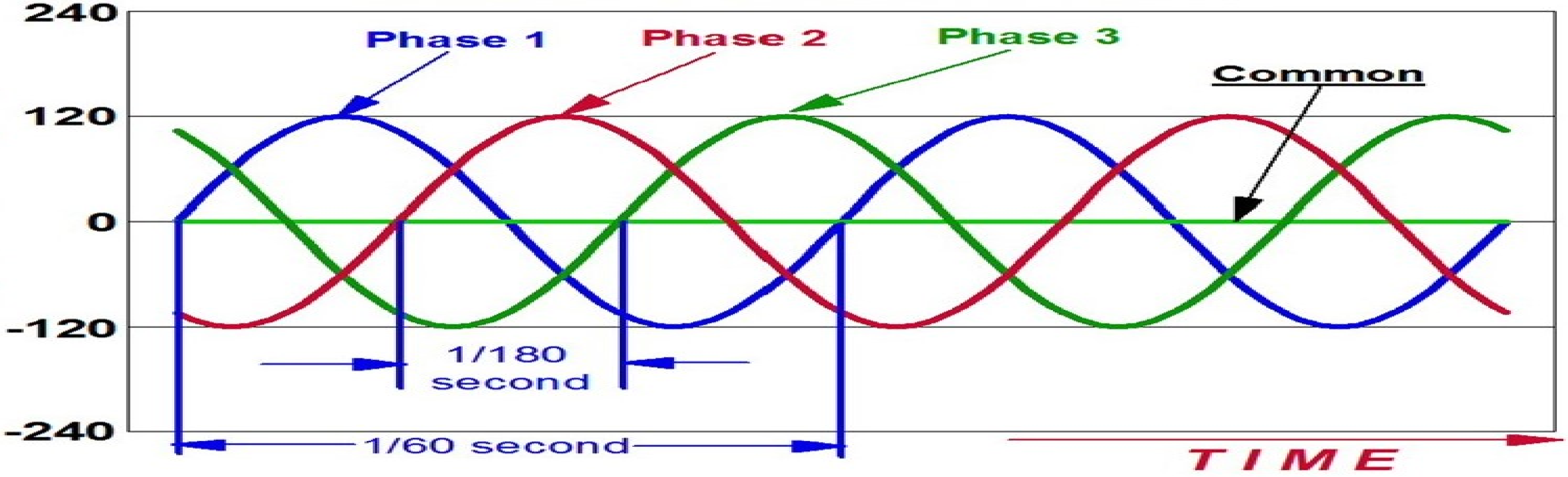


https://circuitglobe.com/generation-of-3-phase-power-in-3-phase-circuits.html

Classification of motors

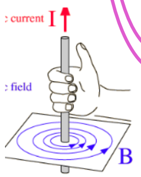
- **AC motors: 3 phase AC current and load at 60Hz**

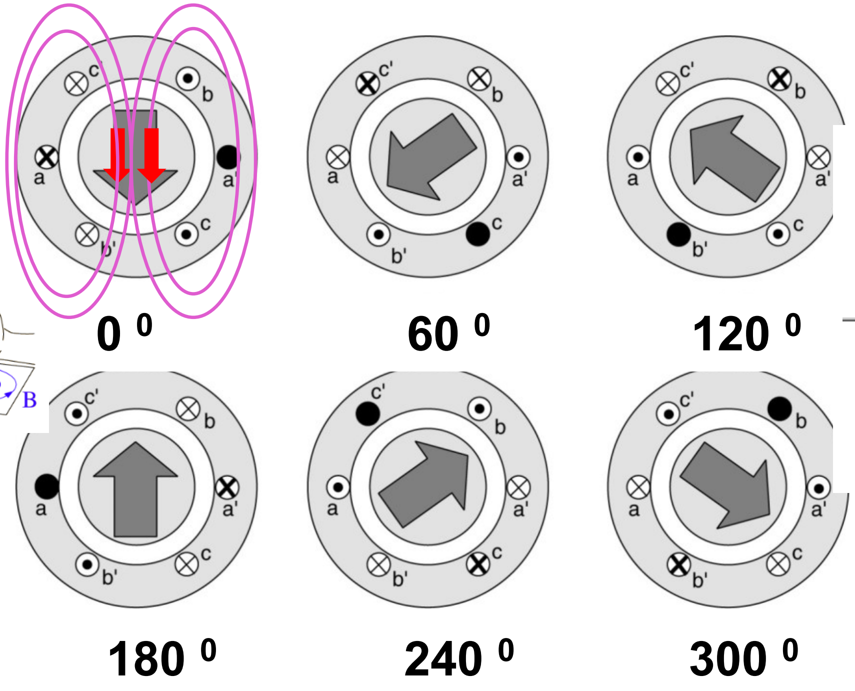


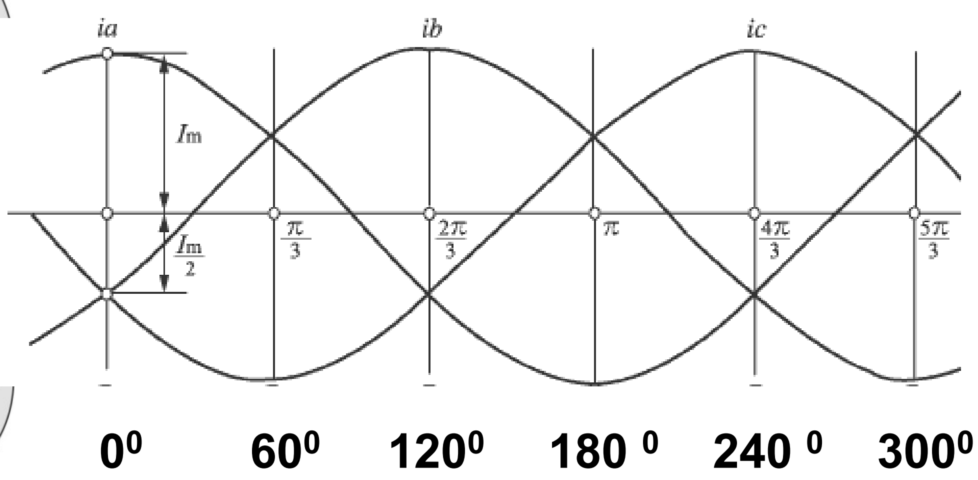


Classification of motors

- AC motors: rotating magnetic field by 3 phase AC current
- Remember !!!!!!!
- Invented by Nikola Tesla: great great invention



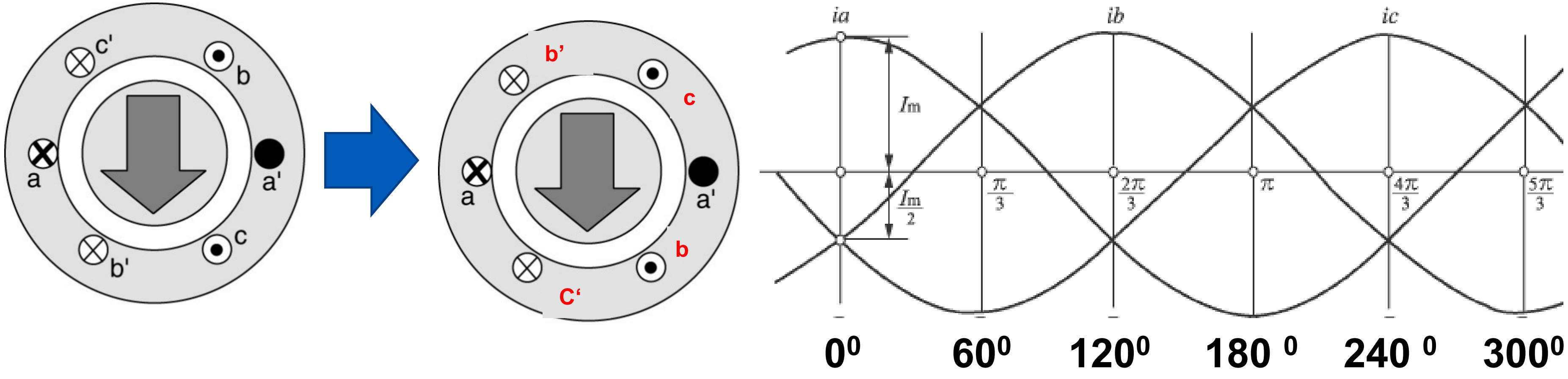




http://electricalacademia.com/synchronous-machines/synchronous-machine-construction-working/attachment/rotating-magnetic-field-created-by-a-three-phase-winding/

Classification of motors

- If coil b and c is changed each other, what will be happed ???
- Home work
- rotating magnetic field is rotating to reverse direction.
- motor is rotating reversely



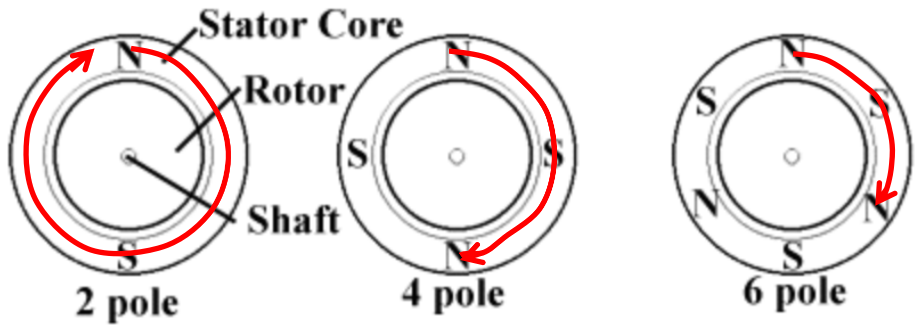
Classification of motors

- **Speed of rotating magnetic field**

- 2 pole 1 Hz = 1 rps
  2 pole 2 Hz= 2 rps
  2 pole 60 Hz= 60 rps

- 4 pole 1 Hz = 1/2 rps
  4 pole 2 Hz= 1 rps
  4 pole 60 Hz= 30 rps

- 6 pole 1 Hz = 1/3 rps
  6 pole 2 Hz= 2/3 rps
  6 pole 60 Hz= 20 rps

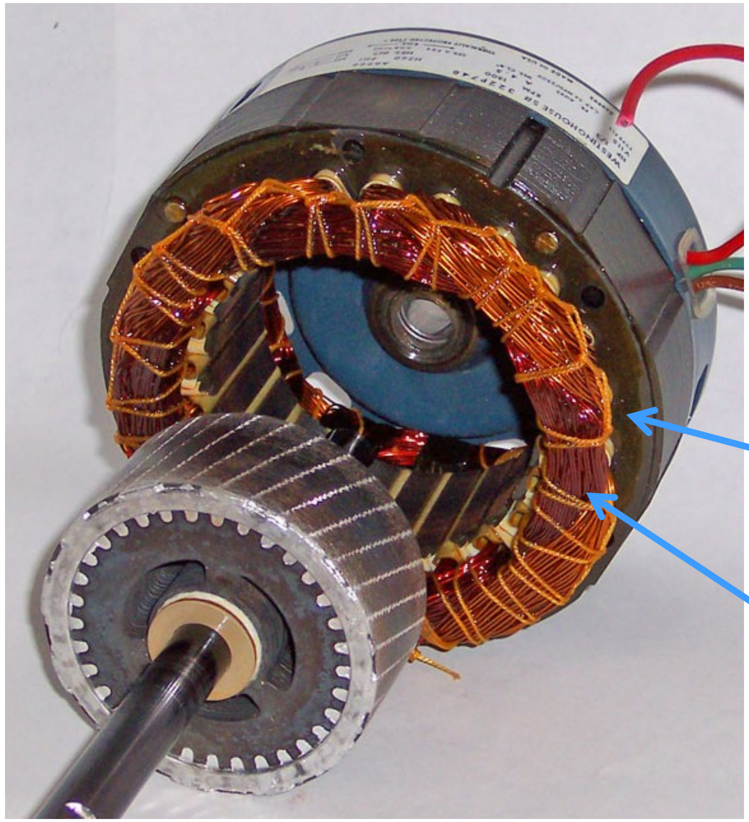


Rotation by 1 Hz

motor speed=120f (frequency) / p (poles) rpm !!!

