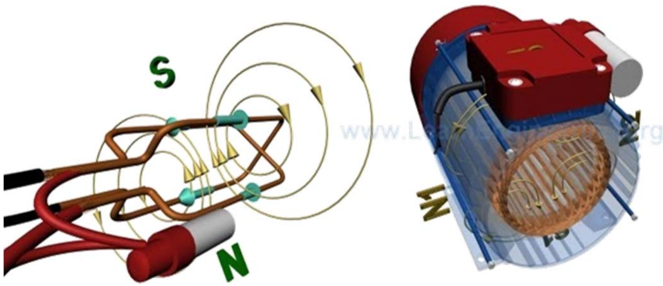
National Cheng Kung University

Chapter 2

Fundamental Principles of Electrical Motor



Professor Min-Fu Hsieh

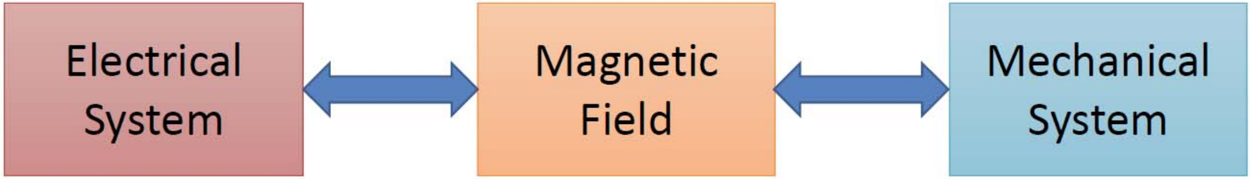
https://www.learnengineering.org/rotating-magnetic-field-synchronous-speed-motor-single-phase.html

Fall Semester - 2022

Energy Conversion Principles in Brief

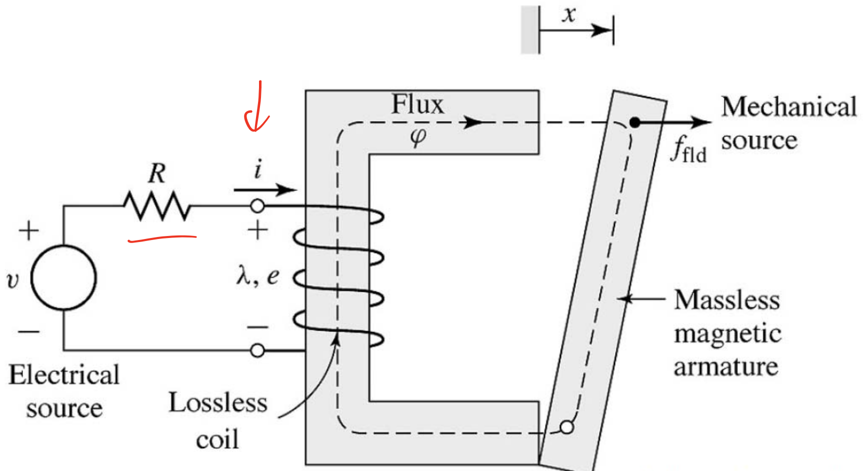
Basic of Electromechanical Energy Conversion

An electromechanical system consists of an electrical system, a mechanical system, and a means whereby the electric and mechanical systems can interact.



Energy in Singly-Excited Magnetic Field Systems

A electromagnetic relay shown schematically in the figure below. The resistance of the excitation coil is shown as an external resistance R, and the mechanical terminal variables are shown as a force f_{fld} produced by the magnetic field directed from the relay to the external mechanical system and a displacement x.



Schematic of an electromagnetic relay.

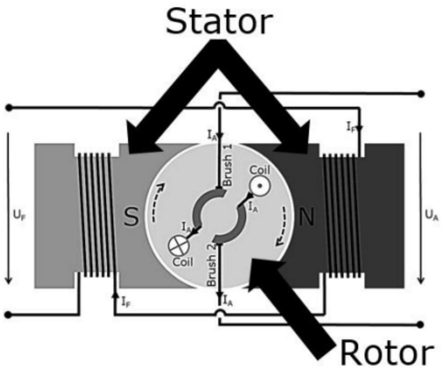
reluctance

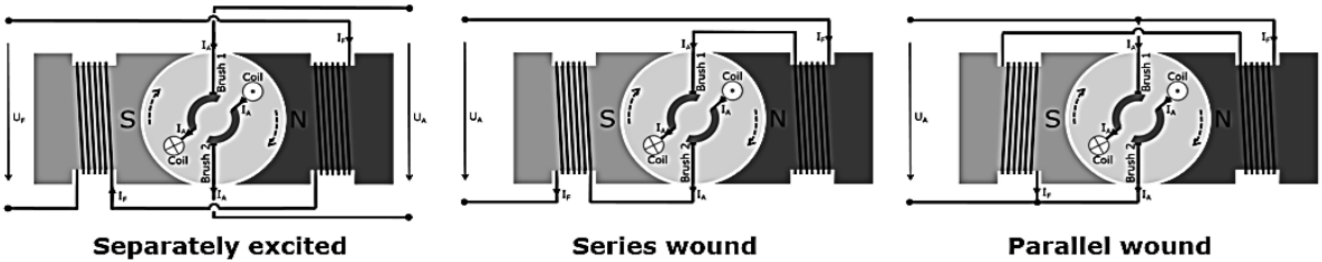
$$e = N\frac{d\phi}{dt} = \frac{di}{dt}$$

$$dW_e = dW_{fld} + dW_{me}$$

Single Phase Brushed DC Motor

Brushed DC Motor

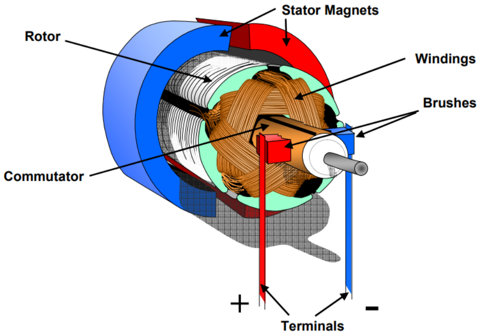


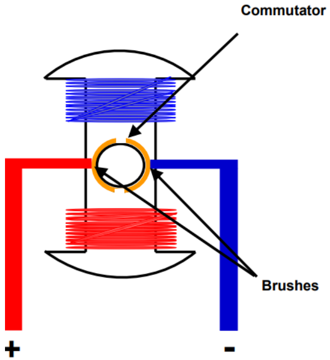


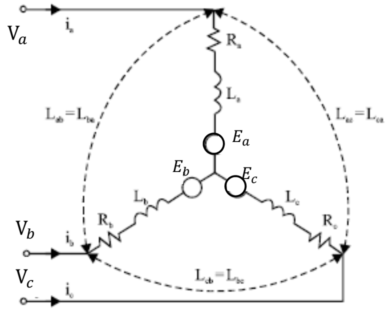
Different DC-motor types

[Handbook of Electric Machines (infineon.com)]

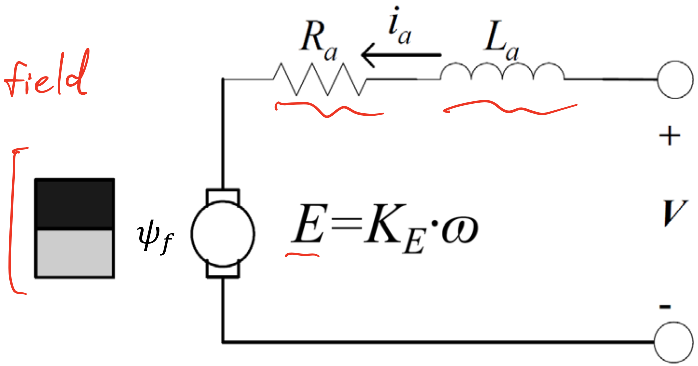
PM Brushed DC Motor's Equivalent Circuit





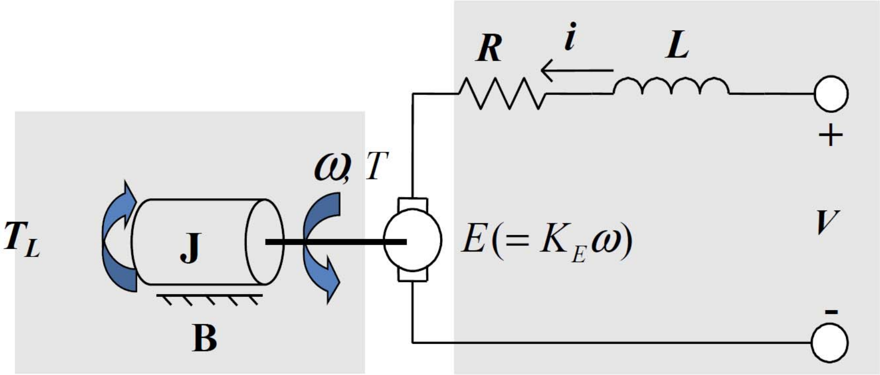


PM
produce field



Index :
- ω : speed
- R_a : armature resistance
- L_a : armature inductance
- K_E : back-EMF constant (related to flux linkage of magnet)
- E : back-EMF
- i_a : armature current
- ψ_f : flux leakage of magnet
- V : voltage

Rotary Machine



$$T = K_T\, i$$

$$E = K_E\, \omega$$

$$V = L\frac{di}{dt} + Ri + E$$

$$T = J\frac{d\omega}{dt} + B\omega + T_L$$

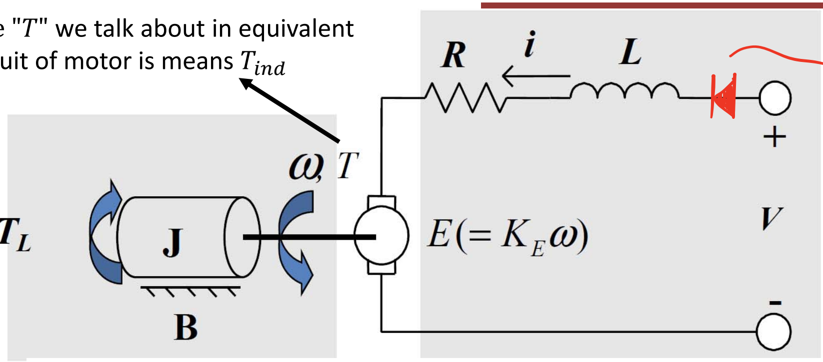
Index :
Wb : weber
A : Ampere
Unit of K_E : $\frac{V}{rad/s} = \frac{Wb}{rad} = Wb$
Unit of K_T : $\frac{N{\cdot}m}{A} = \frac{Joule}{A} = V \cdot s = Wb$
Unit of K_E and K_T is same as flux linkage.

