Modern Electrical Drives: AC Motor Drives (EE6503, AY2019/20, S2)

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Books: Electric Motor Drives – Modeling, Analysis, and Control; R. Khrishnan, Prentice Hall, 2001

Schedules

25/02/2019	Topic 1	• Introduction and preliminary
10/03/2019	Topic 2	• Operation principle of asynchronous motor
17/03/2019	Topic 3	• Characteristics of asynchronous motor
24/03/2019	Topic 4	• Start-up & control of asynchronous motor
31/03/2019	Topic 5	• principle of rectifier and inverters and Quiz
07/04/2019	Topic 6	• Field-oriented control of Asynchronous motor
14/04/2019	Topic 7	• Synchronous motor and its control • Review the knowledge points of AC motor drives

Important Notes on Quiz

There will be **one** quiz for the AC motor drives part at 31/03/2020:

- Quiz (10 marks): Topics to be tested covered **topics 1 to 4**;
- To answer a few compulsory questions within **60 minutes**;
- It is a **closed-book** Quiz;
- Student much present **ID (with photo)** for taking attendance;
- Zero mark will be given for **absentees** without valid reasons;
- Absentees must write into the tutor through email within **THE SAME DAY OR EARLER** of Quiz to request a make-up (Failure to do so will result in a zero mark).

- Welcome to answer questions on the class
- Each answer to the question + 1 points
- The maximum is 5 points
- Please let me know your name and ID after the class

INTRODUCTION AND PRELIMINARY

[25/02/2020]

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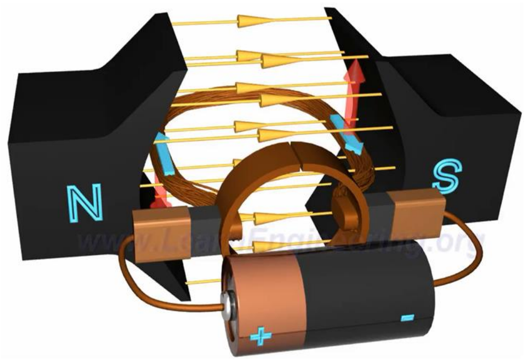
- Why we need to learn AC motor and its control?
- Recall right-hand rule and left-hand rule
- Recall transformer

INTRODUCTION AND PRELIMINARY

[25/02/2020]

- Why we need to learn AC motor and its control?
- Recall right-hand rule and left-hand rule
- Recall transformer

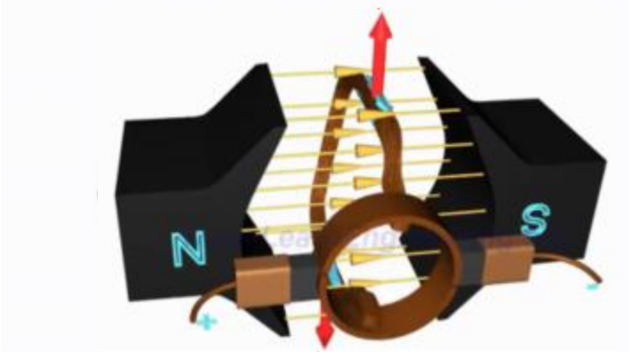
Recall: Structure of the DC motor



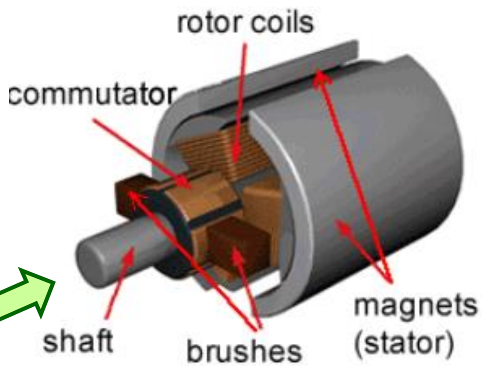
DC voltage → DC motor

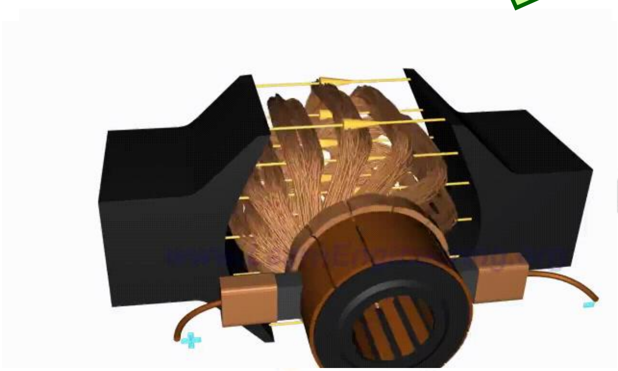
Problem

Torque ≈ 0

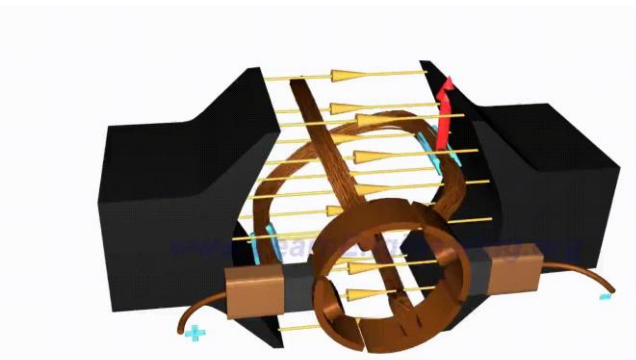


Two windings & commutators



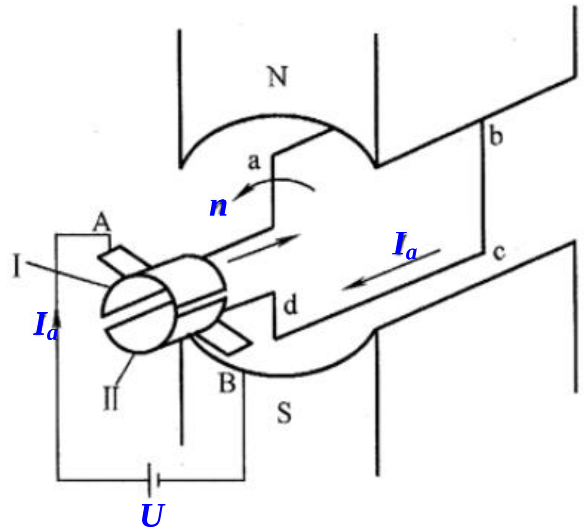


More windings & commutators



Recall: Speed of the DC motor

Simplified DC motor structure:



DC Motor speed n:

$$n \approx \frac{U - I_a \cdot R_a}{K\phi}$$

U: External voltage

I_a: Armature winding current

R_a: Armature winding resistor

ϕ: Magnetic flux

K: Flux index of the DC motor*

- n is proportion to U
- n is inversely proportion to I_a, R_a, ϕ and K*

*K is only determined by the physical structure of the DC motor and cannot be changed

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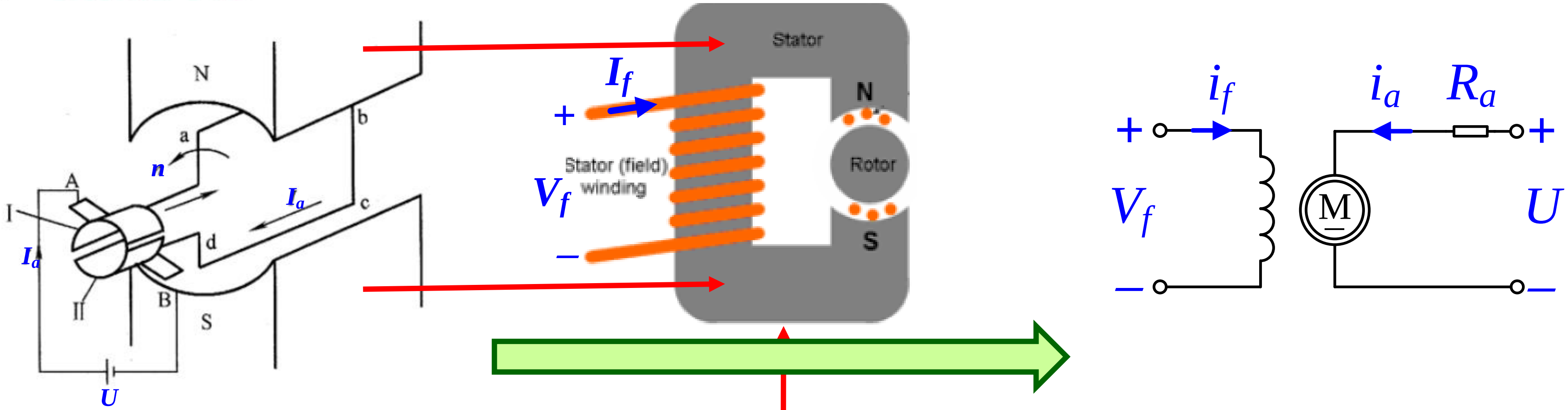
Recall: Speed Control of the DC motor



DC Motor speed n:

$$n \approx \frac{U - I_a \cdot R_a}{K\phi}$$

U: External voltage

I_a: Armature winding current

R_a: Armature winding resistor

ϕ: Magnetic flux

K: Flux index of the DC motor

- n is proportional to U
- n is inversely proportional to I_a, R_a, ϕ

$\phi \propto I_f \,\&\, V_f$

Speed control methods of the DC Motor:

- Regulate U
- Regulate R_a
- Regulate I_f or V_f to regulate ϕ

Straightforward
Easy to control

Application of the DC motor (small power)

Fan

Toy car

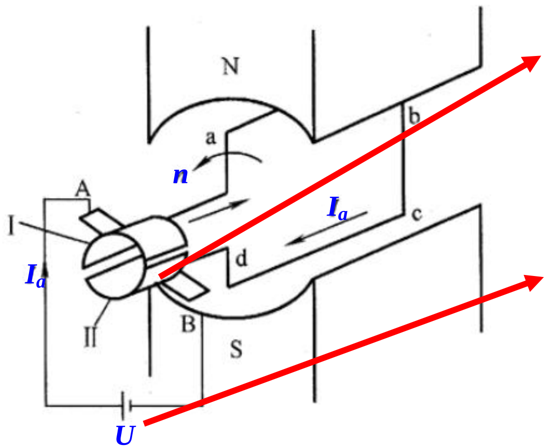
Drones

Hair dryer

Kitchen ventilator

Battery bicycle

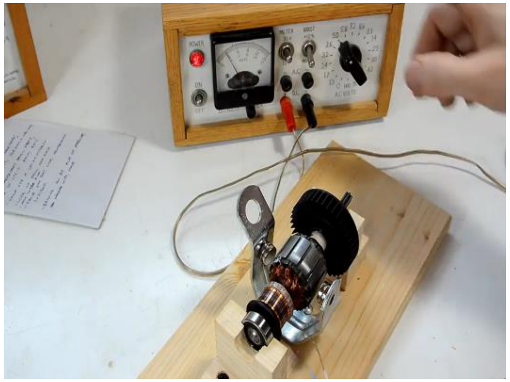
Drawbacks of the DC motor

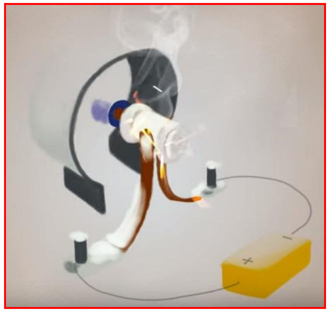


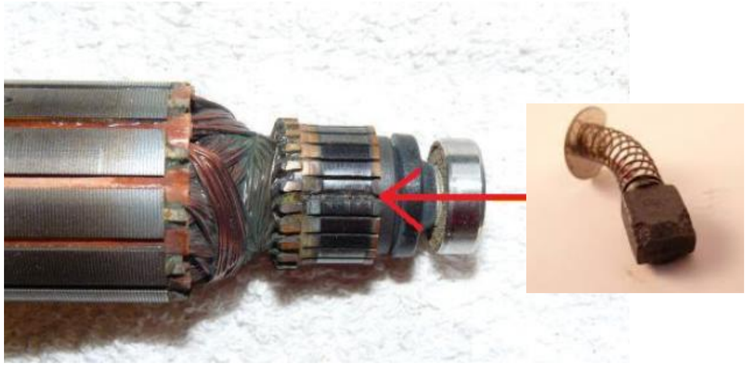
- The use of Brush DC motor could cause the maintenance problem and limits the power-rating and life-time of the DC motor
- Need DC voltage, however our real grid is AC voltage, for instance, 230V AC / 50 Hz at Singapore. So a special DC power supply is needed for DC motor.

Real DC motor speed control
(need DC power supply)

Damaged DC motor carbon brush







- Maximum power of DC motor is 500 kW @ rotate speed = 3000 rad/min
- Carbon brush need to be changed if it works more than 2000 hours.

DC motor is not suitable for the large power application

Electrical vehicle

Mining machinery

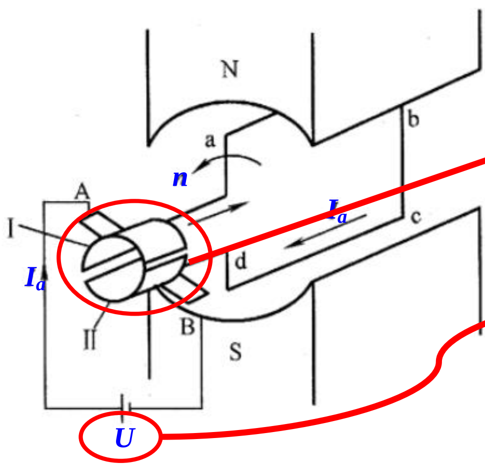
Draught fan

Washing machine

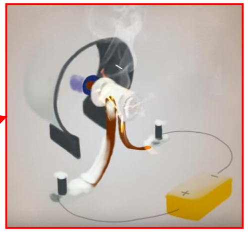
Machine tools

Why AC motor?

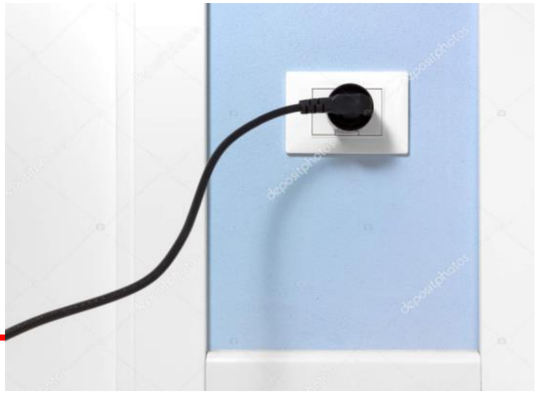
Recall: DC motor limitations



Brush is easy broken

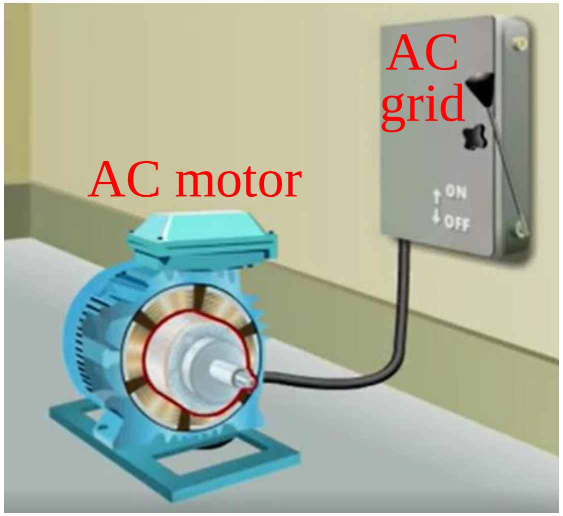


DC power supply



Motivation of AC motor:

Connect to the three phase grid directly



- Utilize the AC grid directly
- No brush in the AC motor

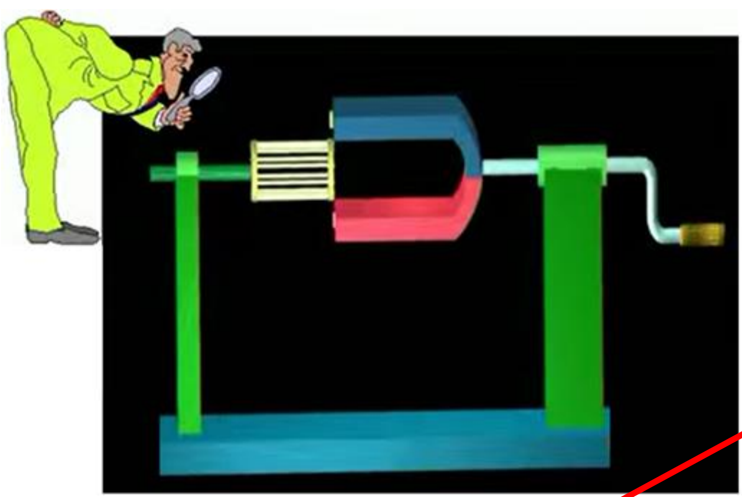
Application of the AC motor

There is no power limit for the AC motor application

Need speed control

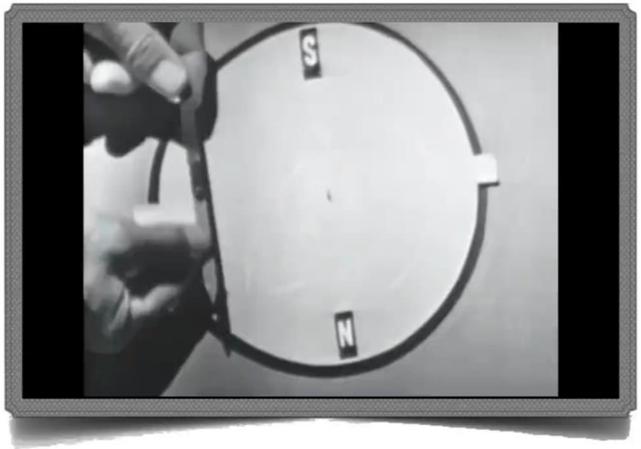
AC vs DC Current War_Nikola Tesla vs Thomas Edison

Key technique support of the AC motor



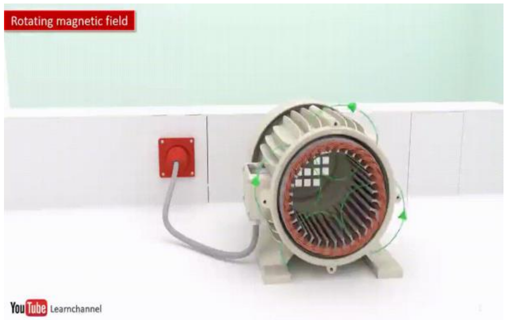
If the horseshoe magnetic core rotates, what will happen to the cage winding?

The cage rotor will follow the rotation of the horseshoe magnetic field.



How to generate the rotated magnetic field automatically instead of using hand?

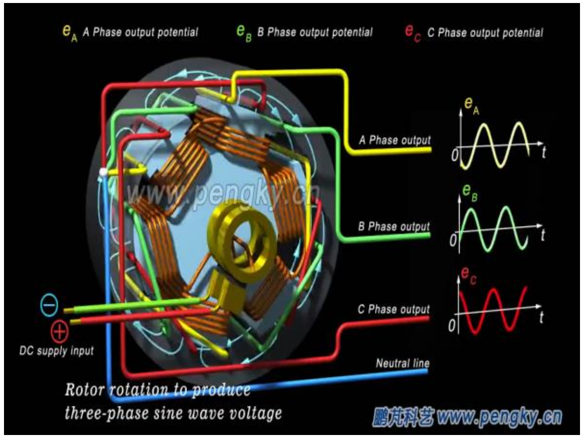
AC grid+winding can generate the rotated field!



Glimpse of the AC motor basic operation principle

Rotated magnetic field by AC grid

Rotated rotor



Basic operation principle of the AC motor:

AC grid generate rotated magnetic field

⇩

Rotor follows the rotated magnetic field

⇩

AC motor works

- Utilize AC grid directly
- No brush

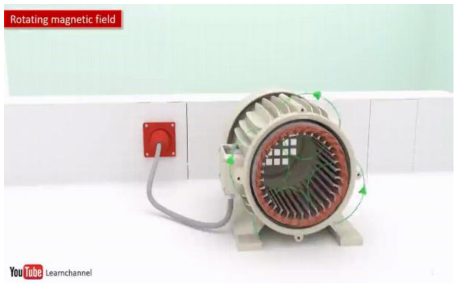
AC rotor works

Classification of the AC motor

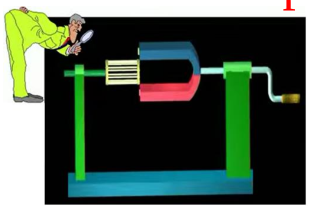
There are two types of speed in an AC motor:

a) speed of the rotated magnetic field n_s; b) speed of the rotor n_r.

n_s



Relationship



n_r

AC motor

Asynchronous AC motor (Induction motor):
AC motor whose $n_r \neq n_s$

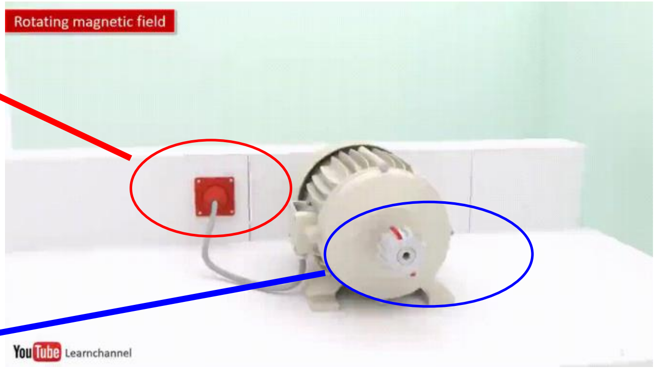
Synchronous AC motor:
AC motor whose $n_r = n_s$

What we will learn in the AC motor part?

Grid voltage is constant, i.e., 230 V 50Hz AC

How to realize the speed control?

Rotor speed need to be changeable according to different Application



- Asynchronous AC motor:
  - Structure and operation principle
  - Speed control methods
- Key technology of AC motor speed control: inverters
- Synchronous AC motor:
  - Structure and operation principle
  - Speed control methods

Can DIY

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INTRODUCTION AND PRELIMINARY

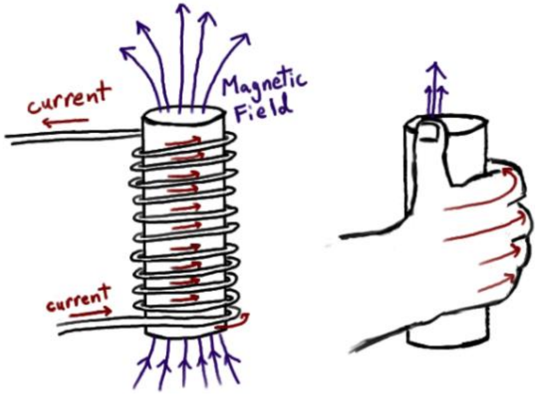
[25/02/2020]

- Why we need to learn AC motor and its control?
- Recall right-hand rule and left-hand rule
- Recall transformer

Right Hand Rule I: simply shows how a current-carrying wire generates a magnetic field.

- If you point your thumb in the direction of the current, as shown, and let your fingers assume a curved position, the magnetic field circling around those wires flows in the direction in which your four fingers point.

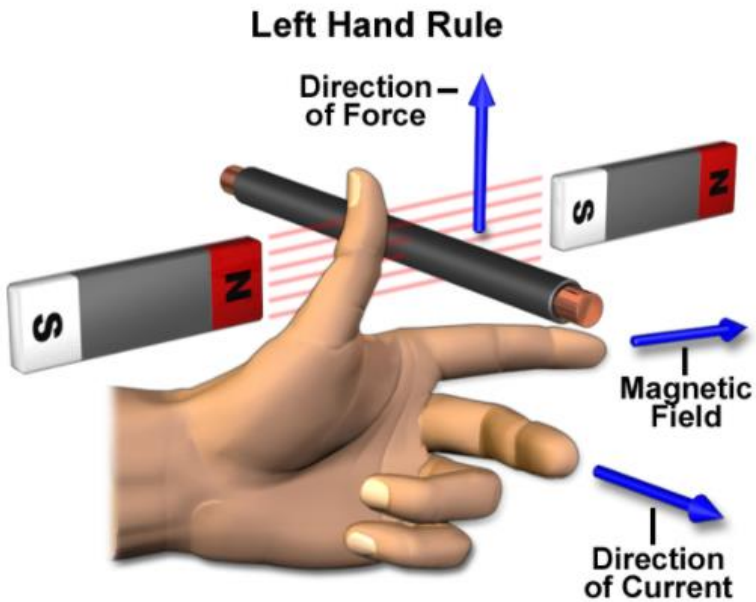
Ampere

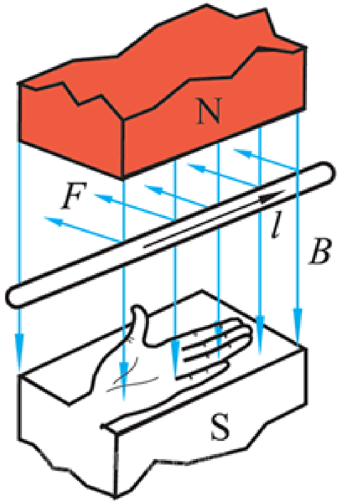


Right Hand Rule II: Determine the direction of the magnetic field of an electro-magnet constructed by wrapping current carrying wire around an iron core.

- Magnetic field direction is in the same direction as the thumb when the right hand is wrapped around the core with the fingers pointing along the direction of the electric current.

Left hand rule



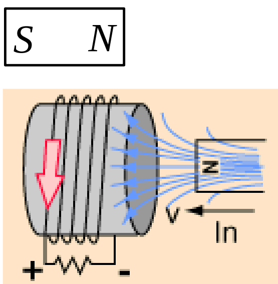


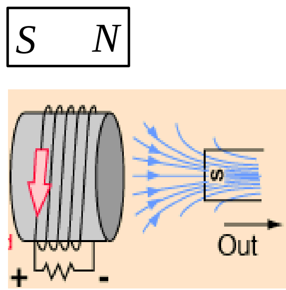
John Ambrose Fleming

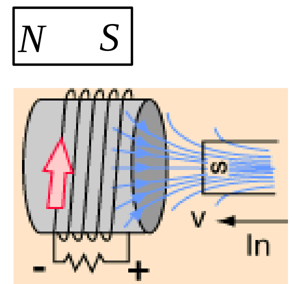
Left Hand Rule: shows what happens when charged particles (such as electrons in a current) enter a magnetic field. You need to contort your left hand in an unnatural position for this rule, illustrated below:

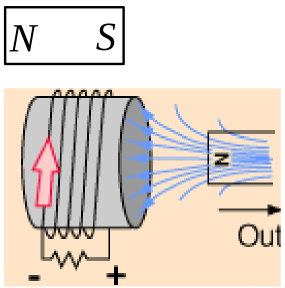
- Your index finger points in the direction of a magnetic field;
- Your middle finger, at a 90 degree angle to your index, points in the direction of the charged particle (as in an electrical current);
- Your extended thumb (forming an L with your index) points in the direction of the force exerted upon that particle.

Lenz's Law: the direction of the induced current is such that it opposes the change that causes it.





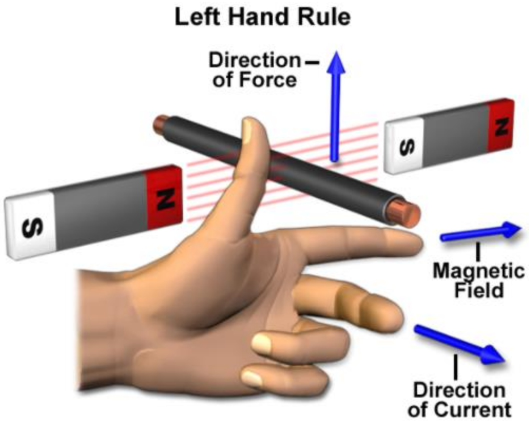


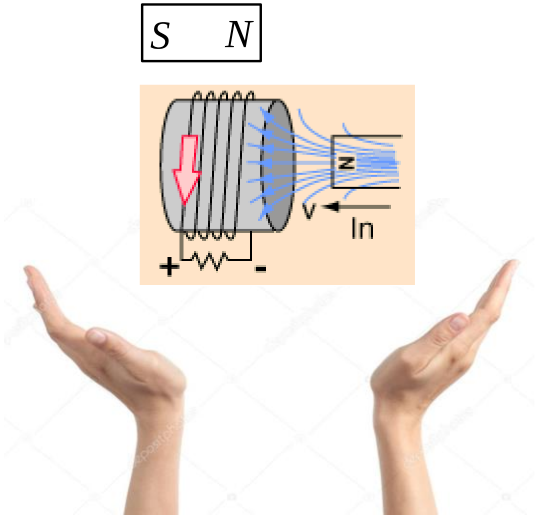


'If you push a wire through a field the induced current makes a force that pushes back'

'If a field is pointing one way and a conductor moves through it, then the induced current makes a field that points the opposite way'


Right Hand Rule
Thumb Points in Direction of Current Flow
Fingers Point in Direction of Magnetic Field
Current-Carrying Wire


Left Hand Rule
Direction of Force
S
N
Magnetic Field
Direction of Current


S N
N
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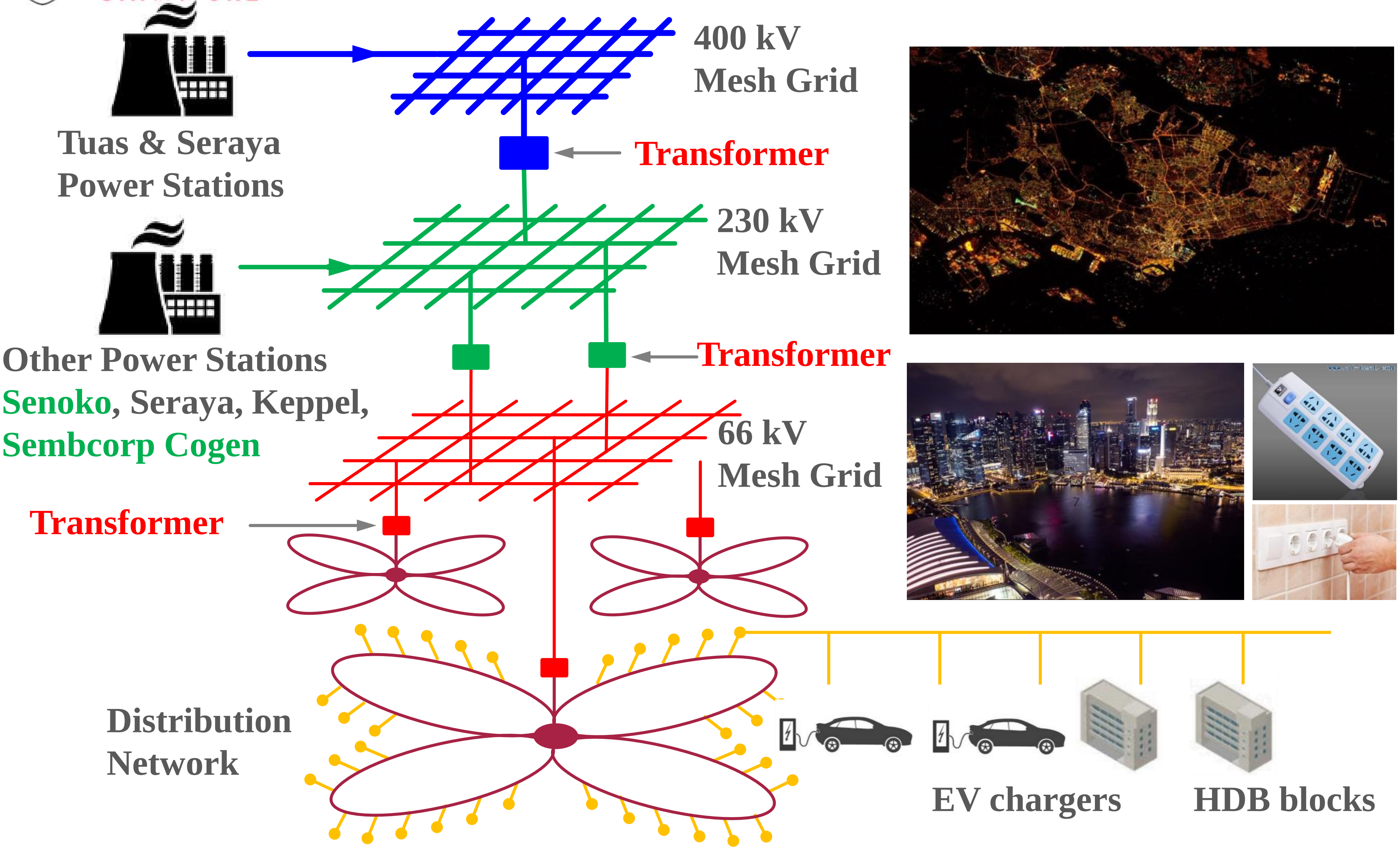
INTRODUCTION AND PRELIMINARY

[25/02/2019]

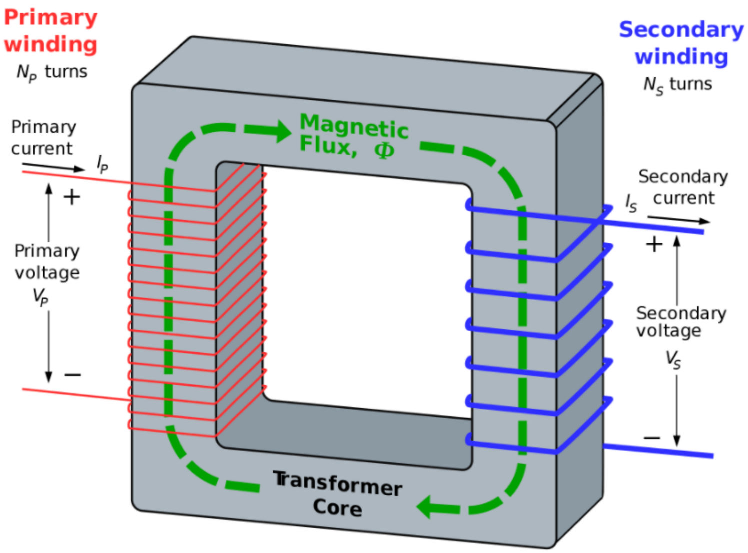
- Why we need to learn AC motor and its control?
- Recall right-hand rule and left-hand rule
- Recall transformer

Applications of transformer in the real life

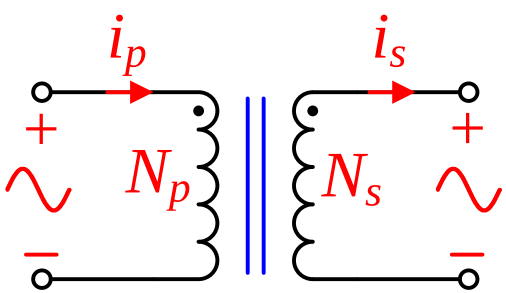


What is the transformer?

