Energy conversion I

Lecture 25:

Topic 6: DC Machines (S. Chapman   ch. 8 &9)

- A Simple Rotating Loop between Curved Pole Faces
- Commutation Problems in Real Machine
- The Construction of DC Machine
- The Internal Voltage and Torque Equations of Real DC Machine
- The Equivalent Circuit of a DC Motor
- Power Flow and Losses in DC Machines
- Separately Excited, Shunt, Permanent-Magnet and Series DC Motors
- DC Motor Starter
- **Introduction to DC Generators**

DC Generators

- **Rotating rotor series / parallel conductors**

- **Flux under poles due to stator winding /Permanent magnets**

- **Induced voltage in the rotor terminals (through brushes)**

$$E_a = K \phi \omega$$

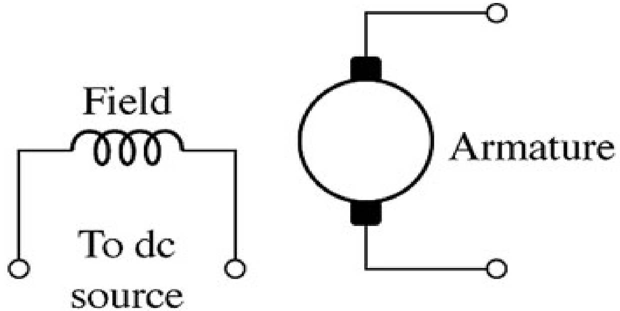
- **Connecting load to motor terminals leads to armature current**

$$T_a = K \phi I_a$$

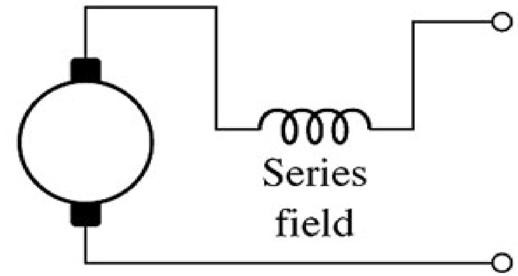
- **Torque balance leads to steady state speed**
- **Power balance leads to steady state operation**

<u>Usually AC generator plus rectifier is used instead of DC generator</u>

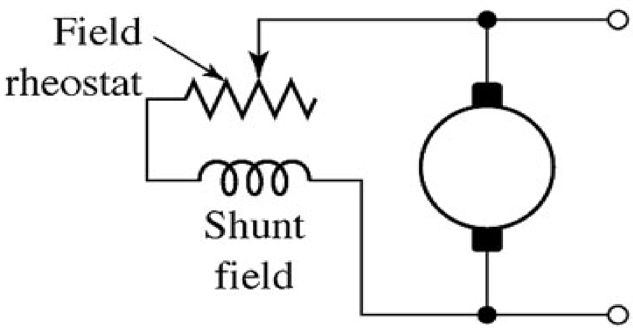
Different DC Generators



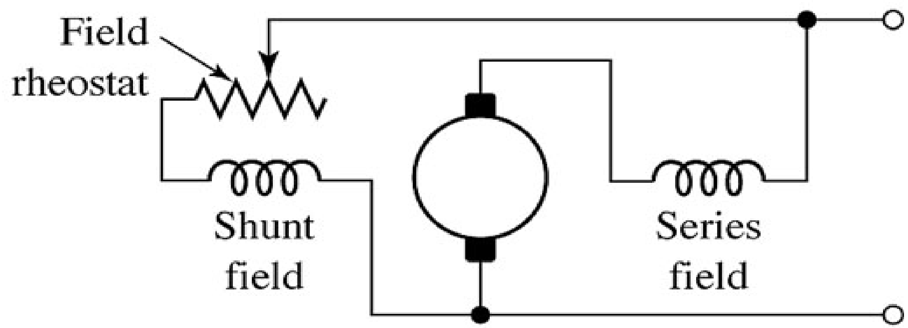
(a) Separately Excited



(b) Series



(c) Shunt



(d) Compound

Very similar to DC motors

Separately excited

PM, Shunt, Series, Compound (self excited generators)

Voltage Regulation

Voltage drop due to load current:

Armature equivalent resistance (R_a)

Armature reaction

$$\boxed{VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\%}$$

VR > 0 **drooping characteristics**

VR < 0 **rising characteristics**

How rising characteristic can be achieved!