Index :

T : torque	E : back-EMF
K_T : torque constant	K_E : back-EMF constant
i : armature current	ω : speed
R : armature resistance	J : inertia
L : armature inductance	B : damping coefficient
V : voltage	T_L : torque of load

DC Motor Power Flow

The "T" we talk about in equivalent circuit of motor is means T_{ind}



voltage drop of the brush

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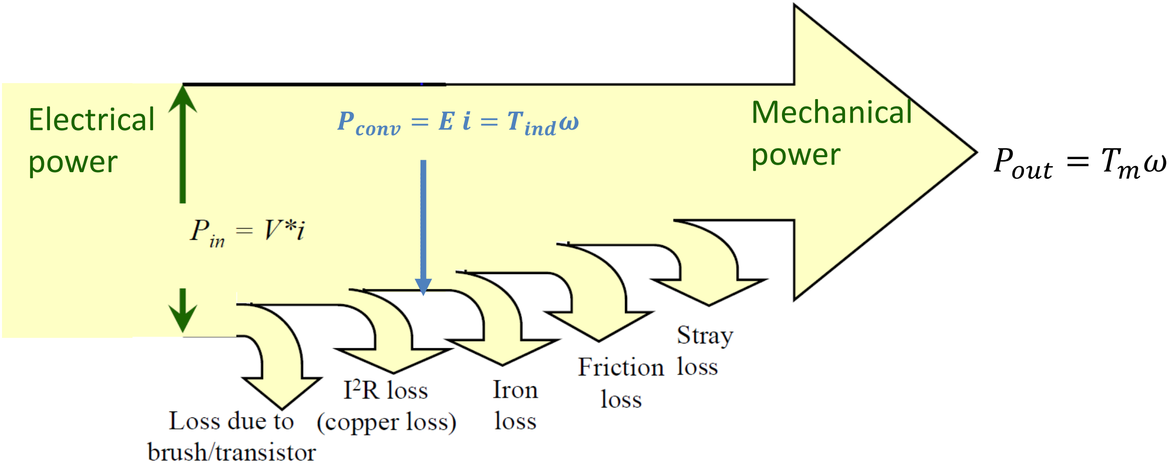


Block diagram of DC Motor

t - domain

$$T = K_T\, i$$

$$E = K_E\, \omega$$

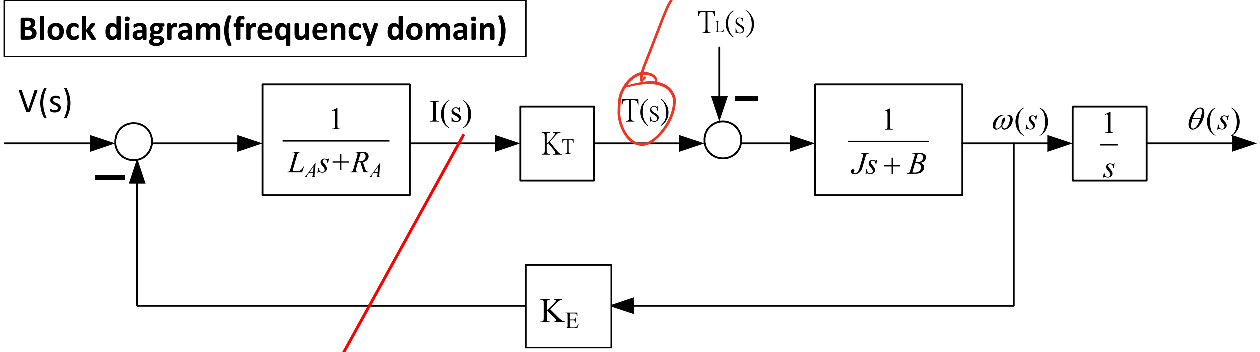
$$V = L\frac{di}{dt} + Ri + E$$

$$T = J\frac{d\omega}{dt} + B\omega + T_L$$

s - domain

induce torque

Block diagram(frequency domain)

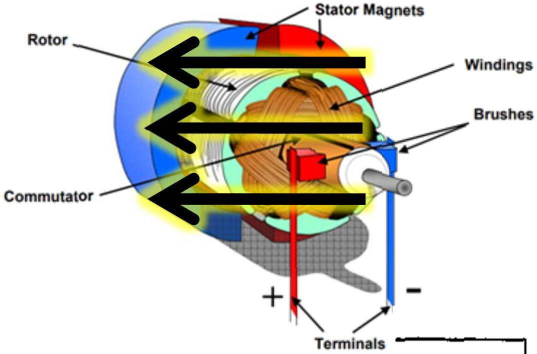


This current is always q-axis current i_q
And, i_d=0 (we will talk in chapter 4).

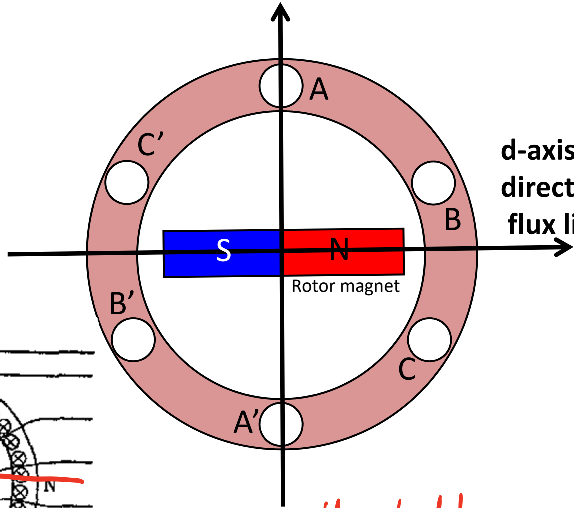
d-axis and q-axis of motor

The d-axis and q-axis is means the direction of magnetic field.

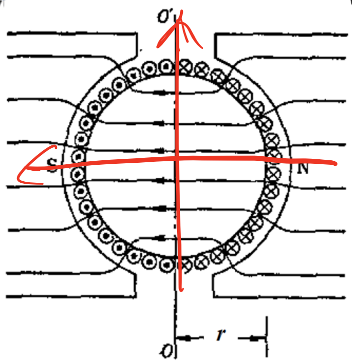
d-axis : direction of magnetic field

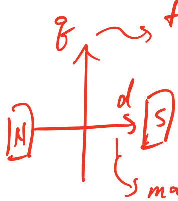


q-axis : perpendicular to d-axis



d-axis : direction of main flux linkage.





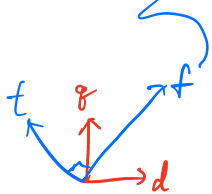
field produced by armature current

main field

direct flux control

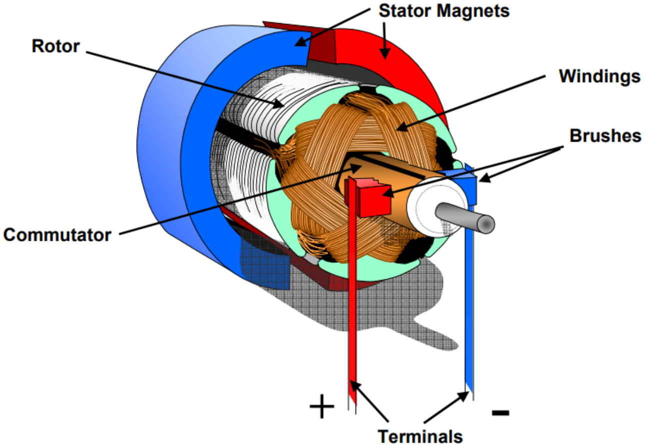
f related to load

cause q & t relate to load also

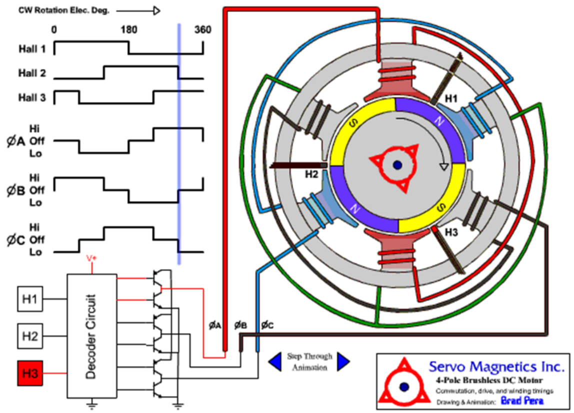


Brushed and brushless motor

Brushed motor



Brushless motor



Magnetic field is fixed.

So the d-axis and q-axis are fixed .