Basic transformer:

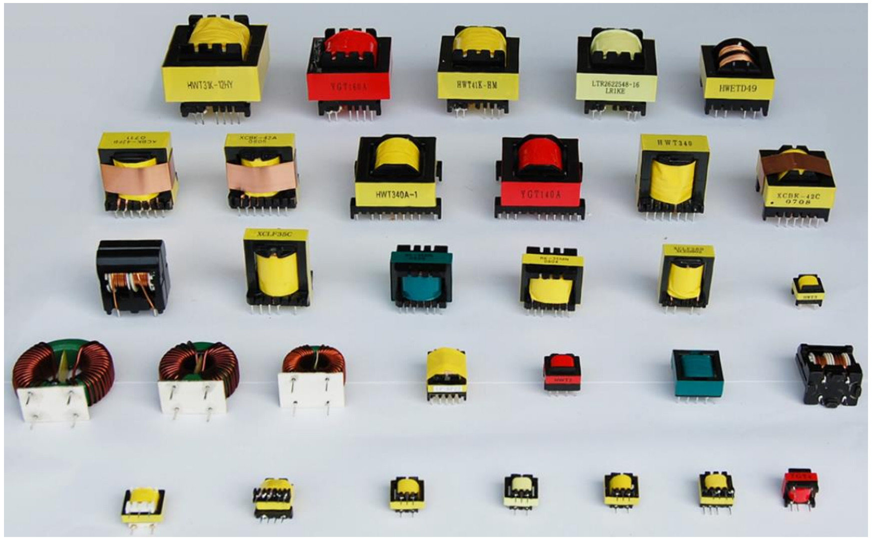


Symbol of the transformer:



Transformer is an electrical device that transfers AC electrical energy between two or more circuits through electromagnetic induction.

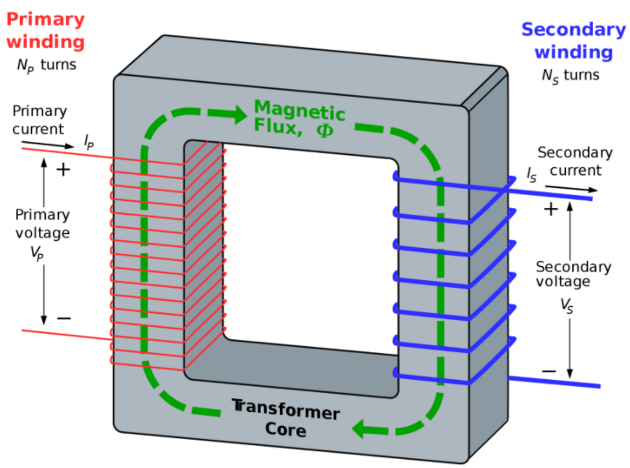
- A varying current in one coil of the transformer produces a varying magnetic field, which in turn induces a voltage in a second coil.
- AC Power can be transferred between the two coils through the magnetic field, without a metallic connection between the two circuits.

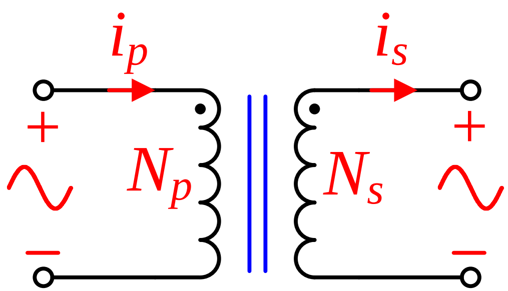


Why we recall the transformer before learning AC motor?

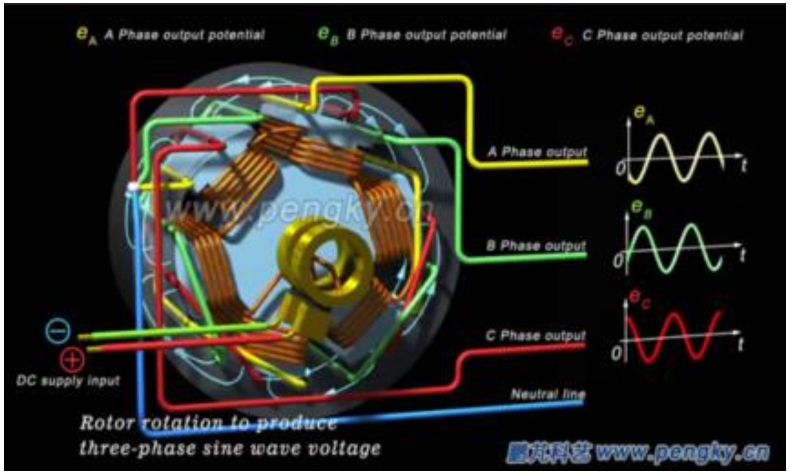
AC motor is essentially a rotated three phase transformer

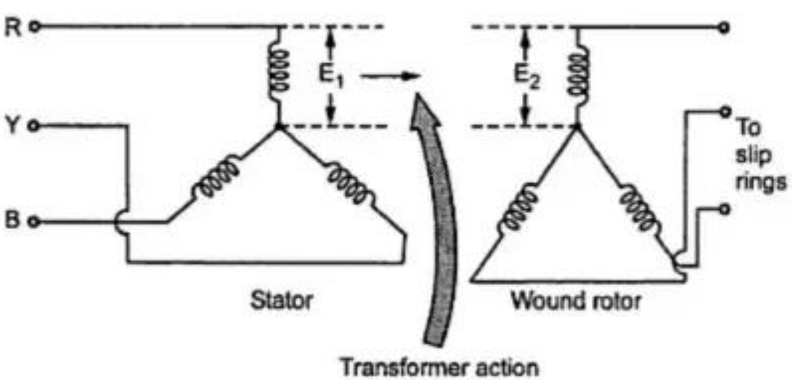
Basic transformer



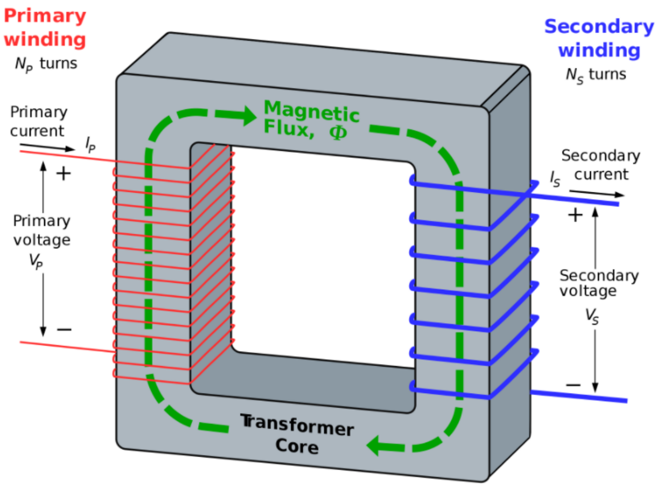


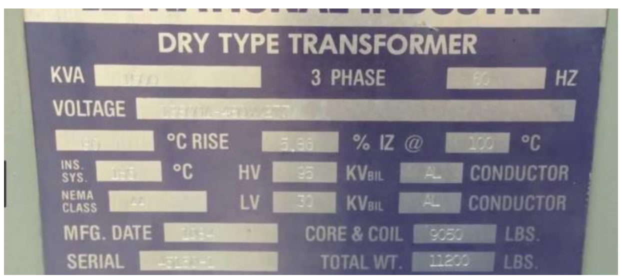
Basic AC motor





Main parameters of the transformer





- Rated capacity S_N

The maximum power transmission capacity of the transformer

$$S_N = U_{PN} I_{PN} = U_{SN} I_{SN}$$

- Rated primary voltage U_{PN}

The permitted normal voltage on the primary winding of the transformer when its secondary winding is open circuit.

- Rated primary current I_{PN}

The permitted normal current on the primary winding of the transformer when its operates at full load.

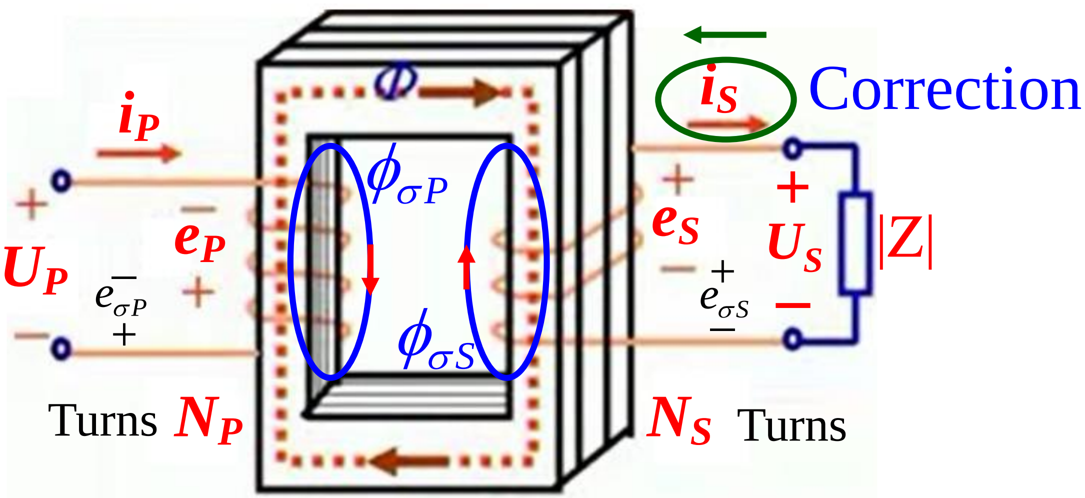
- Rated secondary voltage U_{SN}

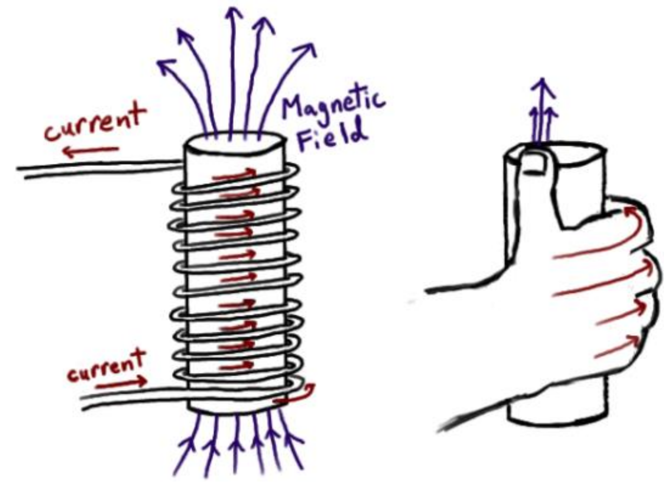
The permitted normal voltage on the secondary winding of the transformer when its secondary winding is open circuit.

- Rated secondary current I_{SN}

The permitted normal current on the secondary winding of the transformer when it operates at full load.

Operation principle of the transformer: Electromagnetic relationship





$U_P \Rightarrow i_P \xRightarrow{\phi \propto i_P N_P} \phi$

$\phi \Rightarrow e_P = -N_P \dfrac{d\phi}{dt}$

$\phi \Rightarrow e_s = -N_S \dfrac{d\phi}{dt}$

$i_P \Rightarrow \phi_{\sigma P} \Rightarrow e_{\sigma P} = -N_P \dfrac{d\phi_{\sigma P}}{dt}$

$e_s \Rightarrow i_S \Rightarrow \phi_{\sigma S} \Rightarrow e_{\sigma S} = -N_S \dfrac{d\phi_{\sigma S}}{dt}$

$i_S \Rightarrow \phi$: Hiders the flux

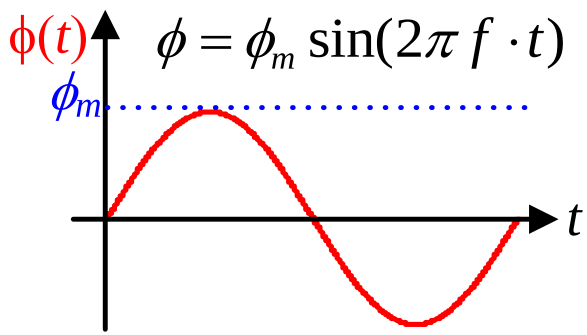
- The final flux ϕ is determined by the primary and secondary coils together.
- Demagnetization each other.

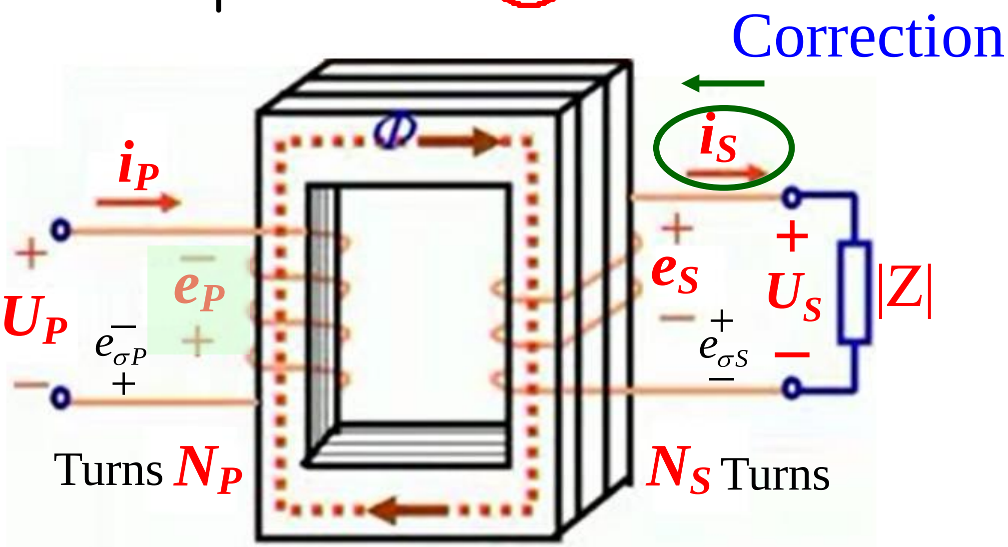
Operation principle of the transformer: Expression of E_p

Definition: e_P: Primary side electromotive force E_P: Root mean square (RMS) of e_p

Flux is changed by sinusoidal form:

$$\phi = \phi_m \sin(2\pi f \cdot t)$$





$$e_P = -N_P \frac{d\phi(t)}{dt}$$

$$\Downarrow$$

$$e_P = -N_P \frac{d\phi_m \cdot \sin(2\pi f \cdot t)}{dt}$$

$$\Downarrow$$

$$e_P = -2\pi f N_P \phi_m \cdot \cos(2\pi f \cdot t)$$

$$\Downarrow$$

$$e_P = -\sqrt{2} \cdot \underbrace{\sqrt{2}\pi f N_P \phi_m}_{E_P} \cdot \cos(2\pi f \cdot t)$$

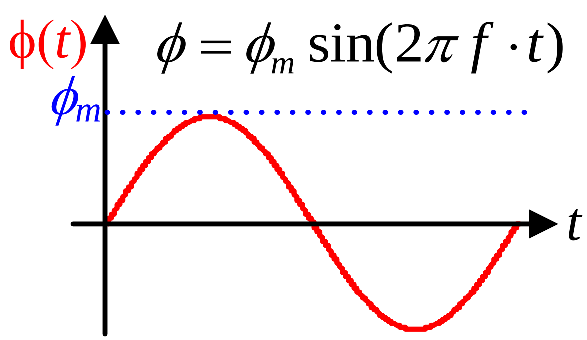
$$\Downarrow$$

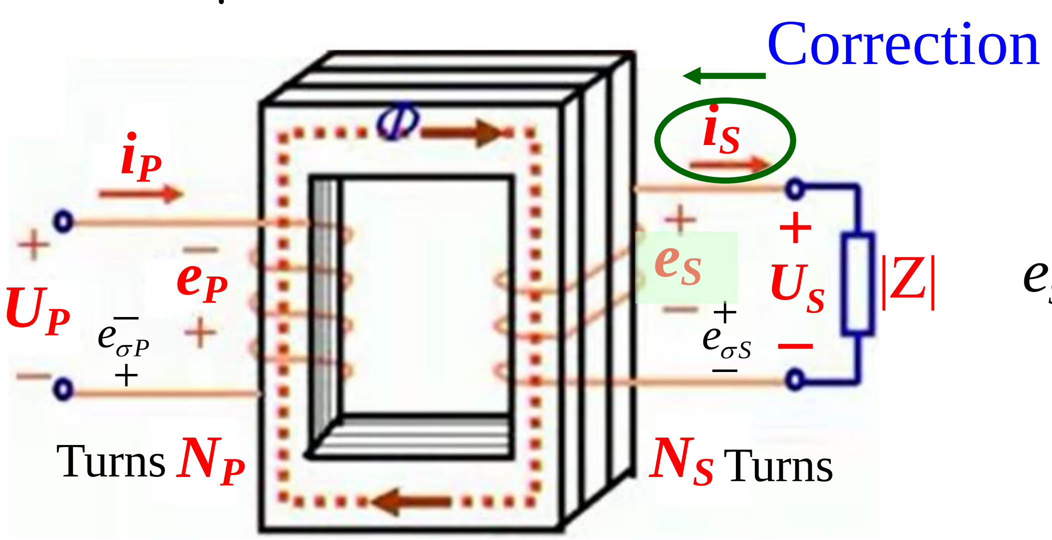
$$E_P = \sqrt{2}\pi f N_P \phi_m \approx 4.44 \cdot f N_P \phi_m$$

Operation principle of the transformer: Expressions of E_S

Definition: e_S: Secondary side electromotive force E_S: Root mean square (RMS) of e_S

Flux is changed by sinusoidal form:





$$e_S = -N_S \frac{d\phi(t)}{dt}$$

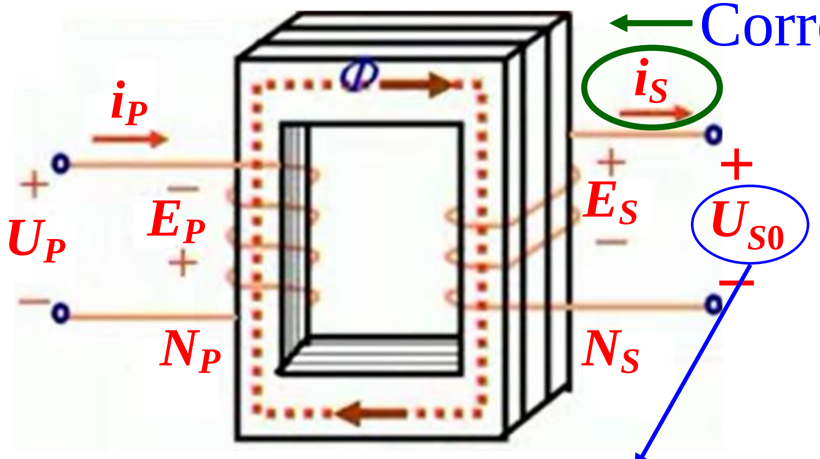
$$e_S = -N_S \frac{d\phi_m \cdot \sin(2\pi f \cdot t)}{dt}$$

$$e_S = -2\pi f N_S \phi_m \cdot \cos(2\pi f \cdot t)$$

$$e_S = -\sqrt{2} \cdot \underbrace{\sqrt{2}\pi f N_S \phi_m}_{E_S} \cdot \cos(2\pi f \cdot t)$$

$$E_S = \sqrt{2}\pi f N_S \phi_m \approx 4.44 \cdot f \cdot N_S \phi_m$$

Operation principle of the transformer: Voltage and current conversion of the transformer



U_{S0} is U_S at no load case

Voltage conversion of the transformer:

$$e_P \approx 4.44 \cdot f \cdot N_P \phi$$

$$e_S \approx 4.44 \cdot f \cdot N_S \phi$$

$$u_P \approx e_P$$

$$u_{S0} \approx e_S$$

$$\boxed{\frac{u_P}{u_{S0}} \approx \frac{e_P}{e_S} = \frac{4.44 \cdot f \cdot N_P \cdot \phi_m}{4.44 \cdot f \cdot N_S \cdot \phi_m} = \frac{N_P}{N_S} = K}$$

K: Turn ratio of the transformer

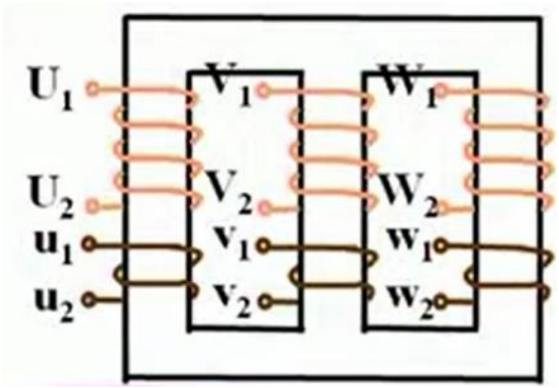
Current conversion of the transformer:

Ampere-turns balance:

$$i_P N_P = i_S N_S$$

$$\boxed{\frac{i_P}{i_S} = \frac{N_S}{N_P} = \frac{1}{K}}$$

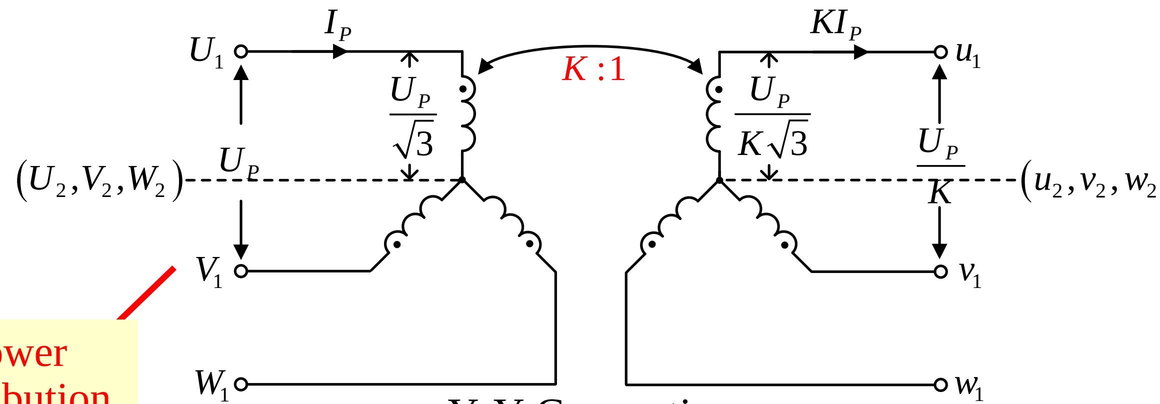
Three phase transformer



Power distribution cabinet

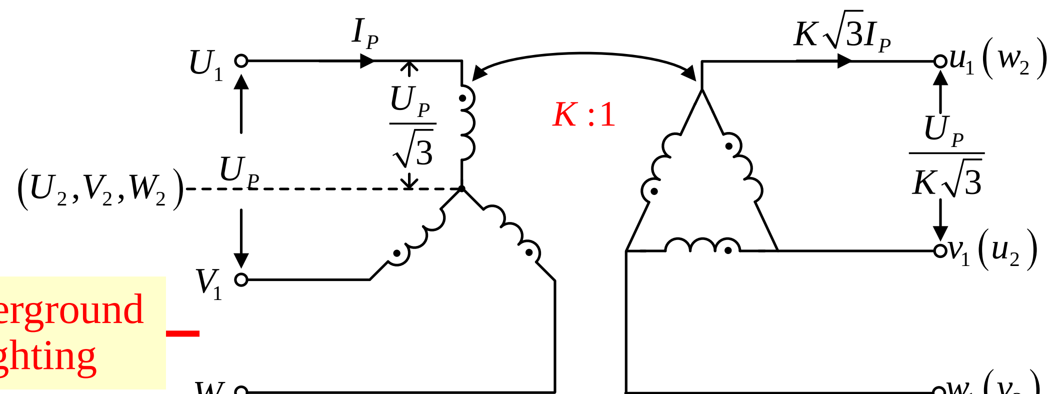
Underground lighting

Y-Y Connection



Y-Y Connection

Δ-Y Connection



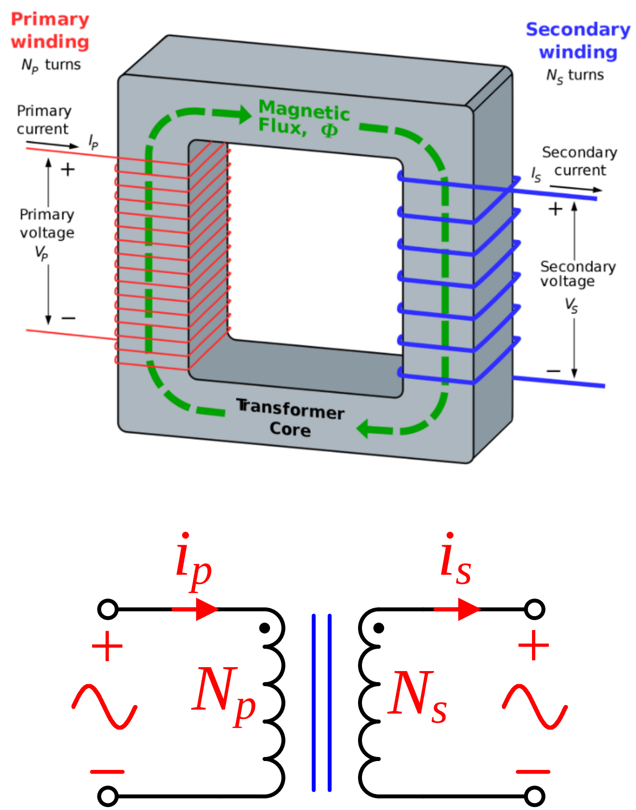
Δ-Y Connection

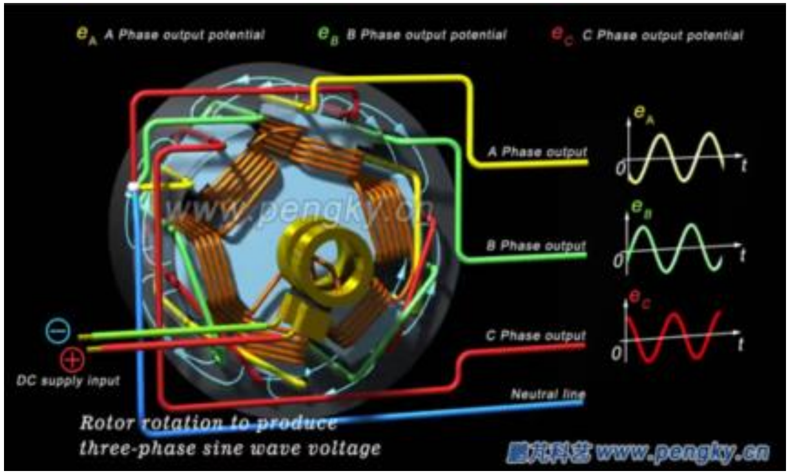
AC motor is essentially a rotated three phase transformer

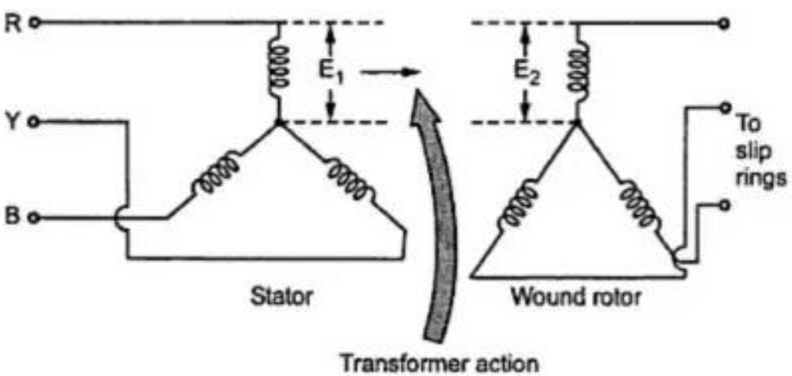
AC motor is essentially a rotated three phase transformer

Basic transformer

Basic AC motor







Oldest transformer (20,000 years before)?

Review of today's topic

- DC motor need DC power supply and brush, as a result, it is inconvenient and not suitable for large power application.
- AC motor is driven by AC power, which can use the grid voltage directly.
- AC motor does not need the brush and do not have power limitation.
- AC motor can be divided into asynchronous motor and synchronous motor.
- Please recall left-hand and right-hand rules to understand the relationship among the current, magnetic field and force.
- AC motor is essential a rotated three phase transformer.
- Please recall the operation principle of the three phase transformer.

INTRODUCTION AND PRELIMINARY

[25/02/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

END OF TOPIC

OPERATION PRINCIPLE OF ASYNCHRONOUS MOTOR

[10/03/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

- Structure of the asynchronous motor
- Operation principle of the asynchronous motor
- Key parameters of the asynchronous motor

OPERATION PRINCIPLE OF ASYNCHRONOUS MOTOR

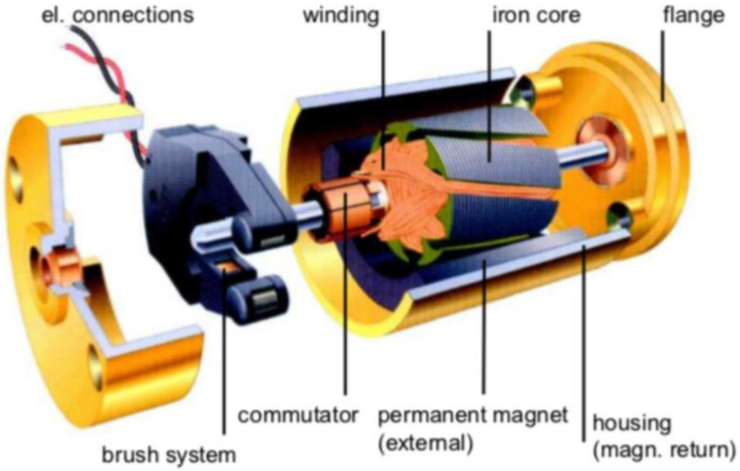
[10/03/2020]

- Structure of the asynchronous motor
- Operation principle of the asynchronous motor
- Key parameters of the asynchronous motor

Please point out the DC motor

Asynchronous motor

Synchronous motor

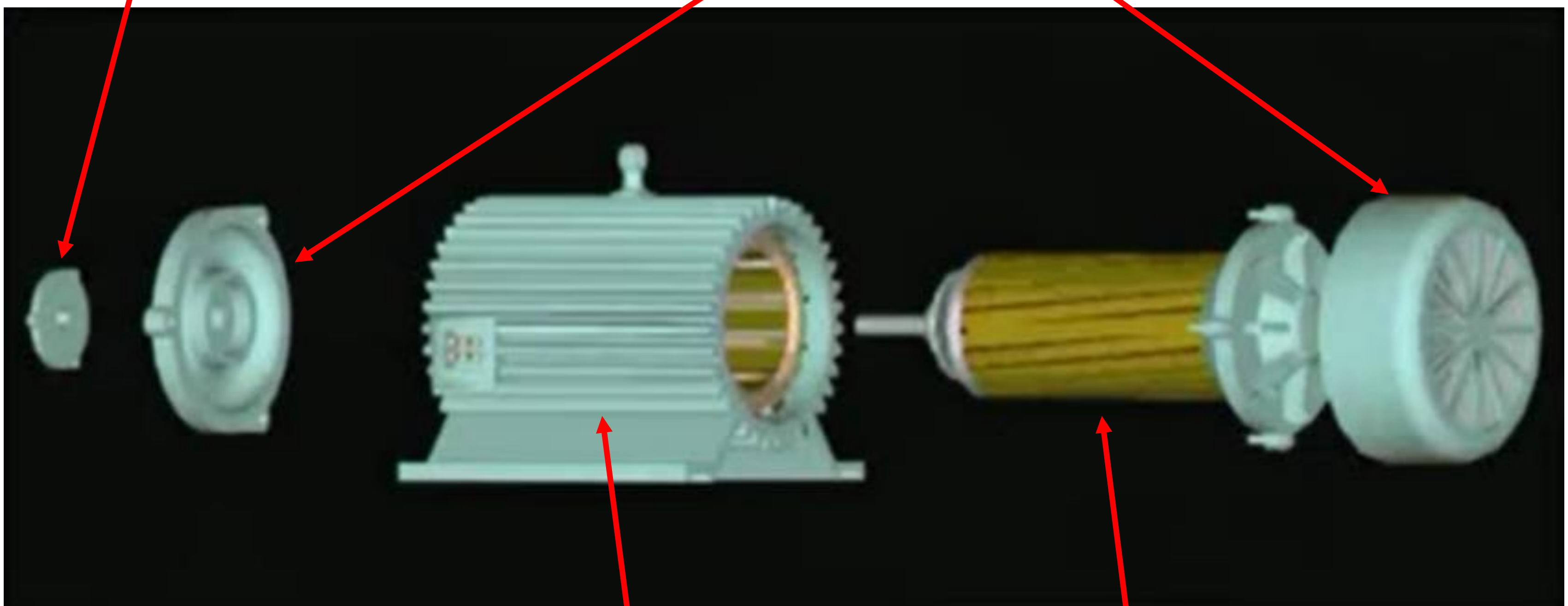


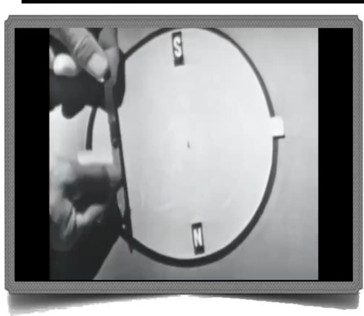
DC motor

Overview of the structure of the AC asynchronous motor

Bearing cap

End Bell





Stator

Rotor

Cage rotor

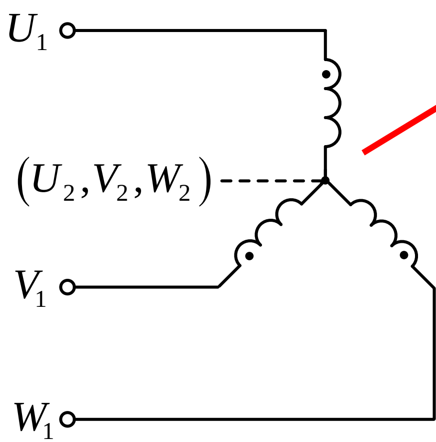
Wound rotor

Main parts

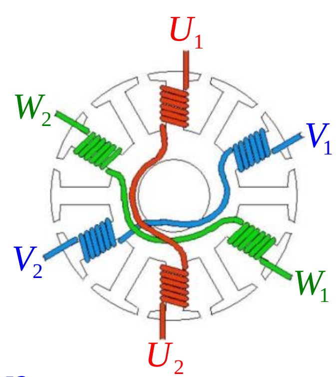
Structure of Stator

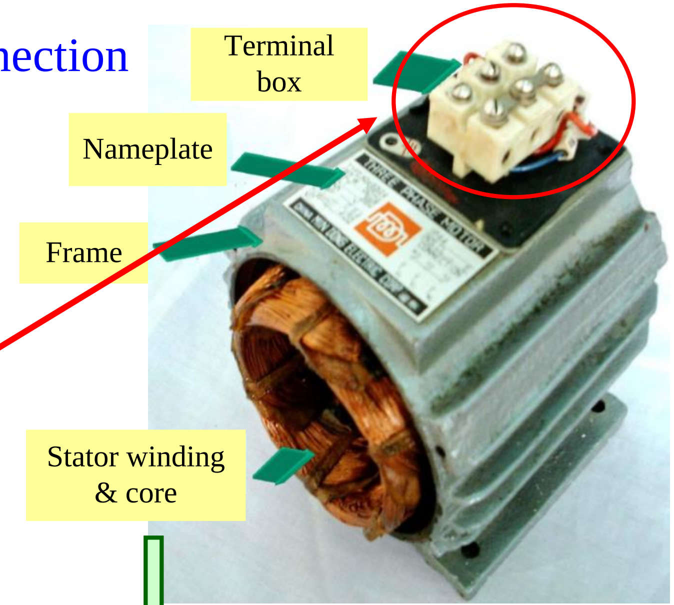
Y connection or Δ connection

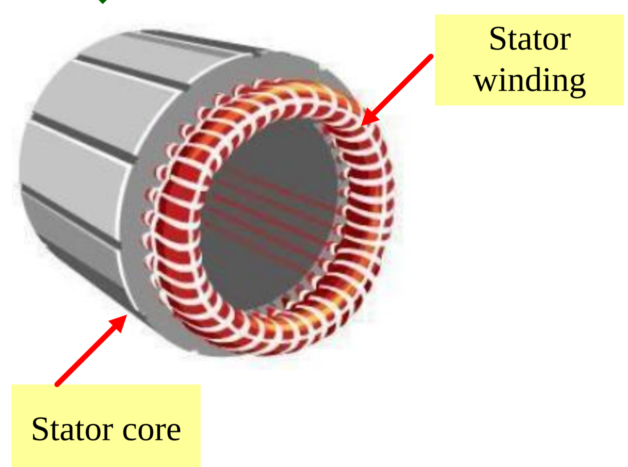
- Stator core: stacked with silicon steel with inner slots (ring magnet)
- Stator winding:



$$\boxed{\begin{array}{l} U_1 \rightarrow U_2 \\ V_1 \rightarrow V_2 \\ W_1 \rightarrow W_2 \end{array}}$$

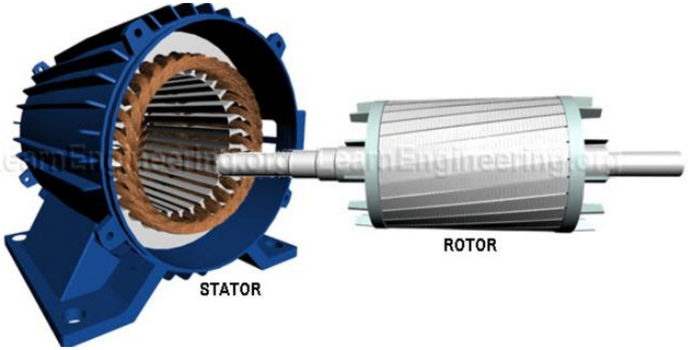






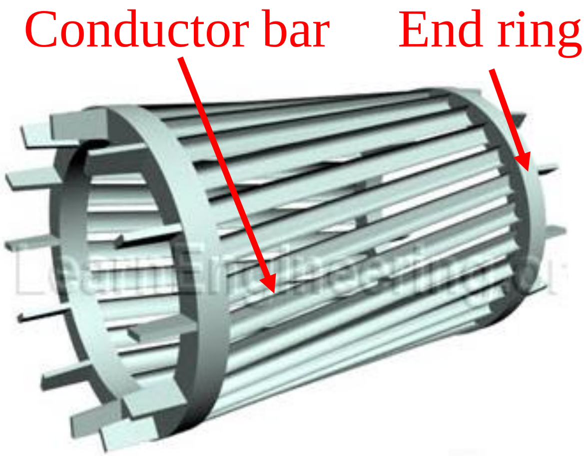
- Frame: Made by cast steel or cast iron

Structure of cage rotor (Rotor type I)



Structure of cage rotor:

- The conductor bar is made of cast iron or aluminum.
- Conductor bars are ended by two short circuit end rings to form rotor winding.
- Rotor core is stacked by silicon steel with outer slots.