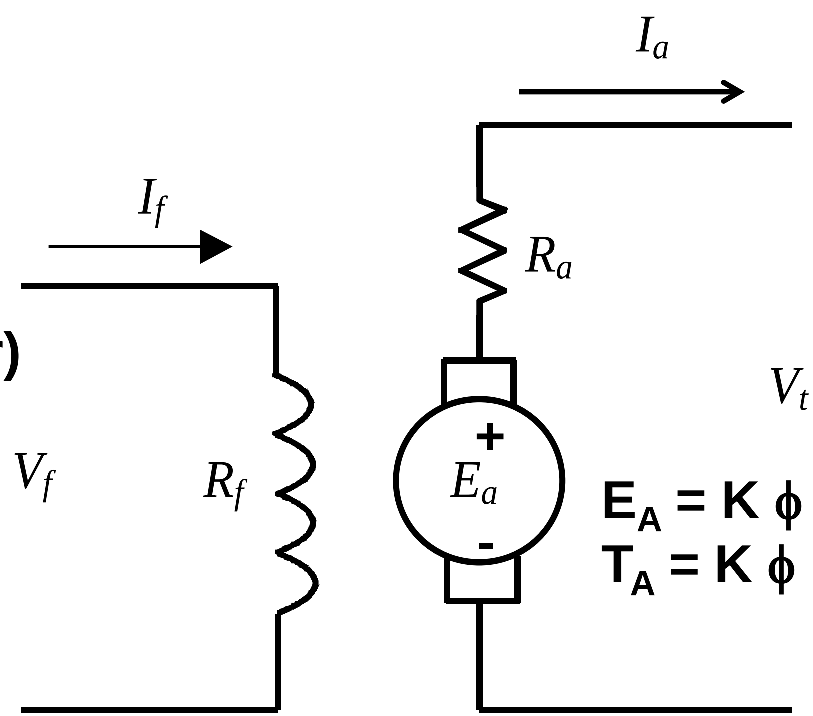
Separately Excited DC Generator

Using modified Armature current

$V_t \times I_a$: Power delivered to the load

T_A : Induced torque (against prime mover)

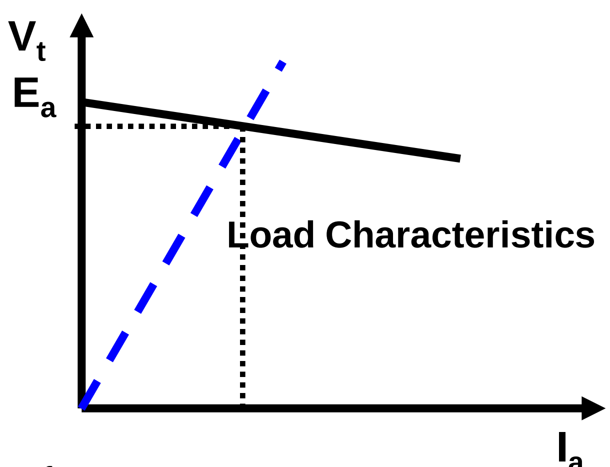
$E_a \times I_a$: Converted power (mechanical to Electrical)



$$E_A = K\,\phi\,\omega$$

$$T_A = K\,\phi\,I_A$$

$$V_t = E_a - R_a\,I_a$$



E_a : No load Voltage

R_a : slop of voltage drop

How armature reaction affects terminal characteristics?

Voltage control of Separately Excited DC Generator

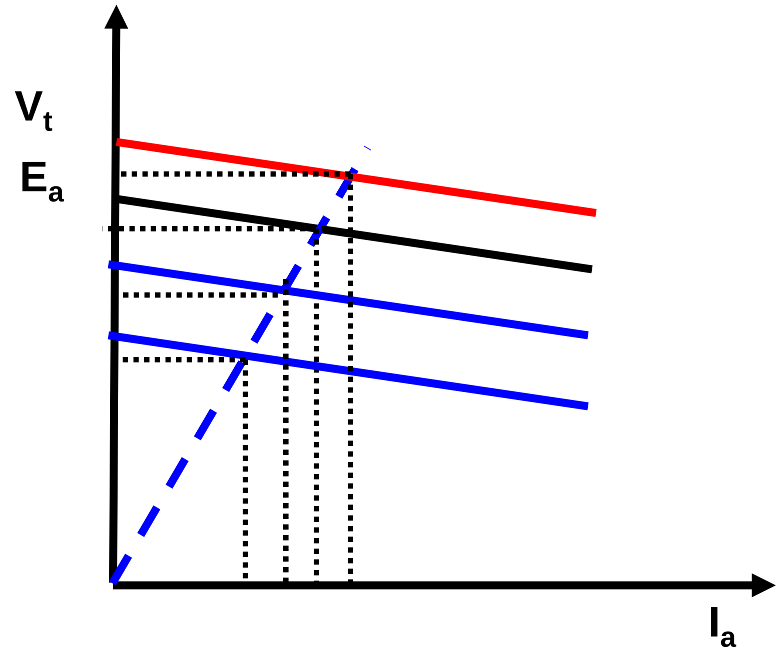
$V_t = E_a - R_a I_a$

Most effective way to control V_t is through E_a

$E_a = k \phi \omega$

ϕ can be decreased from its rated value decreasing I_f

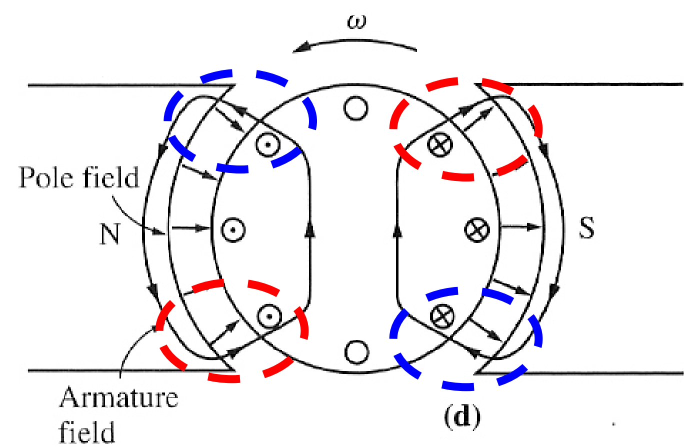
ω can be modified by speed of prime-mover