Classification of motors

- **AC motor stator for rotating magnetic field**

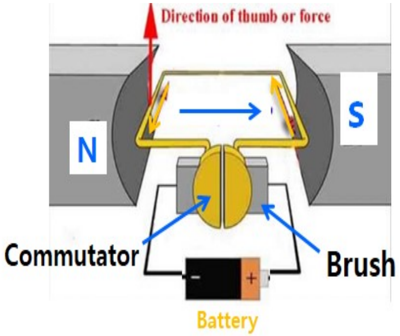


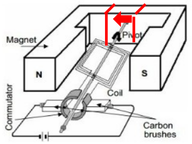
Stator core

Stator winding (copper)

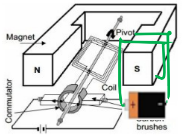
Classification of motors

- Electric Motors
  - DC Motors
    - Brushed
      - Permanent Magnet
      - Separately Excited
    - Brushless
      - Stepper
  - AC Motors
    - Synchronous
      - Reluctance
      - Permanent Magnet
    - Induction





PM



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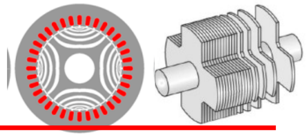
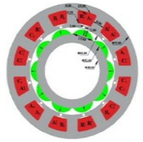
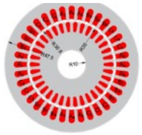
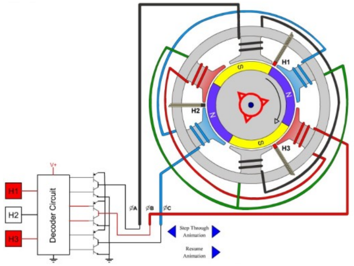
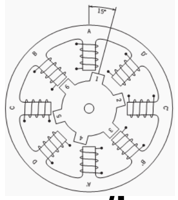








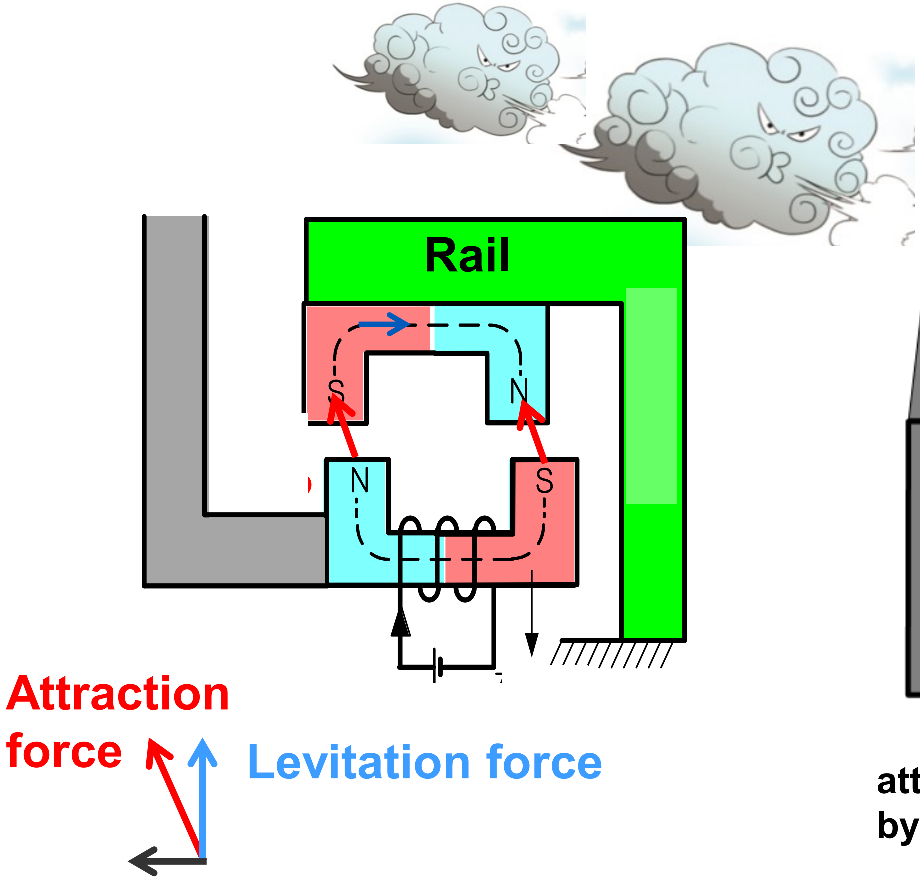


https://electricalbaba.com/brushless-dc-bldc-motor/

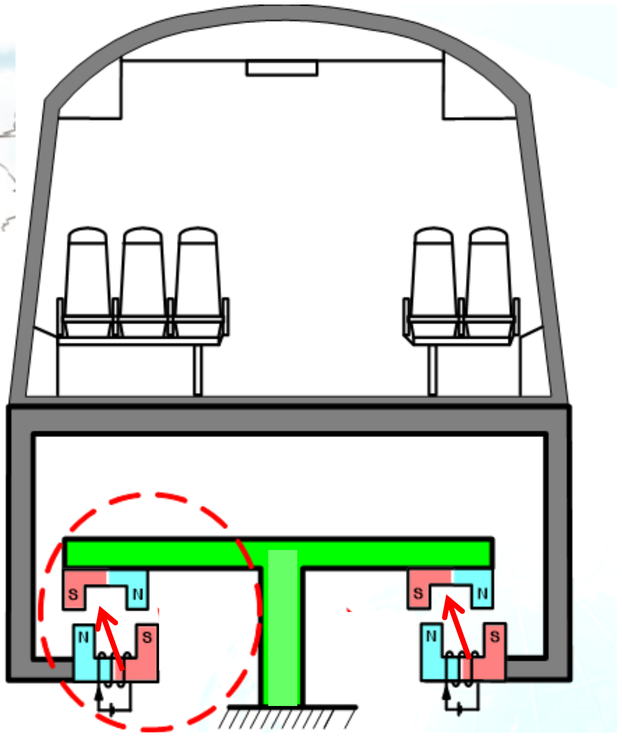
Classification of motors

- **Synchronous motor: reluctance motor**

-magnetic levitation



Guidance force(be used as motor)



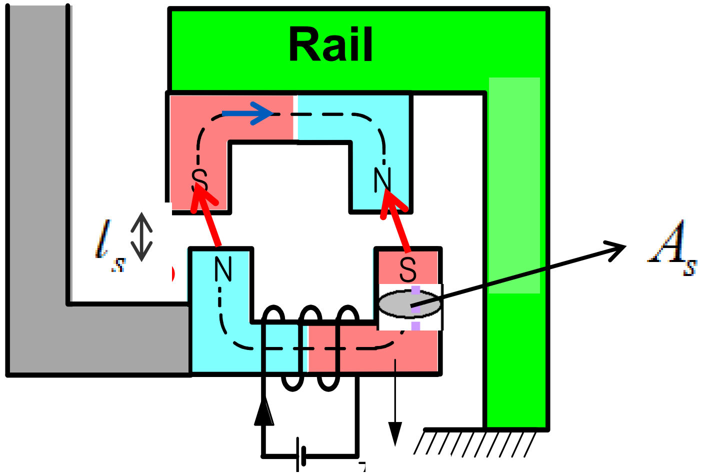
attraction force by electro-magnet

attraction force by electro-magnet

Classification of motors

- **Synchronous motor: reluctance motor**
- Reluctance=inverse of magnetic resistance=$1/R_m$
- Core(motor) is moving to be minimum magnetic resistance
- Core(motor) is moving to be maximum magnetic reluctance
- Reluctance motor is named after magnetic reluctance

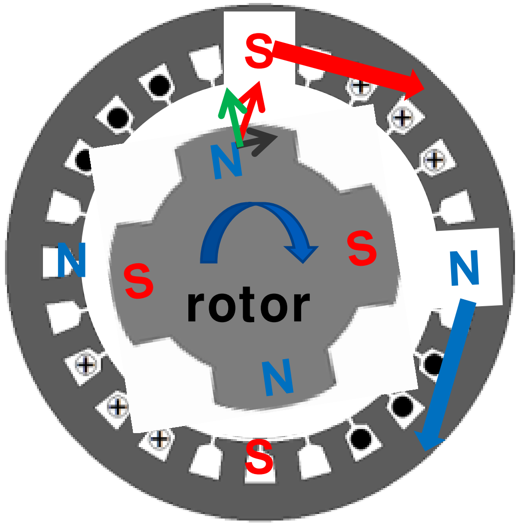
- $R_m = \dfrac{l_s}{\mu_s A_s}$

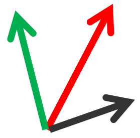


Classification of motors

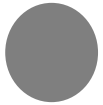
- Synchronous reluctance motor:

−rotating magnetic field is rotating by 3 phase AC current
−rotor is rotating according to rotating magnetic field





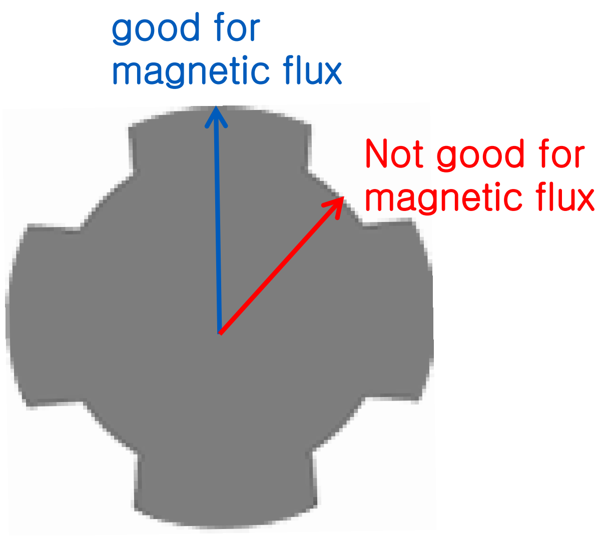
Radial force
Attraction force
Tangential force makes torque

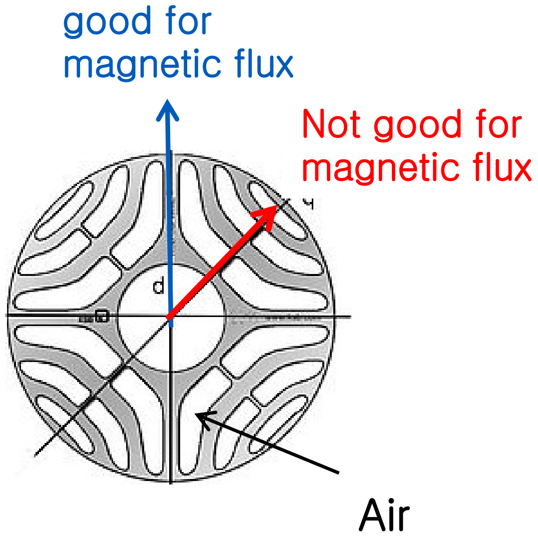
- If rotor is  , there is no force
- Radial force is 4 -6 times higher than tangential force.
- If air-gap length is not equal, more noise and vibration by unsymetric radial force

Classification of motors

- Synchronous reluctance motor:

–Shape of rotor



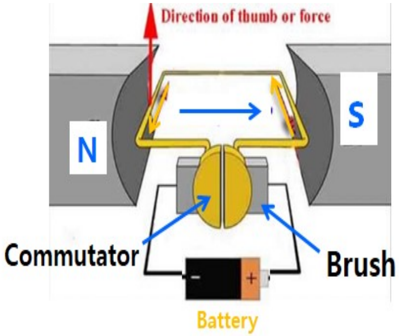


reluctance motor rotor

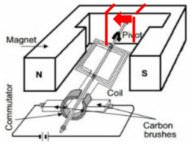
–Advantage : no magnet or no cupper in rotor
–Disadvantage: bigger motor

https://new.abb.com/motors-generators/iec-low-voltage-motors/process-performance-motors/synchronous-reluctance-motors

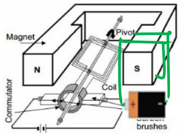
Classification of motors



- Electric Motors
  - DC Motors
    - Brushed
      - Permanent Magnet
      - Separately Excited
    - Brushless
      - Stepper
  - AC Motors
    - Synchronous
      - Reluctance
      - Permanent Magnet
    - Induction



PM



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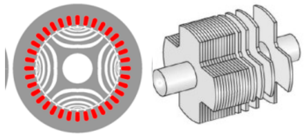
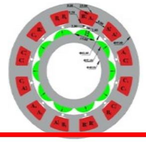
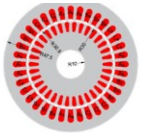
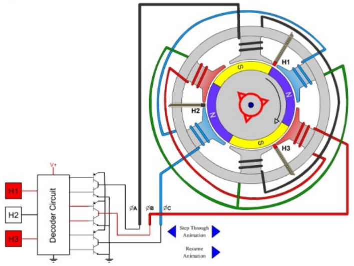
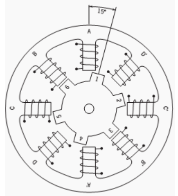










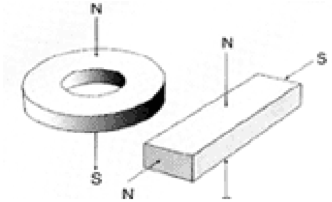
https://electricalbaba.com/brushless-dc-bldc-motor/

Classification of motors

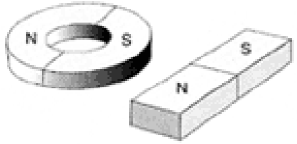
- Permanent magnet motor:

-A **permanent magnet** is an object made from a material that is magnetized by high impulse current and creates its own persistent magnetic field
-The magnetic state (or magnetic phase) of a material depends on temperature and other variables such as the reversely applied magnetic field.