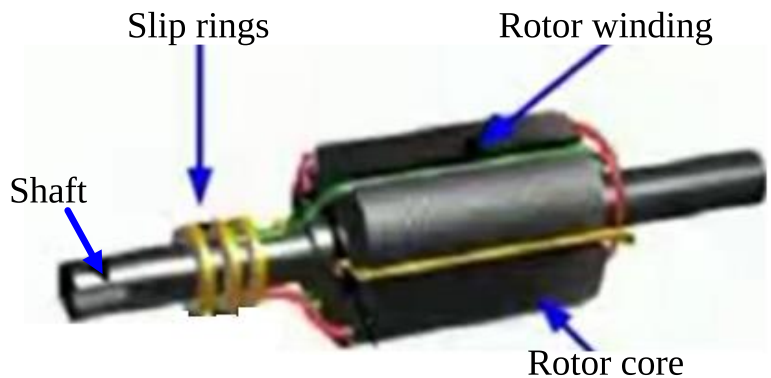
Advantages:

- Simple structure, low-cost, reliable.

Disadvantages:

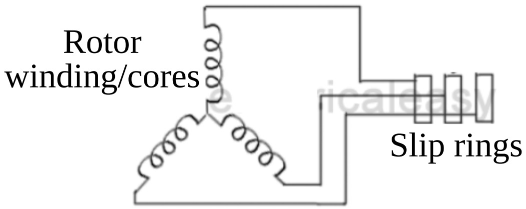
- Cannot change the motor mechanical characteristics due to the fixed rotor structure

Structure of wound rotor (Rotor type II)



Structure of wound rotor:

- Rotor core is stacked by silicon steel with outer slots.
- Rotor windings are in the slots.
- The rotor windings are Y connected.
- The rotor windings are ended by slip rings.



Real wound rotor

Advantages:

- Can change the motor mechanical characteristics by changing the rotor winding.

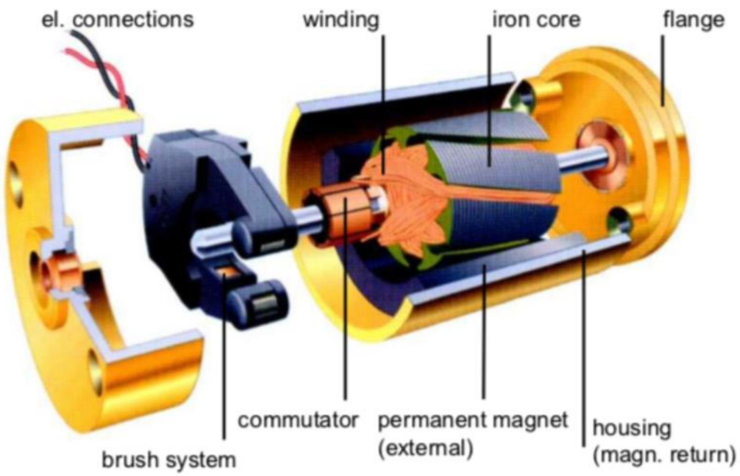
Disadvantages:

- Complex structure, high-cost, not easy to maintain.

Please point out the asynchronous motor

Asynchronous motor

Synchronous motor



DC motor

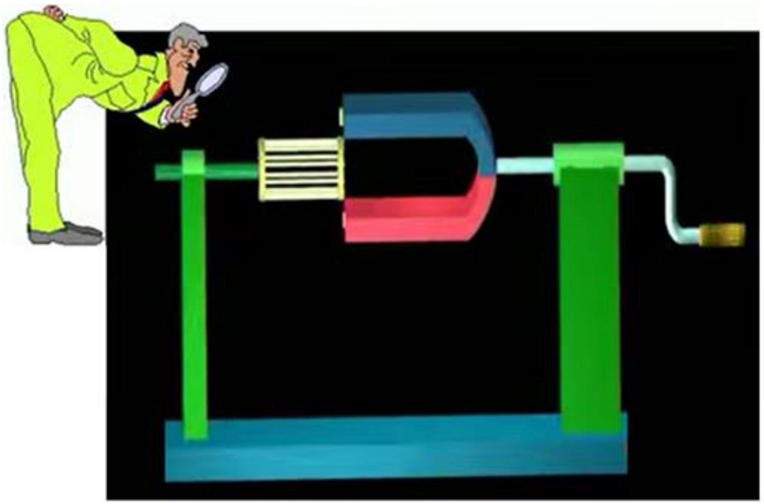
OPERATION PRINCIPLE OF ASYNCHRONOUS MOTOR

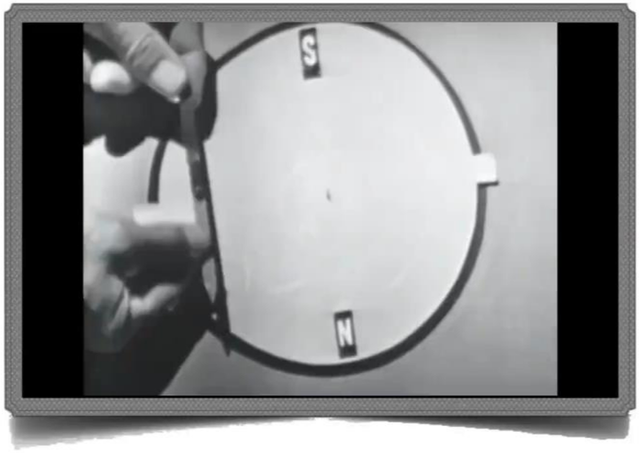
[10/03/2020]

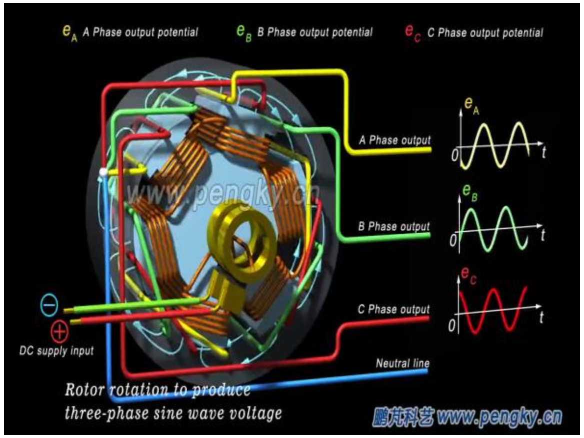
- Structure of the asynchronous motor
- Operation principle of the asynchronous motor
- Key parameters of the asynchronous motor

Recall: the winding is following the rotated magnet

why?



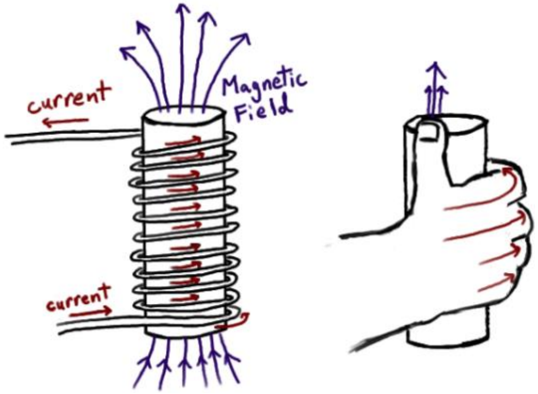




Right Hand Rule I: simply shows how a current-carrying wire generates a magnetic field.

- If you point your thumb in the direction of the current, as shown, and let your fingers assume a curved position, the magnetic field circling around those wires flows in the direction in which your four fingers point.

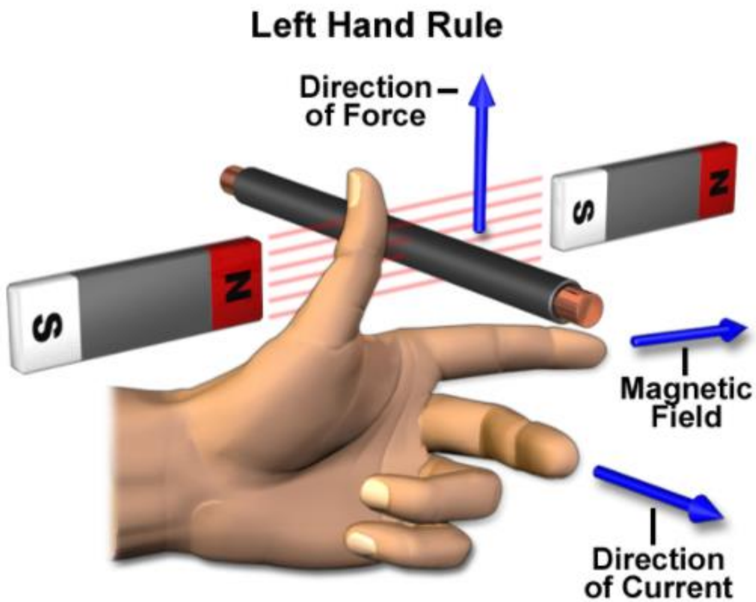
Ampere



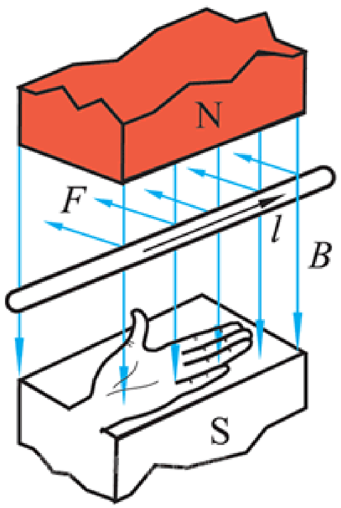
Right Hand Rule II: Determine the direction of the magnetic field of an electro-magnet constructed by wrapping current carrying wire around an iron core.

- Magnetic field direction is in the same direction as the thumb when the right hand is wrapped around the core with the fingers pointing along the direction of the electric current.

Recall: Left hand rule



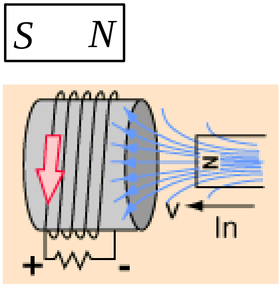
John Ambrose Fleming

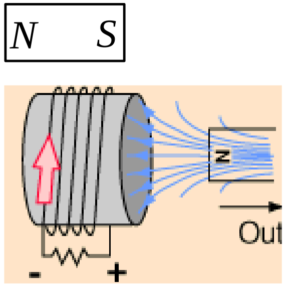


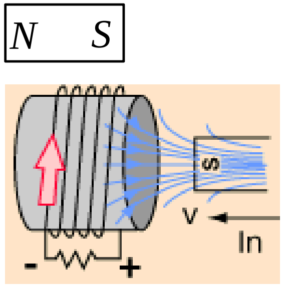
Left Hand Rule: shows what happens when charged particles (such as electrons in a current) enter a magnetic field. You need to contort your left hand in an unnatural position for this rule, illustrated below:

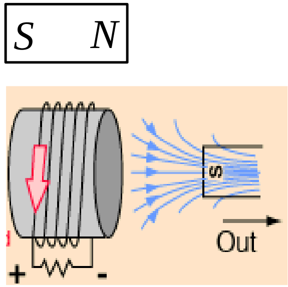
- Your index finger points in the direction of a magnetic field;
- Your middle finger, at a 90 degree angle to your index, points in the direction of the charged particle (as in an electrical current);
- Your extended thumb (forming an L with your index) points in the direction of the force exerted upon that particle.

Lenz's Law: the direction of the induced current is such that it opposes the change that causes it.





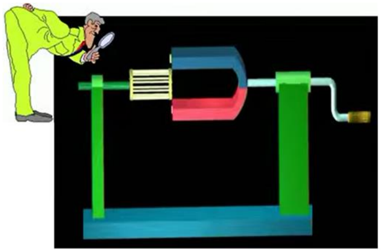


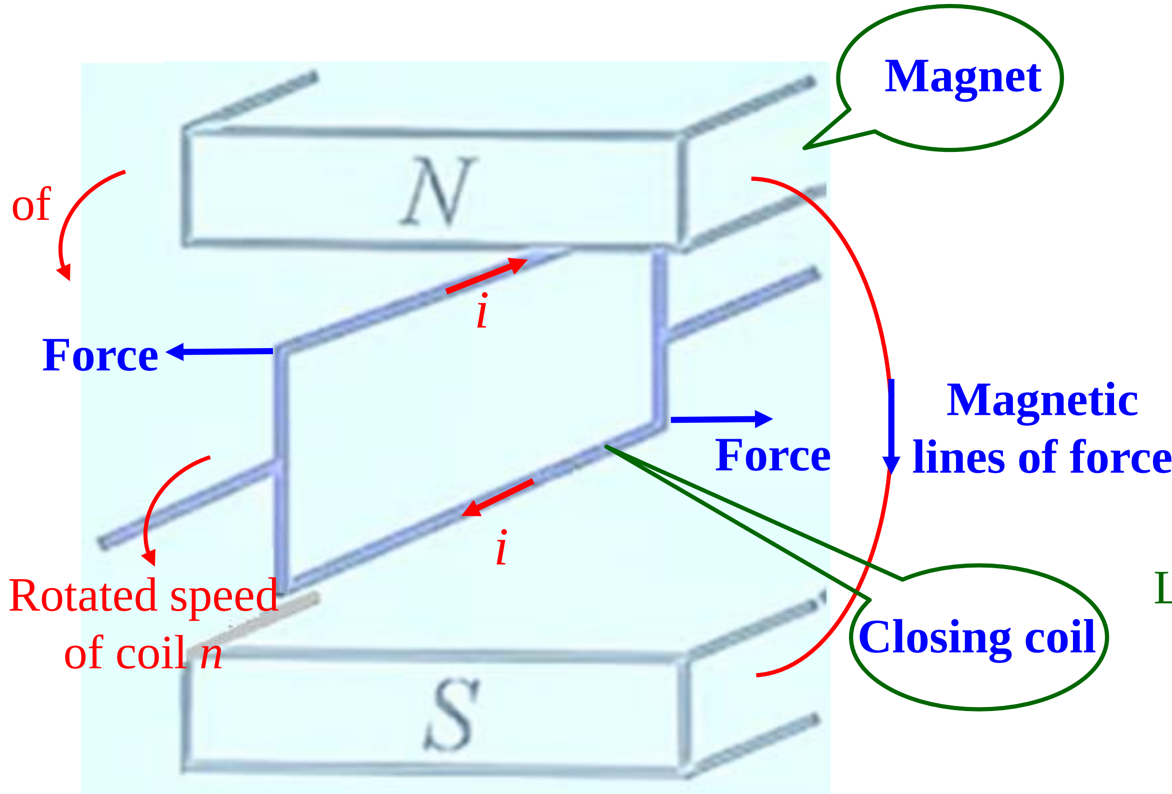


'If you push a wire through a field the induced current makes a force that pushes back'

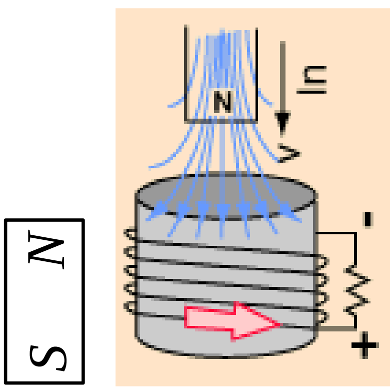
'If a field is pointing one way and a conductor moves through it, then the induced current makes a field that points the opposite way'

Why the winding is following the rotated magnet?

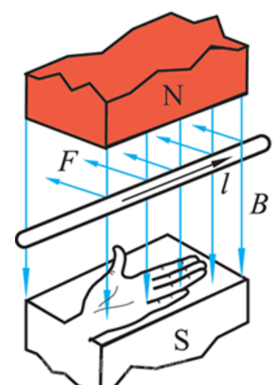




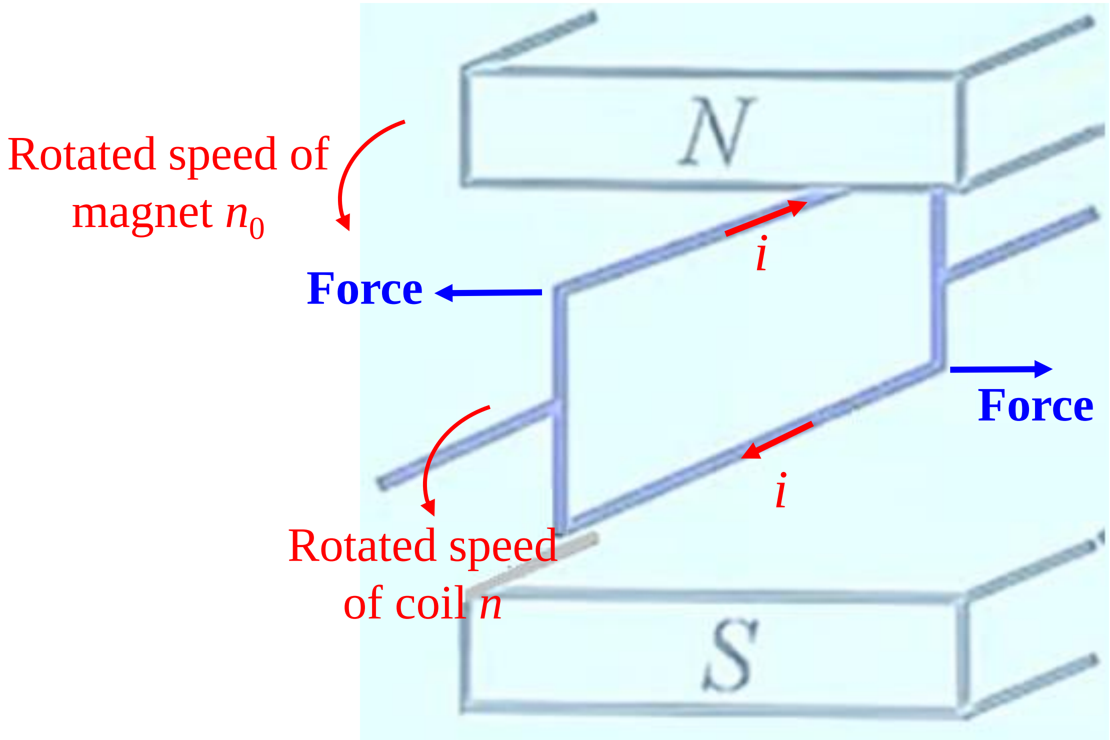
Lenz's Law

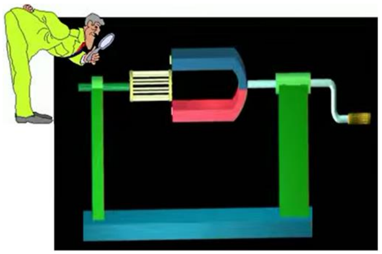


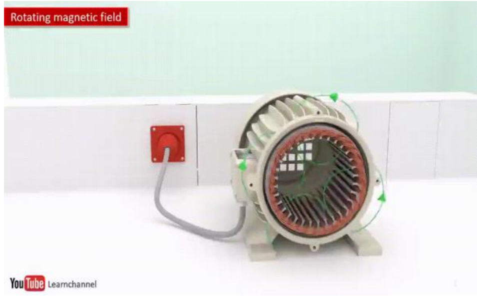
Left-hand rule



Winding is following the rotated magnet: characteristics





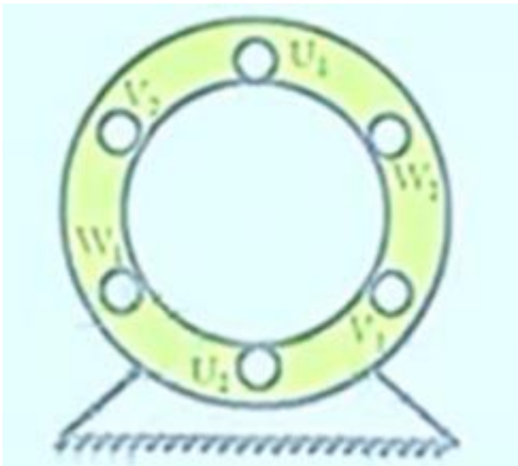


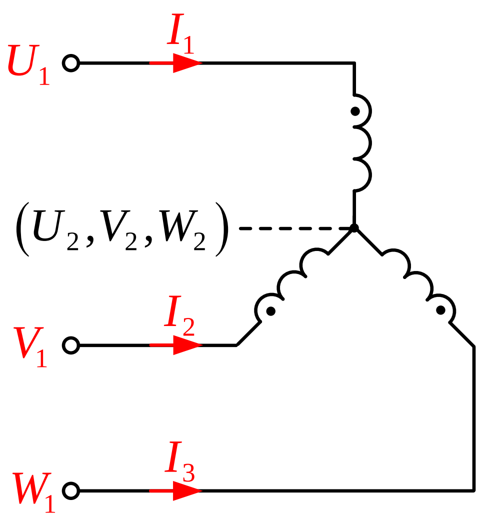
How to generate the rotated magnetic field automatically?

- The coils are rotated follow the rotated magnets and they have the same direction.
- Rotated speed of coils n < Rotated speed of magnet n_o. → Asynchronous

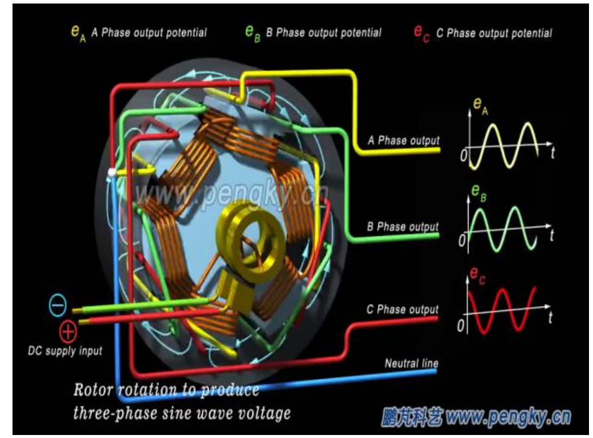
Spatial positions and currents of the windings

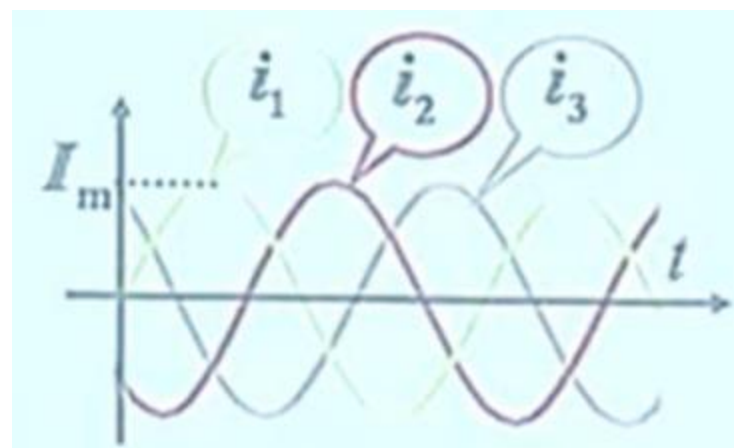
Spatial positions of the windings



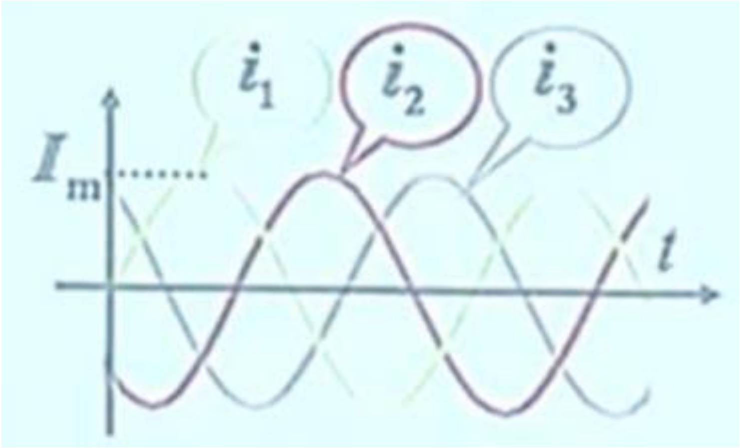


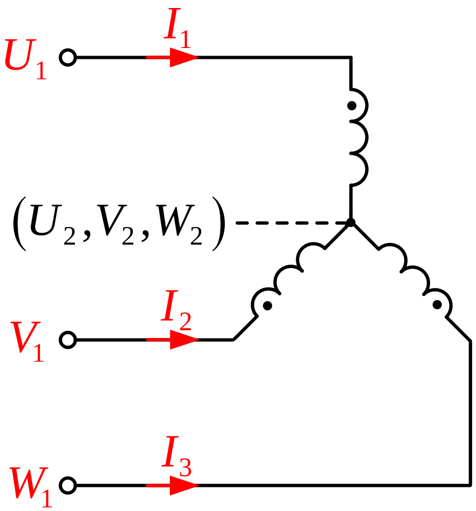
The currents of the windings



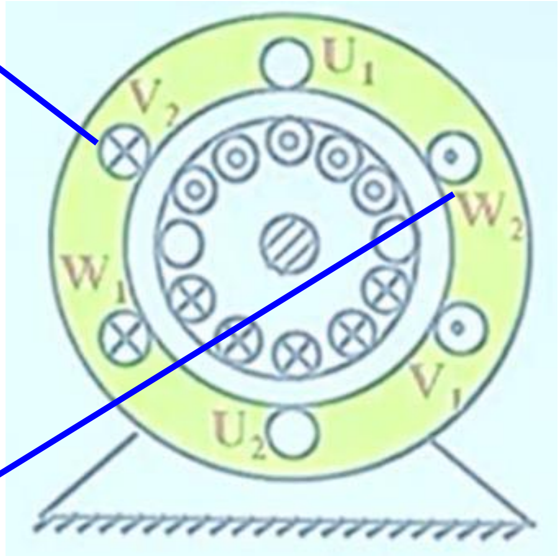


Description of the current direction in the windings



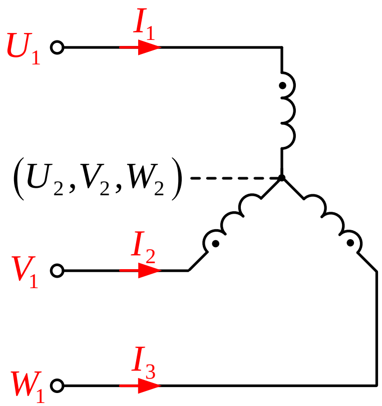


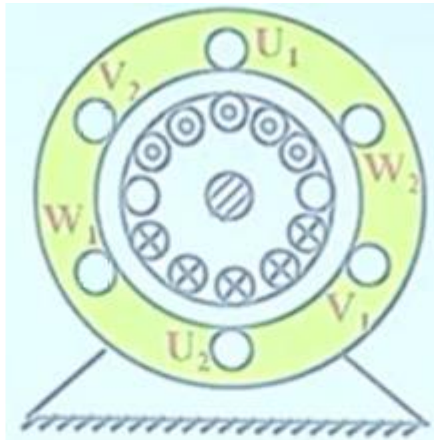
Description:

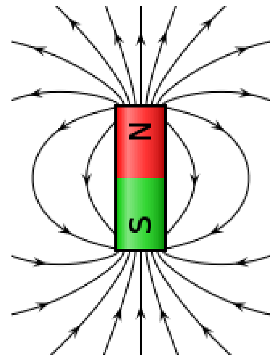


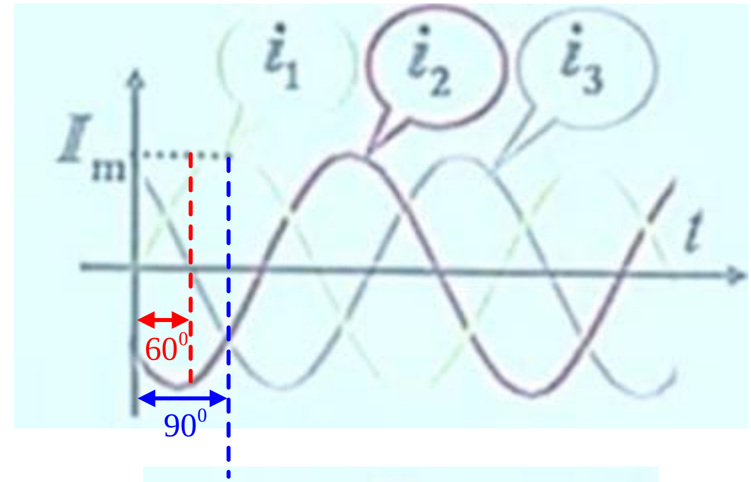
- $i_{(1,2,3)}$: 'Positive' means $U_1/V_1/W_1$ into the motor, $U_2/V_2/W_2$ out from the motor.
- $i_{(1,2,3)}$: 'Negative' means $U_2/V_2/W_2$ into the motor, $U_1/V_1/W_1$ out from the motor.