Armature Reaction

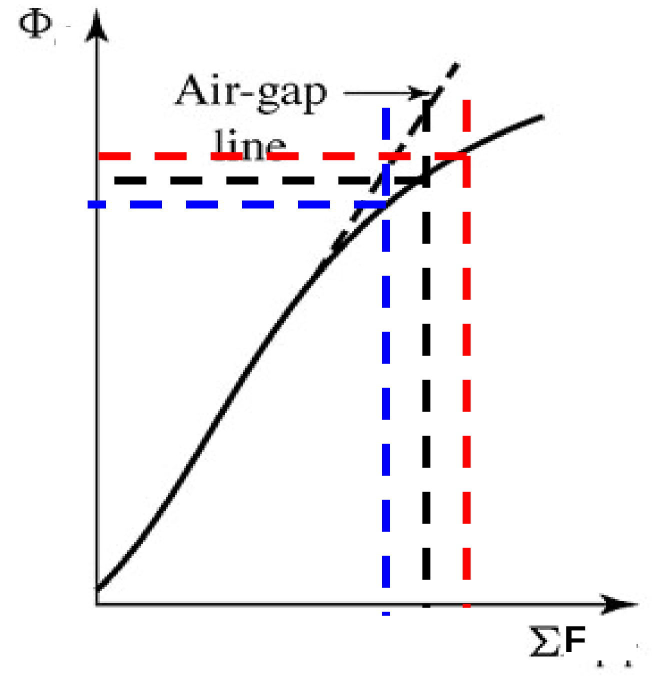
2: Flux weakening

- **Armature reaction decrease flux intensity in some parts of the magnetic poles.**
- **Armature reaction increases flux intensity in some parts of the magnetic poles.**
- **In linear systems the changes compensate each other.**
- **In saturated machines the increase is less than increase in flux.**



- **Reduced equivalent pole flux ϕ**

Reduced induced voltage & higher speed motor



(a)

Armature Reaction Modeling

Armature reaction reduces ϕ

Can be modeled as a reduction in ϕ $\Rightarrow$ E_a

Can be modeled as a reduction in I_f $\Rightarrow$ ϕ $\Rightarrow$ E_a

$$F_{net} = N_F I_F - F_{AR}$$

open circuit

$$I_F^* = I_F - F_{AR} / N_F \Rightarrow E_a$$

The same approach can be used for DC motors!!

Example

A Separately excited DC generator is rated at 172 kW, 400 A, 1800 RPM with a given magnetizing characteristics.

R_a=0.05 Ω, R_F=20 Ω, V_F = 430 V, N_F = 1000 turns/pole, R_{adj} = 0 to 300 Ω

for R_{adj} = 63 Ω and n = 1600 RPM

A: what is the no-load voltage?

B: What is the generator voltage if I_a = 360 A (neglecting AR)

C: Repeat B if AR equivalent MMf@360 A is 450 Aturns.

D: What adjustment could lead to have the no-load voltage while loaded

Solution:

A:

$I_F = V_F / R_F = 430 / (63 + 20) = 5.2$ A

From magnetizing characteristics E_a(@1800RPM) = 430 V

$E_a = 430 * 1600 / 1800 = 382$ V

B:

$$V_T = E_a - R_a I_a = 382 - 360 \times 0.05 = 364\ V$$

C:

AR is modeling using its equivalent MMF:

$$I_F^* = I_F - F_{AR} / N_F = 5.2 - 450/1000 = 4.75\ A$$

From Mag Ch. : for $I_F = 4.75$ Ea(@1800RPM) = 410 V

And therefore : Ea = 1600 / 1800 ×410 = 364 V

$$Vt = 364 - 360 \times 0.05 = 346\ V$$

D:

The voltage drop can be compensated by increasing Ea

$$E_{a,req} = 382 + 360 \times 0.05 = 400\ V$$

The voltage can be calculated @ 1800 RPM:

$$E_{a,req,1800rpm} = 400 \times 1800 / 1600 = 450\ V$$

From Mag Ch. : $I_F = 6.5$ A (neglecting AR)