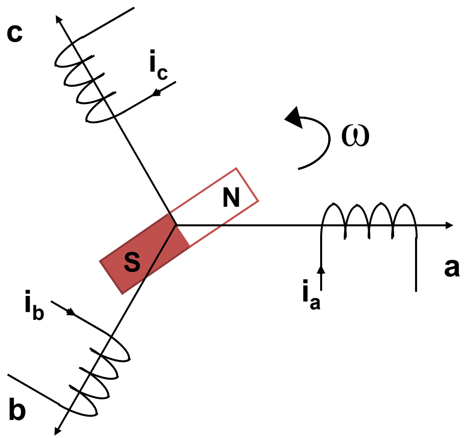
Magnetic field is rotating.

So the d-axis and q-axis are rotating .

Rotating Magnetic Field

Rotating Magnetic Field

- For most three phase PM machines, the winding is stationery, and magnetic field is rotating
- Three phase machines have three stator windings, separated 120° apart physically

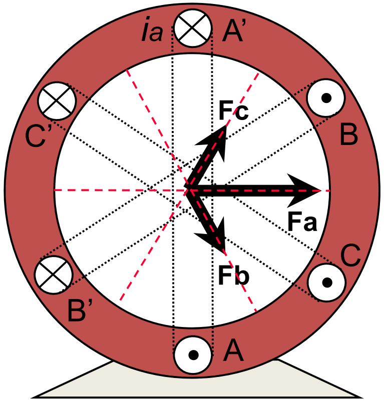


$$\begin{cases} i_a = i_s e^{j\omega t} \\ i_b = i_s e^{j\left(\omega t - \frac{2\pi}{3}\right)} \\ i_c = i_s e^{j\left(\omega t + \frac{2\pi}{3}\right)} \end{cases}$$

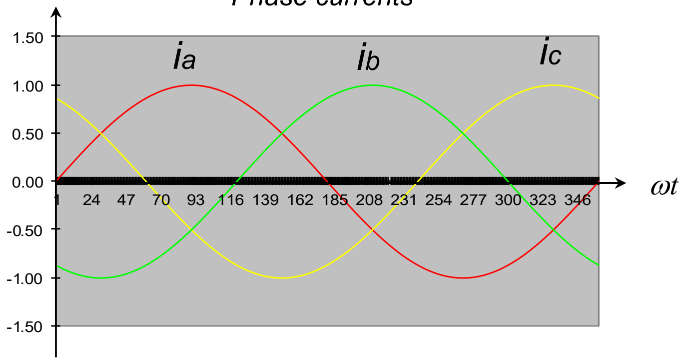
Rotating Magnetic Field

- The three phase winding produces three magnetic fields, which are spaced 120° apart physically.
- When excited with three sine waves that are a 120° apart in phase, there are three pulsating magnetic fields.
- The resultant of the three magnetic fields is a rotating magnetic field.

Three stationary pulsating magnetic fields

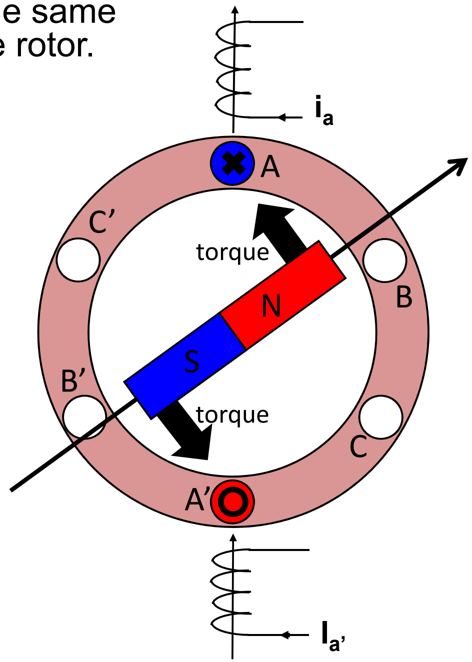


Phase currents



Rotating Magnetic Field

- Rotor is carrying a constant magnetic field created either by permanent magnets or current fed coils
- The interaction between the rotating stator flux, and the rotor flux produces a torque which will cause the motor to rotate.
- The rotation of the rotor in this case will be at the same exact frequency as the applied excitation to the rotor.
- This is synchronous operation.



Rotor mechanical speed :

$$\omega_m = \frac{60f}{p} \text{ (rpm)}$$

f : AC supply frequency (Hz)

p : pole pairs per phase

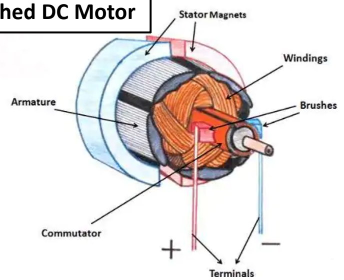
Example: *a 2 poles pair synchronous motor will run at 1500 r.pm for a 50Hz AC supply frequency*

Brushless Permanent Magnet Motor

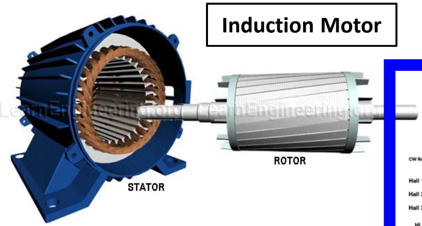
Motor Types

- DC Motor
  - Series
  - Shunt
  - PM
  - Separately Exited

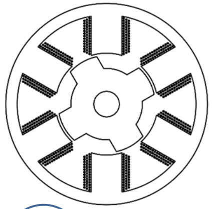
Brushed DC Motor



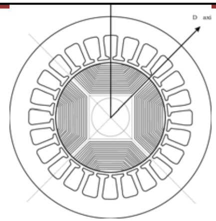
Induction Motor



Switched Reluctance Motor

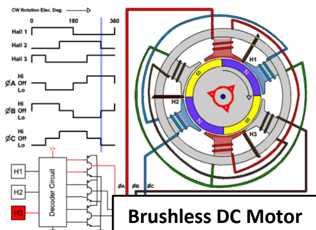


Synchronous Reluctance Motor



- AC Motor
  - Asynchronous
    - Induction Motor
  - Synchronous
    - Permanent Magnet Motor
      - BLDC Motor
      - PMSM
        - Surface PM Motor
        - Interior PM Motor
    - Reluctance Motor
      - Switched Reluctance
      - Synchronous Reluctance

皆為 ac 馬達



Brushless DC Motor

Permanent Magnet Machines

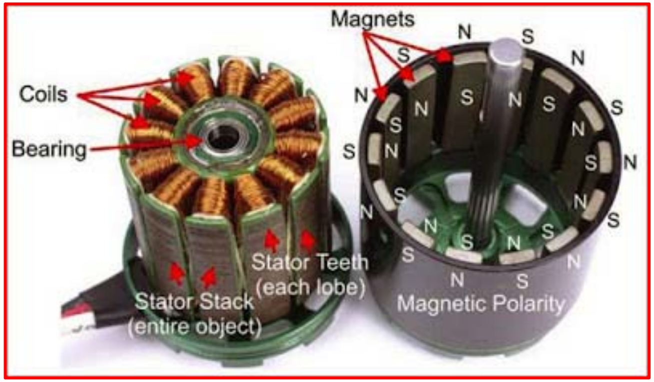
- Based on nature of voltage induced in the stator classified as:

Permanent magnet (PM) Machines → **PM Synchronous Machine (PMSM)**

Permanent magnet (PM) Machines → **Brushless DC Machine (BLDCM)**

Typical PMSM

https://thestockanalysis.com/permanent-magnet-motor-market-2018-global-insights-and-technology-advancements/

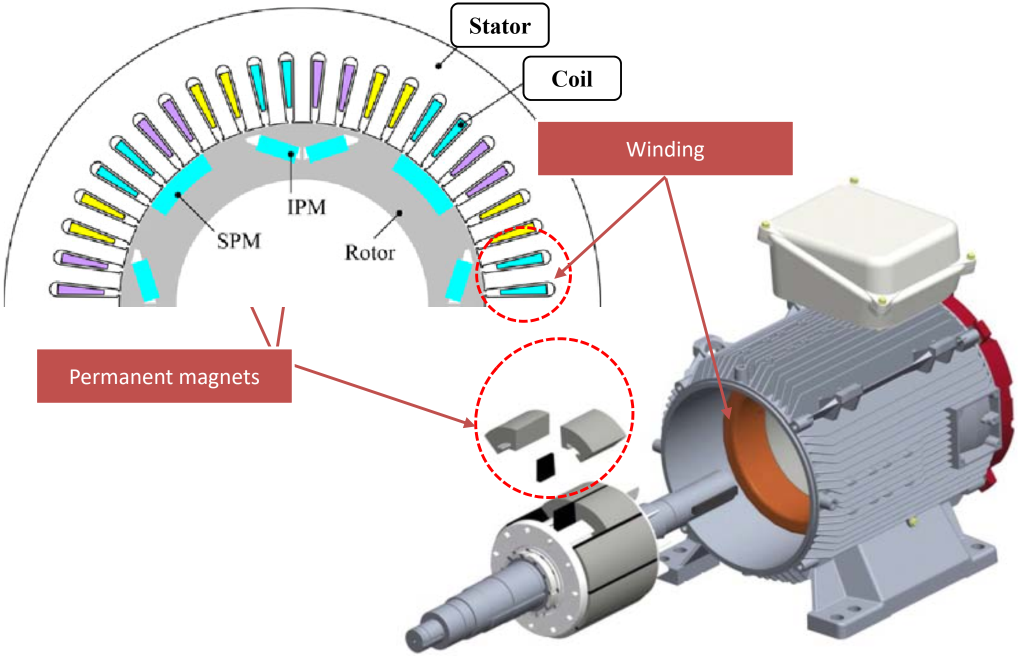


Typical BLDC

https://electrical4dummies.blogspot.com/2016/08/electromagnetism-brushless-motor.html

Structure of Permanent Magnet Motors

- The notation for PMSM is permanent magnet AC motor



Brushless PM Machine

See page 35.