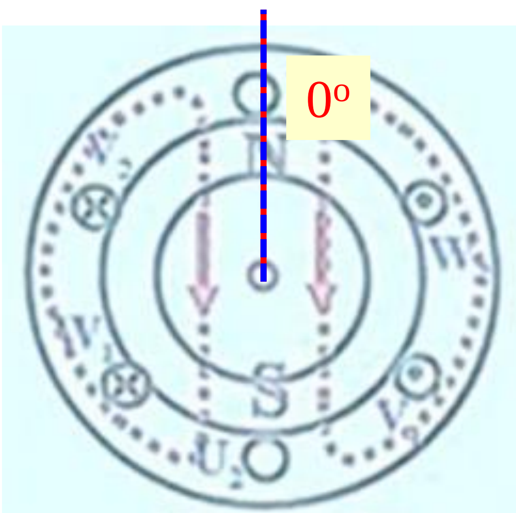
How to generate an automatic rotated magnetic field



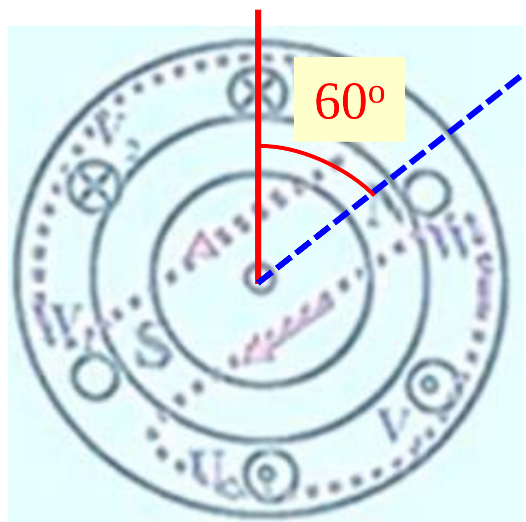




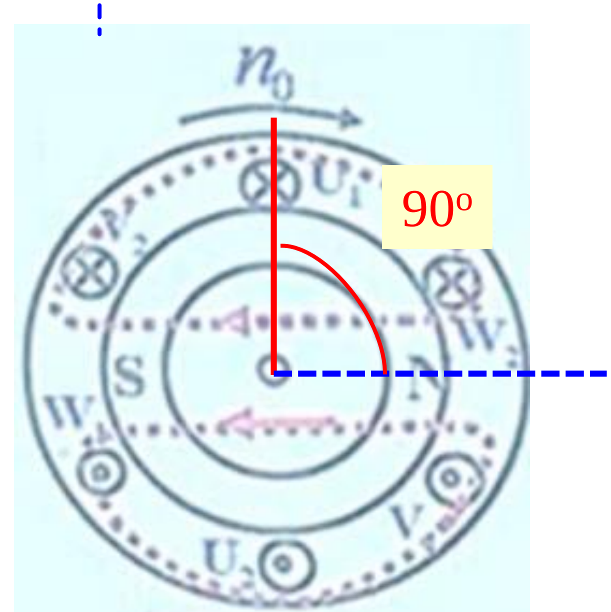




$\omega t = 0^o$



$\omega t = 60^o$

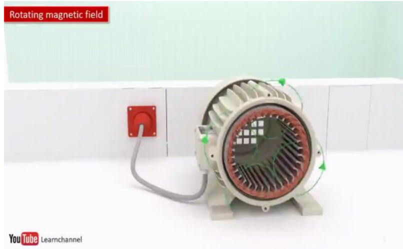


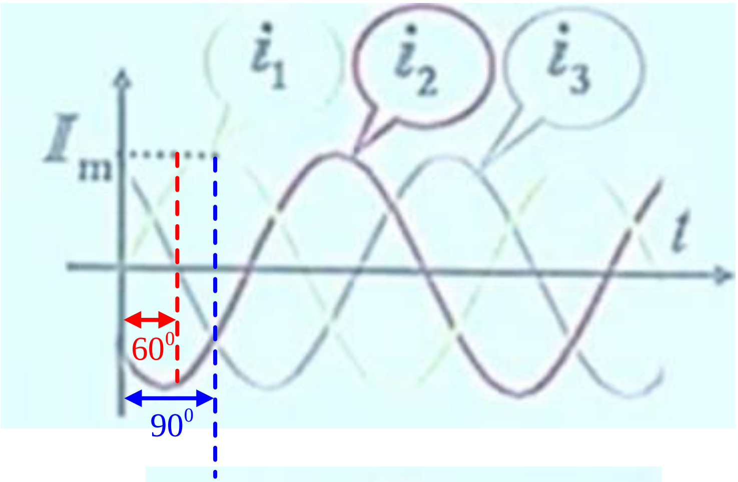
$\omega t = 90^o$

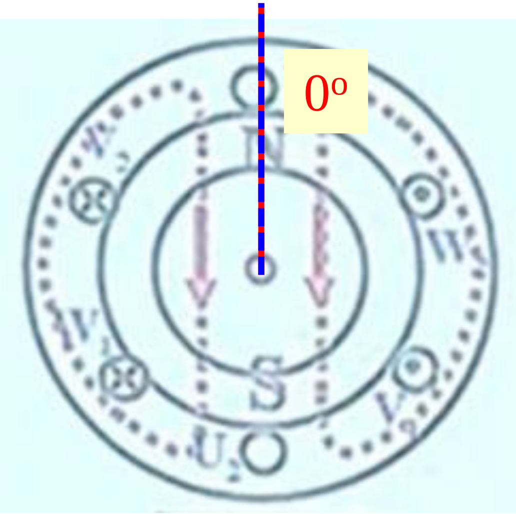
How to generate an automatic rotated magnetic field

- Rotated magnetic field is generated by three phase AC winding current.

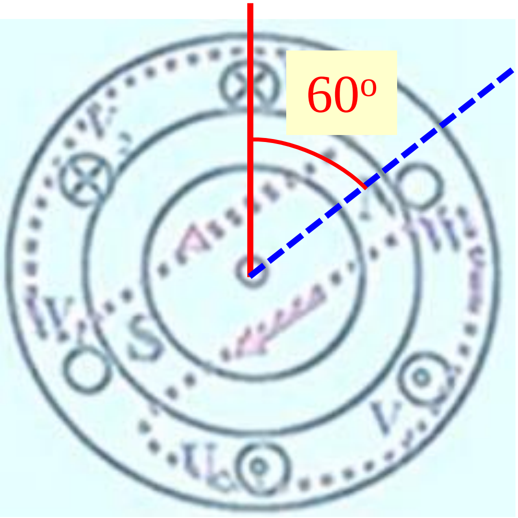
Electrical angle = Space angle



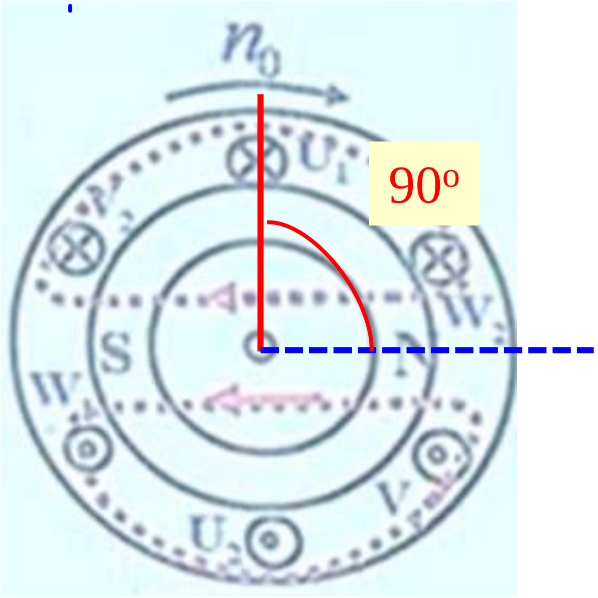




$\omega t = 0^o$

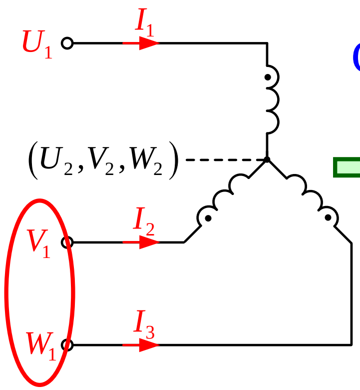


$\omega t = 60^o$

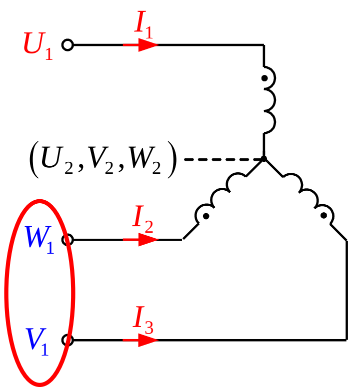


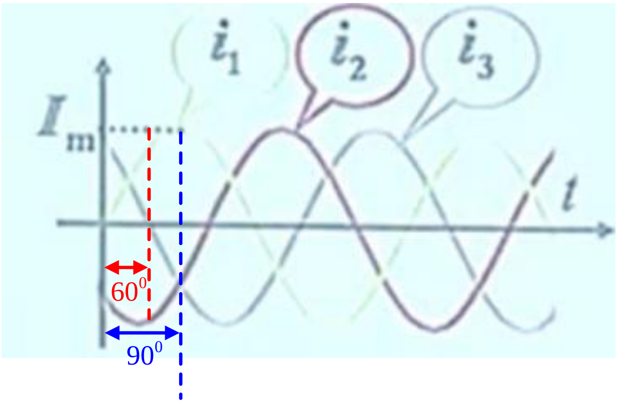
$\omega t = 90^o$

How to change the direction of the rotated magnetic field?

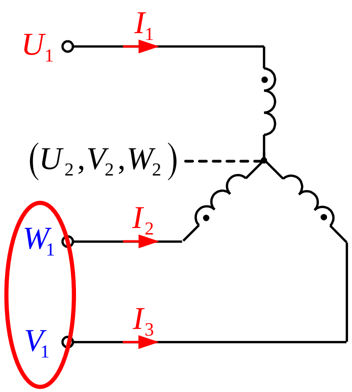


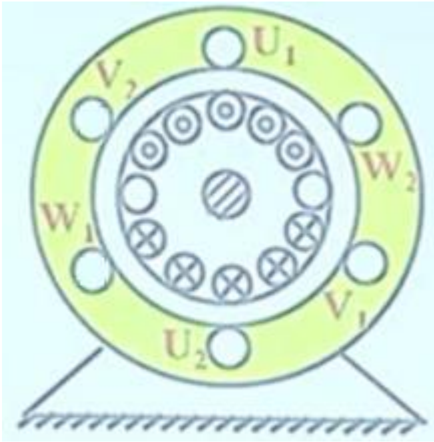
Change the position of W_1 and V_1

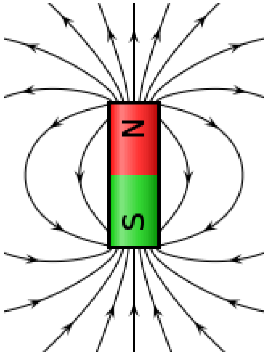


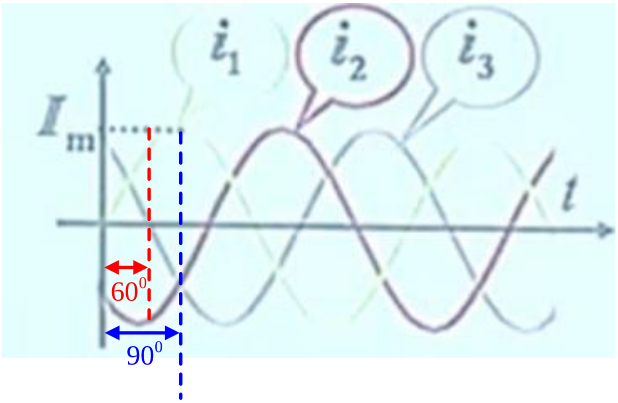


How to change the direction of the rotated magnetic field?

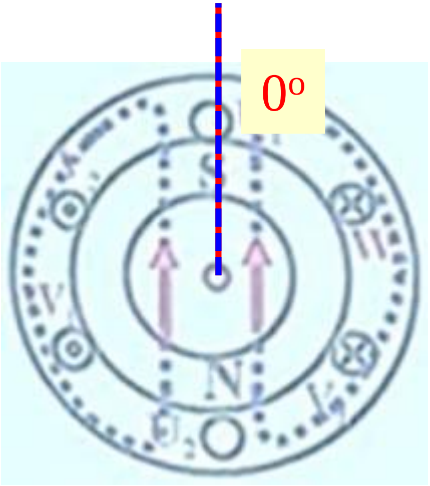




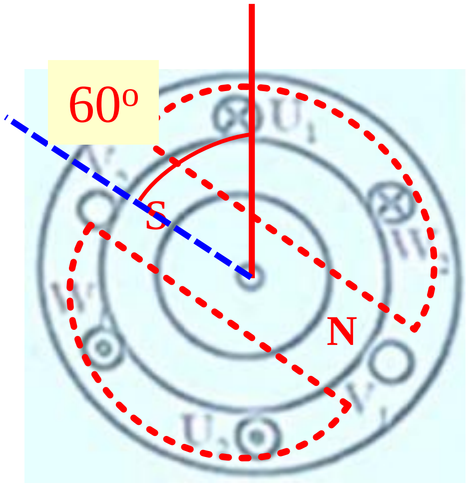




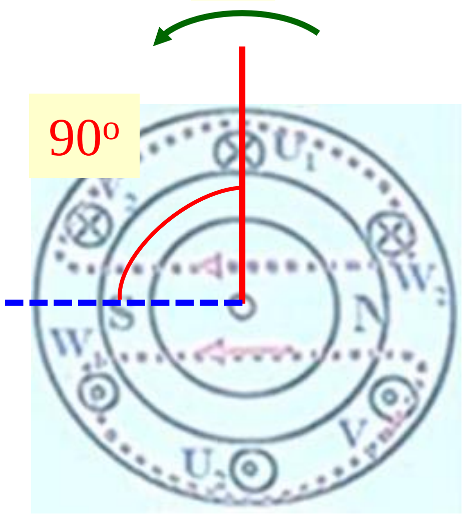
Rotated direction is changed ⟹ n_o



$\omega t = 0^o$

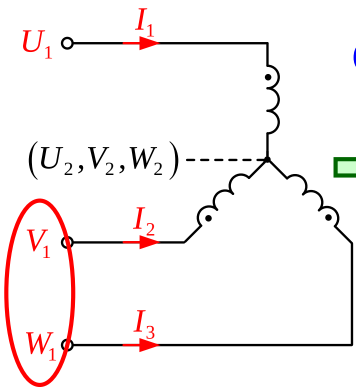


$\omega t = 60^o$

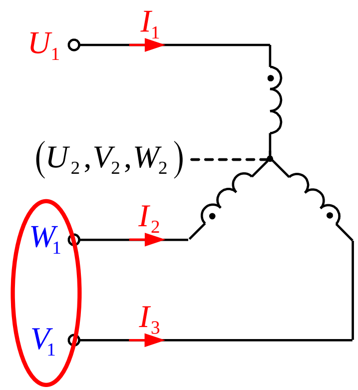


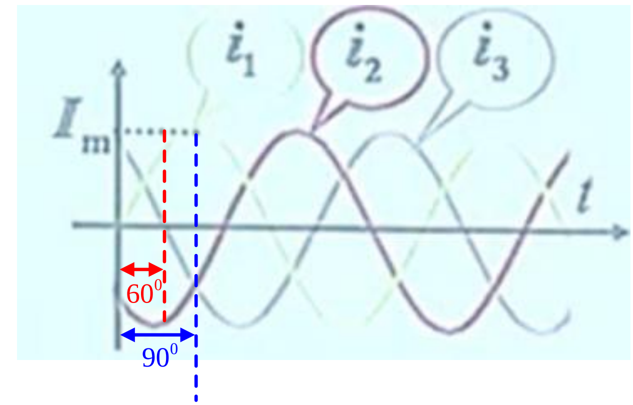
$\omega t = 90^o$

How to change the direction of the rotated magnetic field?

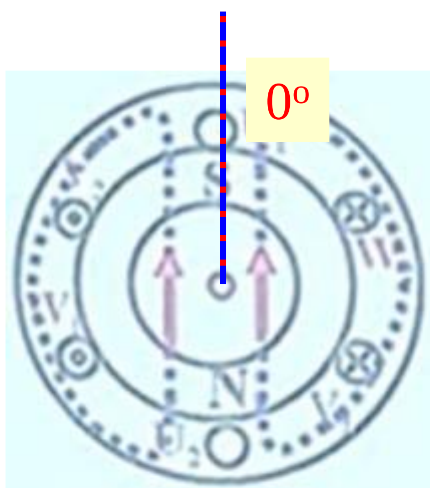


Change the position of W_1 and V_1

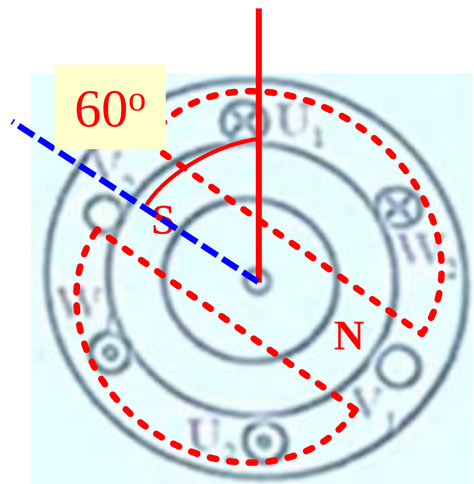




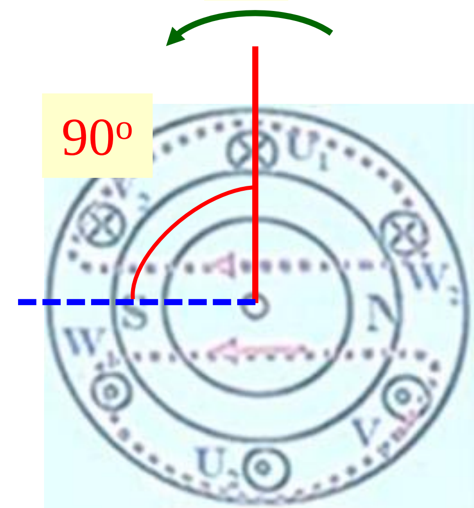
Rotated direction is changed → n_o



$\omega t = 0^o$

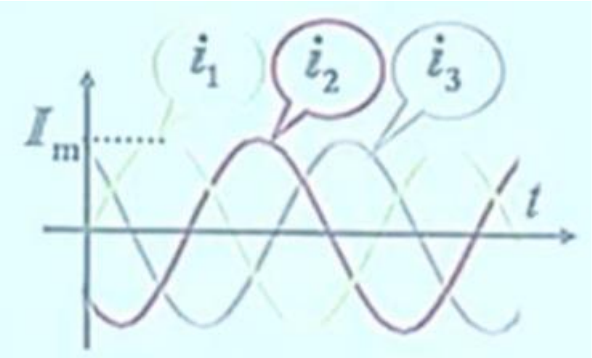


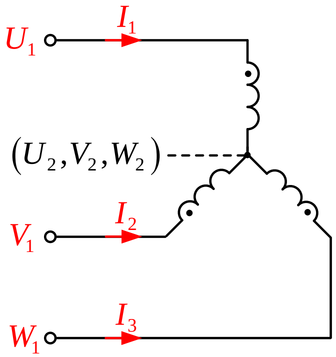
$\omega t = 60^o$

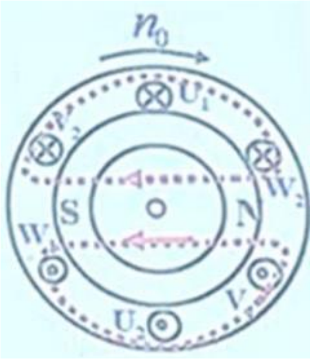


$\omega t = 90^o$

Review the rotated principle of the asynchronous motor

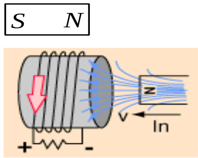


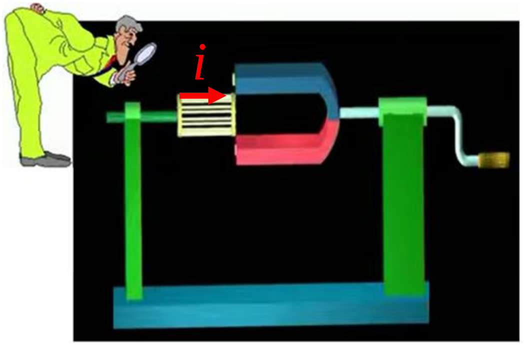




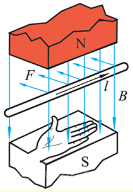
Three phase AC currents generate rotated magnetic field

Lenz's Law





Induce current is generated in the rotor windings to stop its flux change



Electromagnetic force is generated to make the rotor windings follow the rotated magnetic field

Video: quick review of the operation principle of the three phase asynchronous motor

Limitation of the three phase asynchronous motor

Ideal

Need special socket (5 pins)

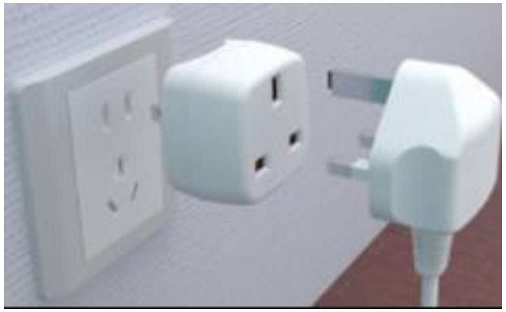
Phase U, V, W, Neutral, ground

Does not match

Real

Commonest socket is single phase socket

Phase, neutral (ground)



Small power appliance usually use single phase socket

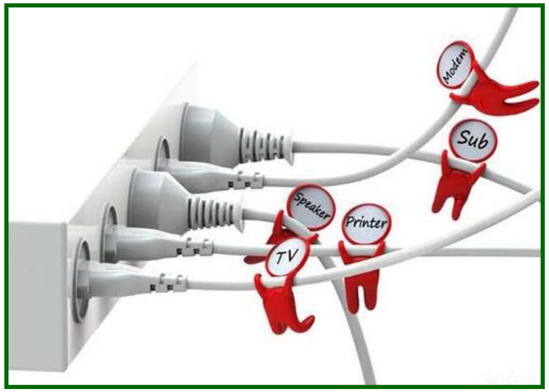
Fridge

Washing machine

Microwave Oven

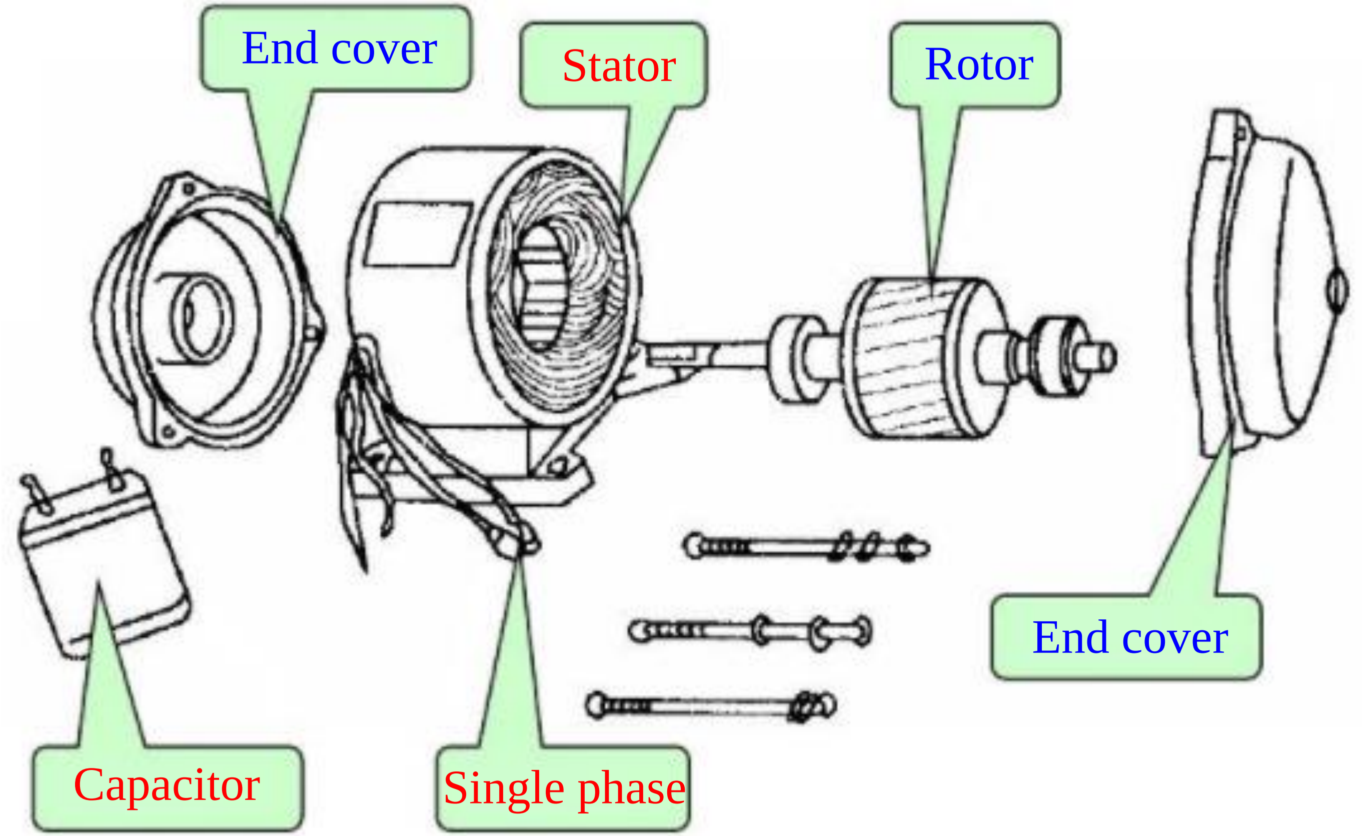
Vacuum cleaner

Most of the appliances use single phase socket



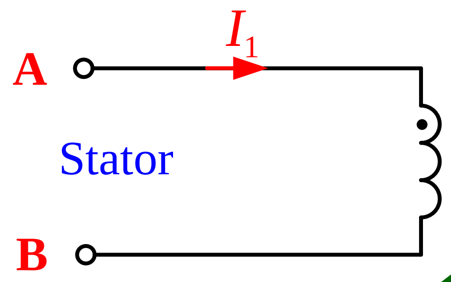
Single phase asynchronous motor is proposed

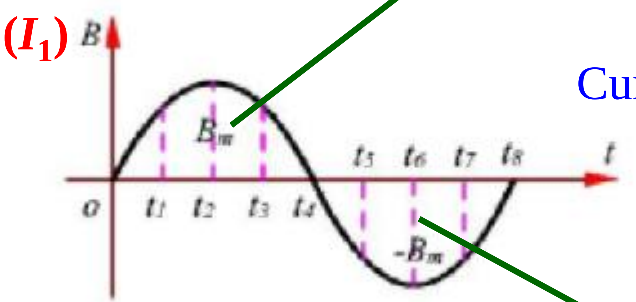
Single phase asynchronous motor



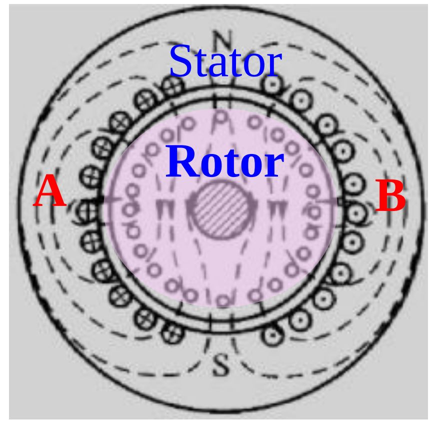
- Only need single phase voltage (current) to let the motor rotated
- Suitable for small power (< 750 W) application

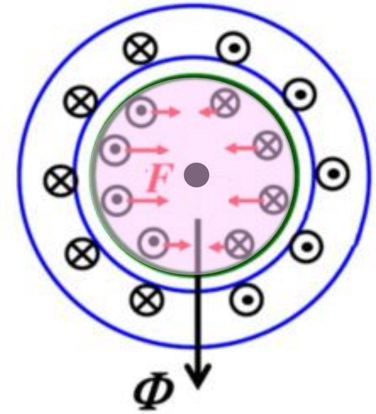
Challenge of the single phase asynchronous motor



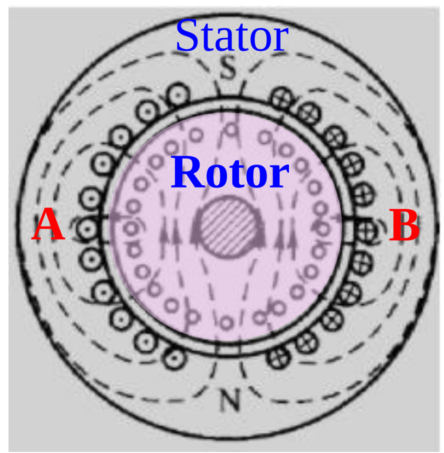


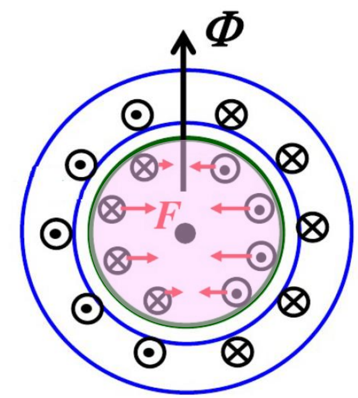
Current at the positive half cycle





Current at the negative half cycle

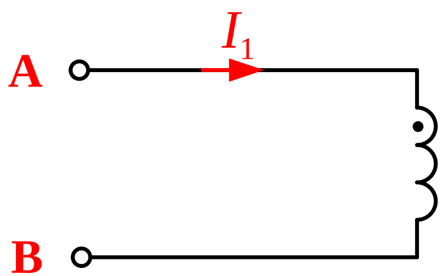


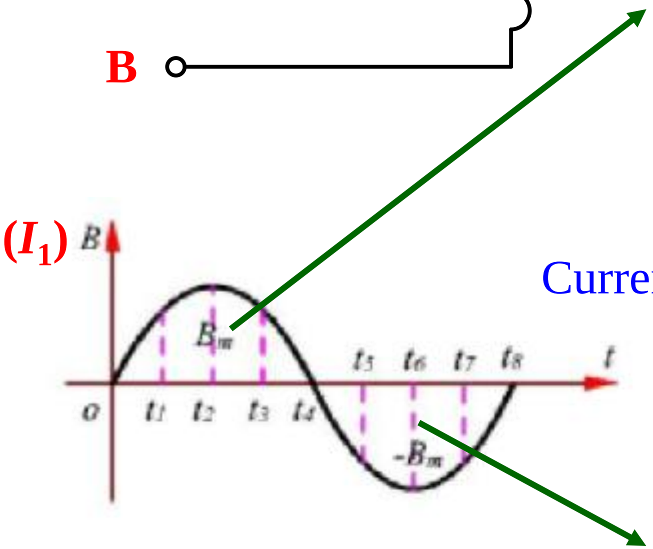


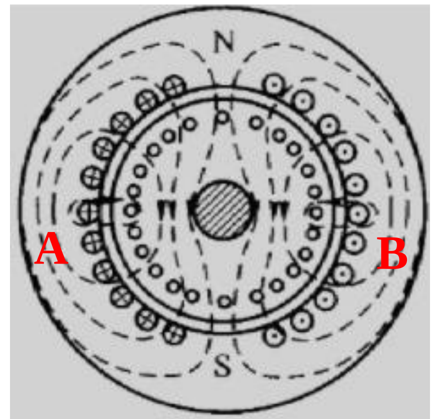
Force (left half rotor)
+Force (right half rotor) = 0
→(rotor cannot be rotated)

Why rotor cannot be rotated?
—basic reason: no rotated magnetic filed

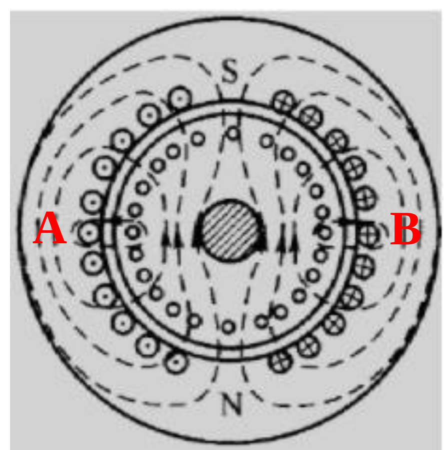
Current at the positive half cycle



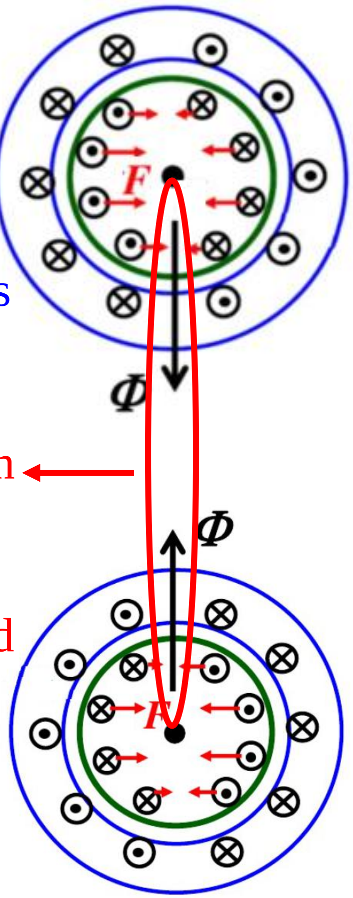




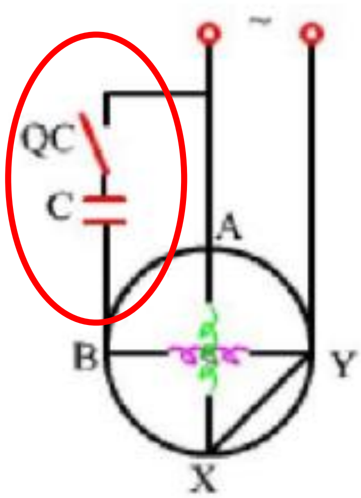
Current at the negative half cycle



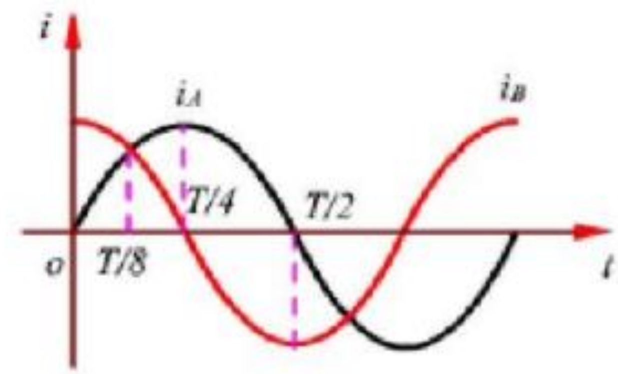
Directions of the magnetic field are in the same axis but not rotated

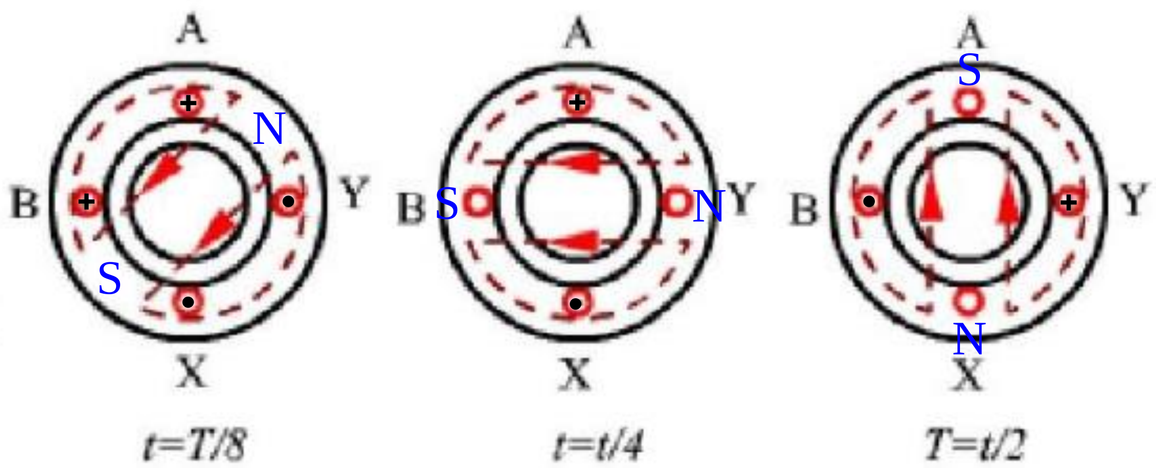


Solution of the single phase asynchronous motor



Capacitor current (phase B current) is 90^{o} ahead of the phase A current





t=T/8 t=t/4 T=t/2

Rotated magnetic field of the stator!