This can be achieved reducing R_{adj} to 50 Ω

Printed Circuit Board DC Motors

Disk shape, nonmagnetic rotor printed in copper armature winding

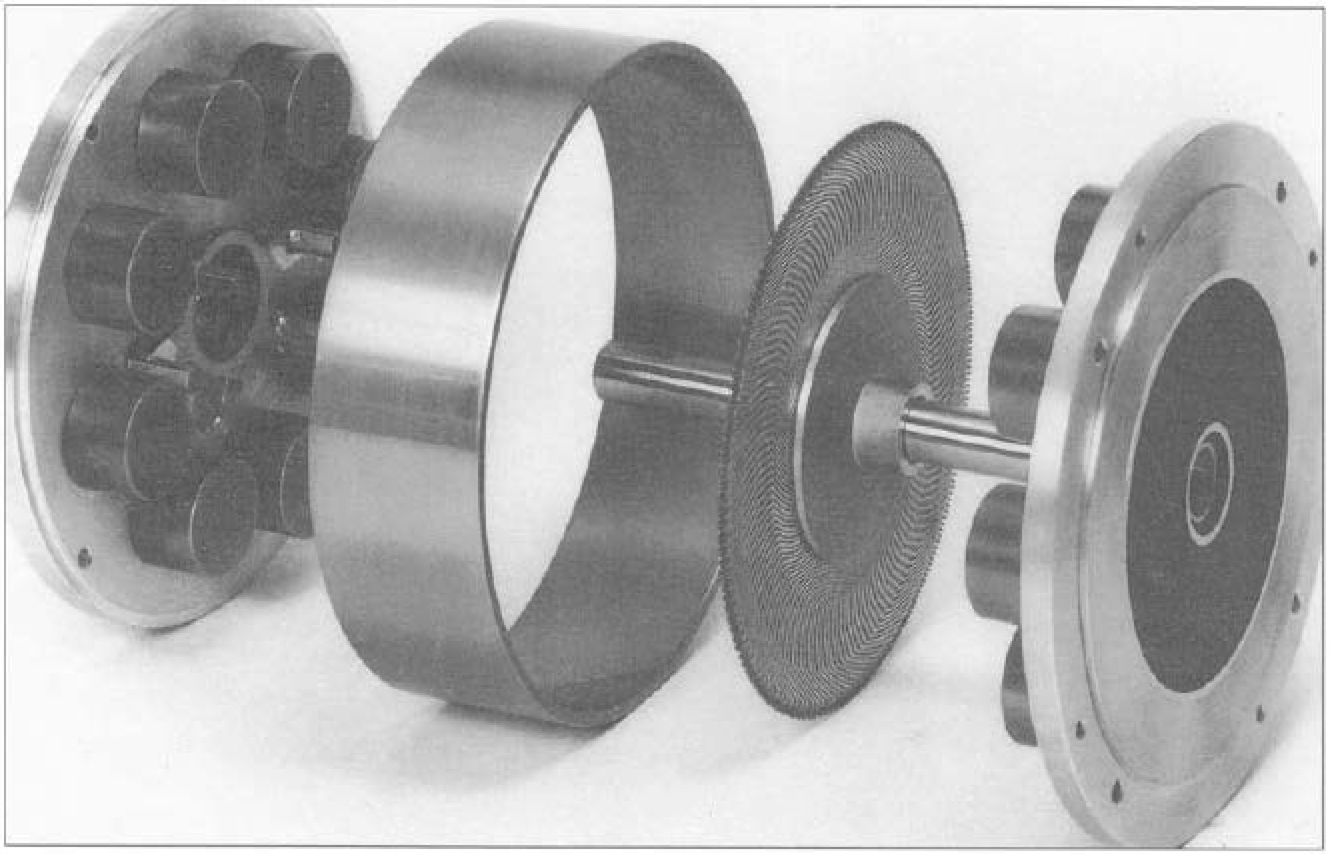
Low rotor inertia, Small armature inductance