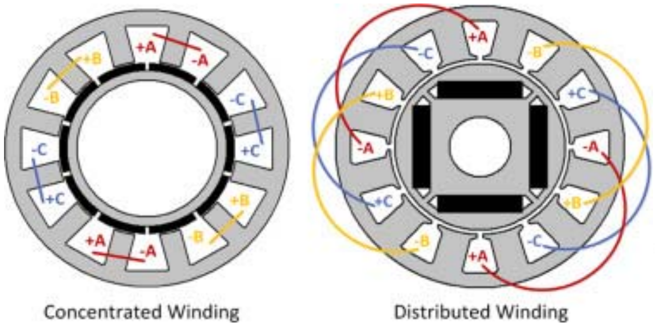
- **Brushless DC motors (BLDCM)**

Typically characterized as having a ***trapezoidal*** *back electromotive force* (EMF) and are typically driven by **rectangular pulse currents**. This mimics the operation of brush DC motors. From this perspective, the name "brushless DC" fits even though it is an AC motor.

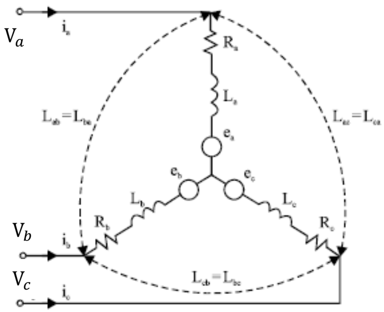
- **PM synchronous motors (PMSM)**

Which differ from brushless DC motors in that they typically have a ***sinusoidal*** *back EMF* and are driven by **sinusoidal currents**.

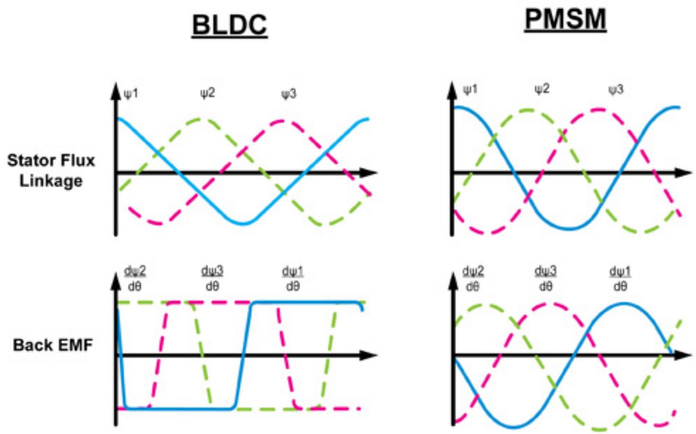
BLDC vs. PMSM



Stator winding examples



Stator winding equivalent circuit



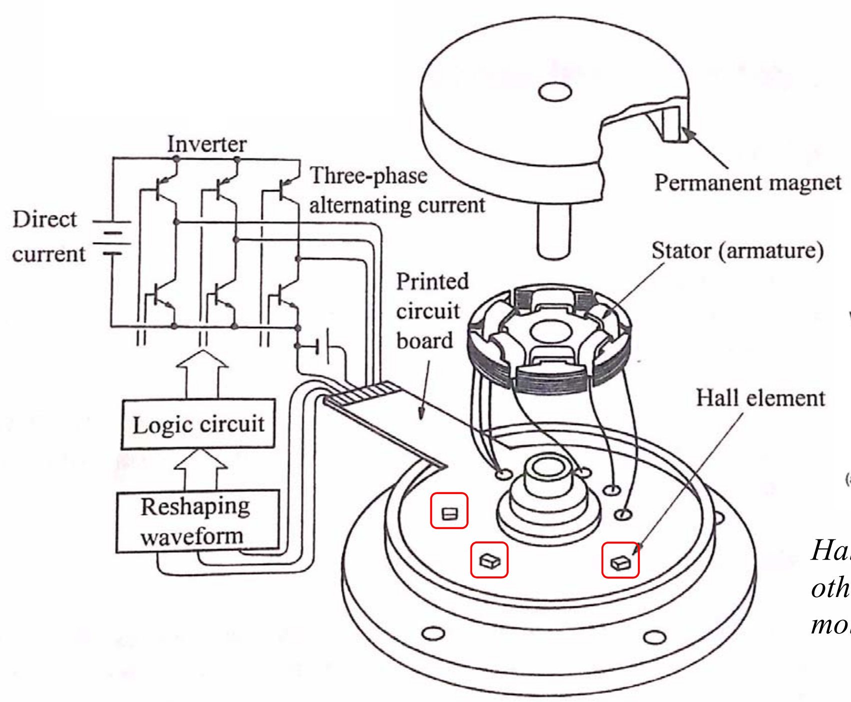
PMSM vs. BLDC Back EMF Waveforms

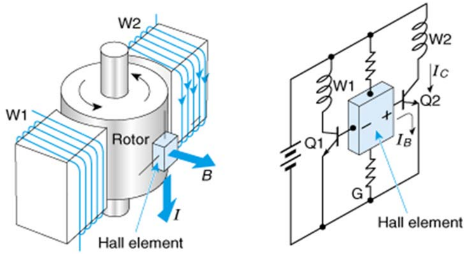
PMSM

Three phase AC power required

Brushless DC (BLDC) Drive

Brushless DC (BLDC) Drive





(a) Hall element placed near side surface of the rotor.

(b) Hall element connected to winding.

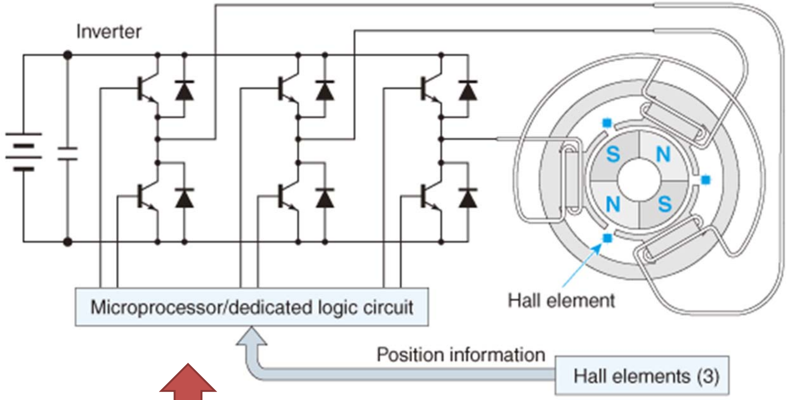
Hall effect sensor can be replaced by other position sensors, depending on motor type (e.g., encoders for PMSM)

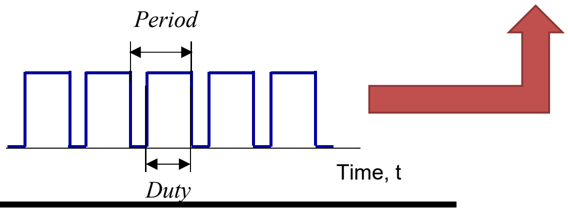
Takashi Kenjo , Shigenobu Nagomori (2003), *Brushless Motors Advanced Theory and Modern Applications*, Sogo Electronics Press

Brushless DC (BLDC) Drive

Pulse width modulation (PWM) technique will be used in motor control, such as Brushless DC motor (BLDC). When the circuit is provided power, the voltage is switched according to the PWM signal, instead of being fully turned on. In this way, the motor can be controlled in speed or torque without changing the DC link voltage.

Micro control system is isolated from motor power, Avoid spur noise current and electromagnetic interference induced by current interruption