The rotor of the single phase asynchronous motor can be rotated

Video 2: Operation principle of the single phase asynchronous motor

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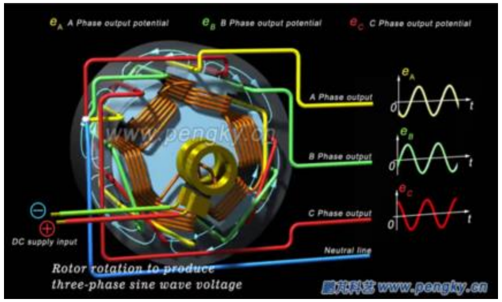
OPERATION PRINCIPLE OF ASYNCHRONOUS MOTOR

[10/03/2020]

- Structure of the asynchronous motor
- Operation principle of the asynchronous motor
- Key parameters of the asynchronous motor

- Pole-pairs of the asynchronous motor
- Rotated speed of the magnetic field of the asynchronous motor
- Slip ratio of the asynchronous motor



- Pole-pairs of the asynchronous motor
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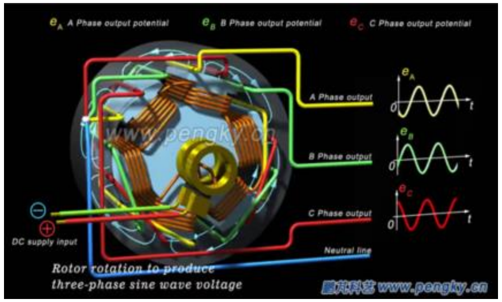
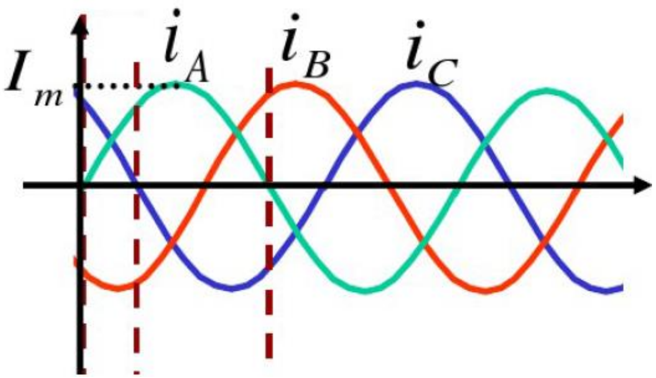
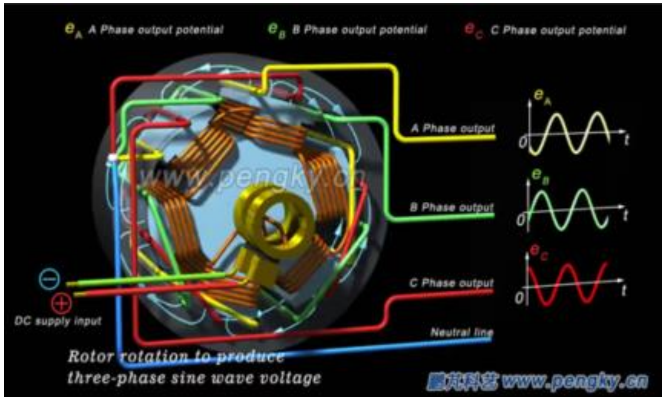
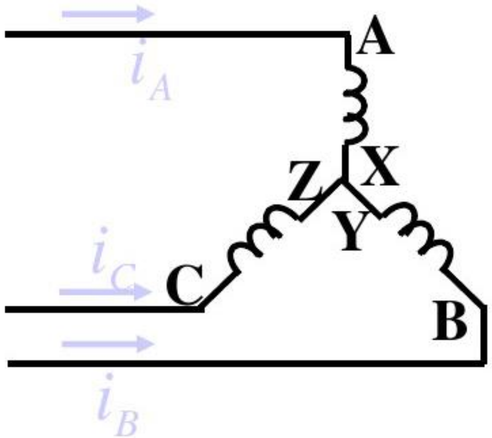
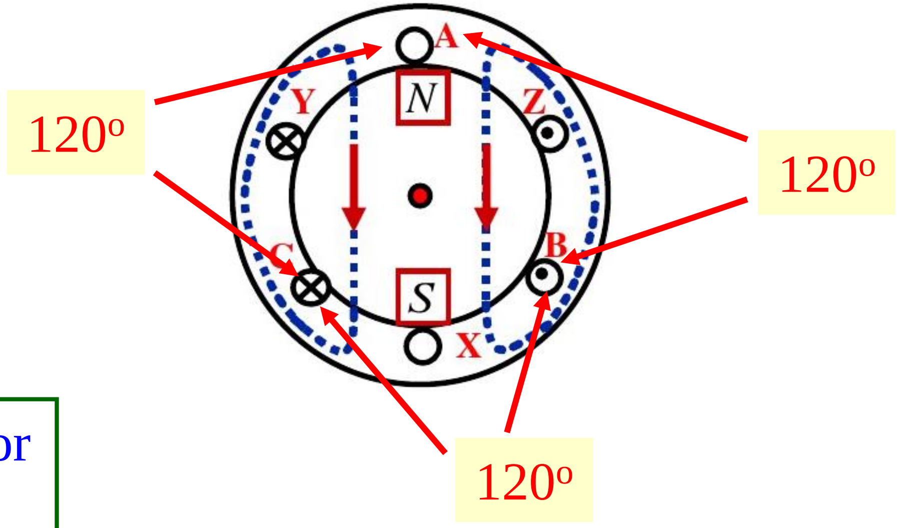


Pole-pairs of the asynchronous motor: P=1 case









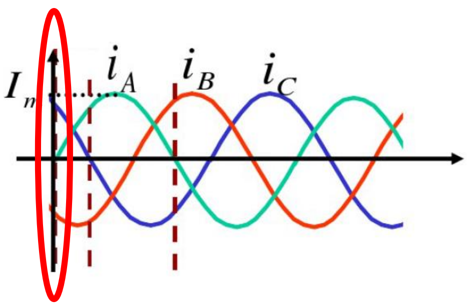
There are 120^0 among the beginning stator winding A, B and C.

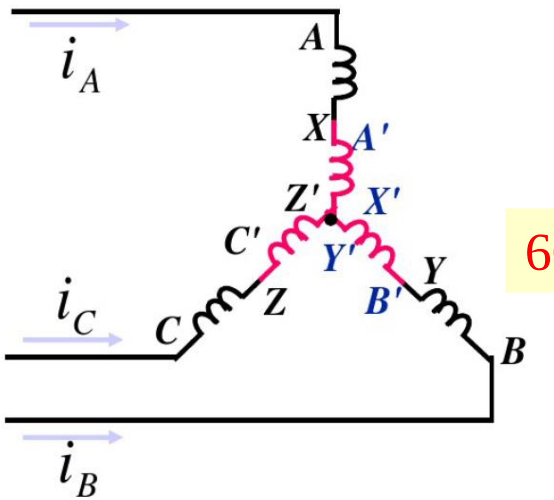
Pole pairs: P=1

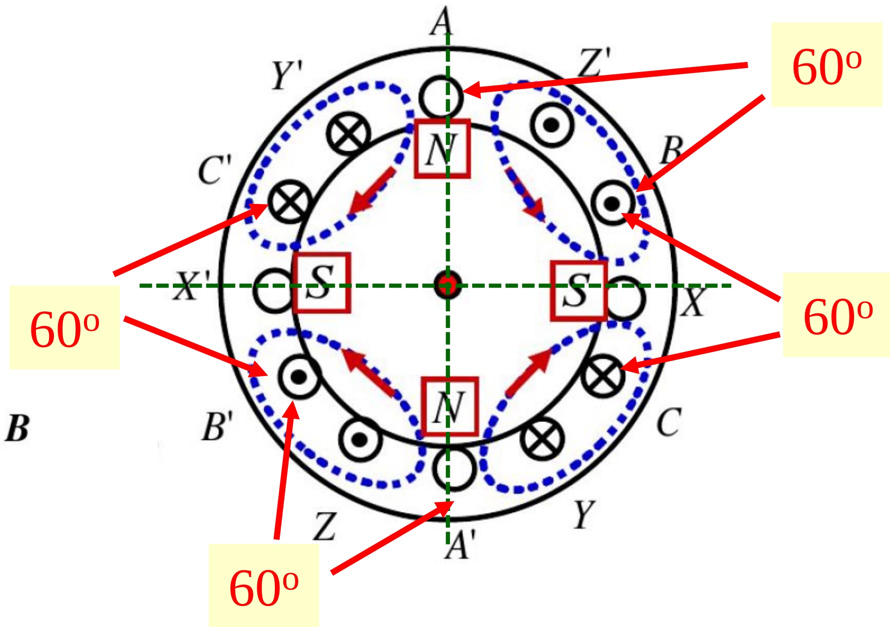
Pole-pairs of the asynchronous motor: P=2 case

The winding is divided into two sections, they are installed into the stator slot according to the right figure:

- There are 60^0 among the beginning stator winding A, B and C.
- There are 60^0 among the beginning stator winding A', B' and C'.
- There are 180^0 among the beginning stator winding A and A'.



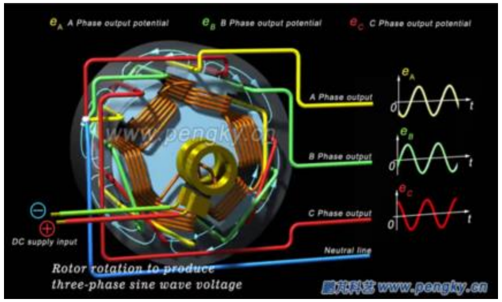




Pole pairs: P=2

Key parameters of the asynchronous motor

- ❑ Pole-pairs of the asynchronous motor
- ❑ **Rotated speed of the magnetic field of the asynchronous motor**
- ❑ Slip ratio of the asynchronous motor



Rotated speed of the magnetic field when P=1

Rotated speed of the magnetic field (Pole pairs P=1):

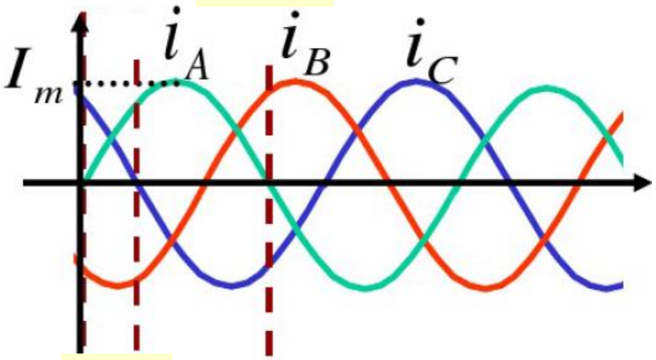
$n_o = f$, (rps, Revolutions Per Second)

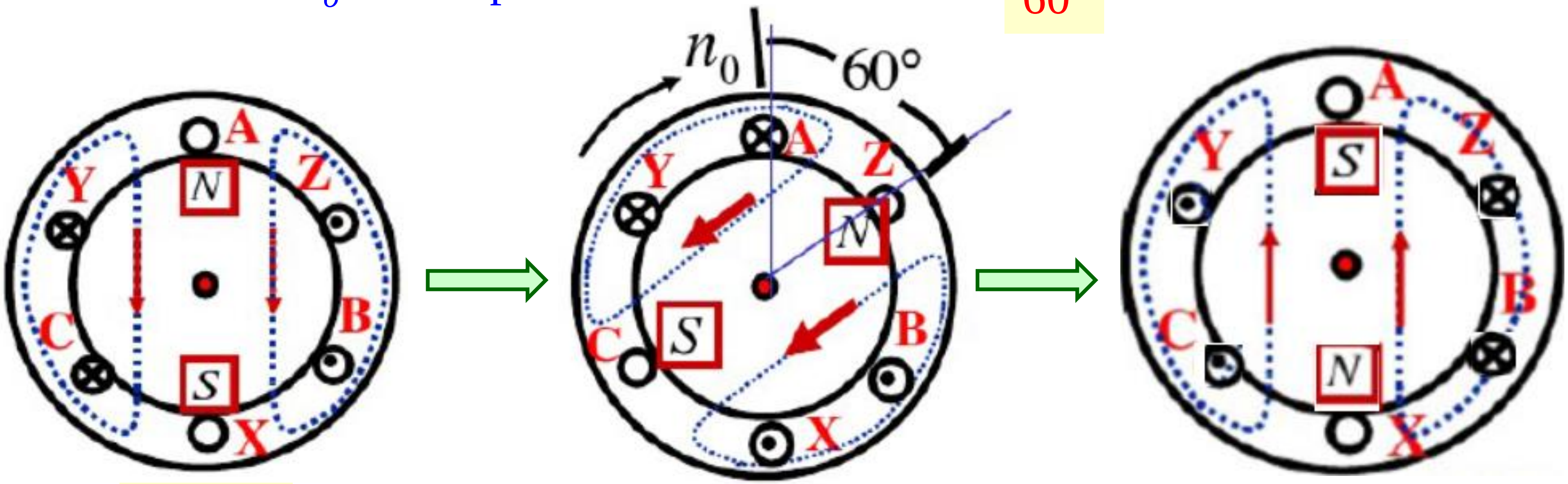
1 minute = 60 seconds

$n_o = 60 \cdot f$, (rpm, Revolutions Per Minute)

f = 50 Hz

n_o=3000 rpm





ωt = 0°

ωt = 60°

ωt = 180°

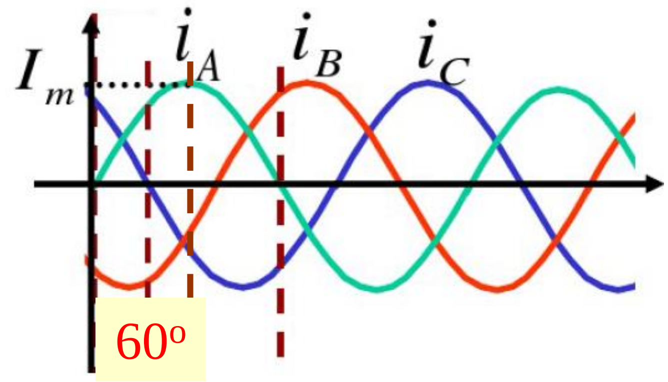
Rotated speed of the magnetic field when P=2

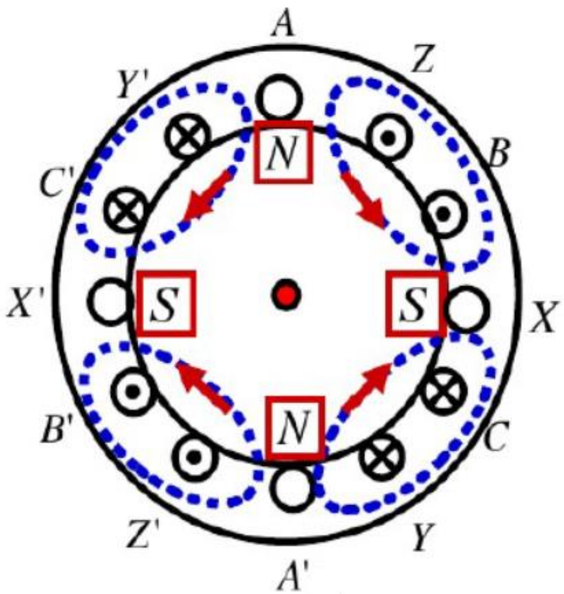
Rotated speed of the magnetic field (Pole pairs P=2):

$$\boxed{n_o = \frac{60\,f}{2} = 1500\ \ (rpm)}$$

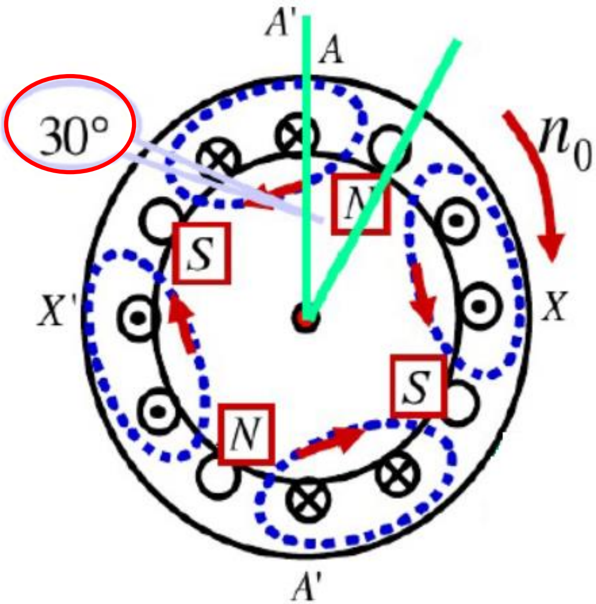
If f=50 Hz

Pole pairs P=2





$\omega t = 0^o$



$\omega t = 60^o$

Summary: rotated speed of the magnetic field

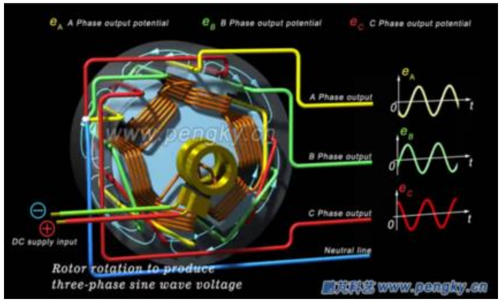
Rotated speed of the magnetic field (Pole pairs P):

$$\boxed{n_o = \frac{60f}{P}\ (rpm)}$$

Pole pairs	The rotated space degree of the magnetic field in each AC current cycle	Rotated speed of the magnetic field (f=50 Hz)
P=1	360^0	3000 rpm
P=2	180^0	1500 rpm
P=3	120^0	1000 rpm
P=4	90^0	750 rpm

Key parameters of the asynchronous motor

- ❑ Pole-pairs of the asynchronous motor
- ❑ Rotated speed of the magnetic field of the asynchronous motor
- ❑ Slip ratio of the asynchronous motor



Relationship between the rotor speed n and the magnetic field speed n_0

- Rotated speed of the magnetic field n_0
- Rotated speed of the rotor n

Rotated speed of the magnetic field *has the same direction* with the Rotated speed of the rotor

However:

$n < n_o$ ⟹ Asynchronous motor

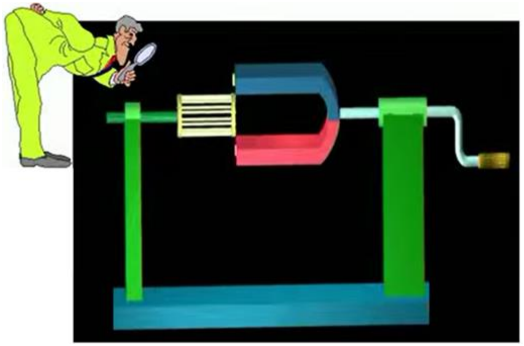
If: $n=n_0$

⟹ There is no relative movement between the rotor and the rotating field

⟹ No induced current

⟹ No electromagnetic force

⟹ Cannot rotate ⟹ *n must smaller than n_o*



Slip ratio of asynchronous motor

Slip ratio: $$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

Range of slip ratio in the normal case:

$$s = 1 \sim 9\%$$

Rotated speed of the rotor n: $$n = (1 - s)\, n_o$$

Example 1: For a three phase asynchronous motor, if its rated rotor speed is n=975r/min, its AC voltage frequency is f=50 Hz, give the pole pairs and slip ratio of this asynchronous motor.

$n_o = 1000 rpm$ $P=3$

$$s = \frac{n_o - n}{n_o} \times 100\%$$

$$= \frac{1000 - 975}{1000} \times 100\% = 2.5\%$$

Pole pairs	The rotated space degree of the magnetic field in each AC current cycle	Rotated speed of the magnetic field (f=50 Hz)
P=1	360^0	3000 rpm
P=2	180^0	1500 rpm
P=3	120^0	1000 rpm
P=4	90^0	750 rpm

Review of today's topic

- What is the structure of the asynchronous motor.
- What is the advantages / disadvantages of the cage & wound rotor?
- How to generate an automatic rotated magnetic field in the stator?
- How to change the direction of the rotated magnetic field in the stator?
- Why the rotor can follow the stator rotated magnetic field? Any limitation to the rotor speed?
- Operation principle of the single phase asynchronous motor.
- Understand the key parameters of the asynchronous motor, such as pole-pairs, slip ratio and rotated speed of the magnetic field.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OPERATION PRINCIPLE OF ASYNCHRONOUS MOTOR

[10/03/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

END OF TOPIC

CHARACTERISTICS OF ASYNCHRONOUS MOTOR

[17/03/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

- Circuit analysis of the asynchronous motor
- Torque of the asynchronous motor
- Stable region of the asynchronous motor

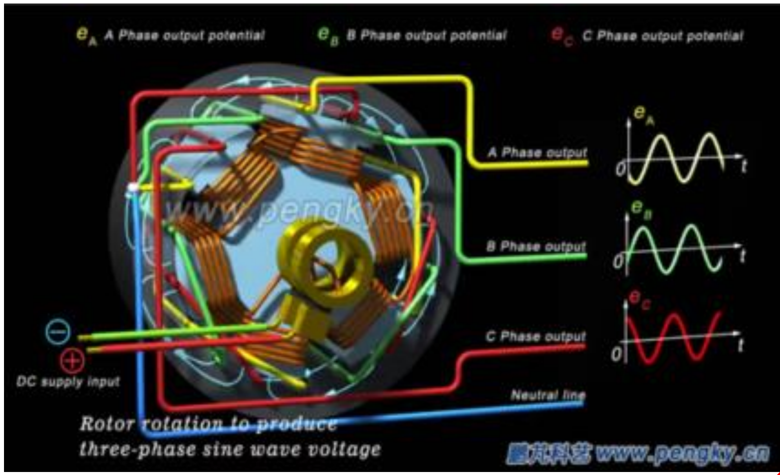
CHARACTERISTICS OF ASYNCHRONOUS MOTOR

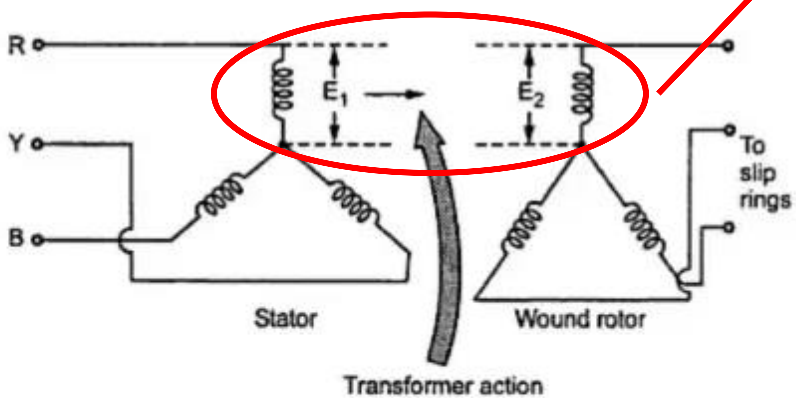
[17/03/2020]

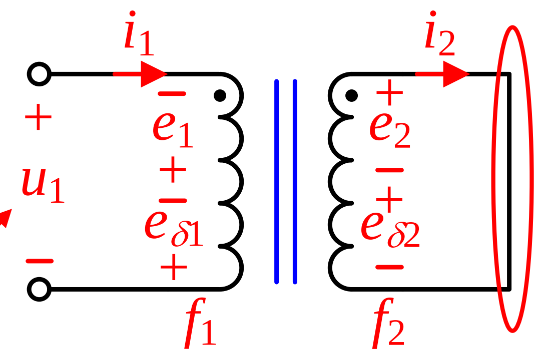
- Circuit analysis of the asynchronous motor
- Torque of the asynchronous motor
- Stable region of the asynchronous motor

Recall: the relationship between transformer and the asynchronous motor

Asynchronous motor is essentially a rotated three phase transformer

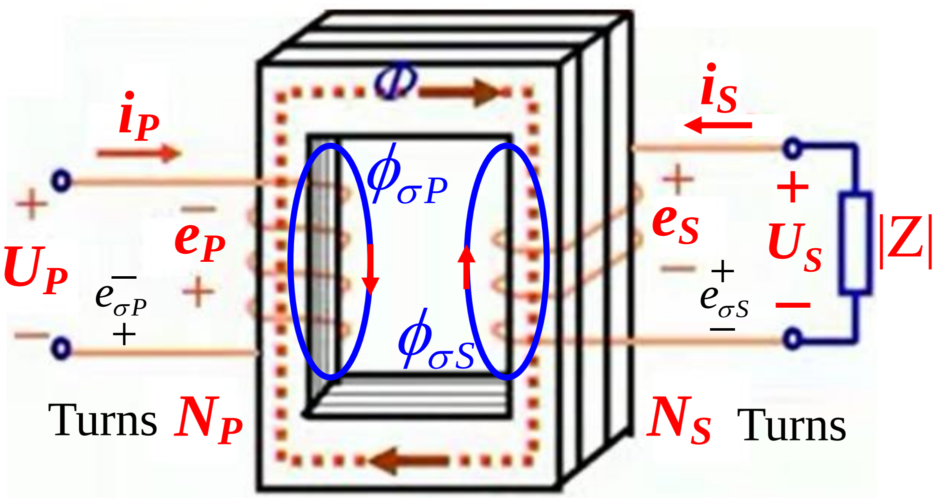


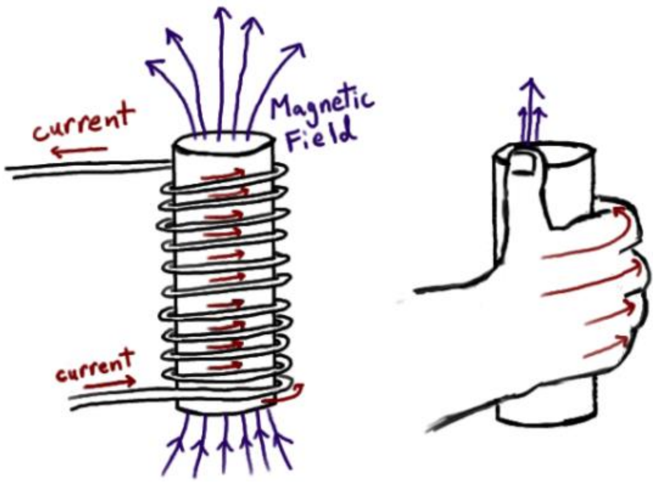




Each phase circuit of the asynchronous motor is actually a single phase transformer

Recall: the circuit analysis of the transformer





$U_P \Rightarrow i_P \xRightarrow{\phi \propto i_P N_P} \phi$

$\phi \Rightarrow e_P = -N_P \dfrac{d\phi}{dt}$

$\phi \Rightarrow e_s = -N_S \dfrac{d\phi}{dt}$

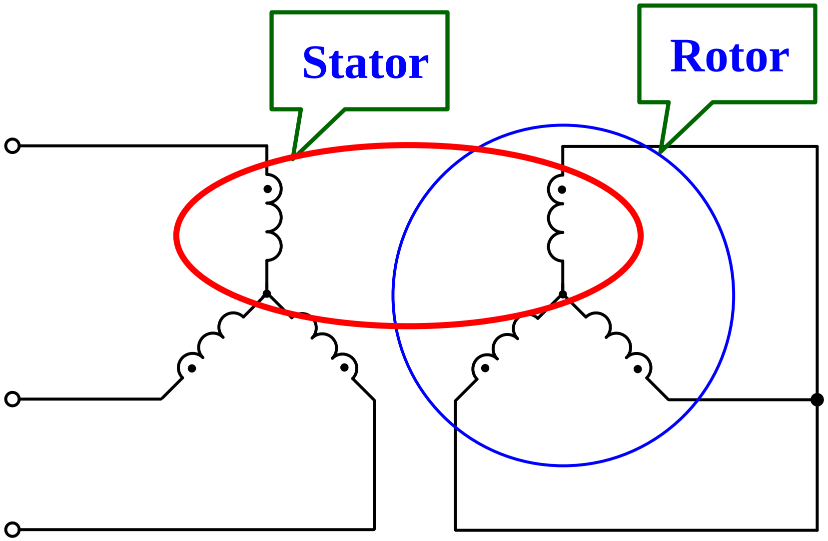
$i_P \Rightarrow \phi_{\sigma P} \Rightarrow e_{\sigma P} = -N_P \dfrac{d\phi_{\sigma P}}{dt}$

$e_s \Rightarrow i_S \Rightarrow \phi_{\sigma S} \Rightarrow e_{\sigma S} = -N_S \dfrac{d\phi_{\sigma S}}{dt}$

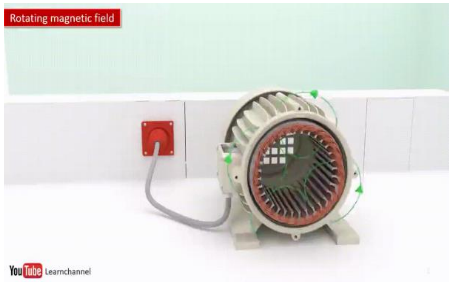
$i_S \Rightarrow \phi$: Hiders the flux

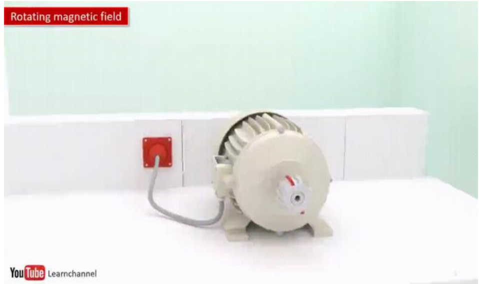
- The final flux ϕ is determined by the primary and secondary coils together.
- Demagnetization each other.

Circuit of the asynchronous motor

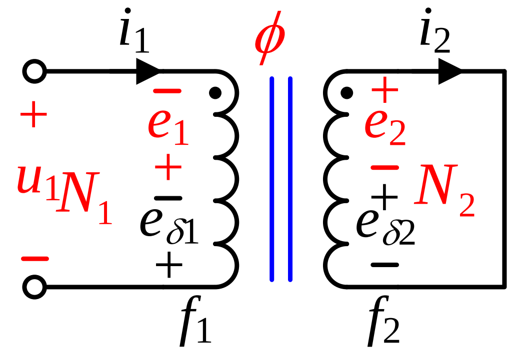


Y-Y Connection





Each phase circuit of the asynchronous motor



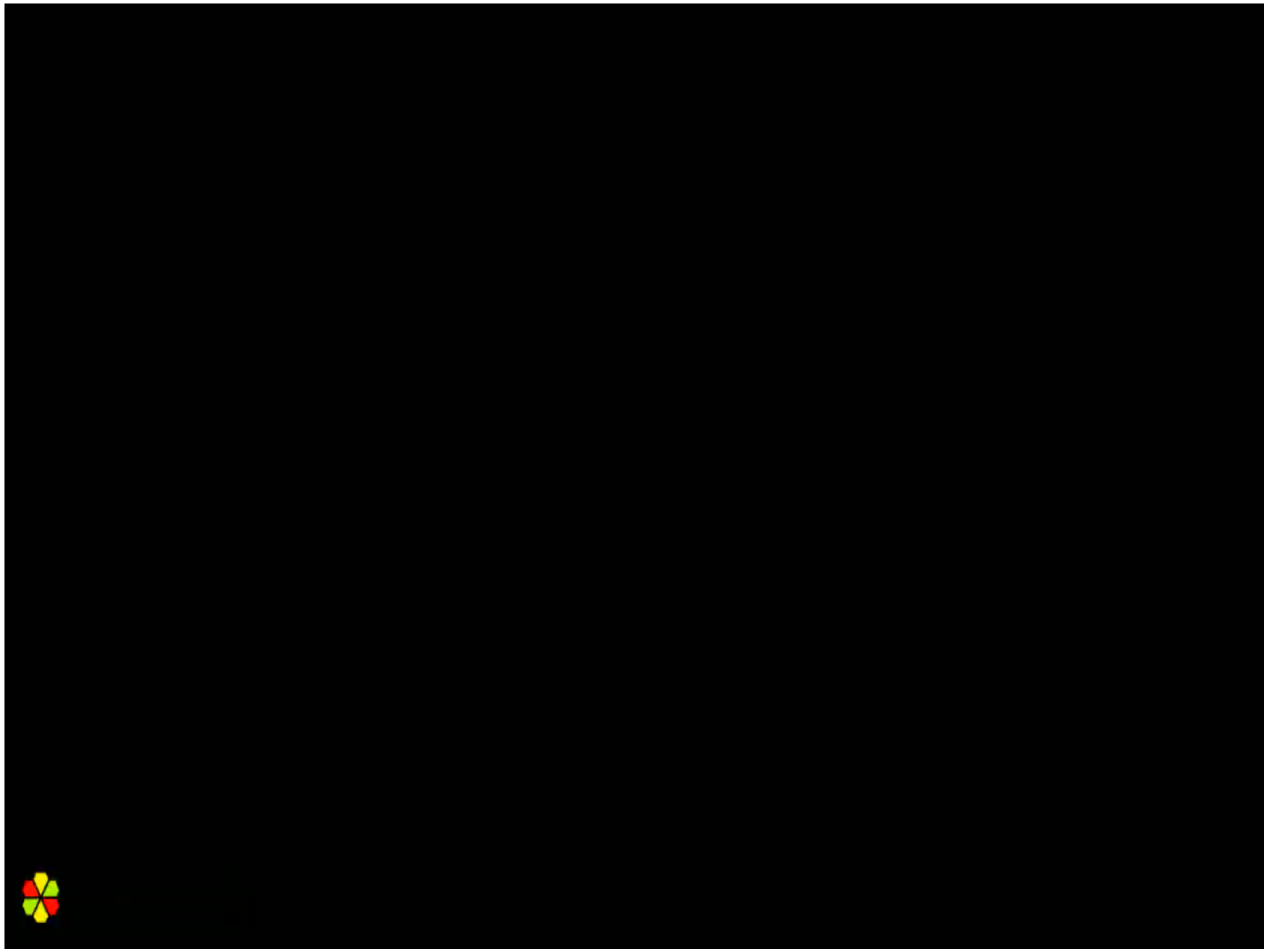
$$U_1 \approx E_1 = 4.44 \cdot N_1 \cdot f_1 \cdot \phi$$

$$E_2 = 4.44 \cdot N_2 \cdot f_2 \cdot \phi$$

$$\phi \approx \frac{U_1}{4.44 \cdot N_1 \cdot f_1}$$

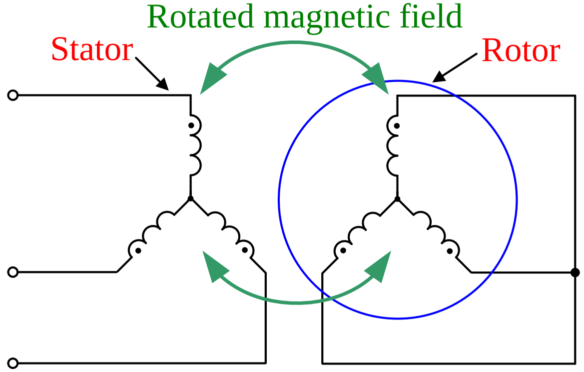
$4.44 \approx \sqrt{2}\pi$ **Refer to Topic 1 Page 30**