Axial flux by PM
Radial current

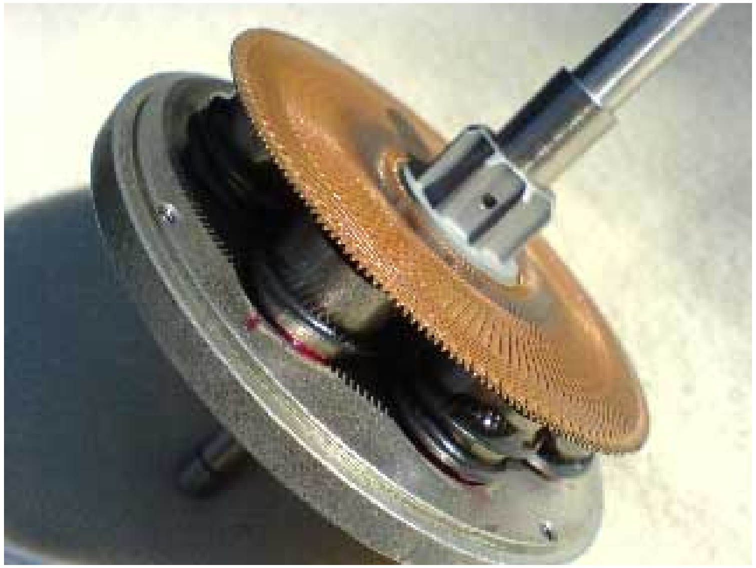
Induced torque

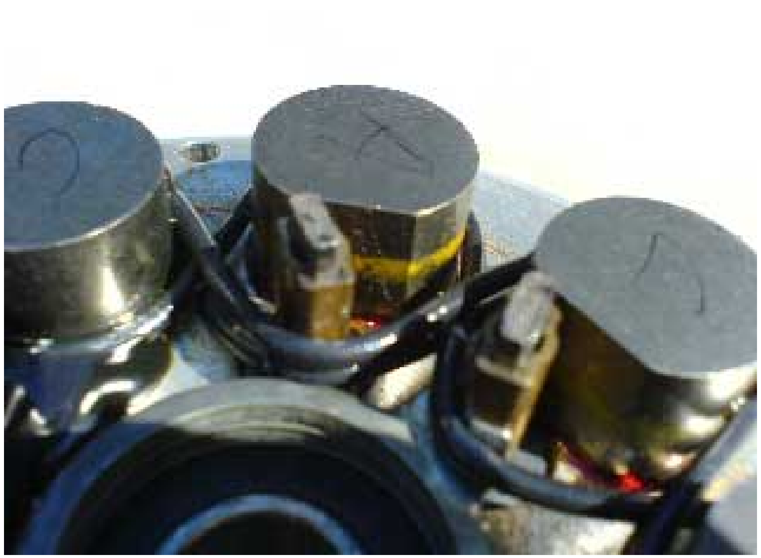
Small Elect and mech
Time constant

Quick motion response



Printed Circuit Board DC Motors



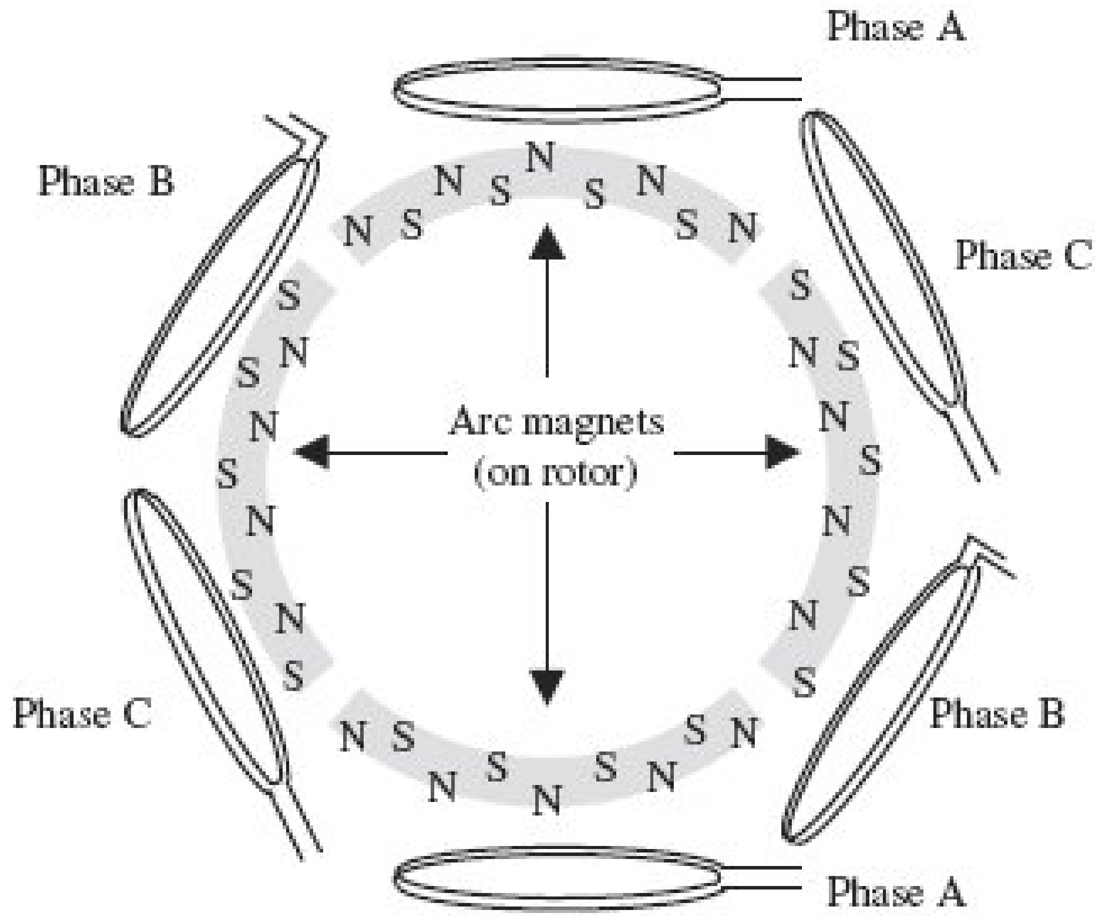


Brushless DC Motors (BLDC)

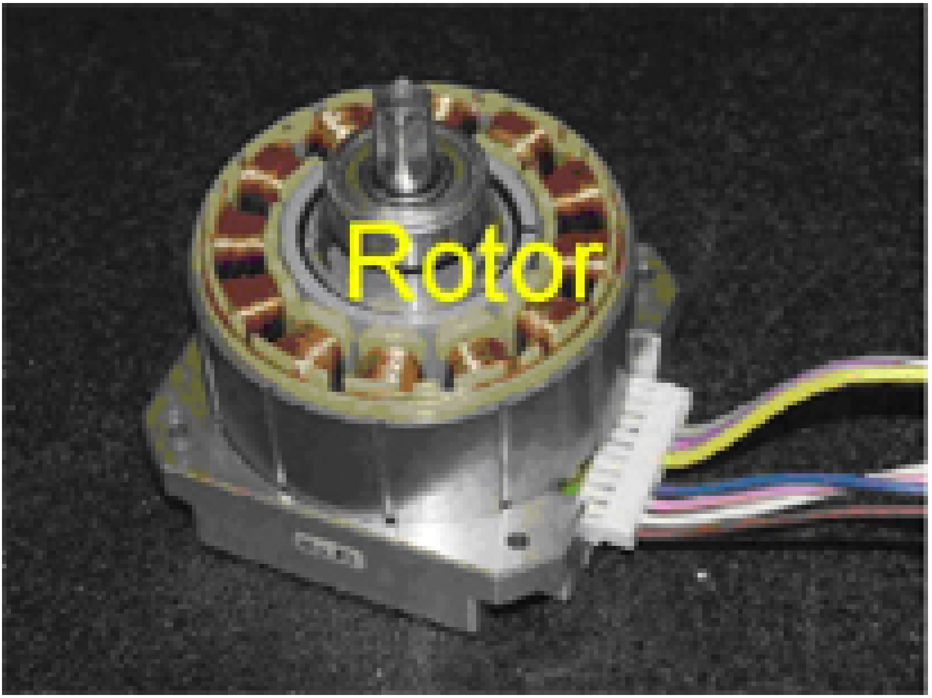
- **Inside out PM DC motor**
  (rotating PM, fixed armature winding)
- **Concentrated three phase winding**
- **Fixed armature winding**