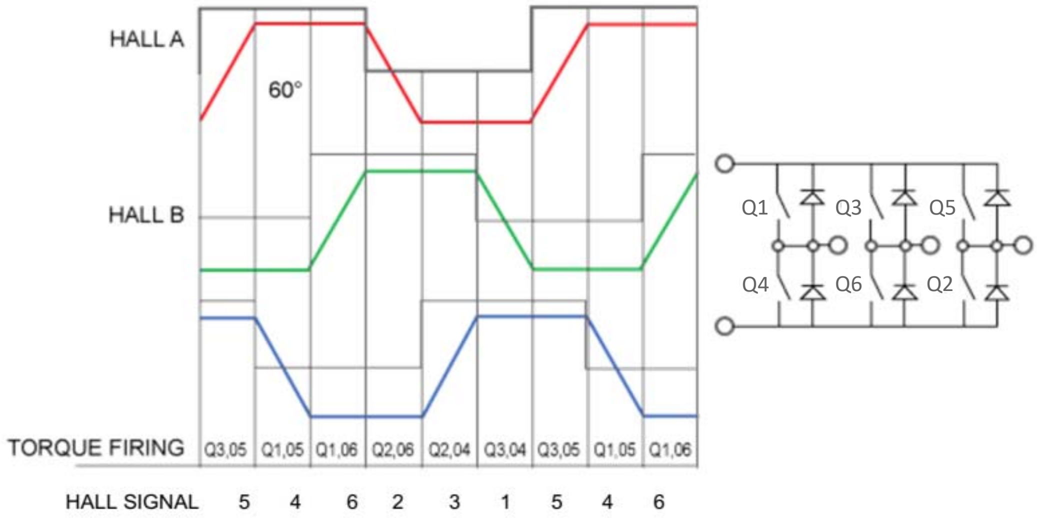




Brushless DC (BLDC) Drive

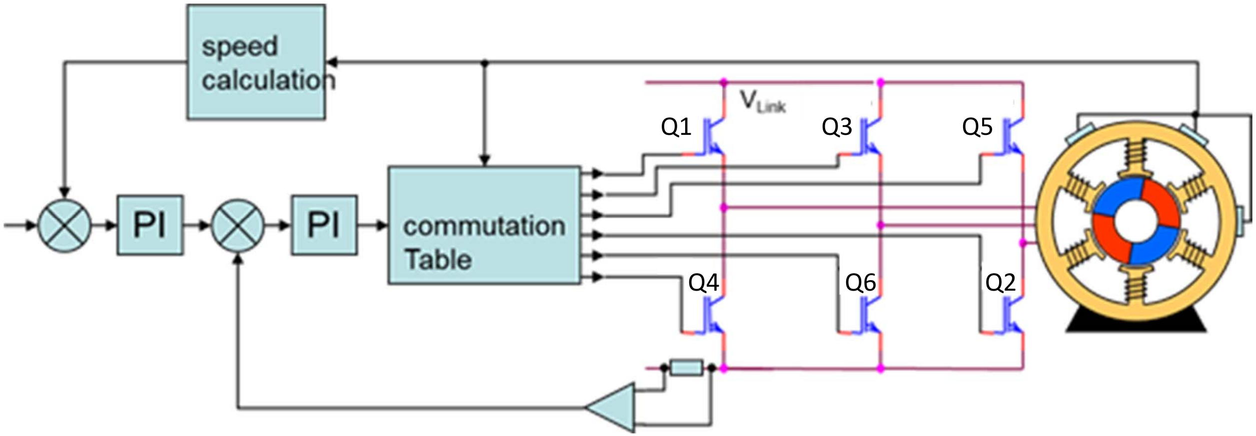
Hall sensors

The Hall element position of BLDCs on the market is the same as its corresponding commutation logic. The following figure shows the relationship between the common 120° commutation logic and **the Hall signal**.



Brushless DC (BLDC) Drive

The commutation table block provides logic sequence to drive 6-switches of inverters and plays a very important role in the 6-step commutation control method. Below figure shows the block diagram of this scheme in which the motor is driven by a 3-phase H-bridge inverter



Brushless DC (BLDC) Drive

The main commutation logic of BLDC has 120 degree conduction and 180 degree conduction. When using 120 degree conduction commutation logic, the continuous conduction time of each transistor switch is 120 degree mechanical angle, and 180 degree conduction is continuous 180 degree mechanical angle.

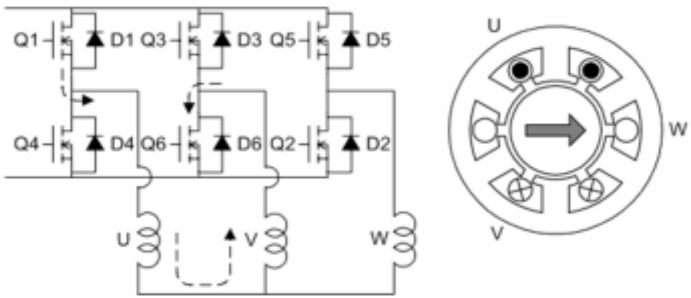
120	0°~60°	~120°	~180°	~240°	~300°	~360
Q1	1	1	0	0	0	0
Q2	0	1	1	0	0	0
Q3	0	0	1	1	0	0
Q4	0	0	0	1	1	0
Q5	0	0	0	0	1	1
Q6	1	0	0	0	0	1

180	0°~60°	~120°	~180°	~240°	~300°	~360°
Q1	1	1	1	0	0	0
Q2	0	1	1	1	0	0
Q3	0	0	1	1	1	0
Q4	0	0	0	1	1	1
Q5	1	0	0	0	1	1
Q6	1	1	0	0	0	1