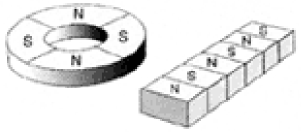
-Magnetized Magnet



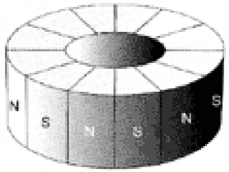
1 face/1 pole

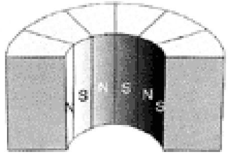


1 face/2 pole

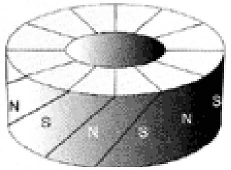


1 face/multi pole





Inner side/outer side pole

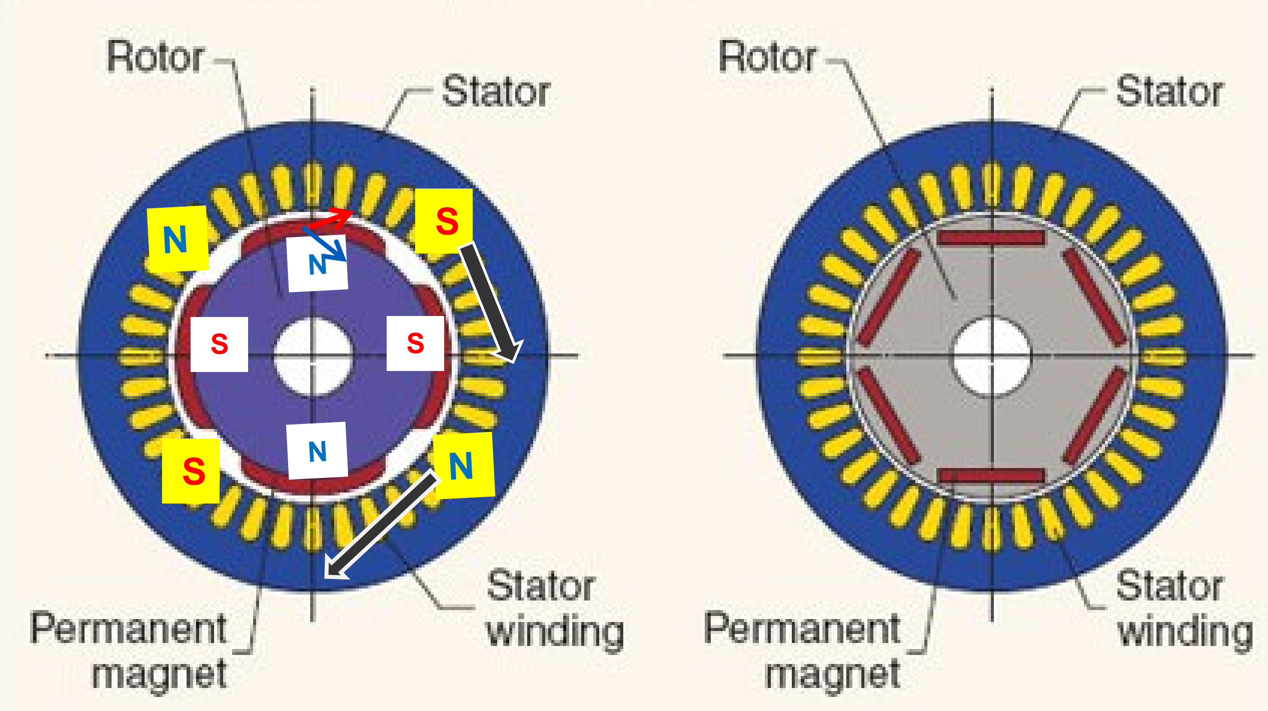


skew pole

Classification of motors

- Permanent magnet motor

-SPM and IPM



Surface mounted permanent magnet motor (SPM).

Interior permanent magnet motor (IPM).

Classification of motors

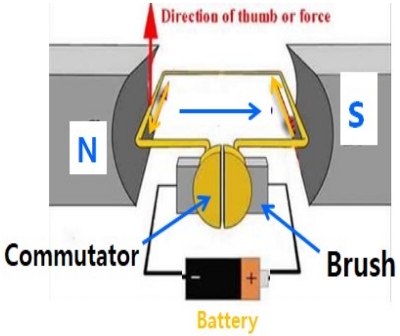
▪ Permanent magnet motor

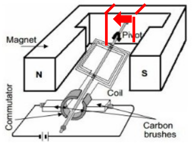
–IPM motors have the permanent magnet imbedded into the rotor itself. Unlike their SPM counterparts, the location of the permanent magnets make IPM motors very mechanically sound, and suitable for operating at very high speeds

–SPM and IPM rotor

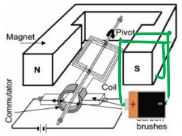
Classification of motors

- Electric Motors
  - DC Motors
    - Brushed
      - Permanent Magnet
      - Separately Excited
    - Brushless
      - Stepper
  - AC Motors
    - Synchronous
      - Reluctance
      - Permanent Magnet
    - Induction





PM



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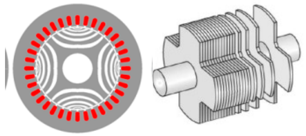
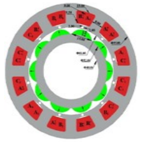
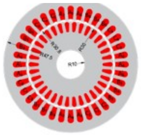
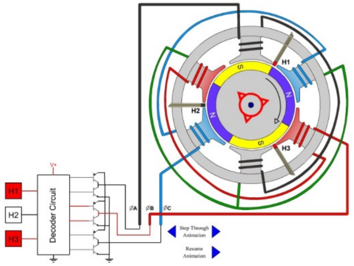
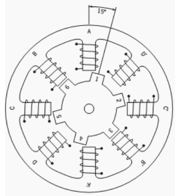










https://electricalbaba.com/brushless-dc-bldc-motor/

Classification of motors

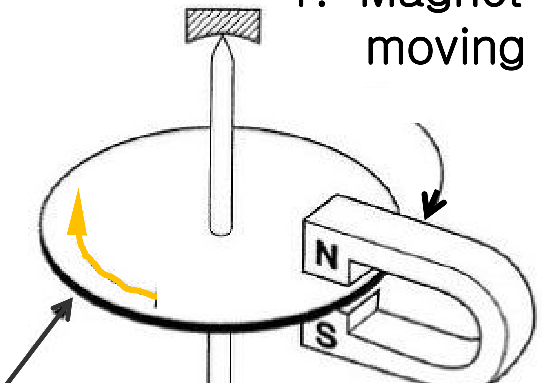
- Induction motor

- Arago's disc is frequently used for explaining AC induction motors. The principle of Arago's disc goes that, when a disc made of copper or aluminum is sandwiched between magnets and the magnets are moved, eddy current is generated on the disc. And this eddy current causes the force that tries to move the disc in the moving direction of the magnets

https://www.youtube.com/watch?v=g0eA5L79PIc

https://www.youtube.com/watch?v=e7ms3ewN_Qw

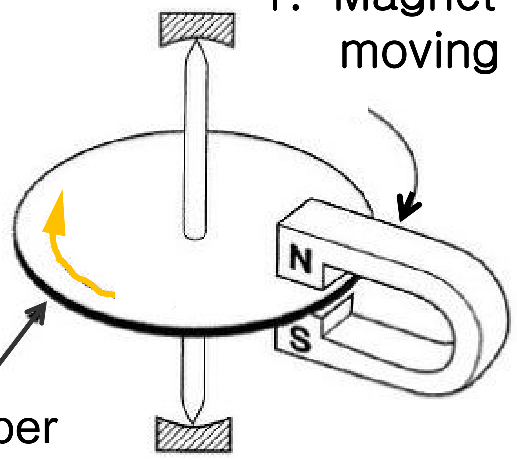
1. Magnet is moving

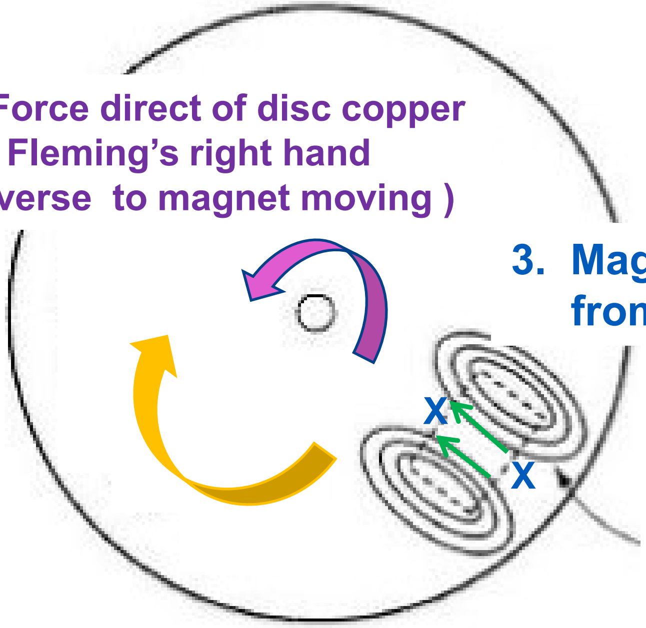


Copper disc moving direction
is same as magnet moving direction

Classification of motors

- Induction motor



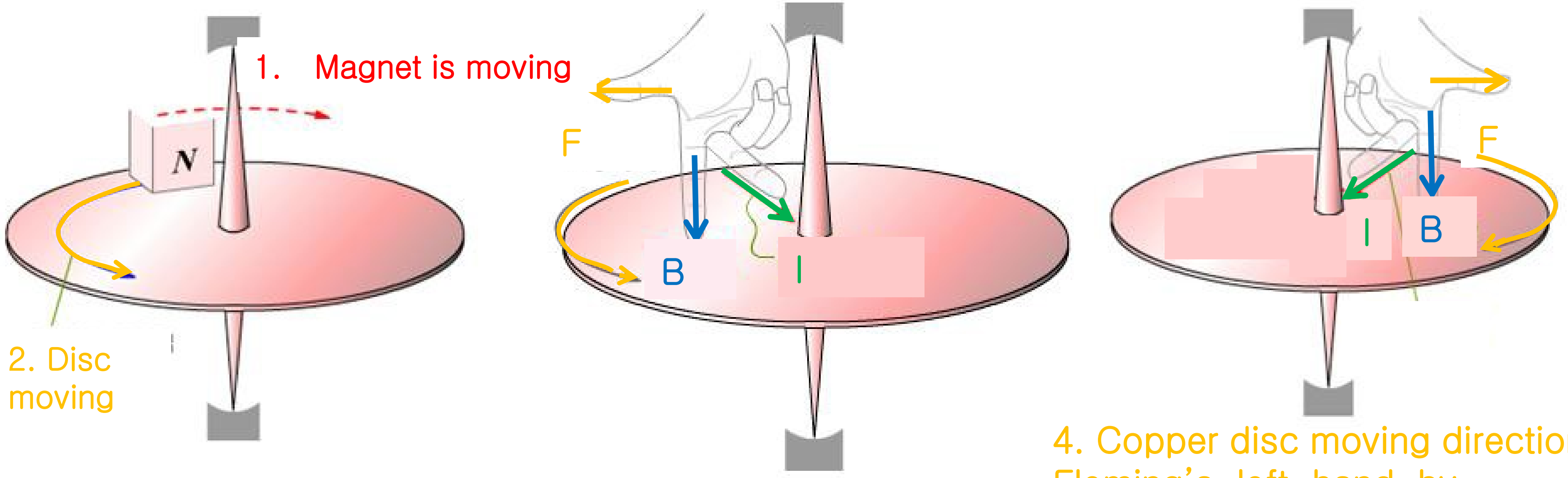


4. Induced Current by Fleming's right hand

5. Copper disc moving direction :
Fleming's left hand by induced current
Induction motor is named after the induced current.