Video: Working principle of the transformer



Main circuit analysis of the asynchronous motor

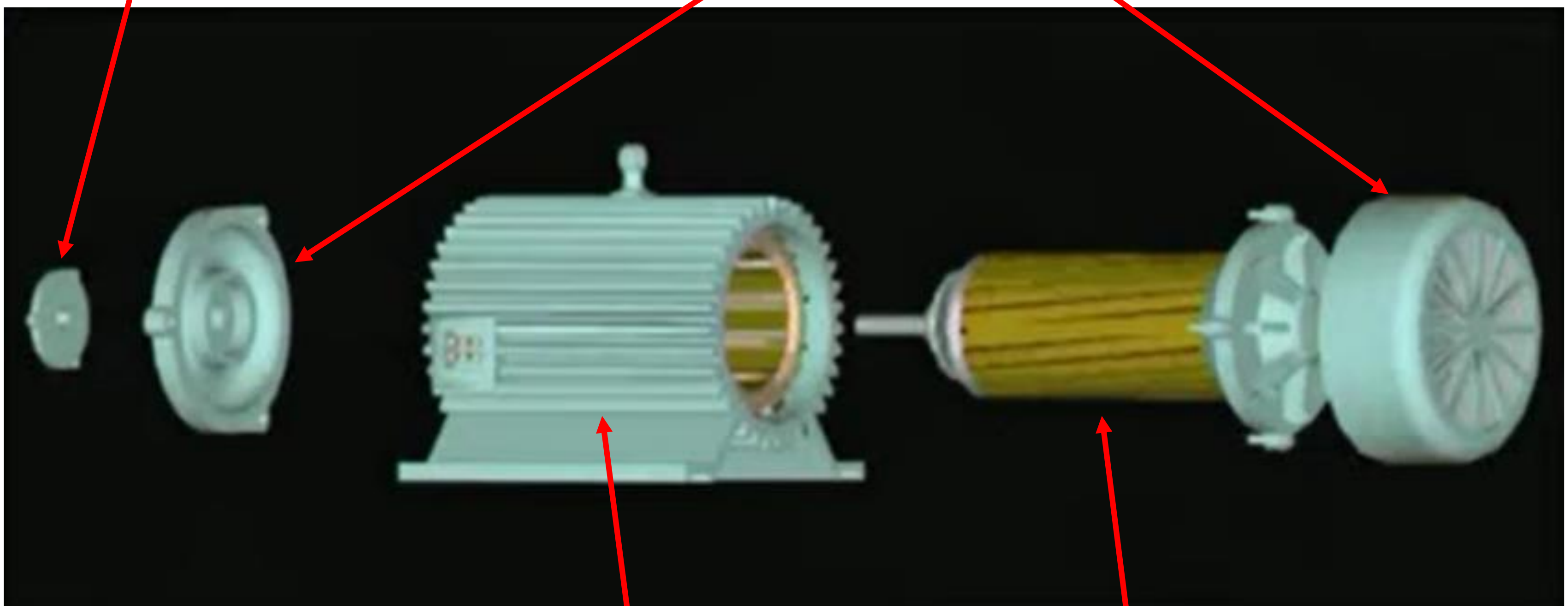
- Stator part of the asynchronous motor
- Rotated magnetic field of the asynchronous motor
- Rotor part of the asynchronous motor



Overview of the structure of the AC asynchronous motor

Bearing cap

End Bell



Stator

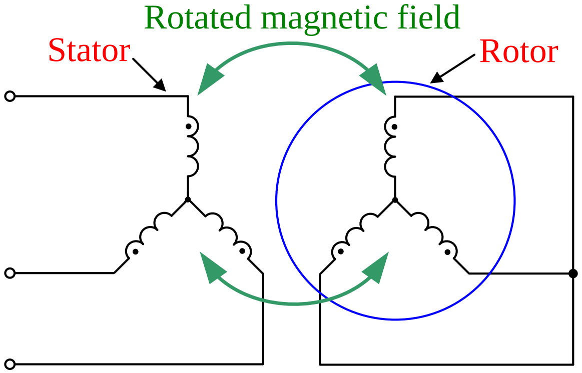
Rotor

Cage rotor

Wound rotor

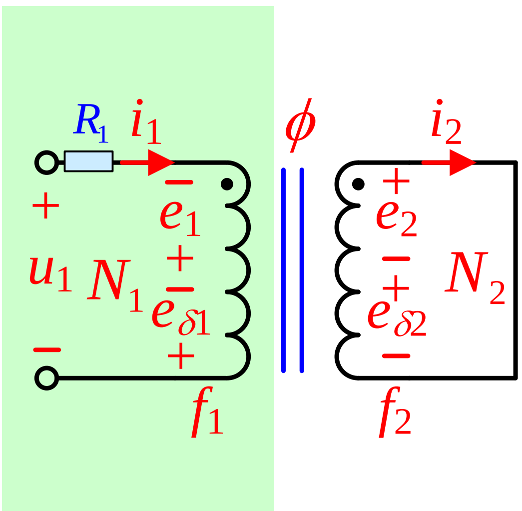
Main parts

- ❑ Stator part of the asynchronous motor
- ❑ Rotated magnetic field of the asynchronous motor
- ❑ Rotor part of the asynchronous motor



Stator of the asynchronous motor

Each phase circuit of the asynchronous motor



Stator circuit

Circuit analysis of the stator of the asynchronous motor

$$u_1 + e_{\sigma 1} + e_1 = R_1 i_1$$

$$u_1 = R_1 i_1 + \left(-e_{\sigma 1}\right) + \left(-e_1\right)$$

$$= R_1 i_1 + L_{\sigma 1}\frac{di_1}{dt} + \left(-e_1\right)$$

Time domain

↓

Phasor

$$\dot{A} = A_m \angle \varphi$$

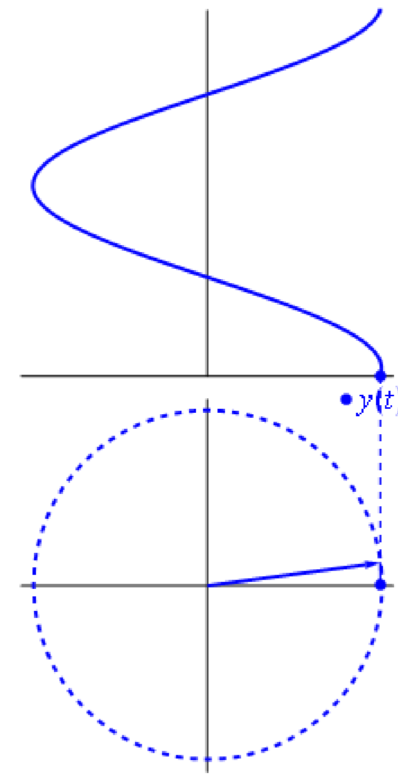
$$= A_m cos\left(\omega t + \varphi\right)$$

$$\dot{U}_1 = R_1 \dot{I}_1 + \left(-\dot{E}_{\sigma 1}\right) + \left(-\dot{E}_1\right)$$

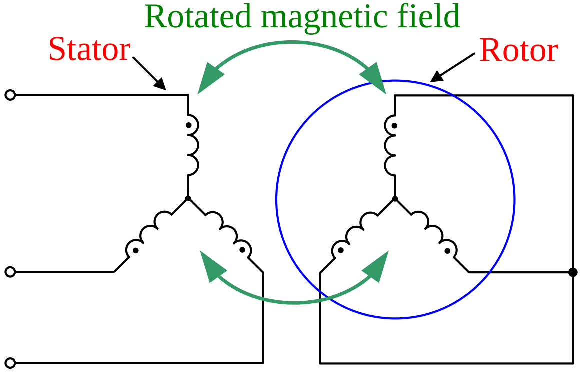
$$= R_1 \dot{I}_1 + j(2\pi f_1 L_{\sigma 1})\dot{I}_1 + \left(-\dot{E}_1\right)$$

$$= R_1 \dot{I}_1 + jX_{\sigma 1}\dot{I}_1 + \left(-\dot{E}_1\right)$$

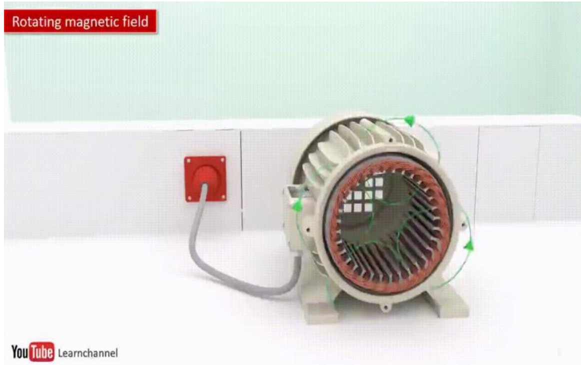
Recall: relationship between time domain and phasor

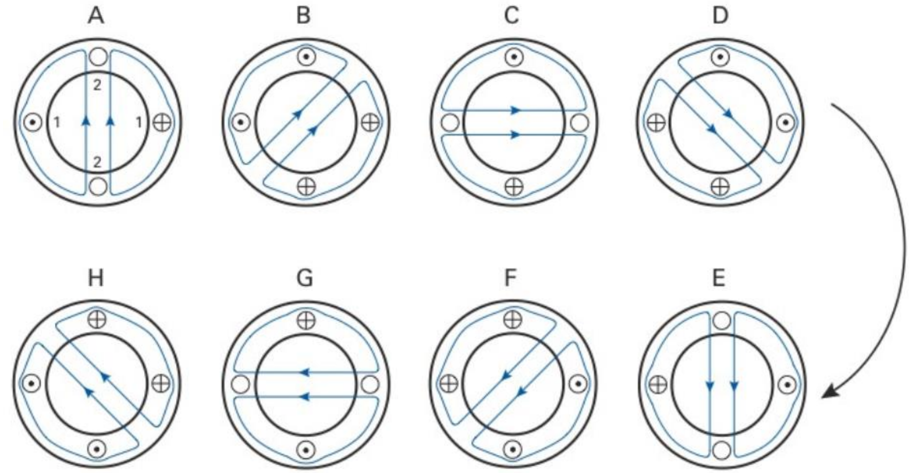


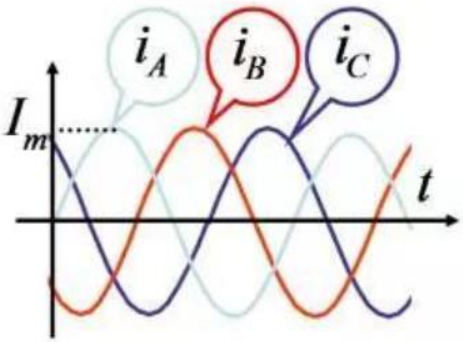
- ❑ Stator part of the asynchronous motor
- ❑ Rotated magnetic field of the asynchronous motor
- ❑ Rotor part of the asynchronous motor



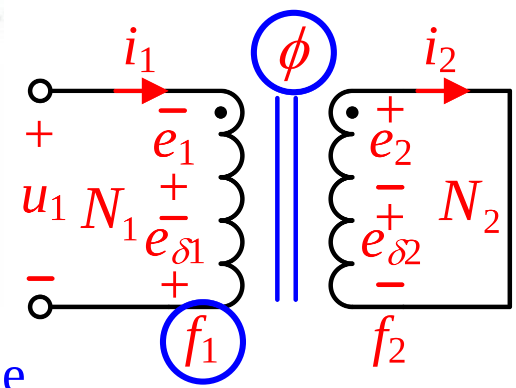
Rotated magnetic field of the asynchronous motor







n_0: Rotated speed of the rotated magnetic field (rpm)



Flux of the rotated magnetic field

- Frequency of the rotated magnetic field ($f_1 \rightarrow$ stator current frequency)

$$n_0 = \frac{60 f_1}{P} \Longrightarrow f_1 = \frac{P n_0}{60}$$

rpm

Pole pairs

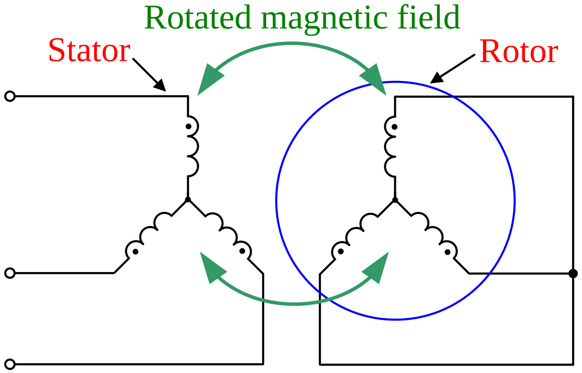
- Flux per magnetic pole

$$\phi \approx \frac{U_1}{4.44 \cdot N_1 \cdot f_1}$$

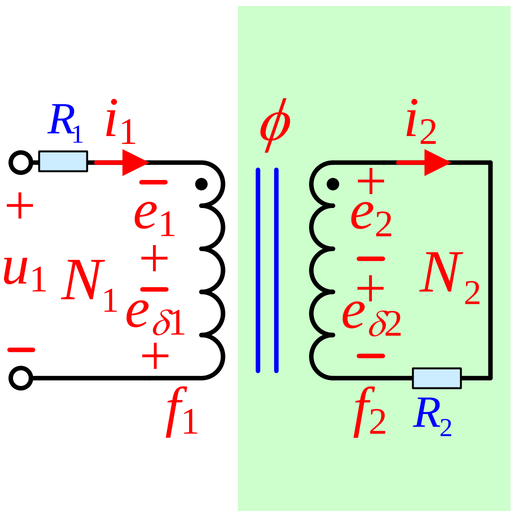
$\phi \propto U_1$

Main circuit analysis of the asynchronous motor

- ❑ Stator part of the asynchronous motor
- ❑ Rotated magnetic field of the asynchronous motor
- ❑ Rotor part of the asynchronous motor



Each phase circuit of the asynchronous motor



Rotor circuit

Circuit analysis of the stator of the asynchronous motor

$$e_{\sigma 2} + e_2 = R_2 i_2$$

$$e_2 = R_2 i_2 + (-e_{\sigma 2})$$

$$= R_2 i_2 + L_{\sigma 2} \frac{di_2}{dt}$$

Time domain

↓

Phasor

$$\dot{A} = A_m \angle \varphi$$

$$= A_m cos(\omega t + \varphi)$$

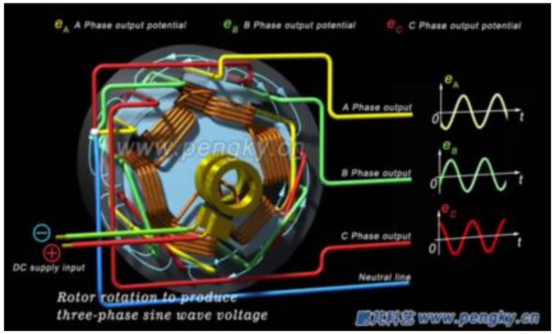
$$\dot{E}_2 = R_2 \dot{I}_2 + (-\dot{E}_{\sigma 2})$$

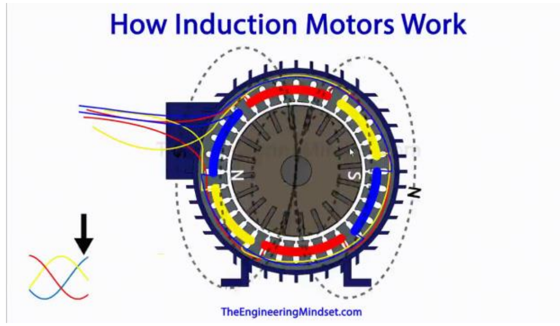
$$= R_2 \dot{I}_2 + j(2\pi f_2 L_{\sigma 2})\dot{I}_2$$

$$= R_2 \dot{I}_2 + jX_{\sigma 2} \dot{I}_2$$

- Electromotive force of the rotor windings E_2
  - Frequency of E_2
  - Characteristics of E_2
- Inductive reactance of the rotor winding $X_{\delta 2}$
- Current of the rotor winding I_2
- Power factor of the asynchronous motor

Frequency of the rotor electromotive force (E_2): f_2



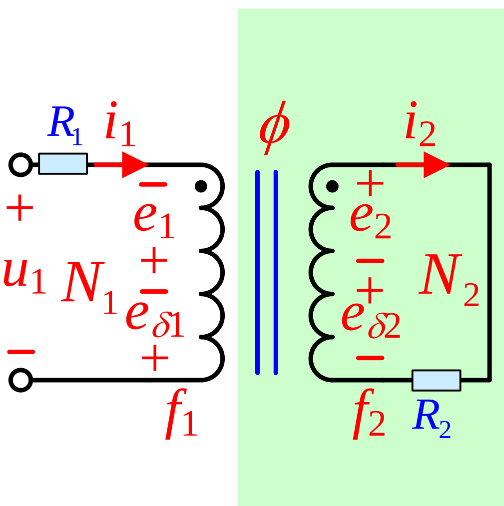


- Rotated speed of the magnetic field n_0
- Rotated speed of the rotor n

$$\boxed{n < n_o} \qquad \boxed{n = (1\text{-}s)\, n_o}$$

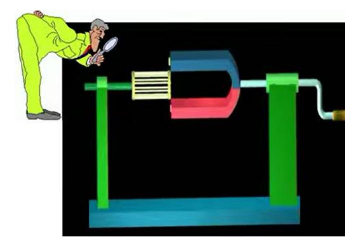
Slip ratio:

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$



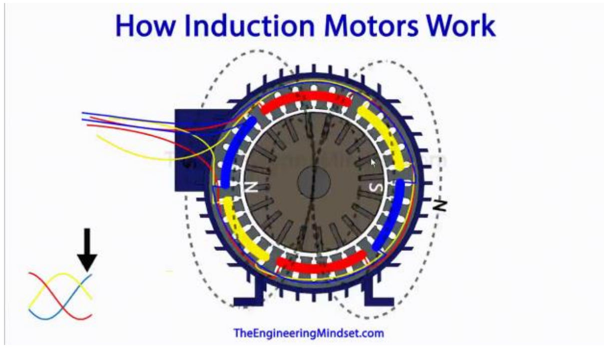
The speed difference between the rotated magnetic field and the rotated rotor generate the electromotive force E_2

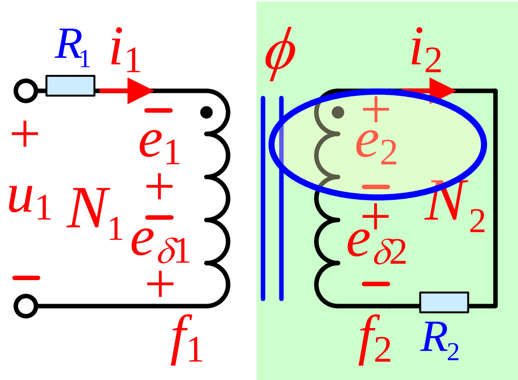
$$\boxed{\Delta n = \frac{60 \cdot f_2}{P}} \rightarrow \boxed{f_2 = \frac{P \cdot \Delta n}{60} = \frac{P \cdot (n_o\text{-}n)}{60}}$$



$$\boxed{f_2 = \frac{P\left(n_o - (1\text{-}s)\, n_o\right)}{60} = \frac{P \cdot s \cdot n_o}{60} = s \cdot \frac{P \cdot n_o}{60} = s \cdot f_1}$$

Characteristics of the rotor electromotive force E_2





$$E_2 = 4.44 \cdot N_2 \cdot f_2 \cdot \phi$$

$\boxed{f_2 = s \cdot f_1}$

$$E_2 = s \cdot 4.44 N_2 f_1 \phi$$

$s = \left(\dfrac{n_0 - n}{n_0}\right) \times 100\%$

$\boxed{s \in [0,1]}$

$$E_{2\max} = 4.44 N_2 f_1 \phi$$ when $s=1$

Maximum E_2

$$\phi \approx \frac{U_1}{4.44 \cdot N_1 \cdot f_1}$$

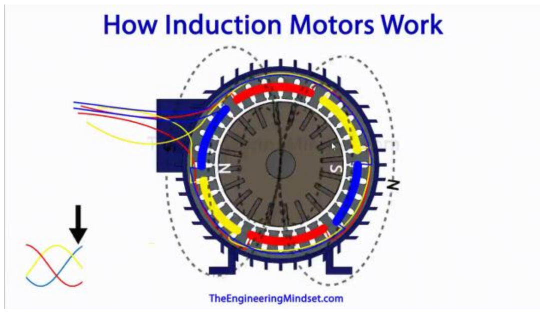
When $s=1$?

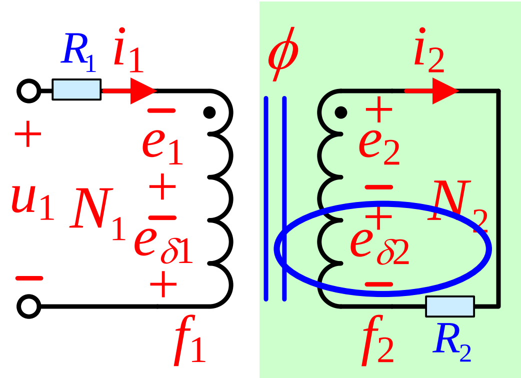
$s = \left(\dfrac{n_0 - n}{n_0}\right) \times 100\%$

$\boxed{\text{if } s = 1?}$

$$\boxed{1 = \frac{n_0 - n}{n_0}} \Rightarrow \boxed{n = 0} \Rightarrow$$ The rotor is not rotated

Inductive reactance of the rotor winding $X_{\delta 2}$





$$X_{\sigma 2} = 2\pi f_2 L_{\sigma 2}$$

Caused by leakage flux

$$\boxed{f_2 = s \cdot f_1}$$

$$X_{\sigma 2} = s \cdot 2\pi f_1 L_{\sigma 2}$$

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$\boxed{s \in [0,1]}$$

$$X_{\sigma 2\max} = 2\pi f_1 L_{\sigma 2}$$

when s=1

Maximum $X_{\delta 2}$

When s=1?

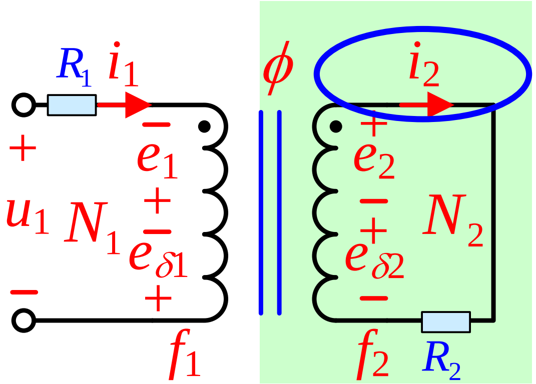
$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$\boxed{s = 1}$$

$$\boxed{1 = \frac{n_0 - n}{n_0}} \Rightarrow \boxed{n = 0} \Rightarrow$$

The rotor is not rotated

Current of the rotor winding I_2



$$\dot{E}_2 = R_2\dot{I}_2 + \left(-\dot{E}_{\sigma 2}\right)$$
$$= R_2\dot{I}_2 + j(2\pi f_2 L_{\sigma 2})\dot{I}_2$$
$$= R_2\dot{I}_2 + jX_{\sigma 2}\dot{I}_2$$

$$\begin{cases} s=0 \quad I_2 = I_{2\min} = \dfrac{E_{2\max}}{\infty} = 0 \\ s=1 \quad I_2 = I_{2\max} = \dfrac{E_{2\max}}{\sqrt{R_2^2 + \left(X_{\sigma 2\max}\right)^2}} \end{cases}$$

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$\boxed{s \in [0,1]}$$

$$I_2 \propto s$$

$$I_2 = \frac{E_{2\max}}{\sqrt{\dfrac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}}$$

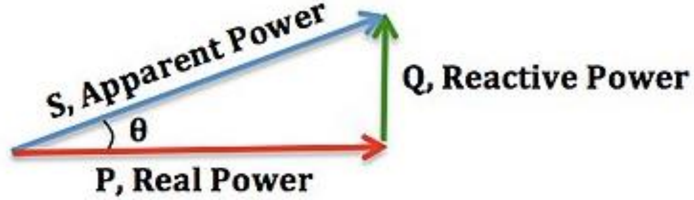
$$I_2 = \frac{E_2}{\sqrt{R_2^2 + X_{\sigma 2}^2}}$$

$$E_2 = s \cdot 4.44 N_2 f_1 \phi = s \cdot E_{2\max}$$
$$X_{\sigma 2} = s \cdot 2\pi f_1 L_{\sigma 2} = s \cdot X_{\sigma 2\max}$$

$$I_2 = \frac{s \cdot E_{2\max}}{\sqrt{R_2^2 + \left(s \cdot X_{\sigma 2\max}\right)^2}}$$

Power factor cosθ of the asynchronous motor

Definition of the power factor

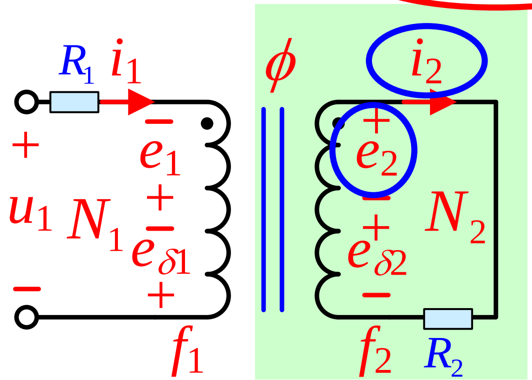


$$S = P + jQ$$

$$|S|^2 = P^2 + Q^2$$

$$|S| = \sqrt{P^2 + Q^2}$$

$$\cos\theta,\ \text{power factor} = \frac{P,\ \text{real power}}{|S|,\ \text{apparent power}}$$



$$\boxed{\dot{E}_2 = R_2 \dot{I}_2 + jX_{\sigma 2} \dot{I}_2}$$

$$S = \dot{E}_2 \cdot \dot{I}_2 = \left(R_2 \cdot I_2^2 + jX_{\sigma 2} I_2^2\right)$$

$$P = R_2 \cdot I_2^2 \qquad Q = X_{\sigma 2} I_2^2$$

$$\cos\theta = \frac{P}{|S|} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{R_2 \cdot \cancel{I_2^2}}{\sqrt{\left(R_2 \cdot \cancel{I_2^2}\right)^2 + \left(X_{\sigma 2} \cancel{I_2^2}\right)^2}}$$

$X_{\sigma 2} = sX_{\sigma 2\max}$

$$\Longrightarrow \cos\theta = \frac{R_2}{\sqrt{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}} = \frac{1}{\sqrt{1 + \left(\frac{sX_{\sigma 2\max}}{R_2}\right)^2}}$$

If $sX_{\sigma 2\max} \gg R_2$

$$\boxed{\left(\frac{sX_{\sigma 2\max}}{R_2}\right)^2 \gg 1} \qquad \cos\theta \approx \frac{1}{\sqrt{\left(\frac{sX_{\sigma 2\max}}{R_2}\right)^2}} = \frac{R_2}{sX_{\sigma 2\max}}$$

If $sX_{\sigma 2\max} \ll R_2$

$$\boxed{\left(\frac{sX_{\sigma 2\max}}{R_2}\right)^2 \ll 1} \qquad \cos\theta \approx 1$$

The curve of rotor current I_2 and motor power factor $\cos\theta$

$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}}$$

$s \nearrow \Rightarrow I_2 \nearrow$

$s \searrow \Rightarrow I_2 \searrow$

$\boxed{s \in [0,1]}$

$I_{2\min} = 0$

$$I_{2\max} = \frac{E_{2\max}}{\sqrt{R_2^2 + \left(X_{\sigma 2\max}\right)^2}}$$

$$\cos\theta = \frac{R_2}{\sqrt{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}}$$

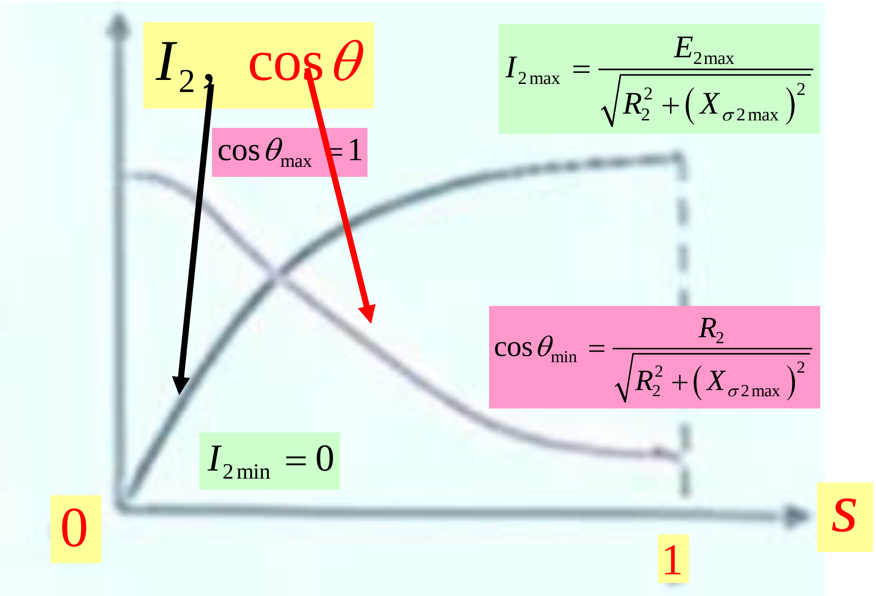
$s \nearrow \Rightarrow \cos\theta \searrow$

$s \searrow \Rightarrow \cos\theta \nearrow$

$\boxed{s \in [0,1]}$

$$\cos\theta_{\min} = \frac{R_2}{\sqrt{R_2^2 + \left(X_{\sigma 2\max}\right)^2}}$$

$\cos\theta_{\max} = 1$



Both the rotor current I_2 and power factor $\cos\theta$ have great relationship with the slip ratio s

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

Both the rotor current I_2 and power factor $\cos\theta$ have great relationship with the rotor speed n

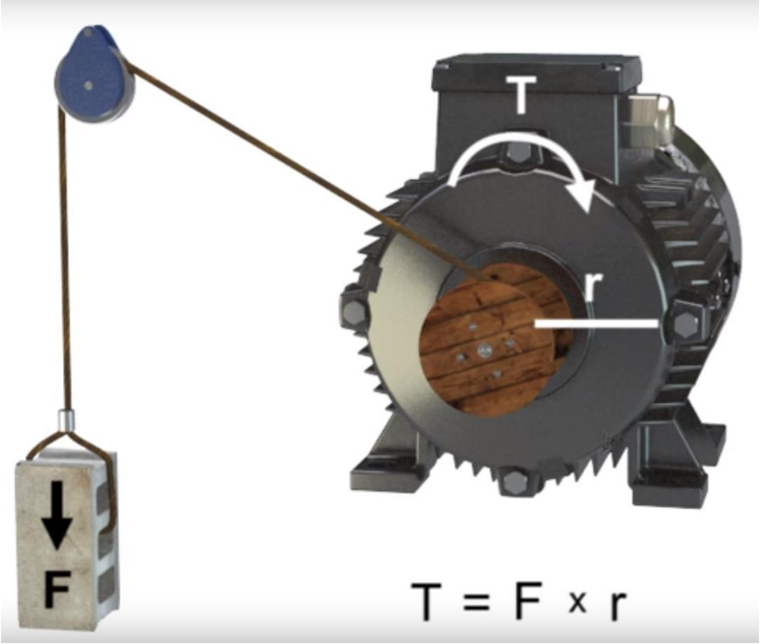
CHARACTERISTICS OF ASYNCHRONOUS MOTOR

[17/03/2020]

- Circuit analysis of the asynchronous motor
- Torque of the asynchronous motor
- Stable region of the asynchronous motor

What is a torque?

- Torque is the rotational force. Just as a linear force is a push or a pull, a torque can be thought of as a twist to an object.