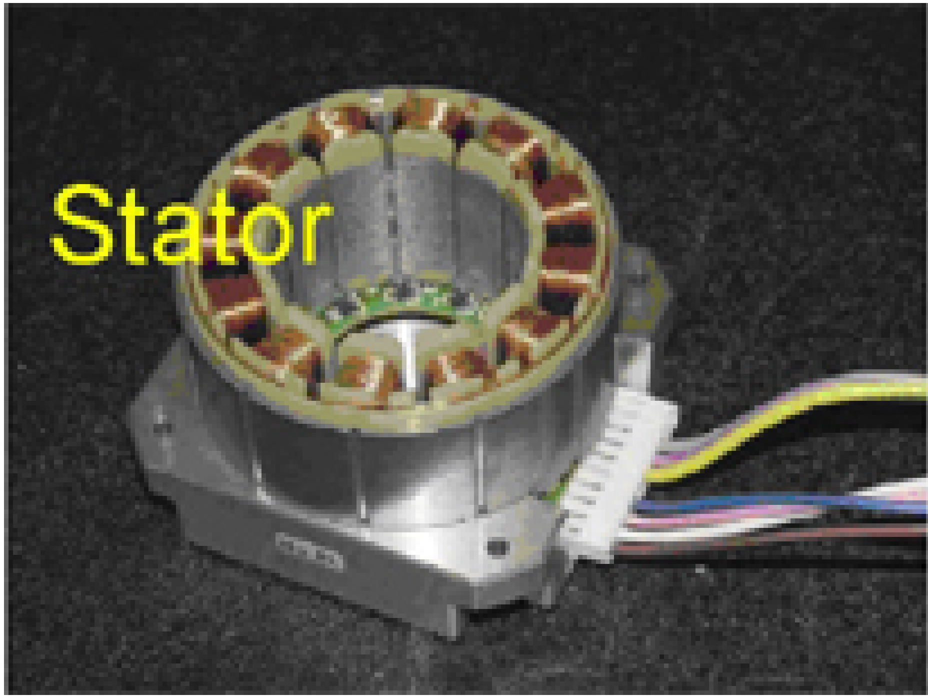
- **Rotating PMs induced AC voltage in armature winding**

- **Electronic converter to rectify induced voltage and commutate current in the stator winding**