Classification of motors

- Induction motor



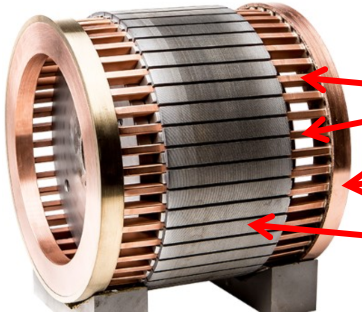
3 Induced Current by Fleming's right hand

4. Copper disc moving direction : Fleming's left hand by induced current.
Induction motor is named after the induced current.

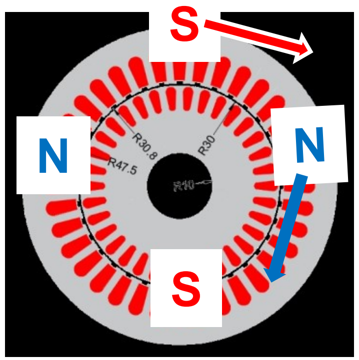
Classification of motors

- Induction motor:

– Stator is same as the reluctance motor and the PM motor
– Rotor has the copper or aluminum bar and iron core



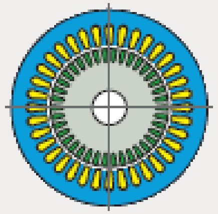
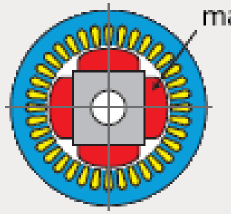
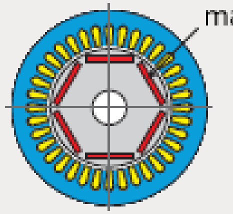
– Rotating magnetic field is rotating by 3 phase AC current



–Rotor is rotating by the induced current in rotor bar (Arago's disc)

Classification of motors

- SPM, IPM and induction motor

	Induction motor	Synchronous motor	
		SPM motor	IPM motor
Rotor structure		 The magnet is attached to the surface of the rotor	 The magnet is embedded in the rotor
Principle	An electric current flows through the rotor and rotates with a delay of the slip speed from the rotating magnetic field speed.	A magnet torque is generated, and the rotor rotates at the same speed as the rotating magnetic feld.	A magnet torque and reluctance torque are generated, and the rotor rotates at the same speed as the rotating magnetic field.
Motor volume	Relatively bigger than synchronous motor	Very small	Small
Effectiveness and power factor	Good	Very good	Very good
Speed	Very fast	Fast	Very fast
Maximum torque	Very big	Big except for the case of servo that is very big	Big
Torque component	Induction	Magnet	Magnet and reluctance

https://www.yaskawa-global.com/product/mc/glossary

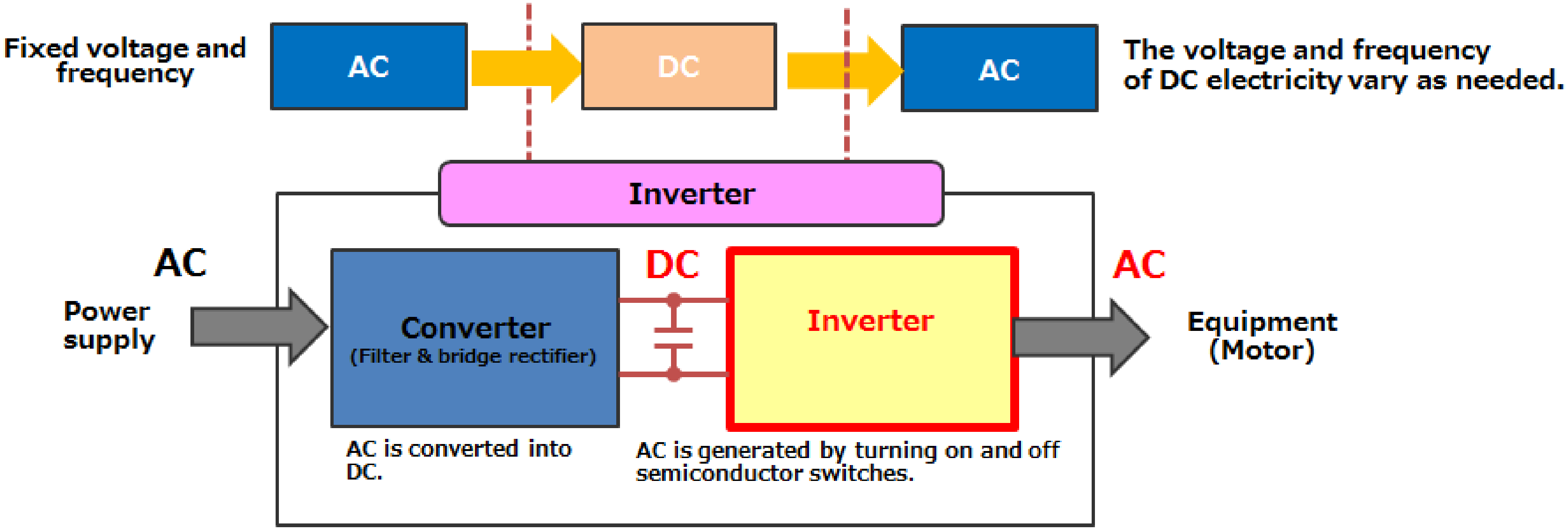
Classification of motors

- Speed changing for AC motor

−motor speed=120f (frequency) / p (poles) rpm !!!