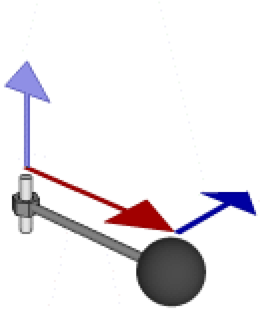


- T: Torque
- F: Force acting on lever arm
- r: Perpendicular distance from the line of action

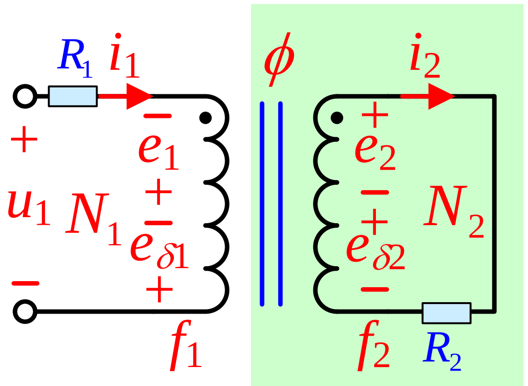
(Unit: Newton) (Unit: Metre)

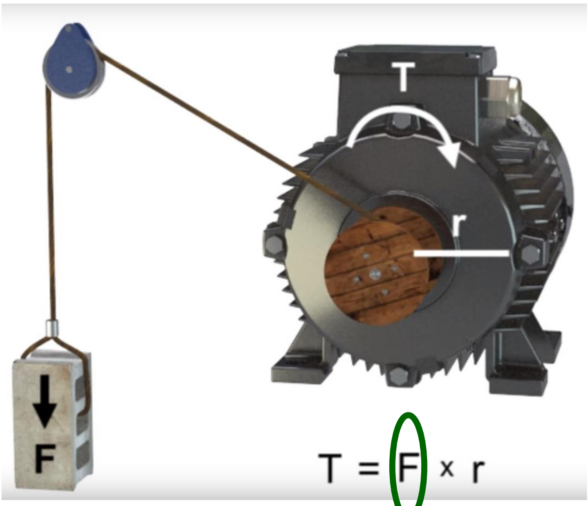
$T=F\times r$

(Unit: Newton · Metre (Nm))



Expression of the torque of the asynchronous motor





$$T \propto \phi, I_2, \cos\theta$$

Motor constant

$$T = K_T \, \phi \cdot I_2 \cdot \cos\theta$$

$$\cos\theta = \frac{R_2}{\sqrt{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}} \qquad I_2 = \frac{sE_{2\max}}{\sqrt{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}}$$

$$T = K_T \cdot \phi \cdot \frac{sE_{2\max}}{\sqrt{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}}$$

$$E_{2\max} = 4.44 N_2 f_1 \phi_m$$

$$T = K_T \cdot \phi_m \cdot s\left(4.44 N_2 f_1 \phi_m\right) \cdot \frac{R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}$$

$$T = K_T \cdot 4.44 N_2 f_1 \left(\phi_m^2\right) \cdot \frac{sR_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}$$

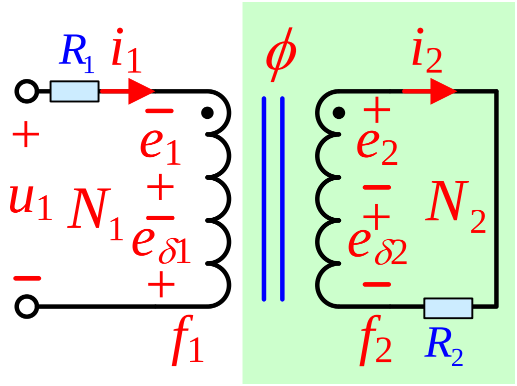
$$\phi_m \approx \frac{U_1}{4.44 \cdot N_1 \cdot f_1}$$

$$T = K_T \cdot \cancel{4.44} N_2 \cancel{f_1} \frac{U_1^2}{4.44^{\cancel{2}} N_1^2 f_1^{\cancel{2}}} \cdot \frac{sR_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}$$

Also a motor constant

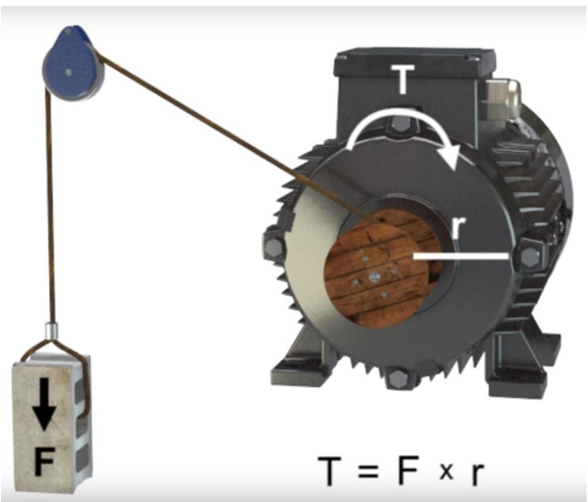
$$T = \frac{K_T N_2}{4.44 \cdot N_1^2 \cdot f_1} \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2 = K \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2$$

Expression of the torque of the asynchronous motor



motor constant

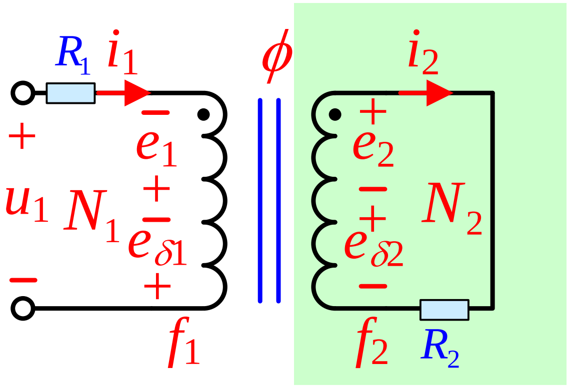
$$T = K \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2$$

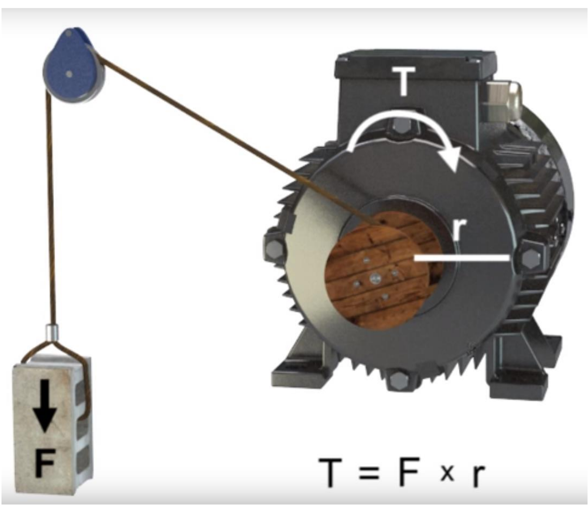


Characteristics:

- Torque is proportional to the square of the voltage of the stator winding, i.e., $T \propto U_1^2$
- If U_1 is constant, and the motor structure is fixed, motor torque T can be changed by the slip ratio s.
- If the rotor resistor R_2 is changed, the motor torque T is also changed.

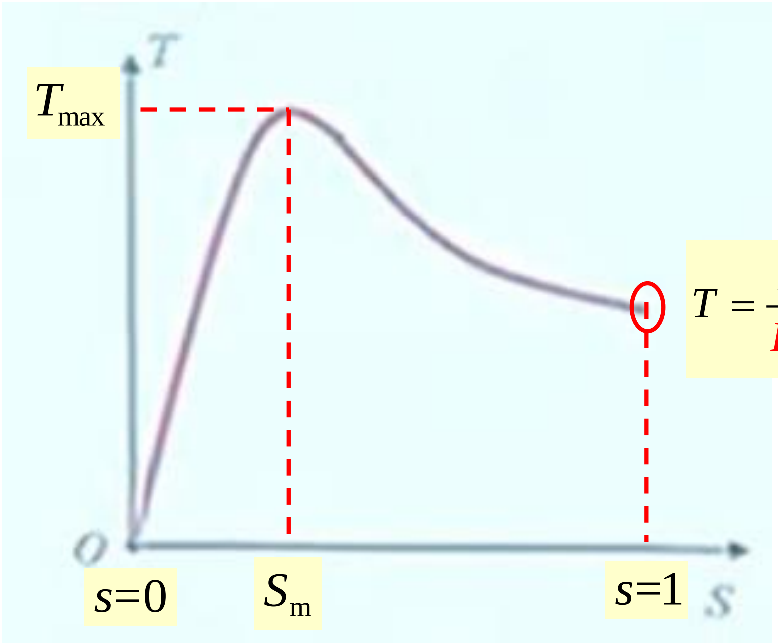
Torque (T) vs slip ratio (s) curve of the asynchronous motor





$$T = K \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2 = K \cdot \frac{R_2}{\frac{R_2^2}{s} + s \cdot X_{\sigma 2\max}^2} \cdot U_1^2$$

- First, T is increased with the increasing of s before it arrives at its maximum value.
- Then, T is decreased with the increasing of s.



$$T = \frac{K \cdot R_2 \cdot U_1^2}{R_2^2 + X_{\sigma 2\max}^2}$$

$$\boxed{s \in [0,1]}$$

$$\frac{R_2^2}{s} = s \cdot X_{\sigma 2\max}^2 \Rightarrow s_m = \frac{R_2}{X_{\sigma 2\max}}$$

Torque (T) vs Rotor speed (n) curve of the asynchronous motor

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

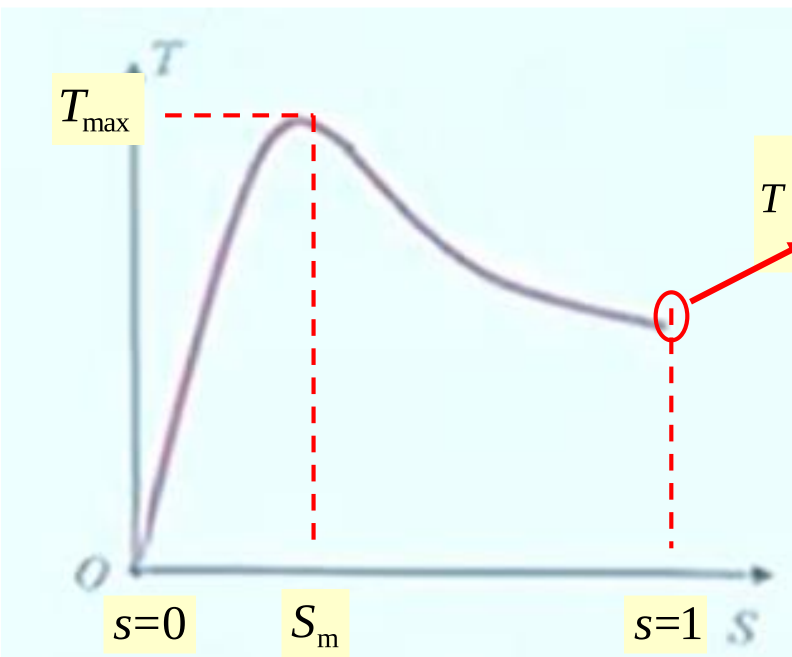
$$T = K \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2 \longrightarrow T = \frac{\left(1 - \dfrac{n}{n_0}\right) K \cdot R_2 \cdot U_1^2}{R_2^2 + \left(1 - \dfrac{n}{n_0}\right)^2 \cdot X_{\sigma 2\max}^2}$$

$s \nearrow \longrightarrow n \searrow$

$s \searrow \longrightarrow n \nearrow$

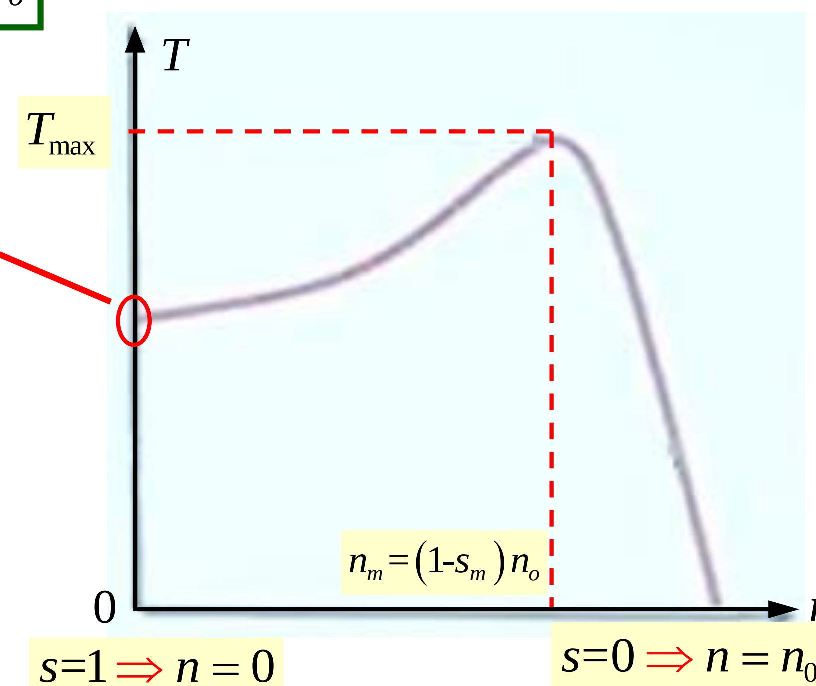
$$\boxed{n = (1-s)\, n_o}$$

T vs s curve

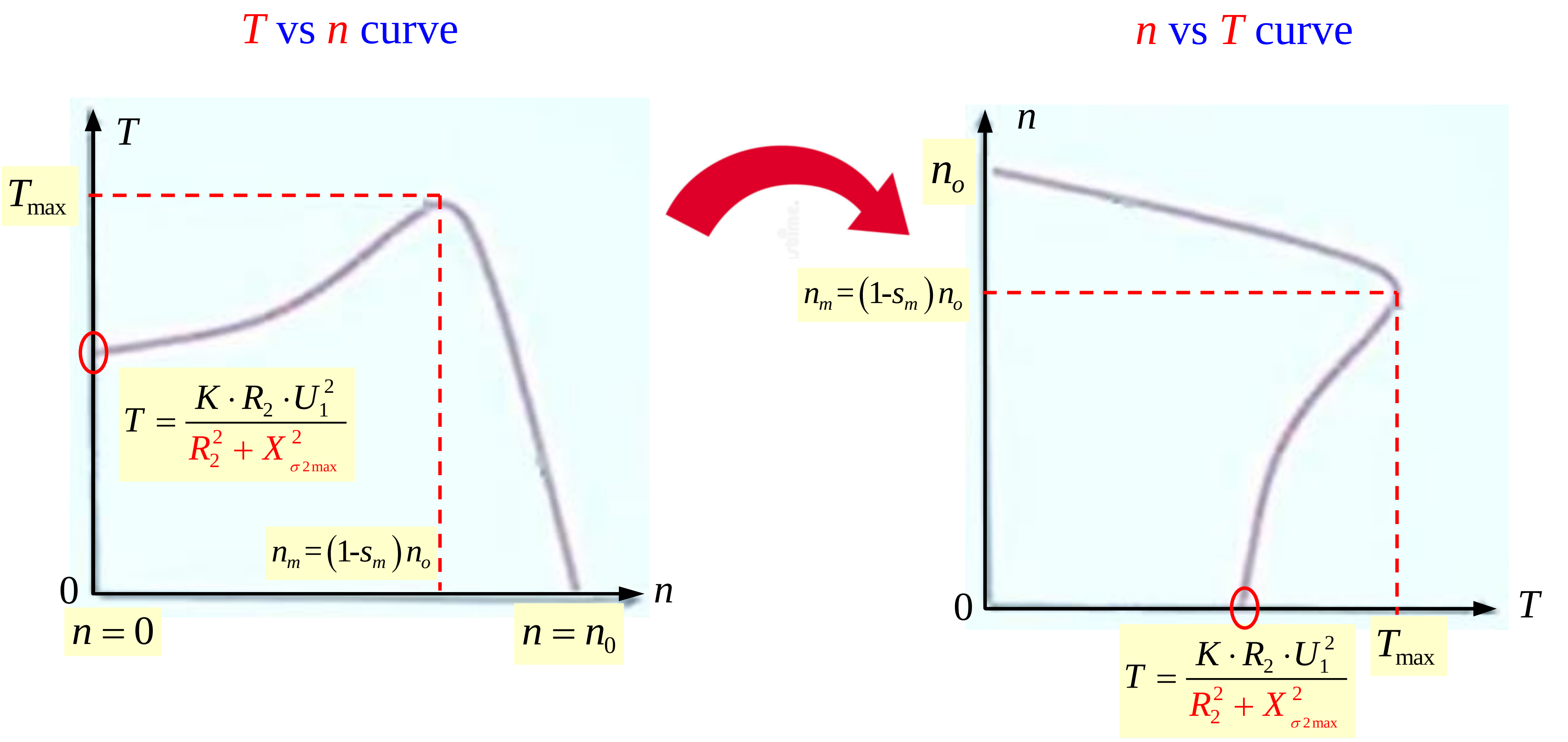


$$T = \frac{K \cdot R_2 \cdot U_1^2}{R_2^2 + X_{\sigma 2\max}^2}$$

T vs n curve



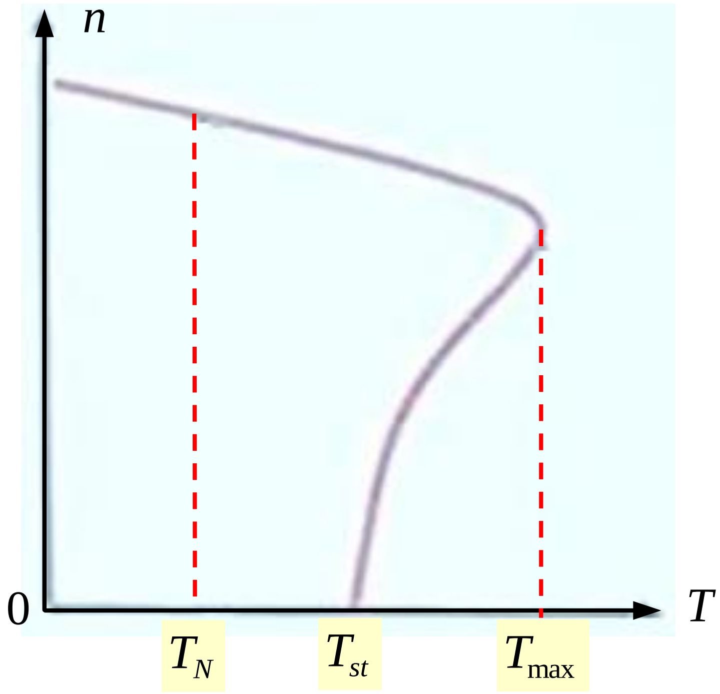
Mechanical characteristics (n vs T) curve of the asynchronous motor



n vs T curve of the asynchronous motor is also called as its mechanical characteristics curve

Three typical torques of the asynchronous motor

Mechanical characteristics curve of the asynchronous motor



- Nominal torque T_N

  Torque of the asynchronous motor at nominal power

- Starting torque T_{st}

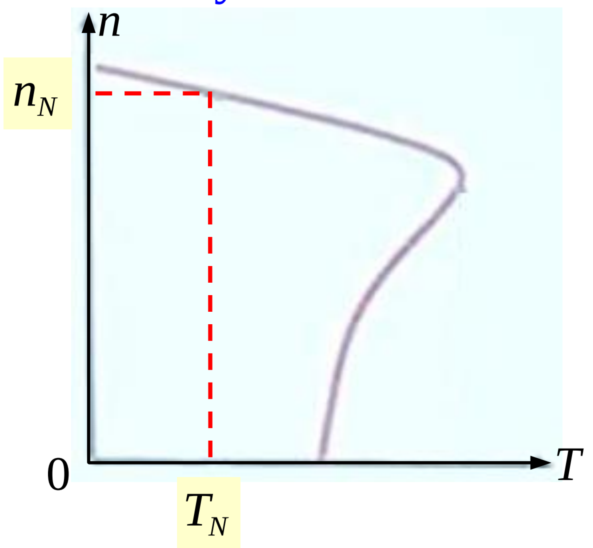
  Torque of the asynchronous motor when the motor is starting (n=0)

- Maximum torque T_{max}

  Torque of the asynchronous motor at maximum power

Nominal torque T_N of the asynchronous motor

Mechanical characteristics curve of the asynchronous motor



Nominal power of the asynchronous motor

$$P_N = F_N \cdot V_N \;\; (Note: Here\ V\ is\ Velocity)$$

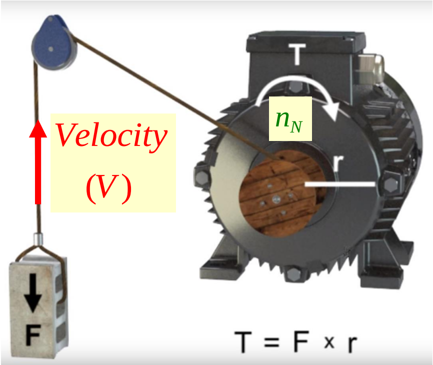
$T=F\times r \rightarrow F=T/r$ $\qquad V=2\pi r\cdot n$

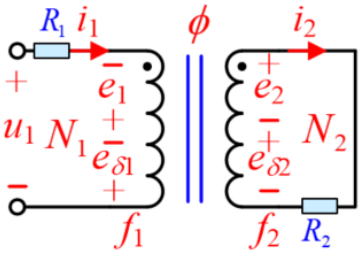
$$P_N = \frac{T_N}{\cancel{r}}\cdot 2\pi \cancel{r}\cdot n_N = T_N \cdot 2\pi n_N$$

$$T_N = \frac{P_N}{2\pi n_N}$$

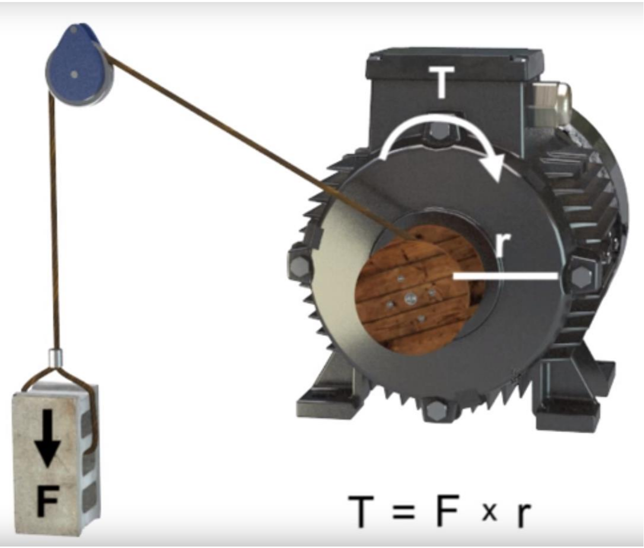
If the unit of n_N is r/mins If the unit of P_N is kW

$$T_N = \frac{1000\cdot P_N}{2\pi \frac{n_N}{60}} = 9550\cdot\frac{P_N\ (kW)}{n_N\ (rpm)}$$





Example 1: For a three phase asynchronous motor, if its rated power is P_N=7.5 kW, its rated speed is n_N=1440r/min, how about its rated torque T_N?

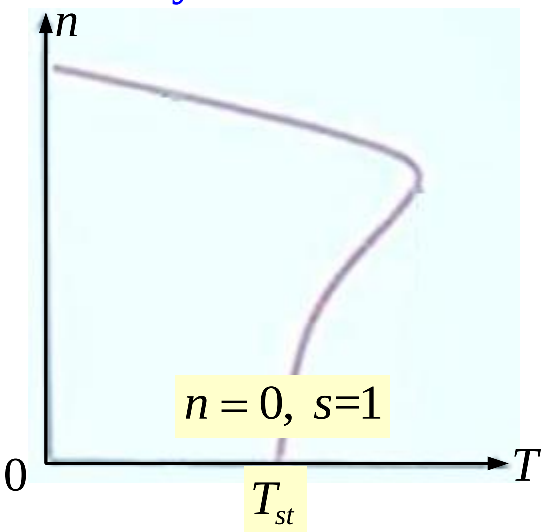


$$T_N = \frac{1000 \cdot P_N}{2\pi \frac{n_N}{60}} = 9550 \cdot \frac{P_N \ (kW)}{n_N \ (rpm)}$$

$$\boxed{T_N = 9550 \frac{P_N}{n_N} = 9550 \frac{7.5}{1440} = 49.5(\mathrm{N \cdot m})}$$

Starting torque T_{st} of the asynchronous motor

Mechanical characteristics curve of the asynchronous motor



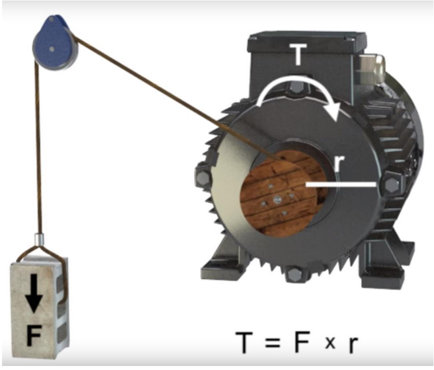
$$T = K \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2$$

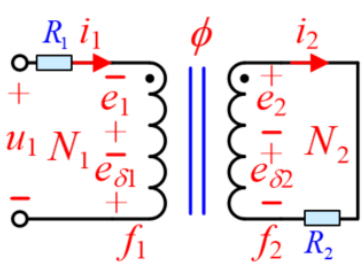
$n = 0,\ s=1$

$$T_{st} = K \cdot \frac{R_2}{R_2^2 + X_{\sigma 2\max}^2} \cdot U_1^2$$

- T_{st} reflect the ability to start the motor with load: if T_{st} < load torque, the motor cannot be started.
- T_{st} can be changed.
  - T_{st} is proportional to $U_1{}^2$
  - T_{st} also can be changed by changing R_2 or $X_{\delta 2}$
- Starting ability of the motor λ_{st}

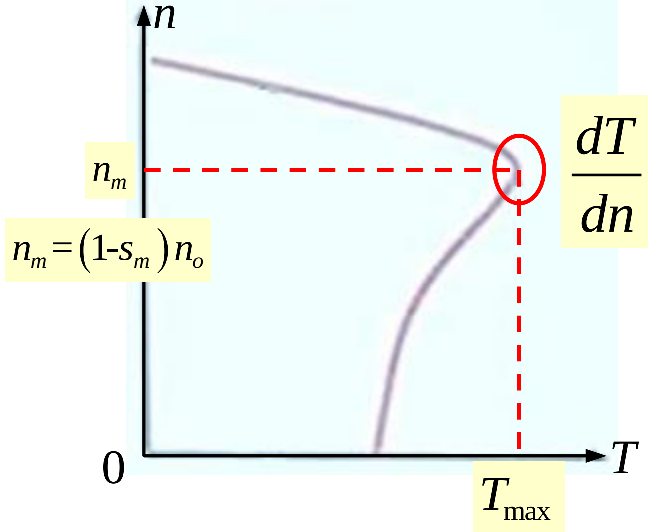
$$\lambda_{st} = \frac{T_{st}}{T_N}$$





Maximum torque T_{max} of the asynchronous motor

Mechanical characteristics curve of the asynchronous motor



$$\frac{dT}{dn}=0$$

$$n=(1-s)n_o$$

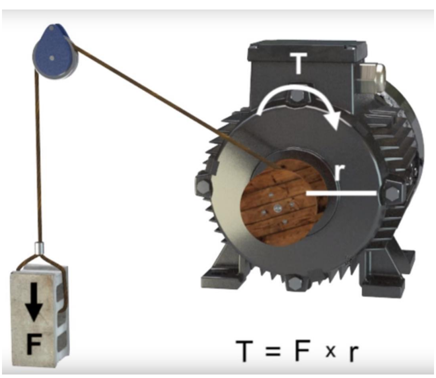
$$T=\frac{K\cdot R_2\cdot U_1^2}{\frac{R_2^2}{s}+s\cdot X_{\sigma 2\max}^2}$$

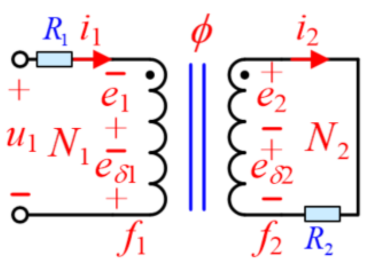
$$\frac{dT}{ds}=0$$

$$s_m=\frac{R_2}{X_{\sigma 2\max}}$$

The load torque of the motor cannot be larger than T_{max}

$$T_{\max}=\left.\frac{K\cdot R_2\cdot U_1^2}{\frac{R_2^2}{s}+s\cdot X_{\sigma 2\max}^2}\right|_{s=\frac{R_2}{X_{\sigma 2\max}}}=\frac{K\cdot U_1^2}{2X_{\sigma 2\max}}$$

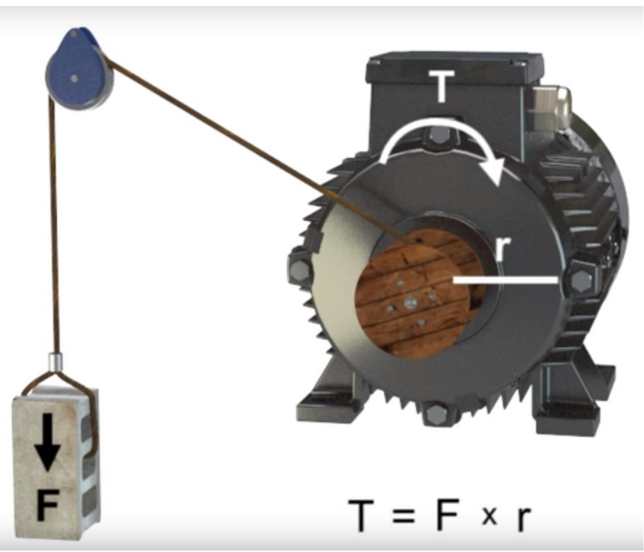




- Overload ability of the motor λ_{max}

Usually $\lambda_{\max}\in(1.8,\ 2.2)$ $\quad \lambda_{\max}=\dfrac{T_{\max}}{T_N}$

Example 2: For a three phase asynchronous motor, if its rated power is P_N=7.5 kW, its rated speed is n_N=1440r/min, its λ_{st}=1.5, λ_{max}=2 how about its start torque T_{st} and maximum torque T_m?



According to Example 1:

$$T_N = 9550\frac{P_N}{n_N} = 9550\frac{7.5}{1440} = 49.5(\text{N}\cdot\text{m})$$

$$\lambda_{st} = \frac{T_{st}}{T_N}$$

$$T_{st} = \lambda_{st}\cdot T_N = 1.5\cdot 49.5 = 74.25(\text{N}\cdot\text{m})$$

$$\lambda_{\max} = \frac{T_{\max}}{T_N}$$

$$T_m = \lambda_{\max}\cdot T_N = 2\cdot 49.5 = 99(\text{N}\cdot\text{m})$$

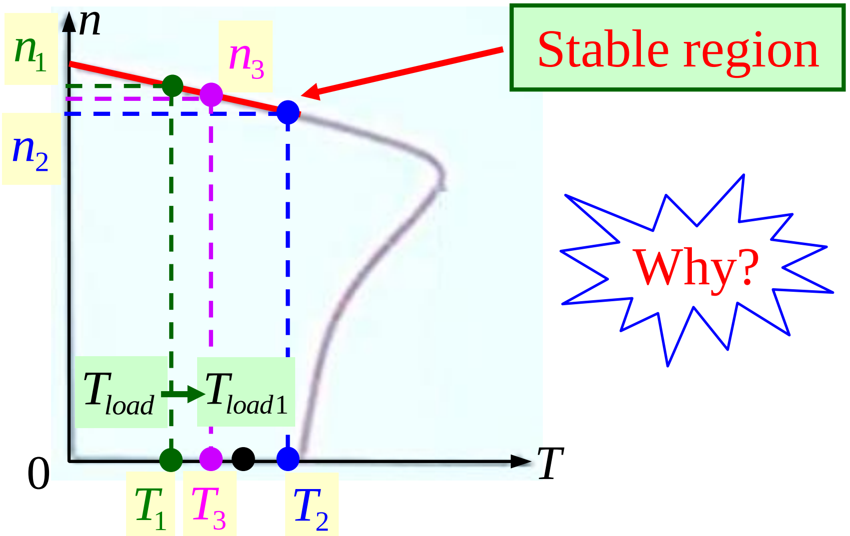
CHARACTERISTICS OF ASYNCHRONOUS MOTOR

[17/03/2020]

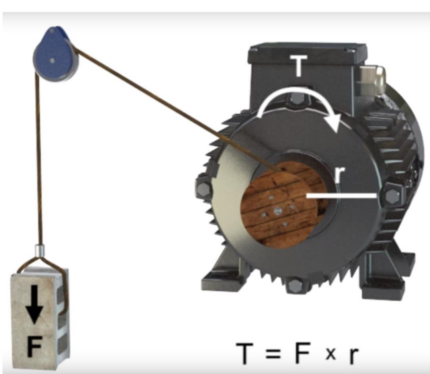
- Circuit analysis of the asynchronous motor
- Torque of the asynchronous motor
- Stable region of the asynchronous motor

Stable region of the mechanical characteristics curve of the asynchronous motor

Mechanical characteristics curve of the asynchronous motor



Why?



● $T_1 = T_{Load}$ $n = n_1$

If T_{load} ↗ ⇒ $T_1 < T_{Load1}$ ⇒ n ↘

Need more Torque

● $n = n_2$

T is increased from T_1 to T_2

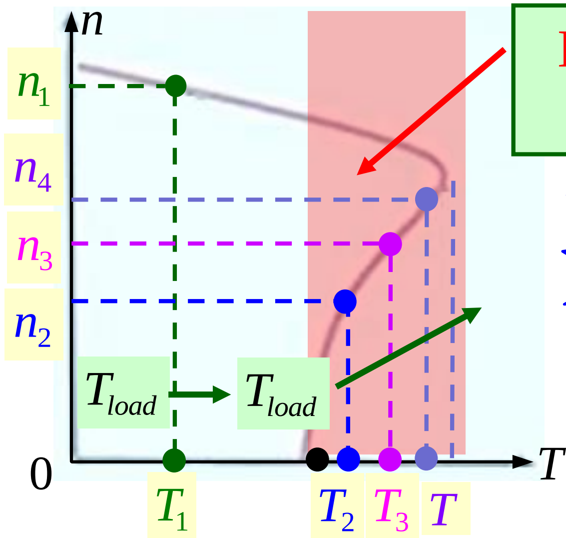
$T_2 > T_{Load1}$

n ↗ ⇒ ● $n = n_3$ ⇒ T is decreased from T_2 to T_3

Motor torque is adaptive to the load torque

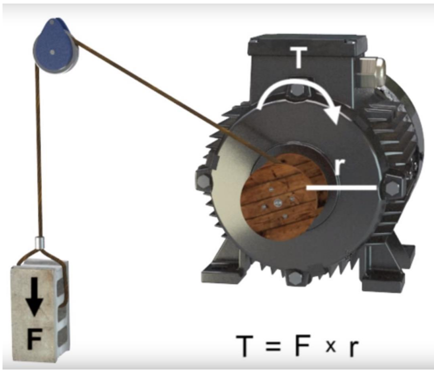
Non-stable region of the mechanical characteristics curve of the asynchronous motor

Mechanical characteristics curve of the asynchronous motor



Non-Stable region

Why?



● $T_1 = T_{Load}$ $n = n_1$

If T_{load} ↗ ⇒ $T_1 < T_{Load}$ ⇒ n ↘

⇓

● $n = n_2$

⇓

T is increased from T_1 to T_2

⇓

$T_2 > T_{Load}$

⇓

n ↗ ⇒ ● $n = n_3$ ⇒

T is still increased from T_2 to T_3

⇑

$T_3 > T_{Load}$

⇑

n ↗

↑

T keep increasing

Example 3: For a three phase asynchronous motor, if its load torque is constant, and if its stator voltage U_1 is decreased, what happened to its motor torque T, rotor current i_2 and rotor speed n?

$T = T_{load}$ $\quad U_1^2 \searrow$

$$T = K \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2$$

$\Downarrow$

$T \searrow$

$\Downarrow$

$T < T_{load}$

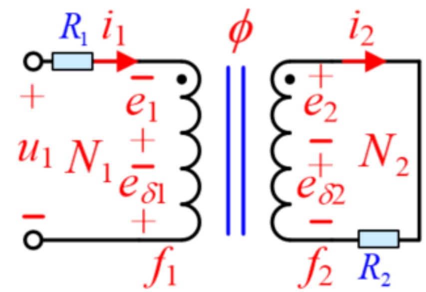
$\Downarrow$

$n \searrow$ $\Rightarrow$ $s \nearrow$

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

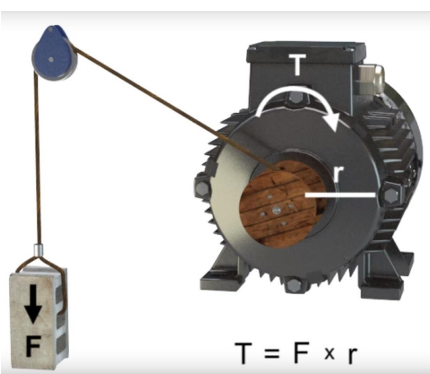
$\Uparrow$

$I_2 \quad T \nearrow$



$$T = K \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2$$

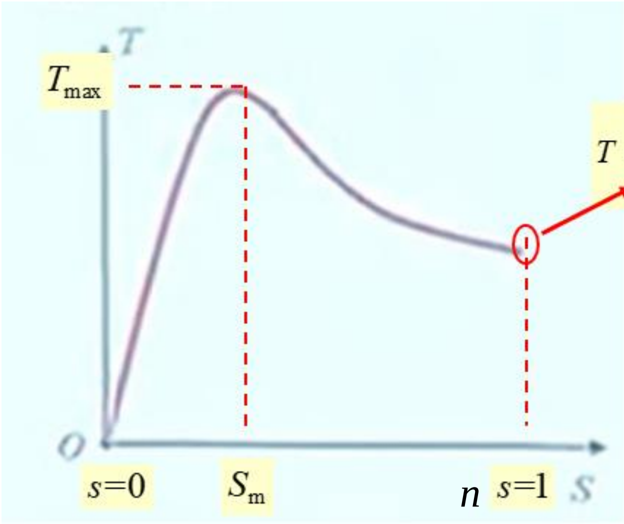
$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}}$$



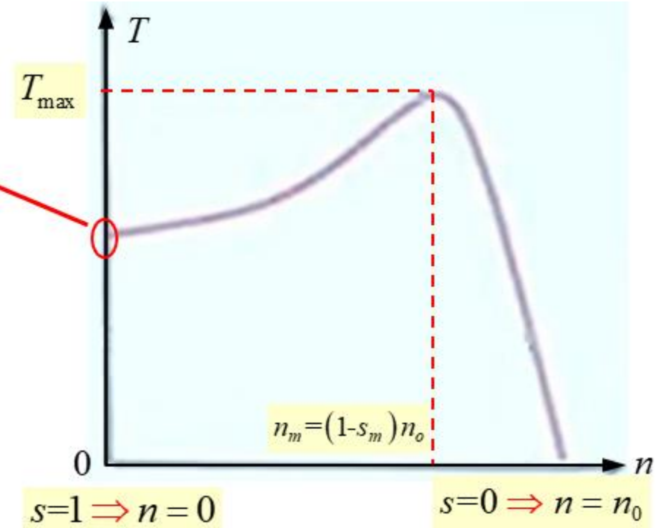
Review of today's topic

- Understand the stator & rotor equivalent circuit of the asynchronous motor.
- Understand the characteristics of the stator rotated magnetic field.
- What is the torque of the asynchronous motor?
- Understand T vs s curve.
- Understand T vs n curve.
- Understand n vs T curve.
- Understand the stable operation region of the asynchronous motor.