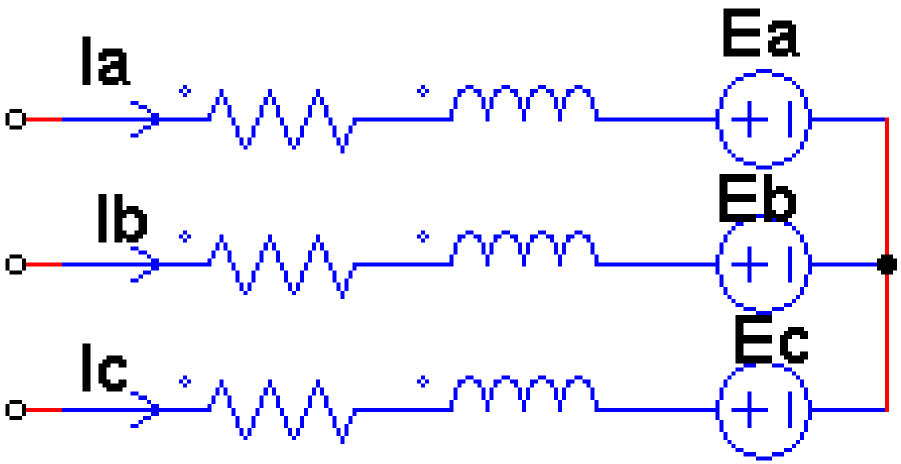


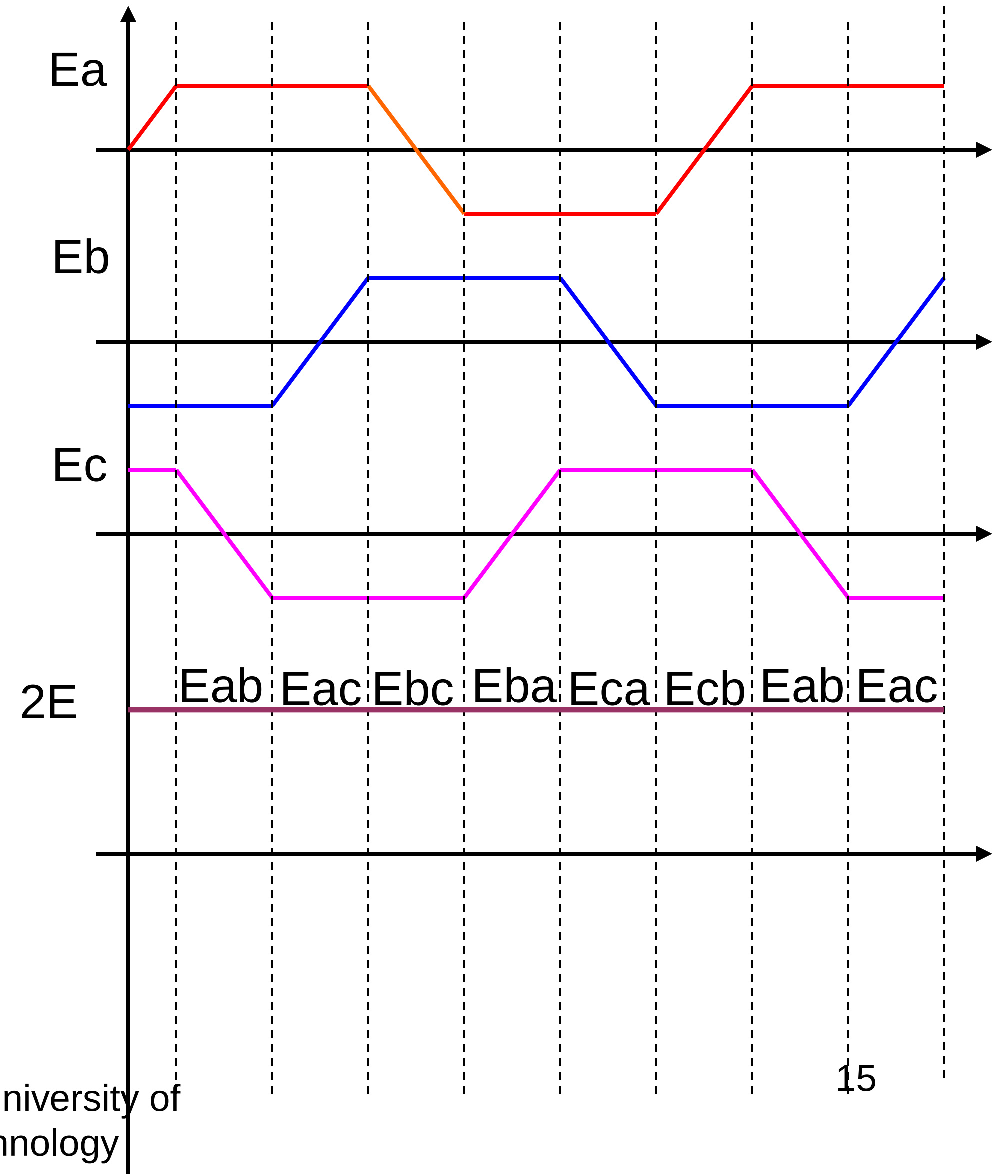
Brushless DC Motors (BLDC)





Induced voltages in BLDC Motors





- **Trapezoidal BMF**
- $\mathbf{E = K\phi \times \omega = K_b \times \omega}$
- $\mathbf{T = (E_a \times I_a + E_b \times I_b + E_c \times I_c) / \omega}$

How torque can be constant?