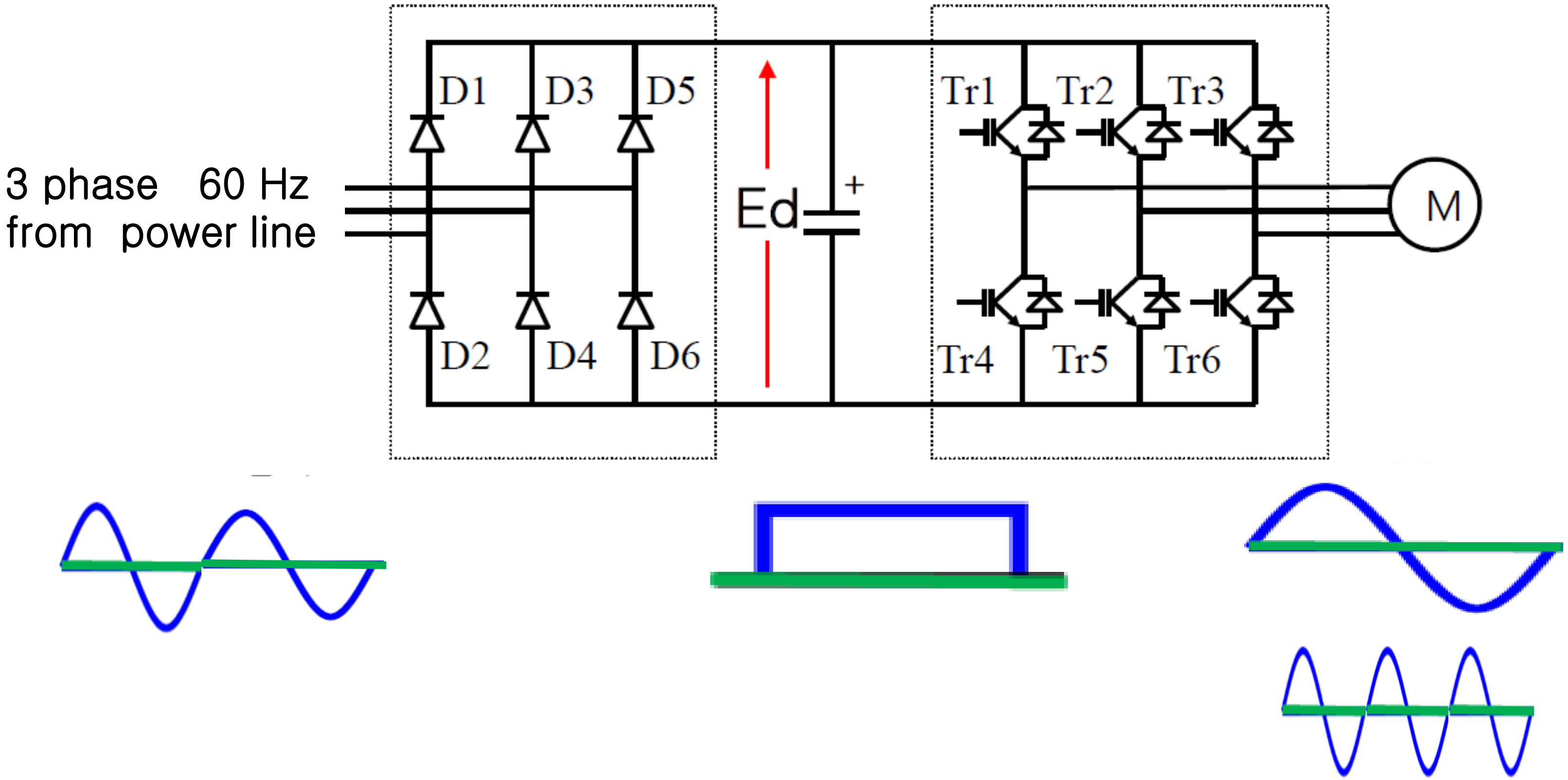
−For changing motor speed

−Changing in put current(voltage) frequency



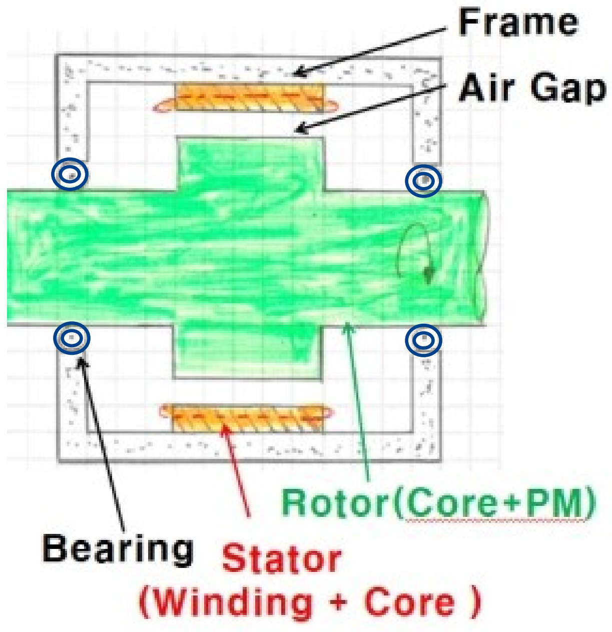
Classification of motors

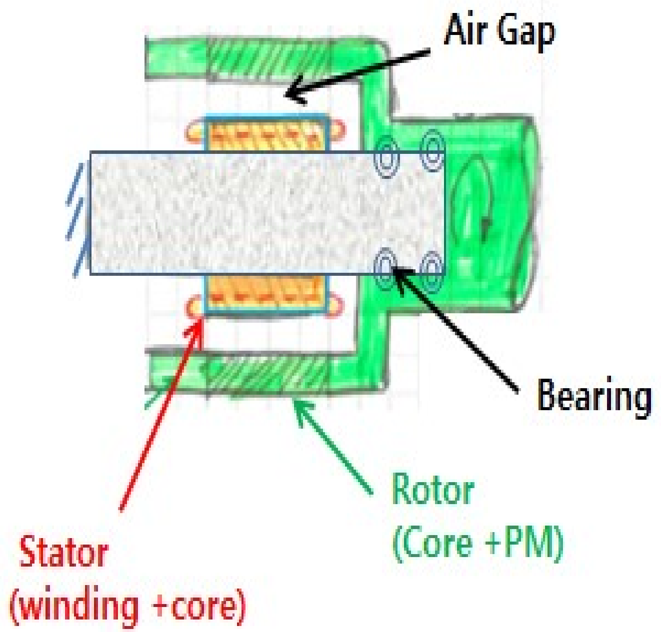
- Speed changing for AC motor



Classification of motors

- **Inner rotor motor and outer rotor motor**



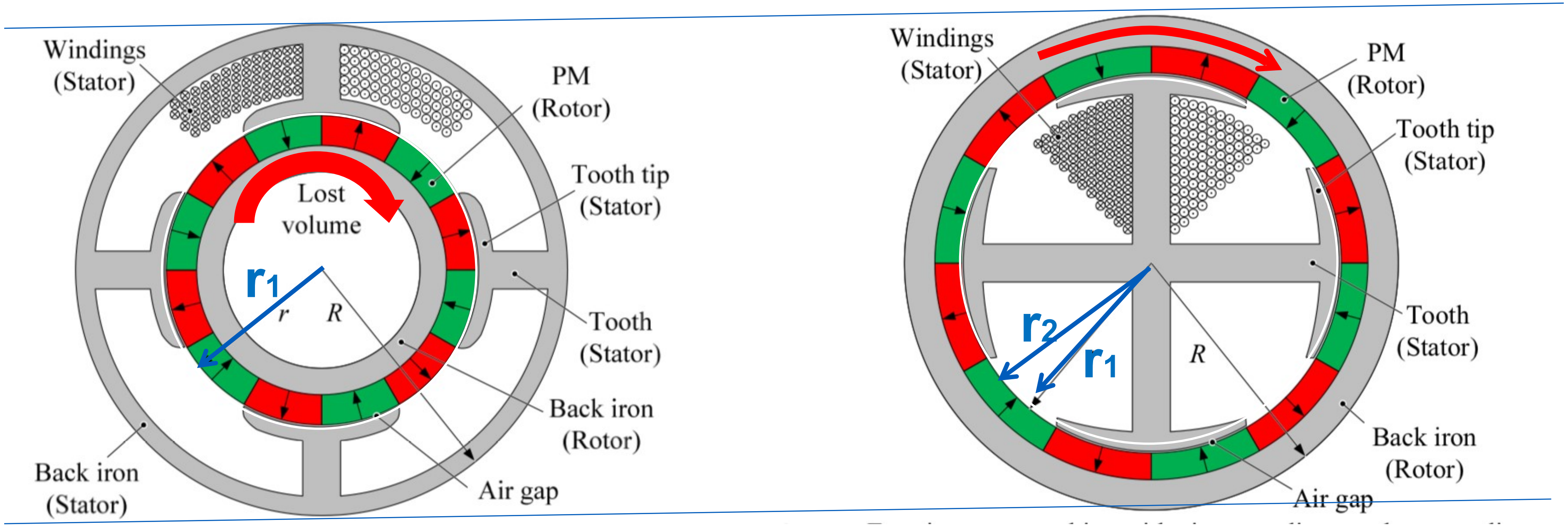


structure (good)
general purpose

structure (not good)
low speed and high torque
(washing machine or fan)

Classification of motors

- **Inner rotor motor and outer rotor motor**



T(torque) = Tangential force $* \, r$

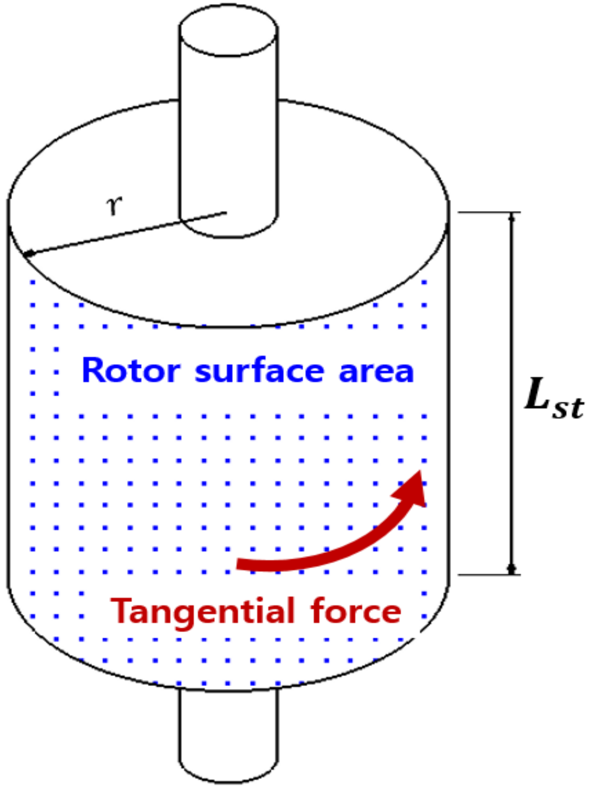
= F_{sd} *Rotor surface area($2\pi r L_{st}$)$* \, r$

= K $* \, r^2$

Classification of motors

- **Inner rotor motor and outer rotor motor**

–Surface force density F_{sd} (N/m²) is Tangential force per Rotor surface area

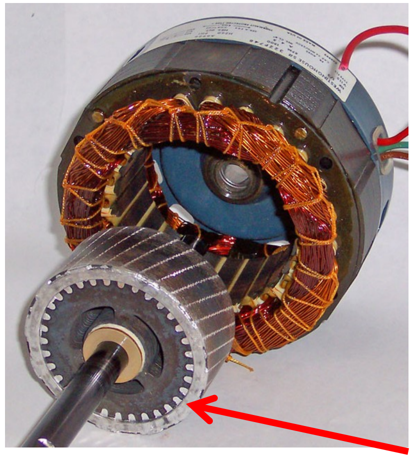


$$F_{sd} = \frac{\text{Tangential force}}{\text{Rotor surface area}(2\pi r L_{st})}$$

$$\begin{aligned} T(\text{torque}) &= \text{Tangential force} * r \\ &= F_{sd} * \text{Rotor surface area}(2\pi r L_{st}) * r \\ &= F_{sd} * \pi L_{st} * r^2 \end{aligned}$$

Classification of motors

- **Inner rotor motor and outer rotor motor**



Inner rotor

Inner rotor motor

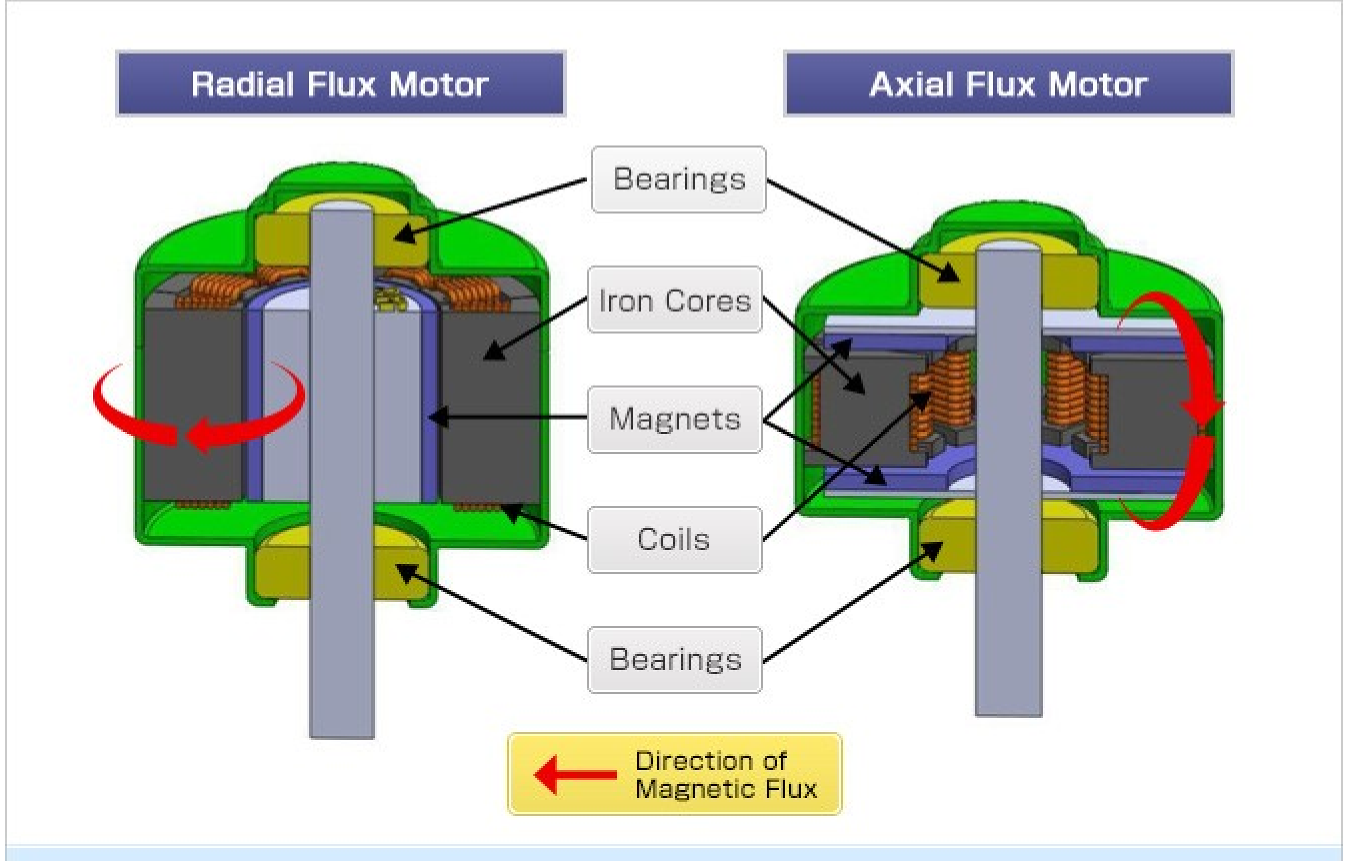
outer rotor

Stator

Outer rotor motor

Classification of motors

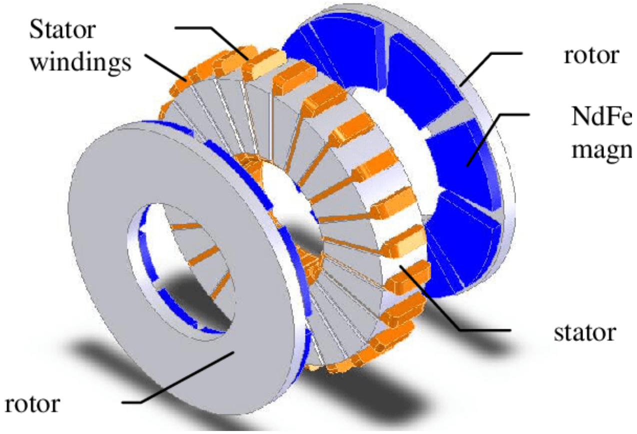
- **Radial flux motor and axial flux(disk) motor**

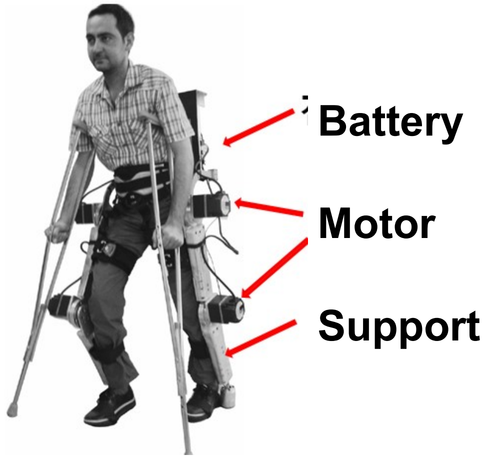


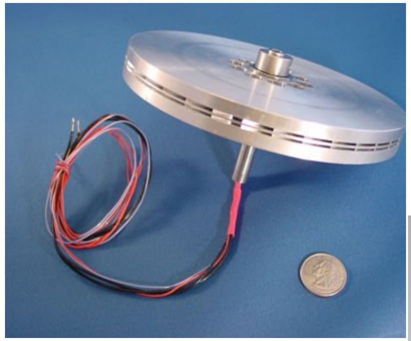
https://www.nidec.com/en-NA/technology/rd/innovative_motor/