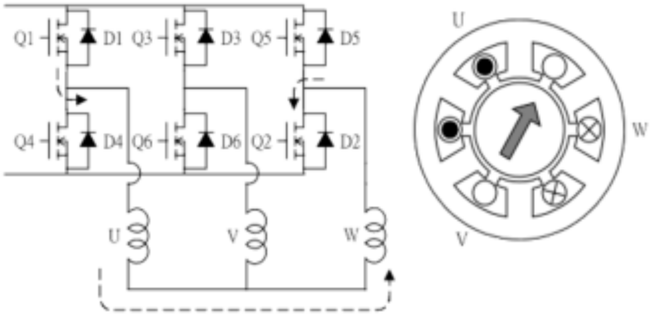
Brushless DC (BLDC) Drive

120 degree conduction commutation logic

	0°~60°
Q1	1
Q2	0
Q3	0
Q4	0
Q5	0
Q6	1



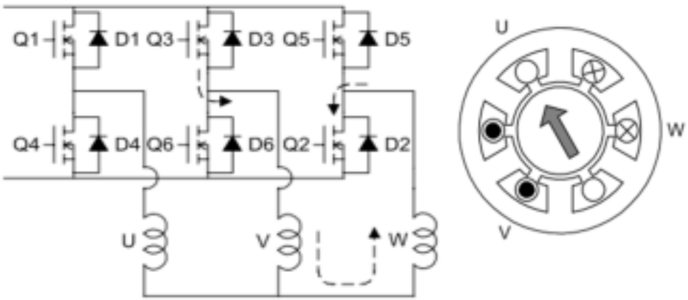
	~120°
Q1	1
Q2	1
Q3	0
Q4	0
Q5	0
Q6	0



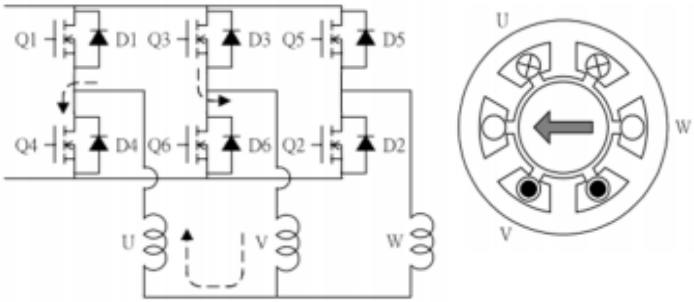
Brushless DC (BLDC) Drive

120 degree conduction commutation logic

	~180°
Q1	0
Q2	1
Q3	1
Q4	0
Q5	0
Q6	0



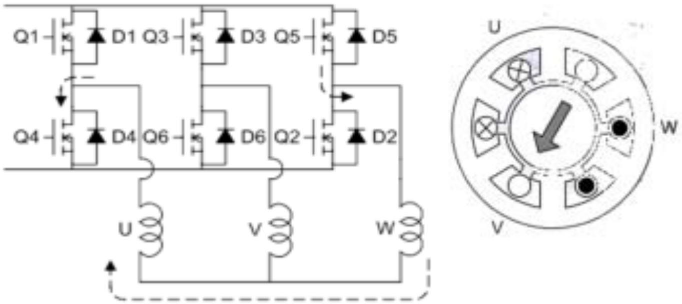
	~240°
Q1	0
Q2	0
Q3	1
Q4	1
Q5	0
Q6	0



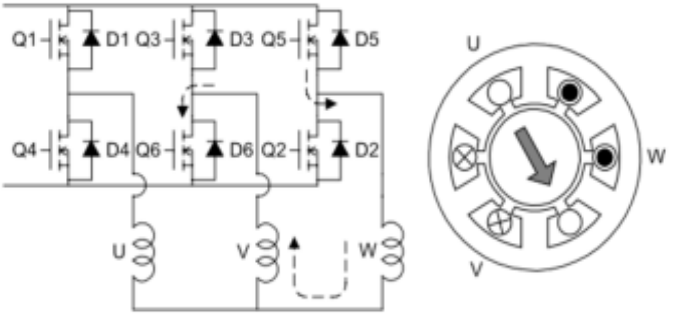
Brushless DC (BLDC) Drive

120 degree conduction commutation logic

	~300°
Q1	0
Q2	0
Q3	0
Q4	1
Q5	1
Q6	0



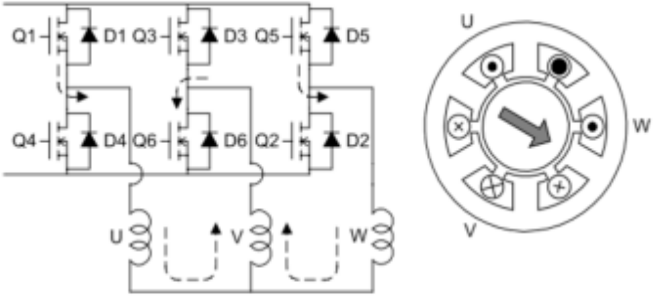
	~360
Q1	0
Q2	0
Q3	0
Q4	0
Q5	1
Q6	1



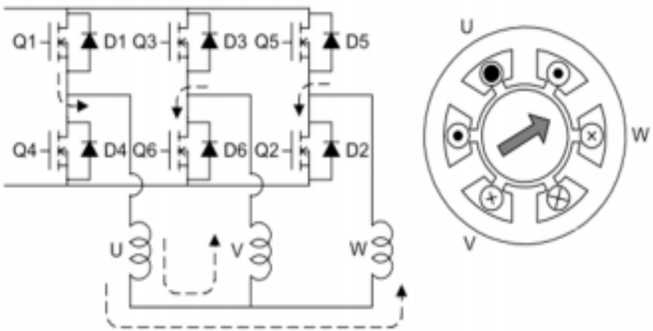
Brushless DC (BLDC) Drive

180 degree conduction commutation logic

	0°~60°
Q1	1
Q2	0
Q3	0
Q4	0
Q5	1
Q6	1



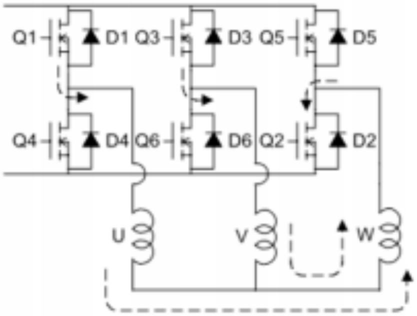
	~120°
Q1	1
Q2	1
Q3	0
Q4	0
Q5	0
Q6	1

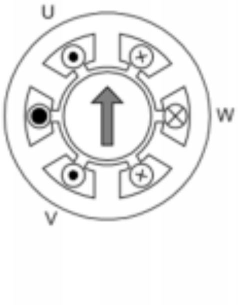


Brushless DC (BLDC) Drive

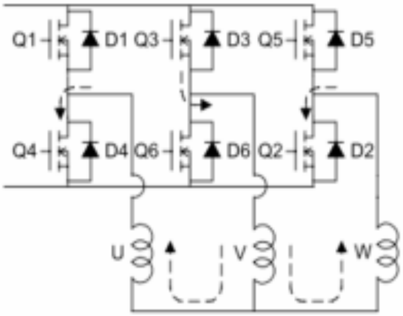
180 degree conduction commutation logic

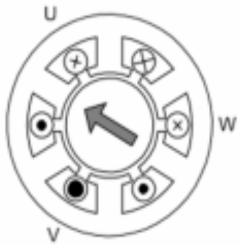
	~180°
Q1	1
Q2	1
Q3	1
Q4	0
Q5	0
Q6	0





	~240°
Q1	0
Q2	1
Q3	1
Q4	1
Q5	0
Q6	0

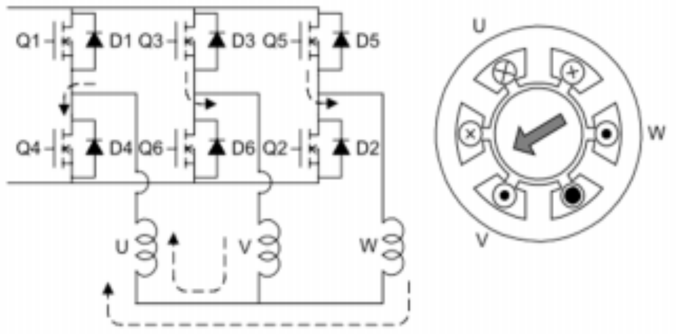




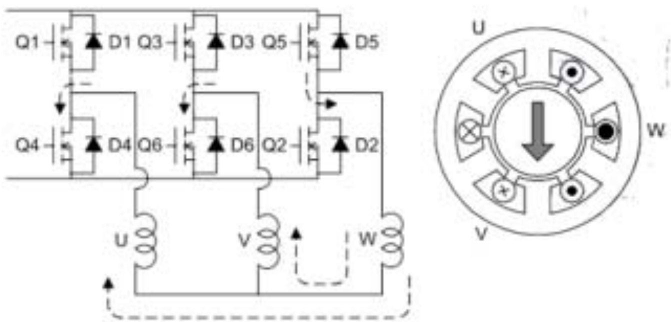
Brushless DC (BLDC) Drive

180 degree conduction commutation logic

	~300°
Q1	0
Q2	0
Q3	1
Q4	1
Q5	1
Q6	0



	~360°
Q1	0
Q2	0
Q3	0
Q4	1
Q5	1
Q6	1



Brushless DC Motor Principle

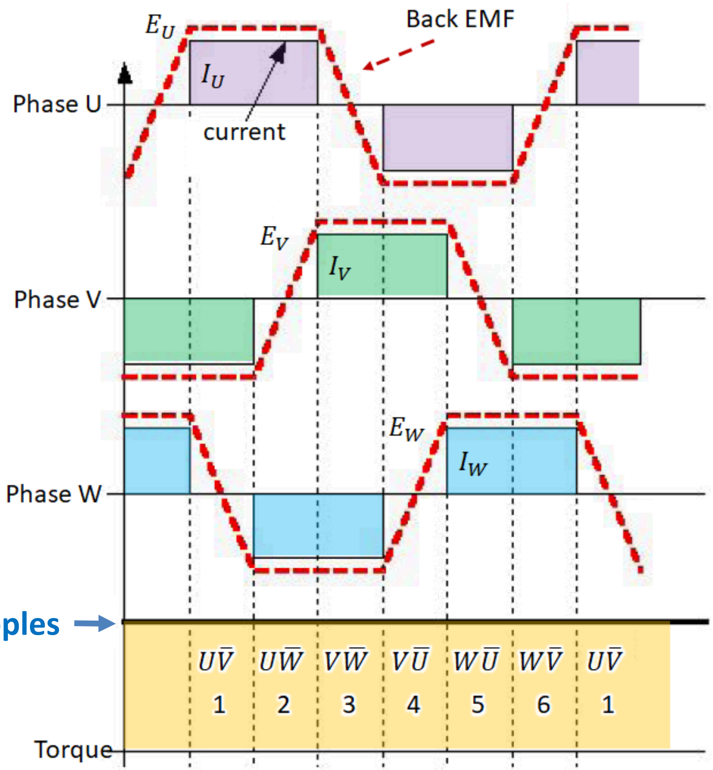
Trapezoidal Drive with Hall Sensors

120 Degree Excitation

$$T = \frac{E_U I_U + E_V I_V + E_W I_W}{\omega}$$

The torque generated by BLDC contain only **electromagnetic torque**. Another type of torque is **reluctance torque** which can be generated by PMSM.

In fact, mostly containing **Torque Ripples**



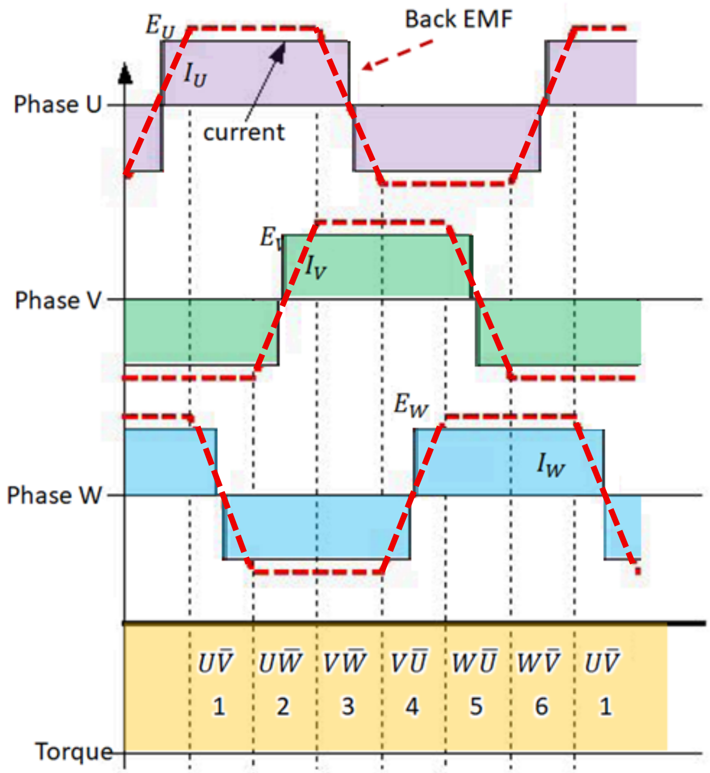
What about sinusoidal Back EMF?

Brushless DC Motor Principle

Trapezoidal Drive with Hall Sensors

180 Degree Excitation

$$T = \frac{E_U I_U + E_V I_V + E_W I_W}{\omega}$$



What about sinusoidal Back EMF?

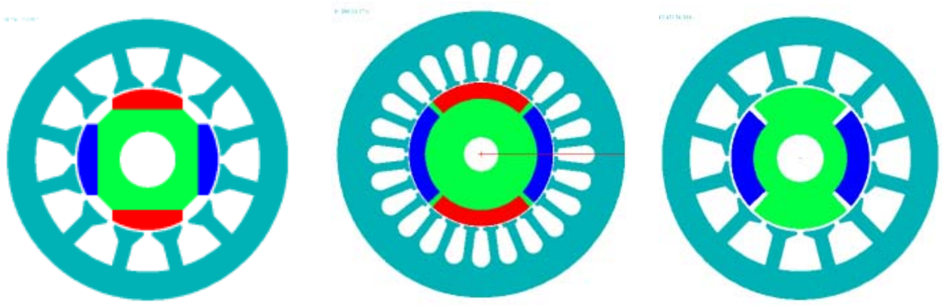
Brief Introduction of Permanent Magnet Synchronous Motor (PMSM)

Department of Electrical Engineering

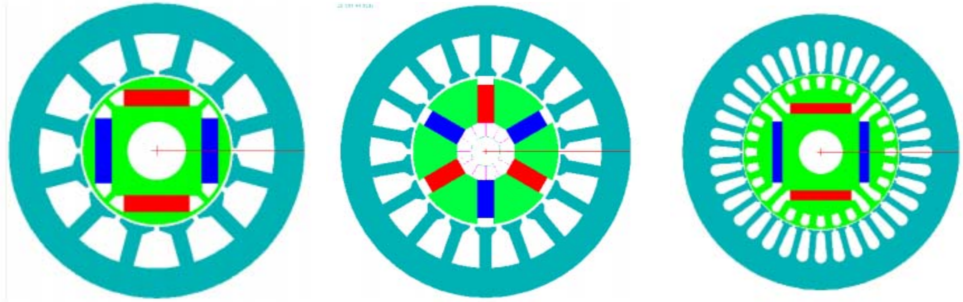
Types of PMSM

Base on configuration of permanent magnet in the rotor classified as:

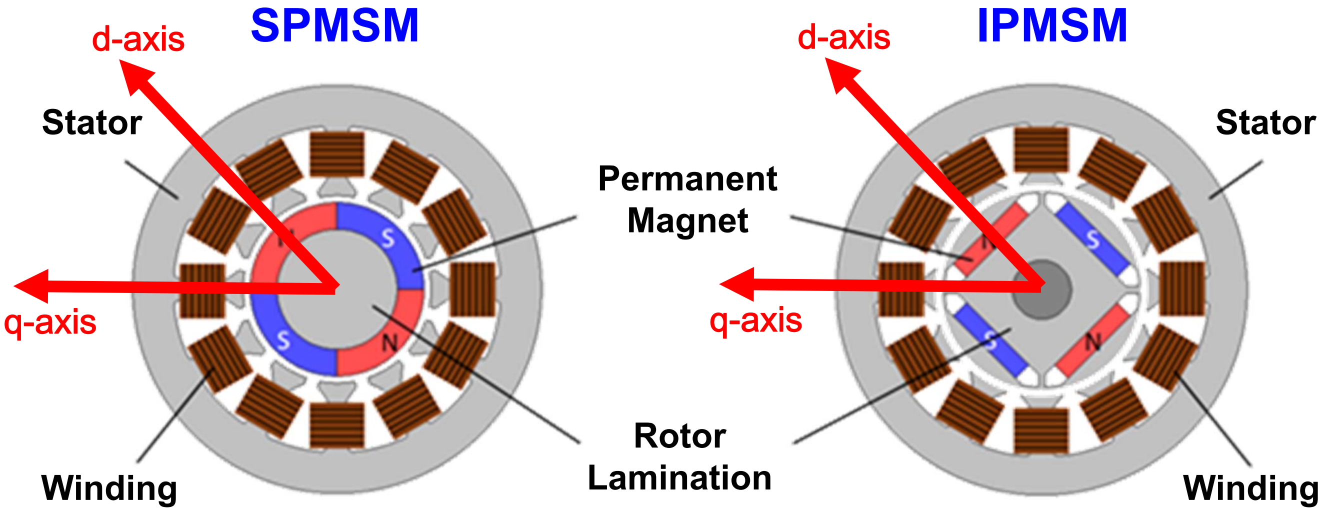
Surface Mounted PMSM (SPMSM)



Interior PMSM (IPMSM)



Comparison of PMSMs



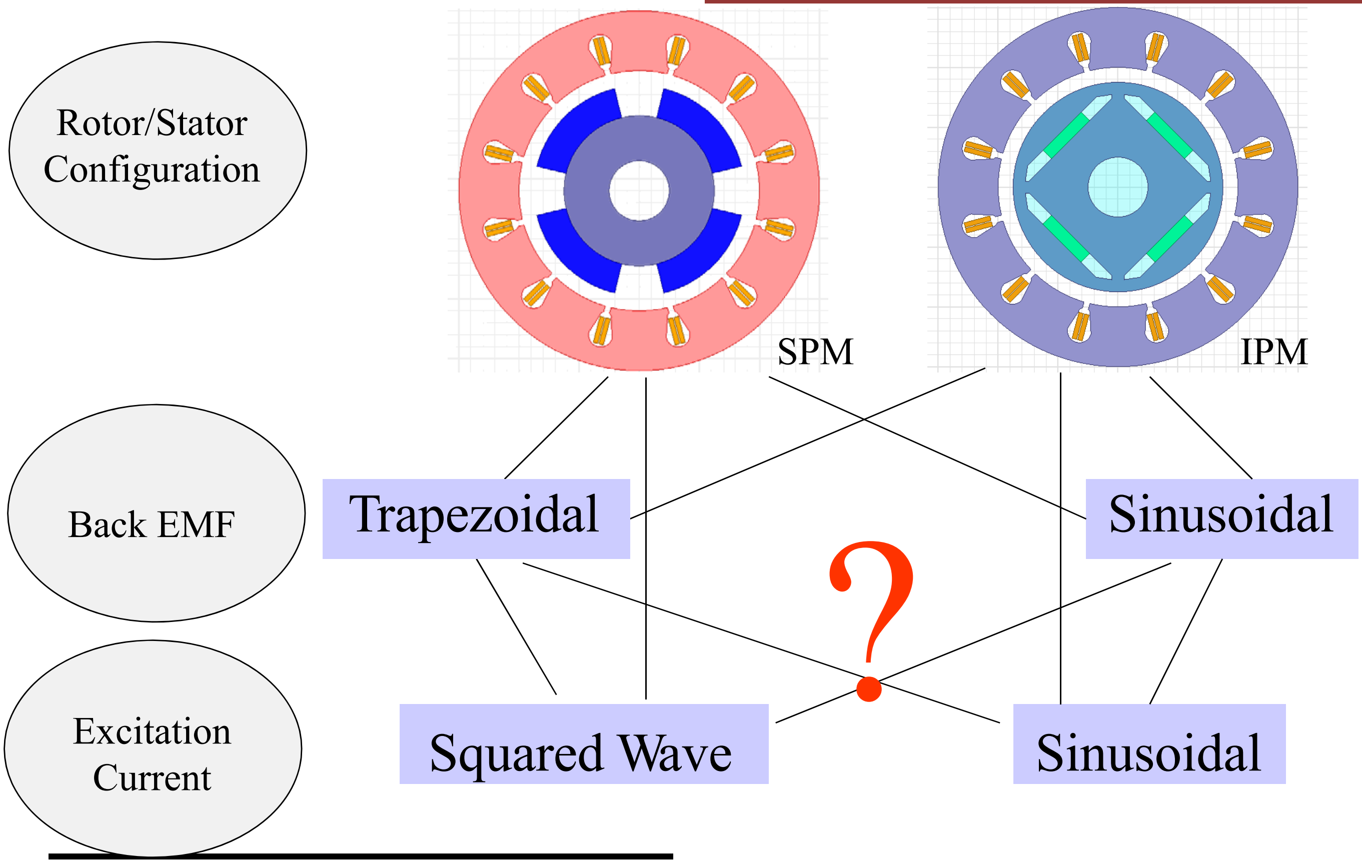
$\mathbf{Non - Salient:}\ \mathbf{L_d = L_q}$

$\mathbf{Salient:}\ \mathbf{L_d < L_q}$

Index :
L_d : d-axis inductance
L_q : q-axis inductance

S.-Y. Wang, "**High Power Factor Control for PMSM Drives Using Reduced DC-link Capacitance**," Master Thesis, National Cheng Kung University, 2018

How are SPM and IPM motors related to BLDCM or PMSM?



Traction Applications

Nissan Leaf 2018

235 miles electric range per charge (NEDC)
110 kW electric drive

Toyota Prius

1.8-Liter, 4-cylinder engine
71 kW electric drive

Tesla Model S

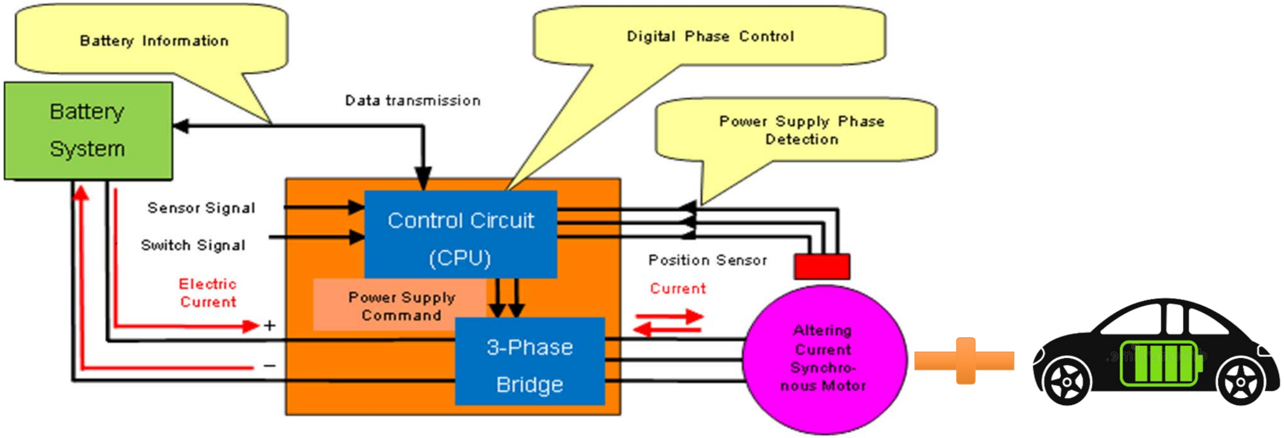
250 mile electric range
270 kW electric drive