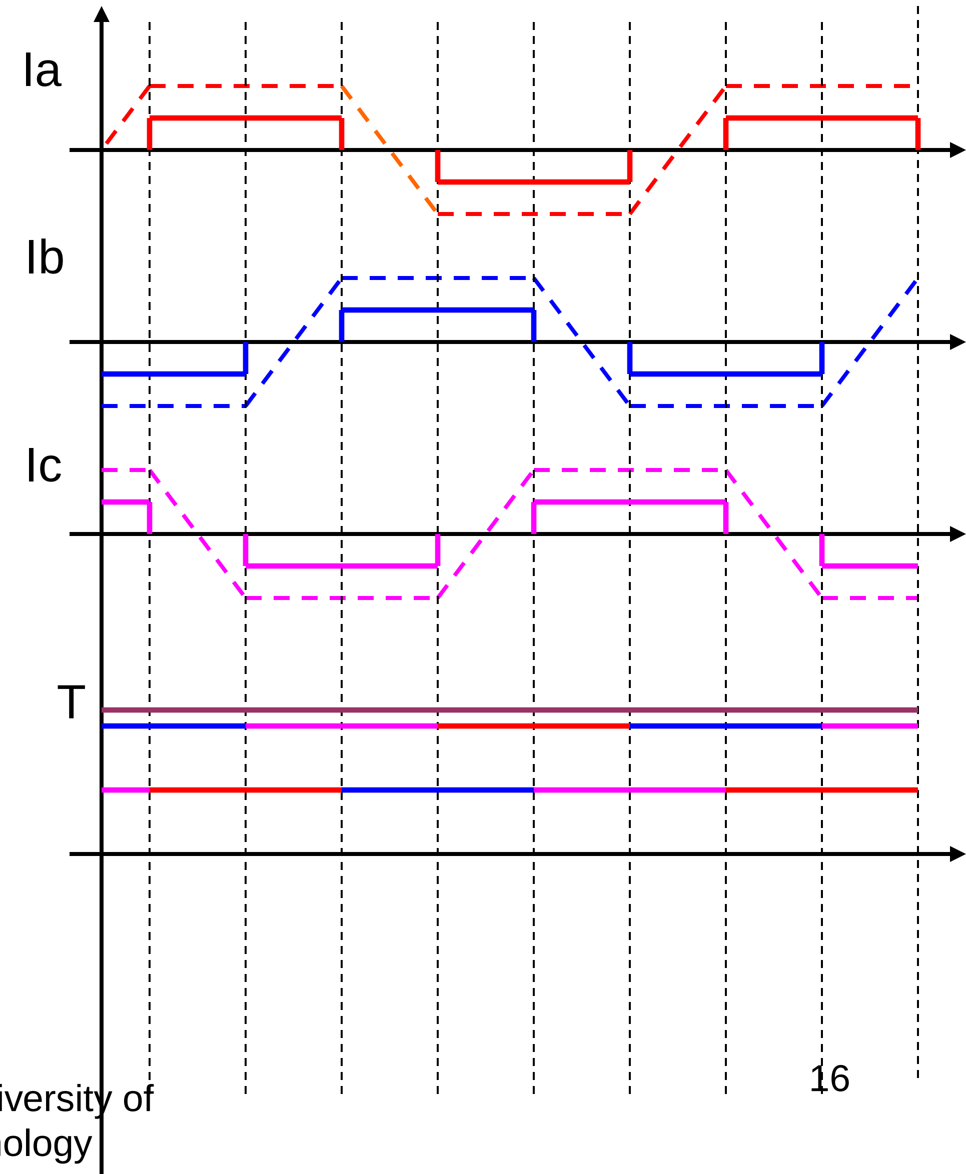
Torque in BLDC Motors

$$T=(E_a \times I_a + E_b \times I_b + E_c \times I_c)/\ \omega$$

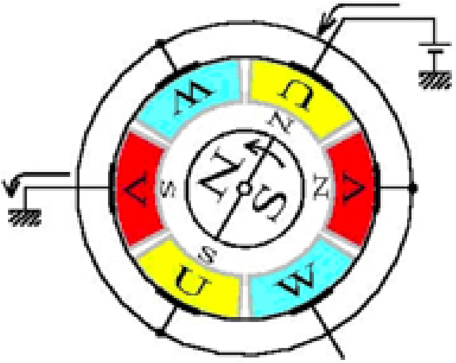
- **Induced voltage is a function of rotor position**

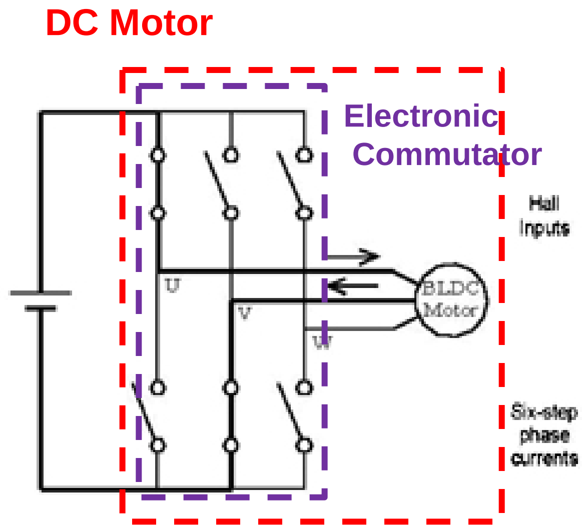
- **Rotor position is required**

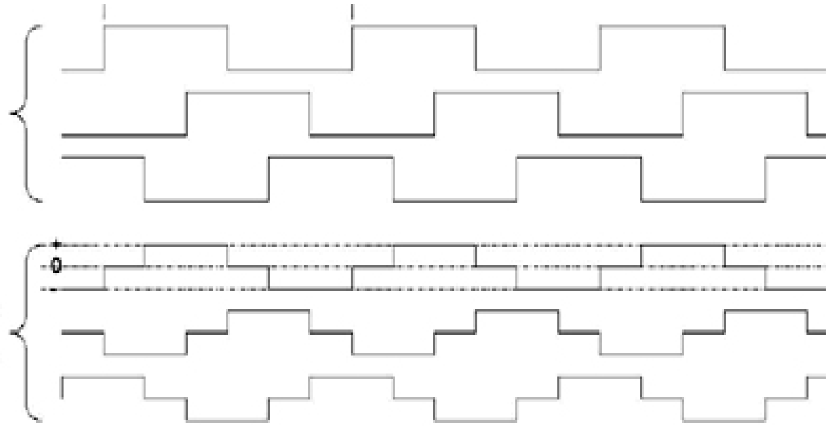
- **Armature current commutation is required**
- **Voltage and current commutations are synchronous**



BLDC Motor Drive







Typical 6-step commutation (only 2 phase conducting at any time)
This is typical of inverters without 3-phase peripheral and PMSM with Hall Effects.