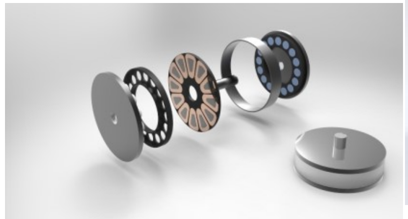
Classification of motors

- **Radial flux motor and axial flux motor**









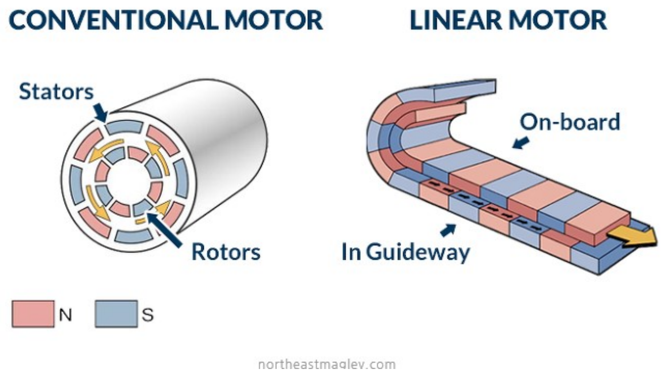
https://www.researchgate.net/figure/8-pole-24-slot-axial-flux-PM-reference-motor_fig2_224393995

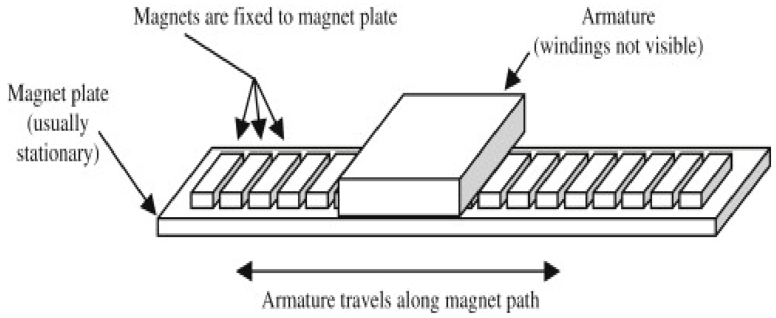
https://endless-sphere.com/forums/viewtopic.php?t=14260

Classification of motors

- Linear motor

A linear motor is an electric motor that has had its stator and rotor "unrolled" thus instead of producing a torque (rotation) it produces a linear force along its length. However, linear motors are not necessarily straight. Characteristically, a linear motor's active section has ends





Classification of motors

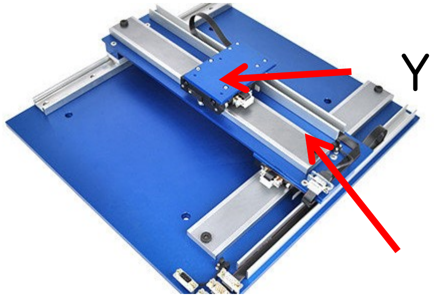
- **Linear motor**

Advantages of linear motors:
- There is no mechanical contact,
- The structure is simple
- Its operation can provide a wide range of speed operation, covering a few microns to several meters per second, especially at high speed is one of its outstanding advantages
- Acceleration, up to 10g
- Accuracy and repeatability are high due to the elimination of the intermediate links that affect accuracy.
- Easy to maintain, due to the small parts, no mechanical contact with the movement, thus greatly reducing the wear and tear of parts

Disadvantages of linear motors:
-One side (on board or in guide way) has long length.(expensive.)
-The dynamic stiffness of the linear motor is extremely low, can not play the role of buffer damping, high-------

Classification of motors

- Linear motor: application
  - X Y stage



Y stage mover

X stage mover

  - High speed magnetic levitation train

Transrapid (500km/h)in Shanghai
German-developed high-speed train

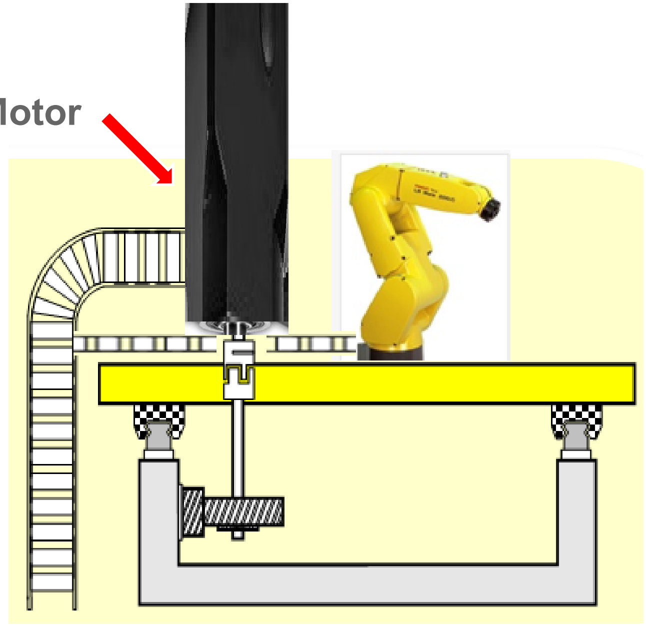
Superconducting a magnetic levitation train in Japan

Classification of motors

- **motor + gear**

- Load asks speed 600rpm and torque 40Nm
- Motor 600rpm and torque 40Nm is too big because of big-torque
- Solution : high-speed motor + gear

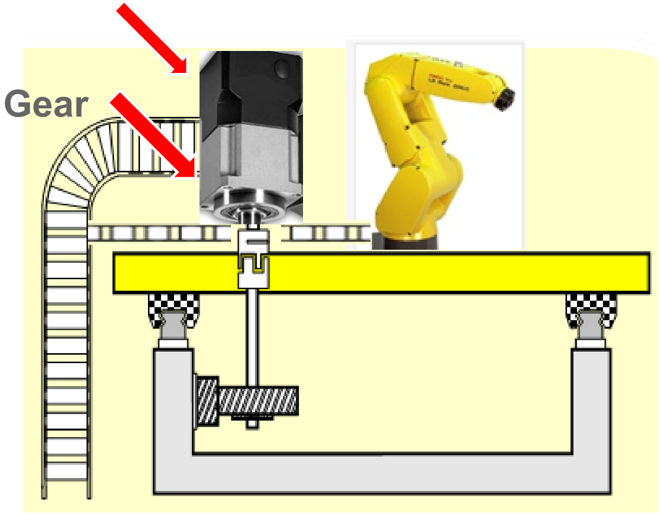
Motor



Motor direct drive
for 600rpm and torque 40Nm

High speed motor

Gear



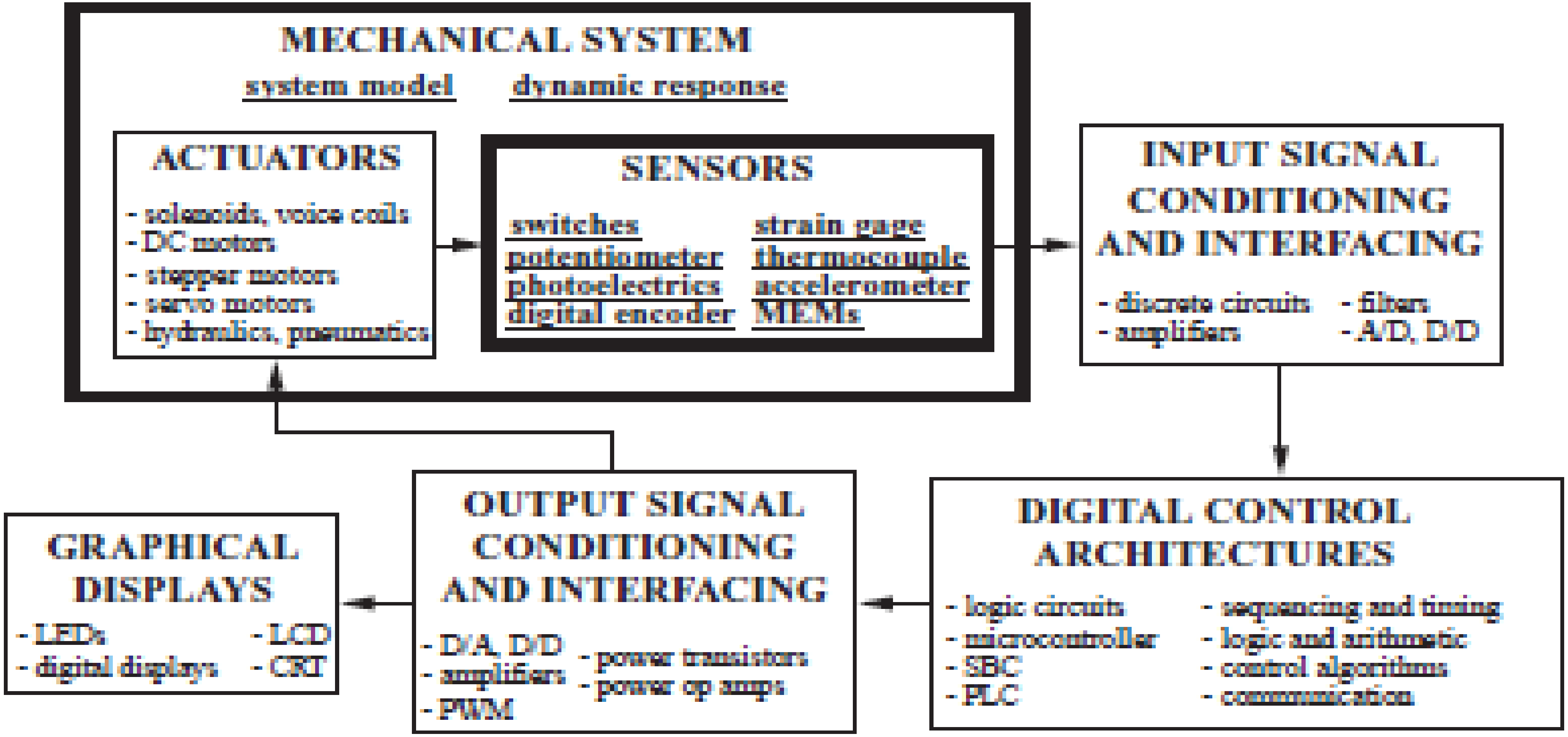
Motor 2400 rpm torque 10Nm
Gear 600 rpm torque 40Nm

Classification of motors

- Electrical and mechanical system analogy

System	Potential	Flow	Resistance	Capacitance	Inductance
Electrical	voltage	current	*R*	*C*	*L*
Mechanical	force	velocity	damper	spring	mass
Fluid	head	vol. flow	flow res.	surf. area	flow inertia
Magnetic	MMF(N*I) (magnetomotive force)	Φ, flux	reluctance		