Traction Applications

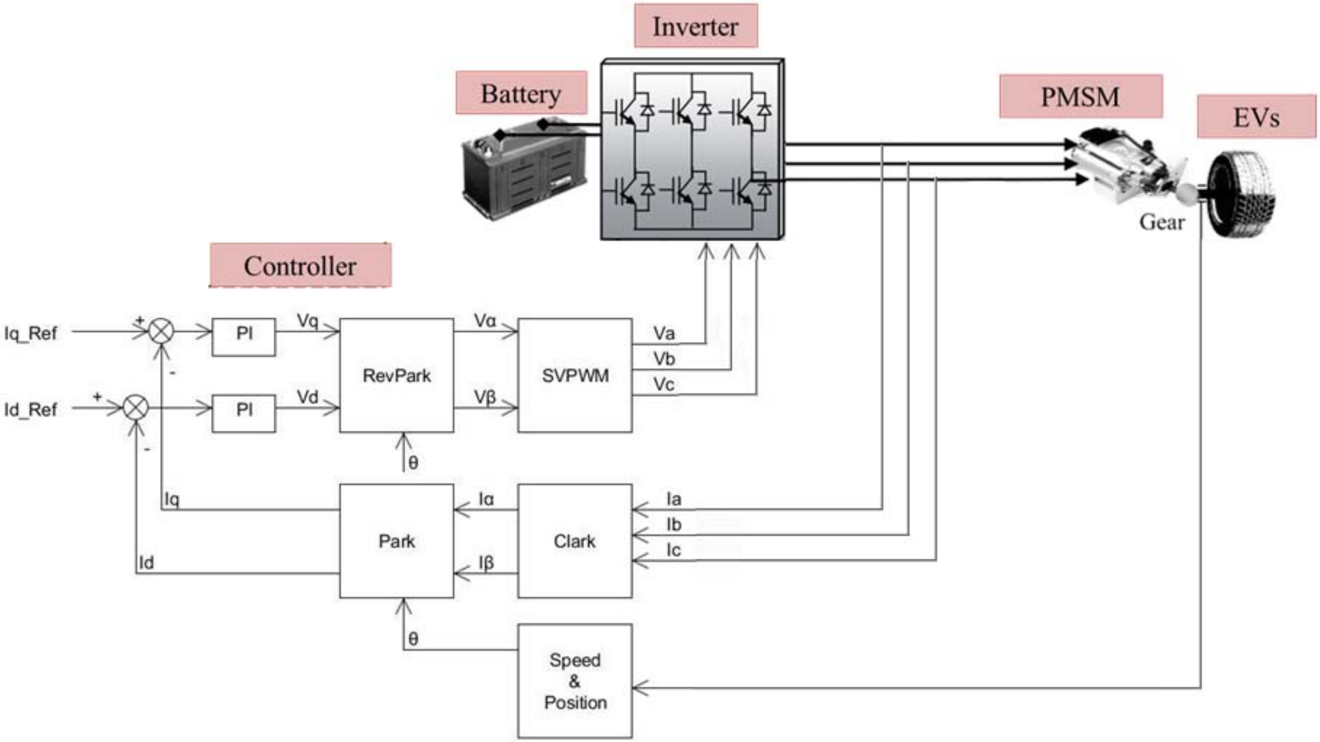
A Sampling of Interior Permanent Magnet (IPM) Rotors

https://cleantechnica.com/2018/05/28/more-tesla-model-3-powertrain-fun-from-carburetors-to-carborundum-youve-come-a-long-way-baby/

Traction Applications

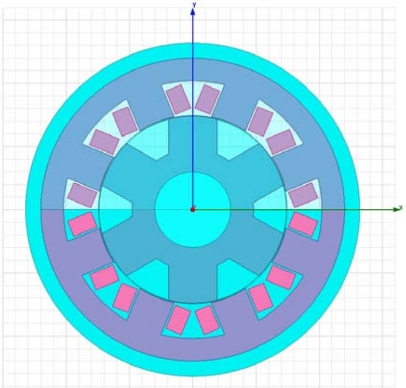


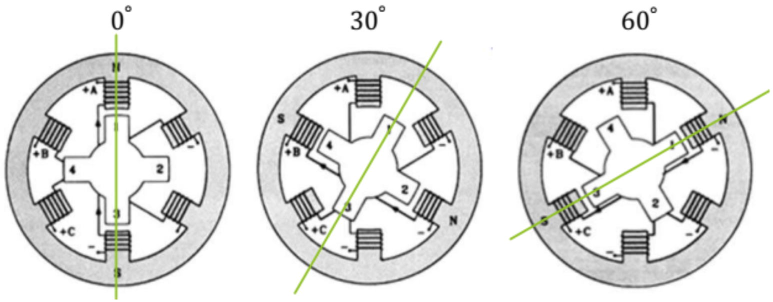
Traction Applications



Appendix:
Other Types of Electric Motors

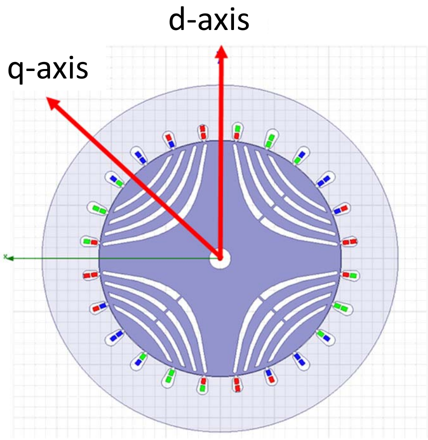
Switched Reluctance Machine (SRM)

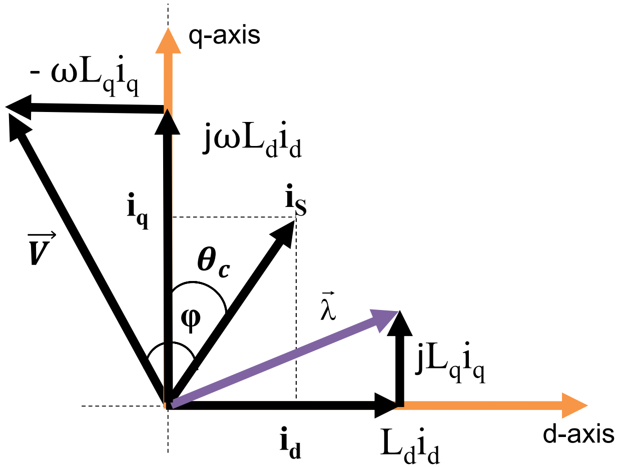




Cycle	Phase A	Phase B	Phase C	Position
1	ON	OFF	OFF	0
	OFF	ON	OFF	30
	OFF	OFF	ON	60
2	ON	OFF	OFF	90
	OFF	ON	OFF	120
	OFF	OFF	ON	150
3	ON	OFF	OFF	180

Synchronous Reluctance Machine (SynRM)





d-q axis flux linkages is defined as follows:

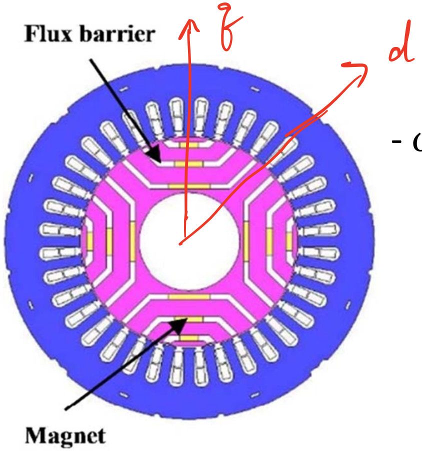
$$\lambda_d = L_d I_d \qquad \lambda_q = L_q I_q$$

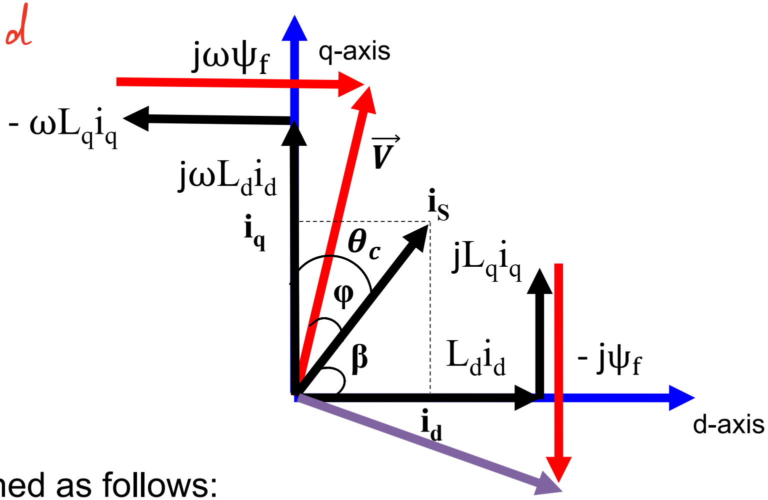
Motor electromagnetic torque of SynRM can be obtained as the following:

$$T_{e\_SynRM} = \frac{3}{2}\frac{p}{2}\left(\lambda_d I_q - \lambda_q I_d\right) = \frac{3p}{4}\left(\left(L_d - L_q\right) I_d I_q\right)$$

Assisted dq 定與 PMSM 不同

PM ~~Assistant~~-Synchronous Reluctance Machine (PMa-SynRM)





d-q axis flux linkages is defined as follows:

$$\lambda_d = L_d I_d \qquad \lambda_q = L_q I_q + \lambda_m$$

Motor electromagnetic torque of PMa-SynRM can be obtained as the following:

$$T_{e\_PMa-SynRM} = \frac{3}{2}\frac{p}{2}\left(\lambda_d I_q - \lambda_q I_d\right) = \frac{3p}{4}\left(L_d I_d I_q - \left(L_q I_q + \lambda_m\right) I_d\right) = \frac{3p}{4}\left(\left(L_d - L_q\right) I_d I_q - \lambda_m I_d\right)$$

$$\boxed{T_{e\_PMa-SynRM} = T_{e\_SynRM} + \frac{3p}{4}\left(-\lambda_m I_d\right) = T_{e\_SynRM} + T_{PM}}$$