Sensor

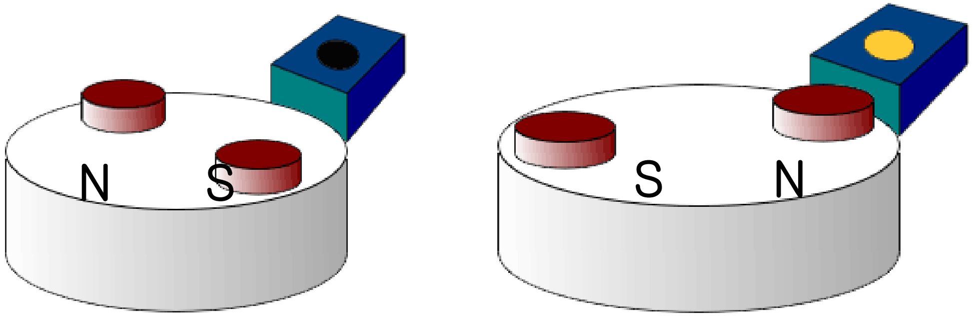


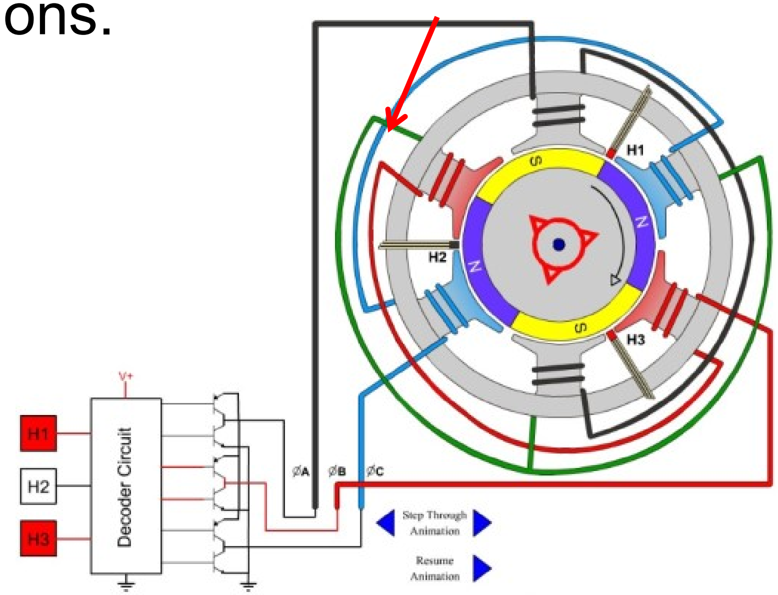
MECHANICAL SYSTEM
system model
dynamic response
ACTUATORS
- solenoids, voice coils
- DC motors
- stepper motors
- servo motors
- hydraulics, pneumatics
SENSORS
switches
potentiometer
photoelectrics
digital encoder
strain gage
thermocouple
accelerometer
MEMs
INPUT SIGNAL CONDITIONING AND INTERFACING
- discrete circuits
- amplifiers
- filters
- A/D, D/D
DIGITAL CONTROL ARCHITECTURES
- logic circuits
- microcontroller
- SBC
- PLC
- sequencing and timing
- logic and arithmetic
- control algorithms
- communication
OUTPUT SIGNAL CONDITIONING AND INTERFACING
- D/A, D/D
- amplifiers
- PWM
- power transistors
- power op amps
GRAPHICAL DISPLAYS
- LEDs
- digital displays
- LCD
- CRT

Sensor

- Hall sensor

A **Hall effect sensor** is a device that is used to measure the magnitude of a magnetic field. Its output voltage is directly proportional to the magnetic field strength through it.
Hall effect sensors are used for proximity sensing, positioning, speed detection, and current sensing applications.

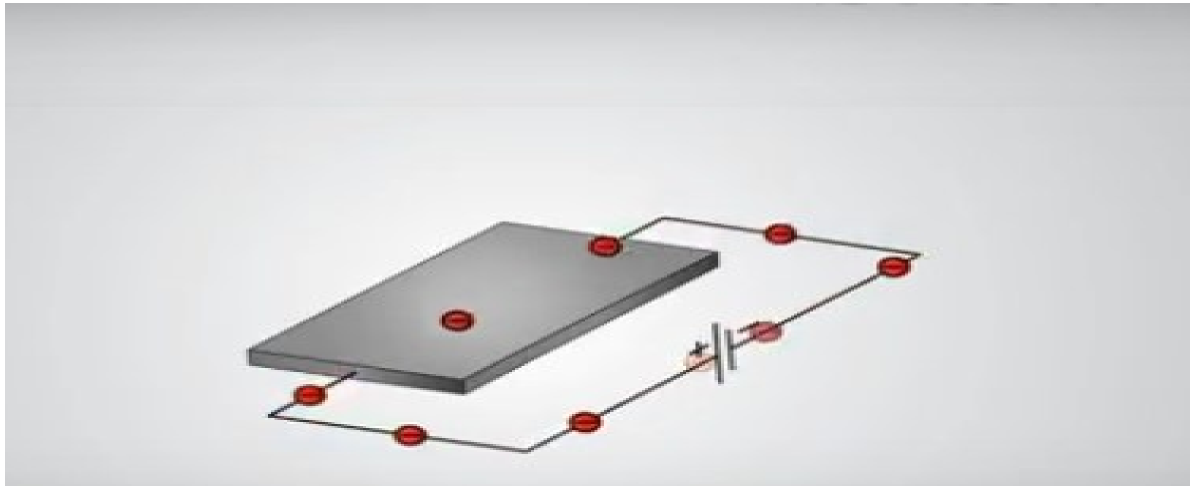


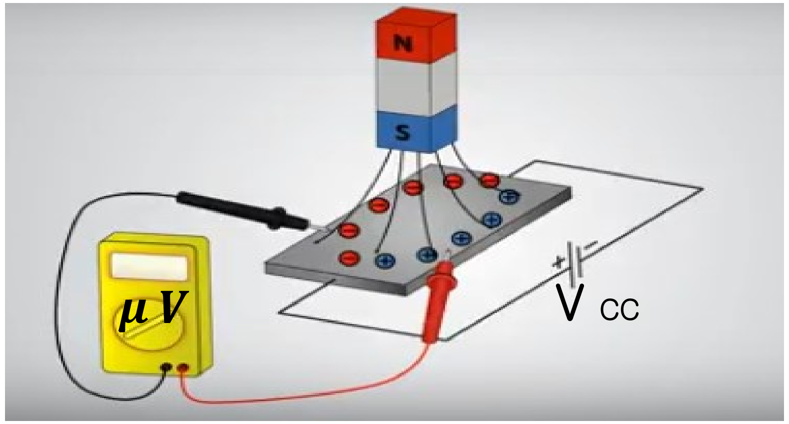


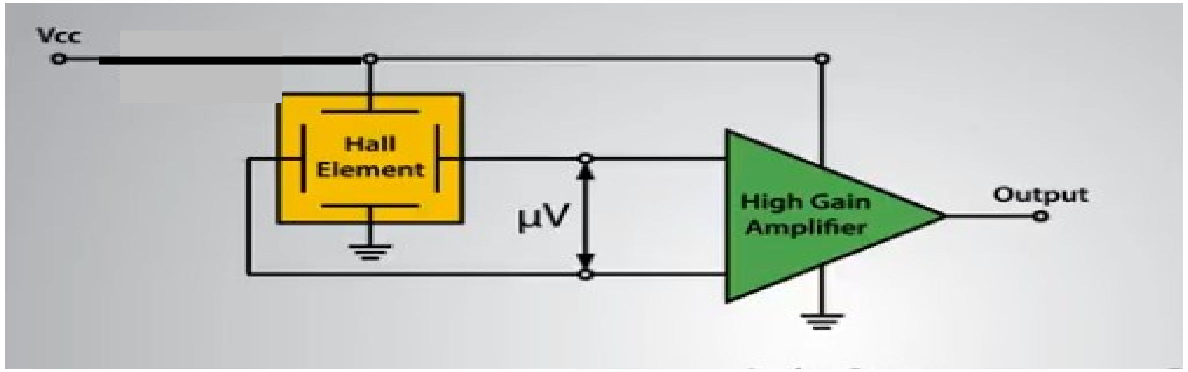
https://upload.wikimedia.org/wikipedia/commons/7/7e/Hall_sensor_tach.gif

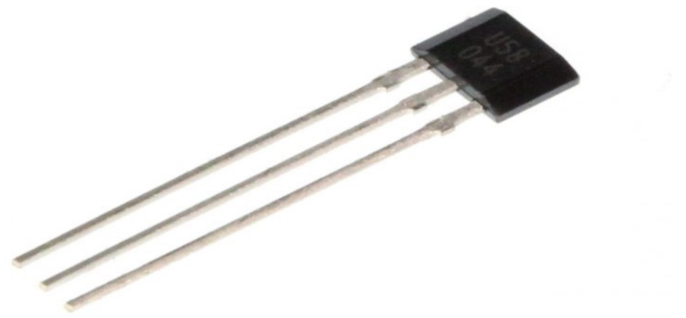
Sensor

- Hall sensor





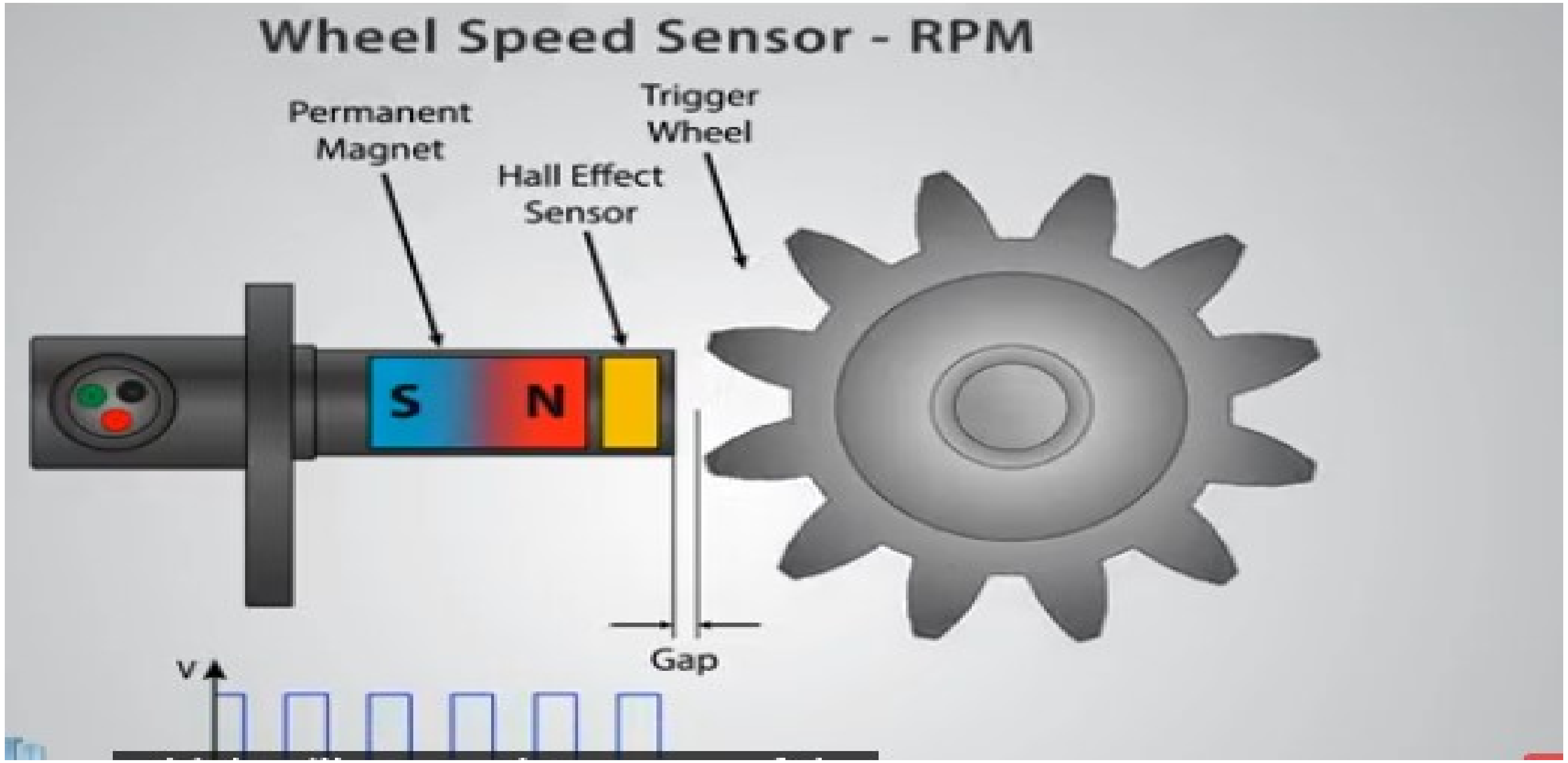




https://blog.naver.com/nissei-gtr/221599187446

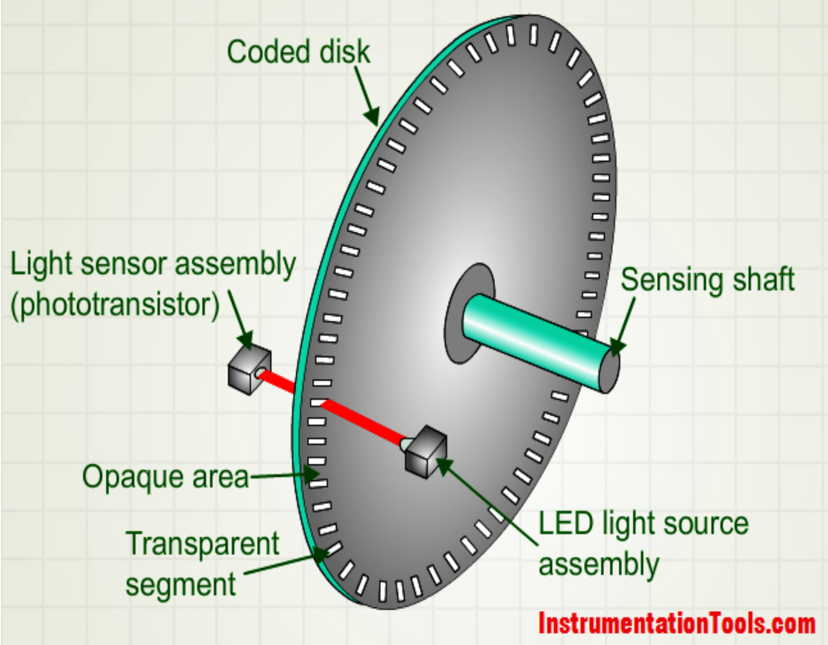
Sensor

- Hall sensor

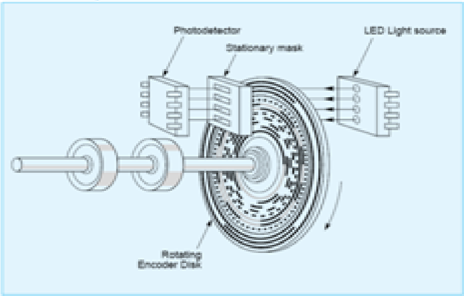


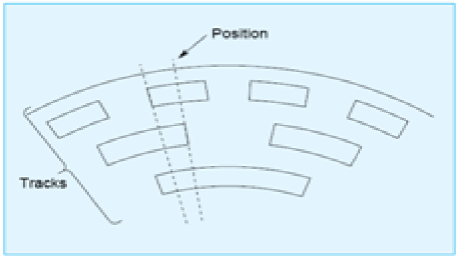
Sensor

- Rotor position sensor : Rotary Encoder

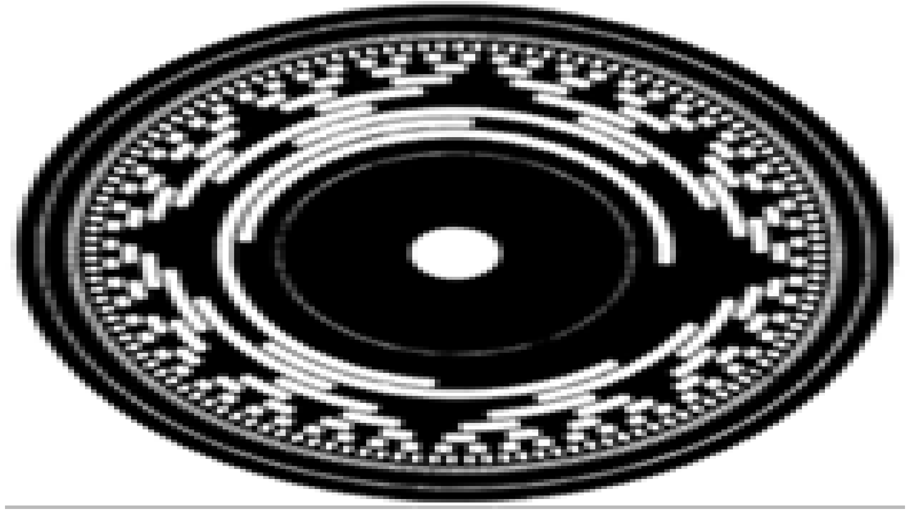


Absolute Rotary Encoder





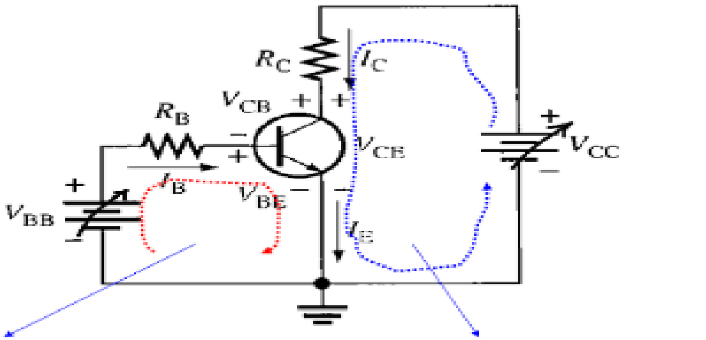
Typical disk pattern showing radial scanning method used to read position.



Encoder disk

Principle of Transistor

Figure1



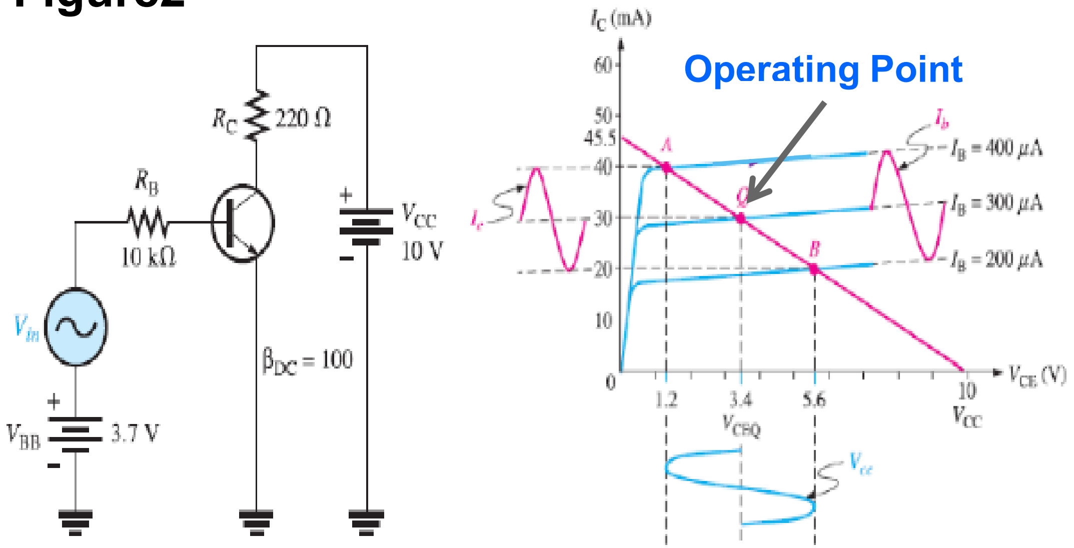
$V_{BB} = I_B R_B + V_{BE}$

$I_B = \frac{V_{BB} - V_{BE}}{R_B}$

$V_{cc} = I_c R_c + V_{CE}$

$V_{CE} = V_{cc} - I_c R_c$

Figure2



Explain based on Figure 2. Set the I_B to 300μA and interpret it.

1) Flow 300μA of I_B in the circuit shown in Figure 2.

$I_B = \frac{V_{BB} - V_{BE}}{R_B}$ = (3.7-0.7) V / 10000 Ω = 0.0003A = 300μA

2) In Figure 2, increase the V_{CC} until I_C reaches 30mA.
As the I_C value increases, the V_{CE} value also increases linearly. (=resistance)
resistance to V_{CE} = 0.7V / 0.03A = 23.3 Ω (**Figure3** saturation region)
and V_{CC} = V_{R_C} +V_{CE} = 220*0.03 [V]+ 0.7 [V] =7.3V

3) if Ic =10 mA -> V_{CC} = V_{R_C} +V_{CE} = 220*0.01 [V] + 23.3*0.01 [V] =2.433V
If Ic =20 mA -> V_{CC} = V_{R_C} +V_{CE} = 220*0.02 [V] + 23.3*0.02 [V] =4.866V
If Ic =30 mA -> V_{CC} = V_{R_C} +V_{CE} = 220*0.03 [V] + 23.3*0.03 [V] =7.3V
This means that the V_{CC} value up to 7.3 Volts increases the current linearly as voltage increases. (**Figure3** saturation region)

4) If V_{CC} is increased by 7.3 volts or more

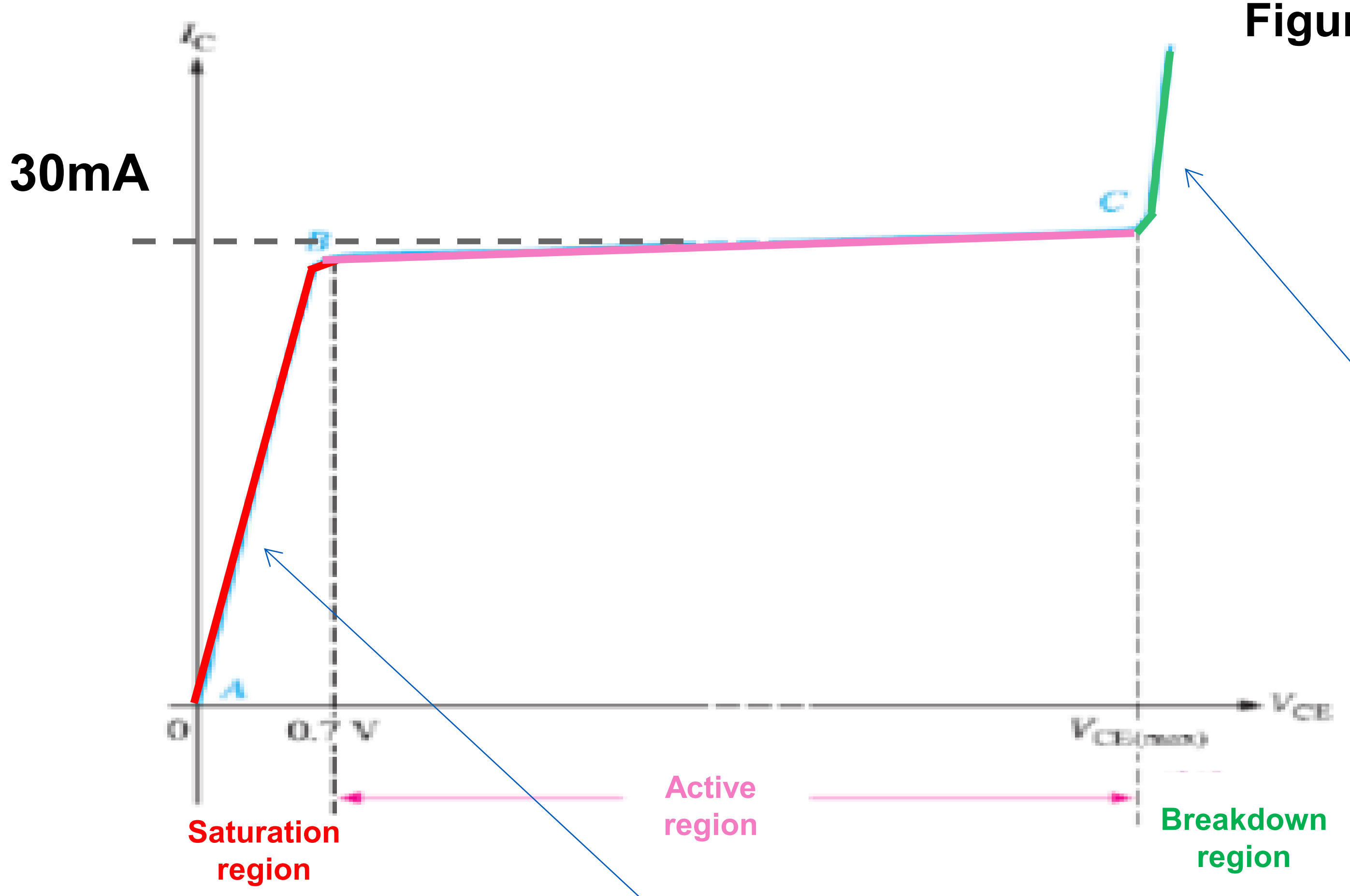
V_{CC} = V_{R_C} +V_{CE}

4-1) if V_{CC} = 8V -> 8V = 220*0.03V + 1.4V
4-2) if V_{CC} = 9V -> 9V = 220*0.03V + 2.4V
4-3) if V_{CC} = 10V -> 10V = 220*0.03V + 3.4V
(**Figure3** Active region)

TR does amplification. In other words, we can get a large I_C **(30 mA)** by flowing a small I_B **(300μA)**

Principle of Transistor

Figure3



The resistance is very low
because it increases linearly very steeply.

The saturation area of the graph has a resistance component.
This part corresponds to 0.7V /0.03A = 23.3 Ω in the preceding content
and the larger the slope, the smaller the resistance.