Review of today's topic

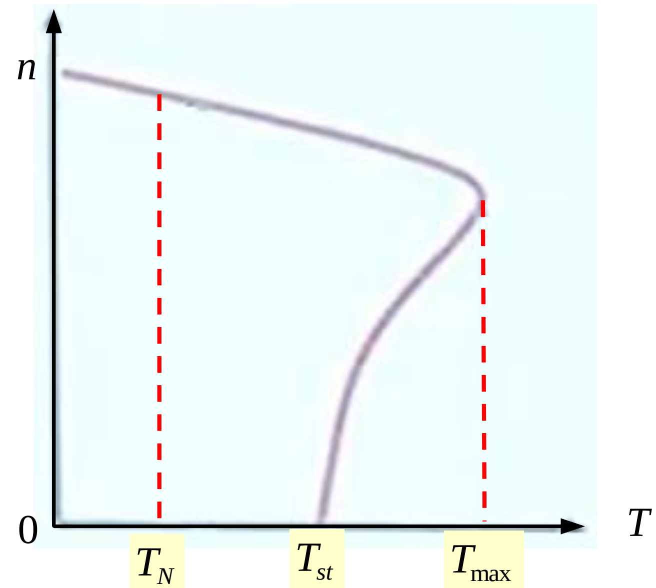


$$T = \frac{K \cdot R_2 \cdot U_1^2}{R_2^2 + X^2_{\sigma 2\max}}$$



$$T = K \cdot \frac{s \cdot R_2}{R_2^2 + \left(sX_{\sigma 2\max}\right)^2} \cdot U_1^2$$

$$\frac{R_2^2}{s} = s \cdot X^2_{\sigma 2\max} \Rightarrow s_m = \frac{R_2}{X_{\sigma 2\max}}$$



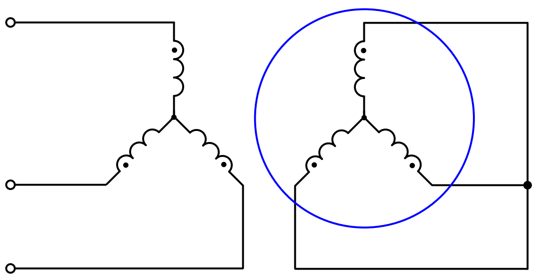
An example to review the knowledge points

Example 4: A 5 Pole-pairs, 50 Hz, Y connection, 3-phase asynchronous motor having a rated 60 kW output power and 415 V input line voltage. The slip ratio of this motor is 5% at 0.6 power factor (lagging). If the full load efficiency is 90%, please calculate:

a) Input power;
b) Input line current and phase current;
c) Speed of the rotor (rpm);
d) Frequency of the rotor;
e) Torque developed by the motor (ignore any frication)

Solutions:

a) $$\boxed{\eta = \frac{P_{out}}{P_{in}} = 0.9 \Rightarrow P_{in} = \frac{P_{out}}{0.9} = \frac{60kW}{0.9} = 66.67KW}$$



Y-Y Connection

b) Since it is Y connection,

line current I_L=phase current I_ϕ

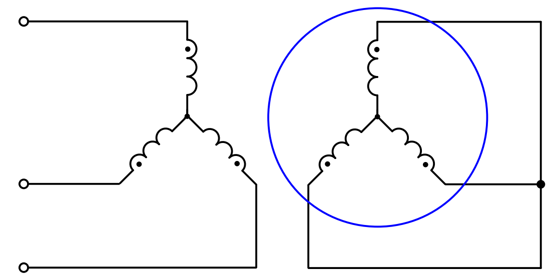
$$\boxed{Phase\ voltage\ V_\phi = \frac{1}{\sqrt{3}} \cdot Line\ voltage\ V_L}$$

An example to review the knowledge points (continue)

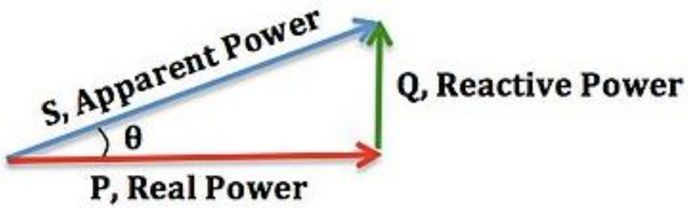
Solutions:

b) Since it is Y connection,

line current I_L=phase current I_ϕ



$$\boxed{Phase\ voltage\ V_\phi = \frac{1}{\sqrt{3}} \cdot Line\ voltage\ V_L}$$



$$\boxed{P_{in} = 3V_\phi I_\phi \cos\theta = \sqrt{3}V_L I_L \cos\theta}$$

$$\boxed{I_L = \frac{P_{in}}{\sqrt{3}V_L \cos\theta} = \frac{66.67kW}{\sqrt{3}(415)(0.6)} = 154.59A}$$

$$\boxed{I_\phi = I_L = 154.59\angle\theta = 154.59\angle(\arccos 0.6) = 154.59\angle(-53.13°)}$$

An example to review the knowledge points (continue)

Example 4: A 5 Pole-pairs, 50 Hz, Y connection, 3-phase asynchronous motor having a rated 60 kW output power and 415 V input line voltage. The slip ratio of this motor is 5% at 0.6 power factor (lagging). If the full load efficiency is 90%, please calculate:

a) Input power;
b) Input line current and phase current;
c) Speed of the rotor (rpm);
d) Frequency of the rotor;
e) Torque developed by the motor (ignore any frication)

Solutions:

c)

$$n_0 = \frac{60 \cdot f}{P} = \frac{60 \cdot (50)}{5} = 600(\text{rpm})$$

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$s = \frac{n_0 - n}{n_0} \Rightarrow n = n_0 (1 - s) = 600 \cdot (1 - 5\%) = 570(\text{rpm})$$

An example to review the knowledge points (continue)

Example 4: A 5 Pole-pairs, 50 Hz, Y connection, 3-phase asynchronous motor having a rated 60 kW output power and 415 V input line voltage. The slip ratio of this motor is 5% at 0.6 power factor (lagging). If the full load efficiency is 90%, please calculate:

a) Input power;
b) Input line current and phase current;
c) Speed of the rotor (rpm);
d) Frequency of the rotor;
e) Torque developed by the motor (ignore any frication)

Solutions:

d)

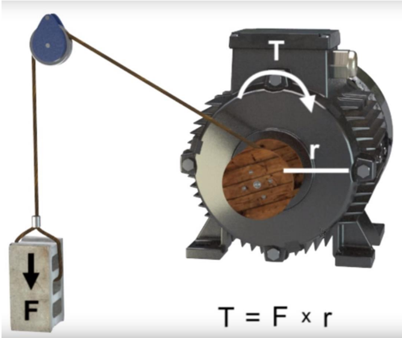
$$\boxed{n_0 - n = \frac{60 \cdot f_r}{P}}$$

$$\boxed{s \cdot n_0 = \frac{60 \cdot f_r}{P} \Rightarrow f_r = \frac{s \cdot n_0 \cdot P}{60} = \frac{5\% \cdot 600 \cdot 5}{60} = 2.5Hz}$$

An example to review the knowledge points (continue)

Example 4: A 5 Pole-pairs, 50 Hz, Y connection, 3-phase asynchronous motor having a rated 60 kW output power and 415 V input line voltage. The slip ratio of this motor is 5% at 0.6 power factor (lagging). If the full load efficiency is 90%, please calculate:

a) Input power;
b) Input line current and phase current;
c) Speed of the rotor (rpm);
d) Frequency of the rotor;
e) Torque developed by the motor (ignore any frication)



Solutions:

e)
$$\boxed{T_N = 9550\frac{P_N}{n_N} = 9550\frac{P_{out}(kW)}{570(rpm)} = 9550\frac{60(kW)}{570(rpm)} = 1005(\mathrm{N\cdot m})}$$

$$T_N = \frac{1000\cdot P_N}{2\pi\frac{n_N}{60}} = 9550\cdot\frac{P_N\ (kW)}{n_N\ (rpm)}$$

$$\boxed{n = 570(\mathrm{rpm})}$$

Video: Relationship among Torque, speed and horsepower

CHARACTERISTICS OF ASYNCHRONOUS MOTOR

[17/03/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

END OF TOPIC

START-UP AND CONTROL OF THE ASYNCHRONOUS MOTOR

[24/03/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

- How to start-up an asynchronous motor
- How to control the rotor speed of an asynchronous motor

START-UP AND CONTROL OF THE ASYNCHRONOUS MOTOR

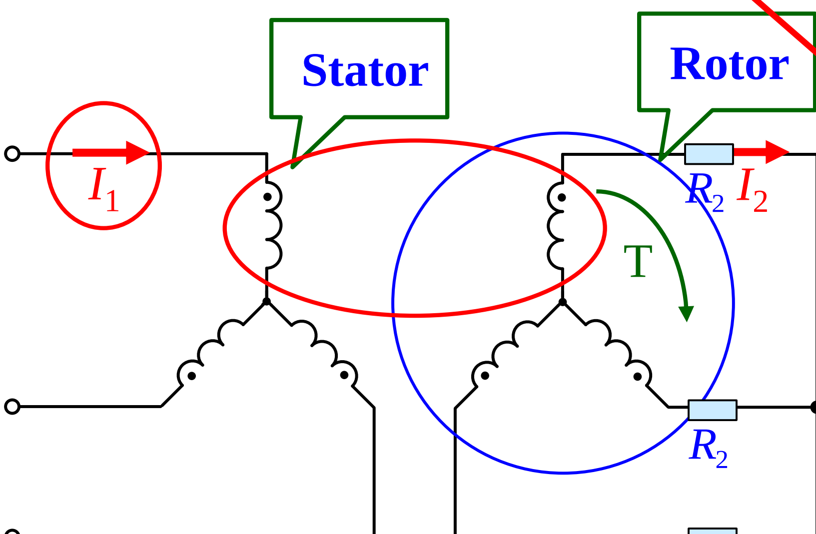
[24/03/2020]

- How to start-up an asynchronous motor
- How to control the rotor speed of an asynchronous motor

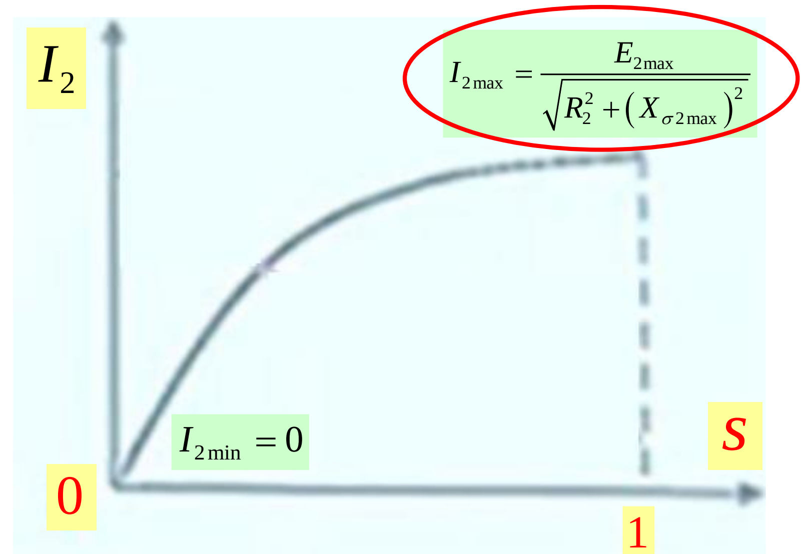
Review the start-up current of the asynchronous motor

$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}}$$

Slip ratio



Y-Y Connection



$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

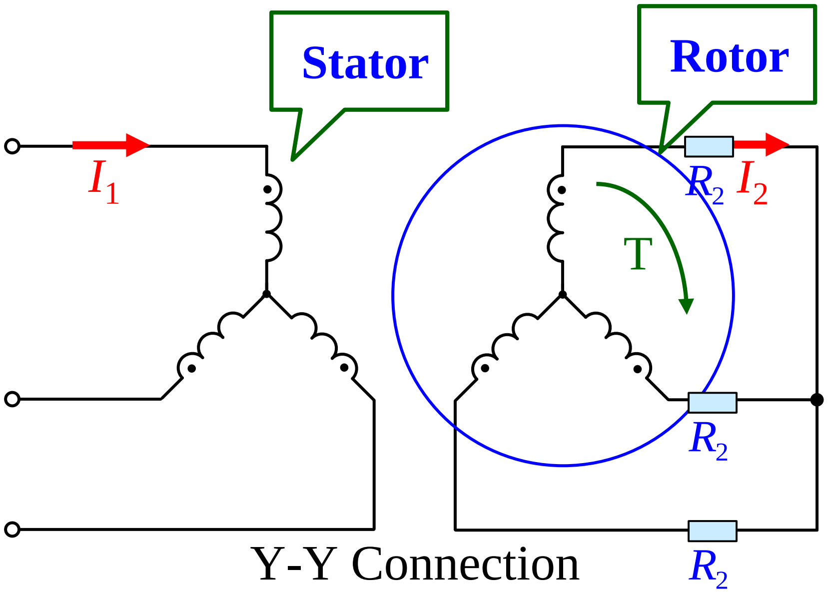
$n = 0$ (start) $\Rightarrow$ $s = 1$

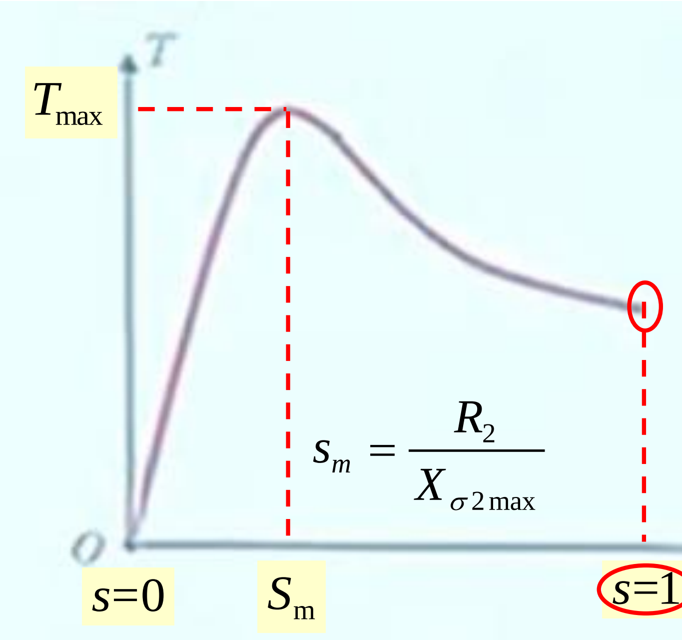
- Speed of the rotor n
- Speed of the magnetic field n_0
- Before start-up, n=0

- Before starting the asynchronous motor, it has maximum rotor current I_2
- Before starting the asynchronous motor, it has maximum stator current I_1

Review the start-up torque of the asynchronous motor

$$T=\frac{K\cdot R_2\cdot U_1^2}{\frac{R_2^2}{s}+s\cdot X_{\sigma 2\max}^2}$$





$$T=\frac{K\cdot R_2\cdot U_1^2}{R_2^2+X_{\sigma 2\max}^2}$$

$$s=\left(\frac{n_0-n}{n_0}\right)\times 100\% \quad \xrightarrow[n=0]{} \quad s=1$$

- ❑ Before start-up, n=0

➢ Before starting the asynchronous motor, its torque is not the maximum torque

Start-up problem of the asynchronous motor I: large start up current

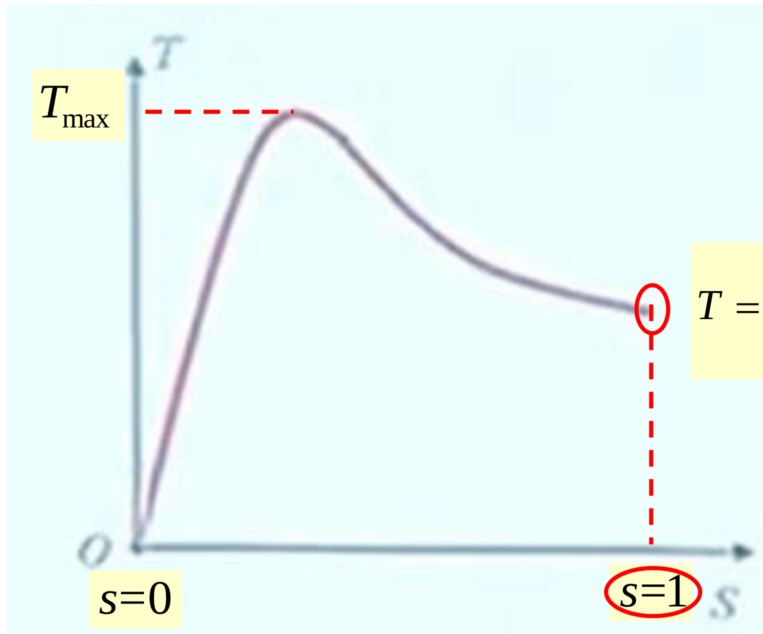
- Before starting the asynchronous motor, it has maximum rotor current I_2
- Before starting the asynchronous motor, it has maximum stator current I_1

The stator current I_1 also goes through the power grid

Large power loss

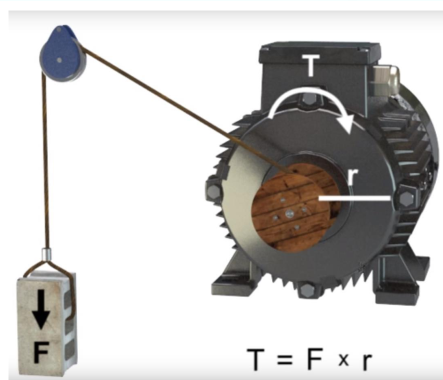
Start-up problem of the asynchronous motor II: Torque is not enough

➤ Before starting the asynchronous motor, its torque is not the maximum torque



$$T = \frac{K \cdot R_2 \cdot U_1^2}{R_2^2 + X_{\sigma 2 max}^2}$$

If the torque is small, it may not star up the motor



Practical motor start problem

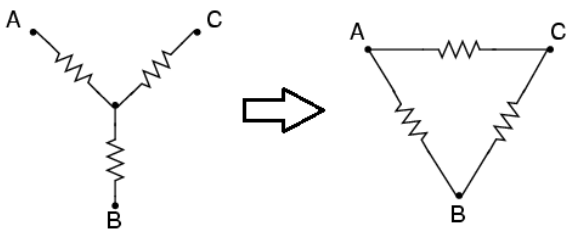
Typical start-up methods of the asynchronous motor

Method I: Connect to the grid and star-up the asynchronous motor directly

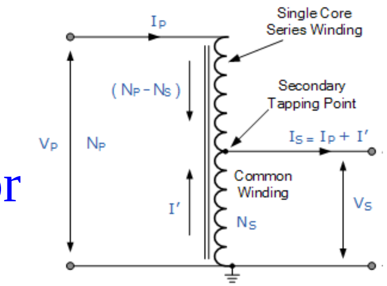
Do nothing

Small power asynchronous motor:
Power < 20 or 30 kW

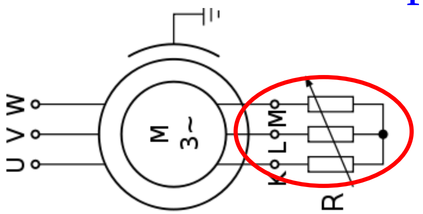
Method II: Y-Δ Changing structure of the stator to start up the asynchronous motor



Method III: Use auto-transformer to start up the asynchronous motor



Method IV: Increase the rotor resistor to star up the asynchronous motor



$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}} \qquad T = \frac{K \cdot R_2 \cdot U_1^2}{\frac{R_2^2}{s} + s \cdot X_{\sigma 2\max}^2}$$

Typical start-up methods of the asynchronous motor

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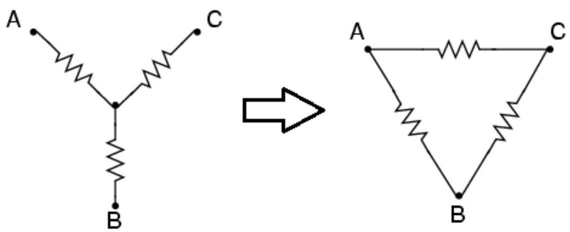
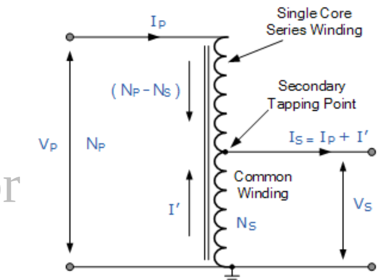
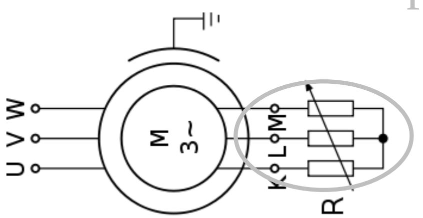


Method III: Use auto-transformer to start up the asynchronous motor



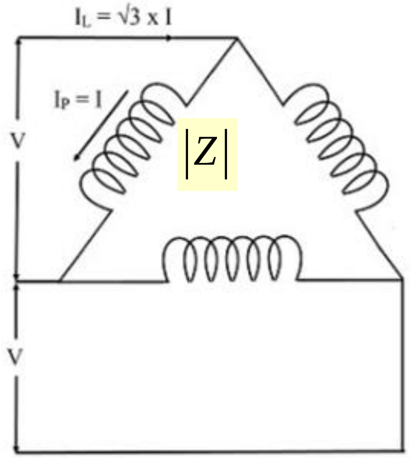
Method IV: Increase the rotor resistor to star up the asynchronous motor



$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}} \qquad T = \frac{K \cdot R_2 \cdot U_1^2}{\frac{R_2^2}{s} + s \cdot X_{\sigma 2\max}^2}$$

Y-Δ Changing structure of the stator to start up the asynchronous motor

Normal operation



Delta

Define: the impedance of each phase of the motor is $|Z|$

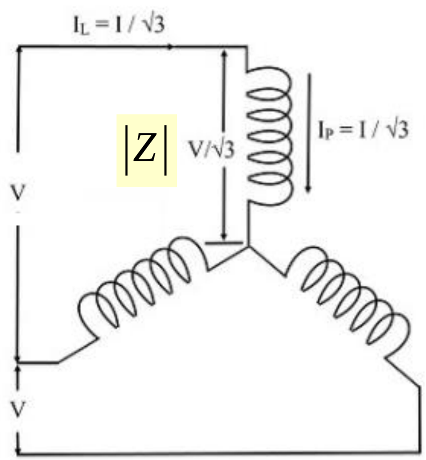
Input current

$$I_{L\Delta normal} = \sqrt{3}\frac{V}{|Z|}$$

Application: Require the stator winding is connected by Δ structure in normal case

$$\frac{I_{LYstart}}{I_{L\Delta normal}} = \frac{\dfrac{V}{\sqrt{3}\cdot|Z|}}{\sqrt{3}\dfrac{V}{|Z|}} = \frac{1}{3}$$

Start-up



Star

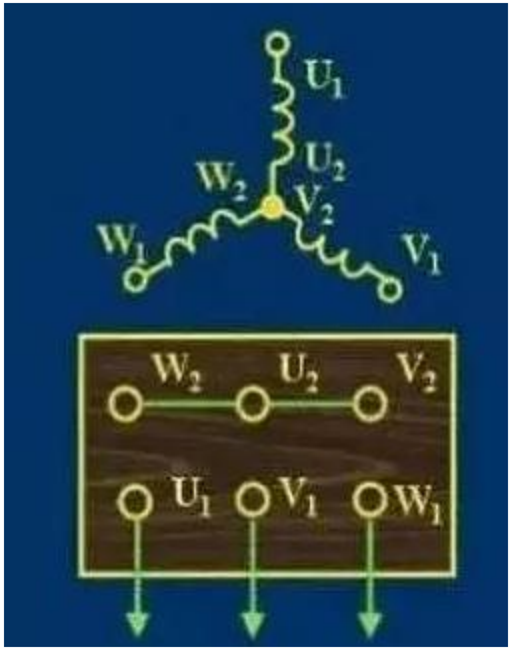
Input current

$$I_{LYstart} = \frac{V}{\sqrt{3}\cdot|Z|}$$

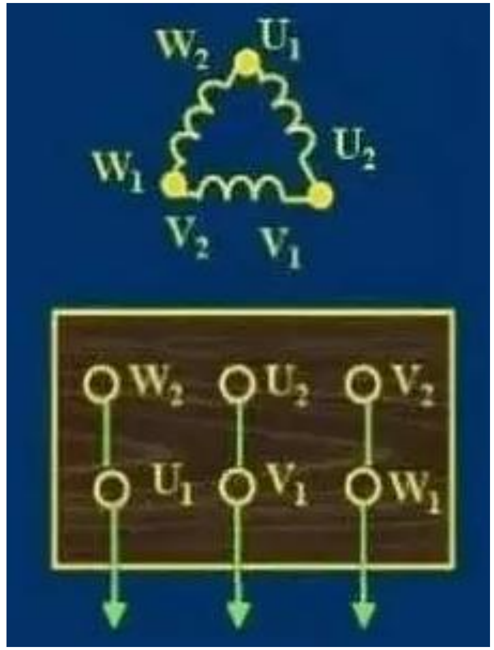
Decrease the input current of the motor

How to realize Y-Δ Changing structure start-up method?

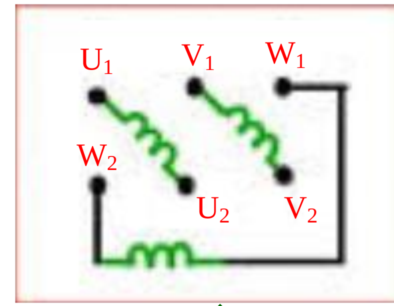
Star (Y) connection



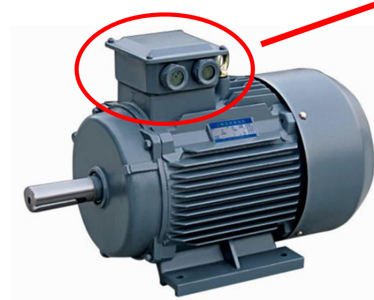
Delta (Δ) connection

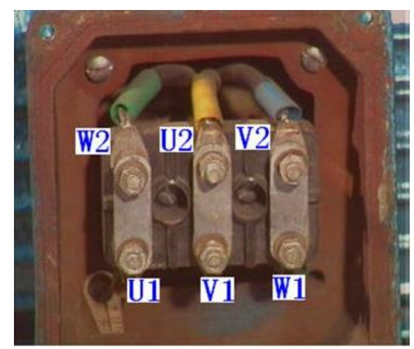


Terminal box



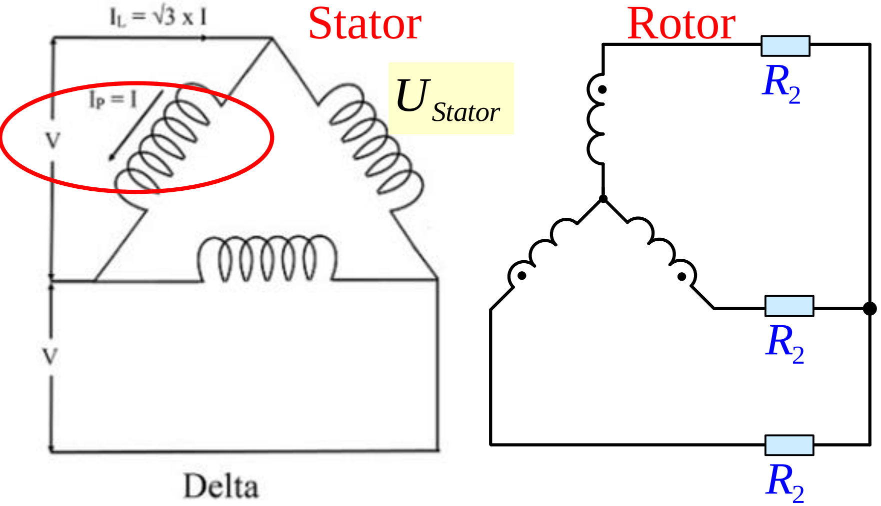
Select



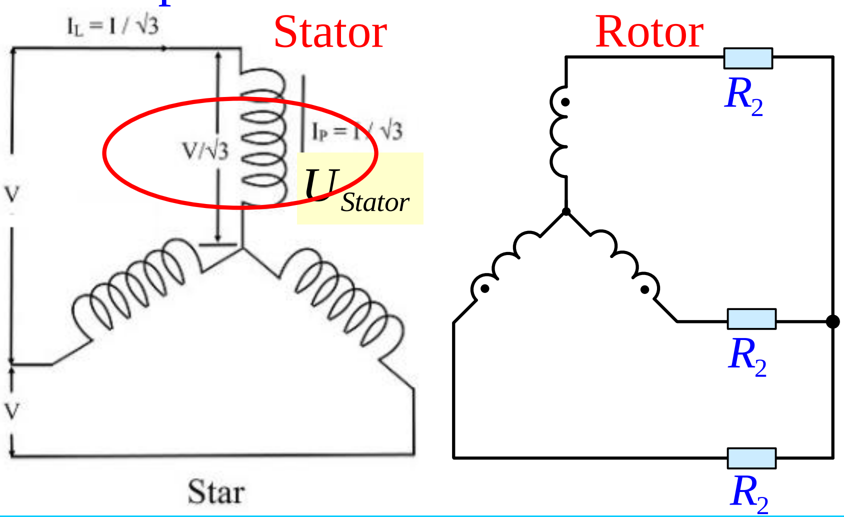


Limitation of the Y-Δ Changing structure start up method: small start up torque

Normal operation



Start-up



$$T = \frac{K \cdot R_2 \cdot U_{stator}^2}{\frac{R_2^2}{s} + s \cdot X_{\sigma 2 \max}^2} \qquad T \propto U_{stator}^2$$

Normal operation

$$U_{stator} = V$$

Start-up

$$U_{stator} = \frac{V}{\sqrt{3}}$$

Torque becomes smaller at start-up case

$$T_{start-up} = \left(\frac{1}{\sqrt{3}}\right)^2 T_{normal} = \frac{1}{3} T_{normal}$$

Example 1: For a three phase asynchronous motor, its stator winding is connected via Δ type. Its load torque is 510.2 N·m, T_{st}=551.8 N·m when it connected to the grid directly. If we use Y-Δ start, can we start the motor? If the load torque is decreased to 20%, can we start it using Y-Δ start?

$$T_{st\_Y-\Delta} = \frac{1}{3} \cdot T_{st\_normal} = \frac{1}{3} \cdot 551.8 = 183.9 N.m < 510.2 N.m$$

Can not start at normal load torque

$$T_{st\_Y-\Delta} = \frac{1}{3} \cdot T_{st\_normal} = \frac{1}{3} \cdot 551.8 = 183.9 N.m > 20\% \cdot 510.2 N.m = 102.4 N.m$$

Can start at 20% load torque

Video: Y-Δ Changing structure start up

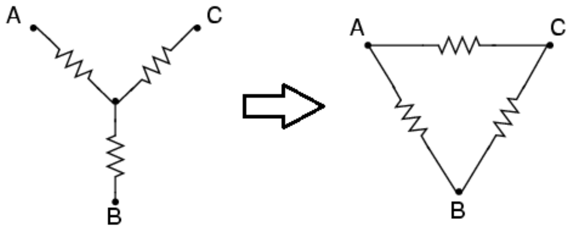
Typical start-up methods of the asynchronous motor

~~Method~~ I: Connect to the grid and star-up the asynchronous motor directly

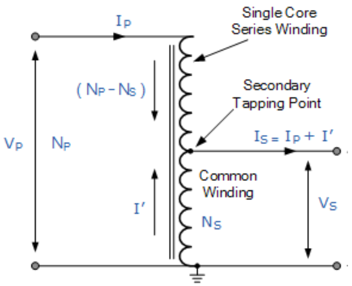
Do nothing

Small power asynchronous motor:
Power < 20 or 30 kW

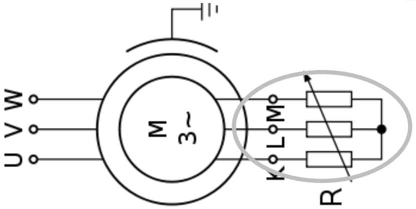
Method II: Y-Δ Changing structure of the stator to start up the asynchronous motor



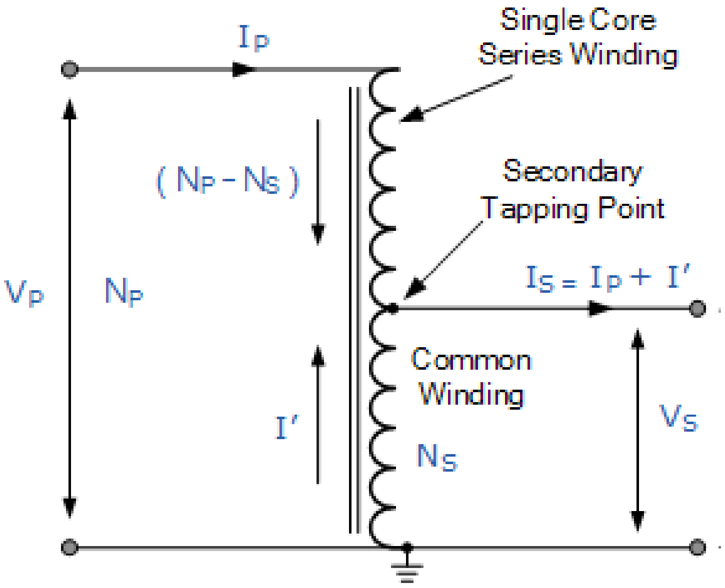
Method III: Use auto-transformer to start up the asynchronous motor



Method IV: Increase the rotor resistor to star up the asynchronous motor

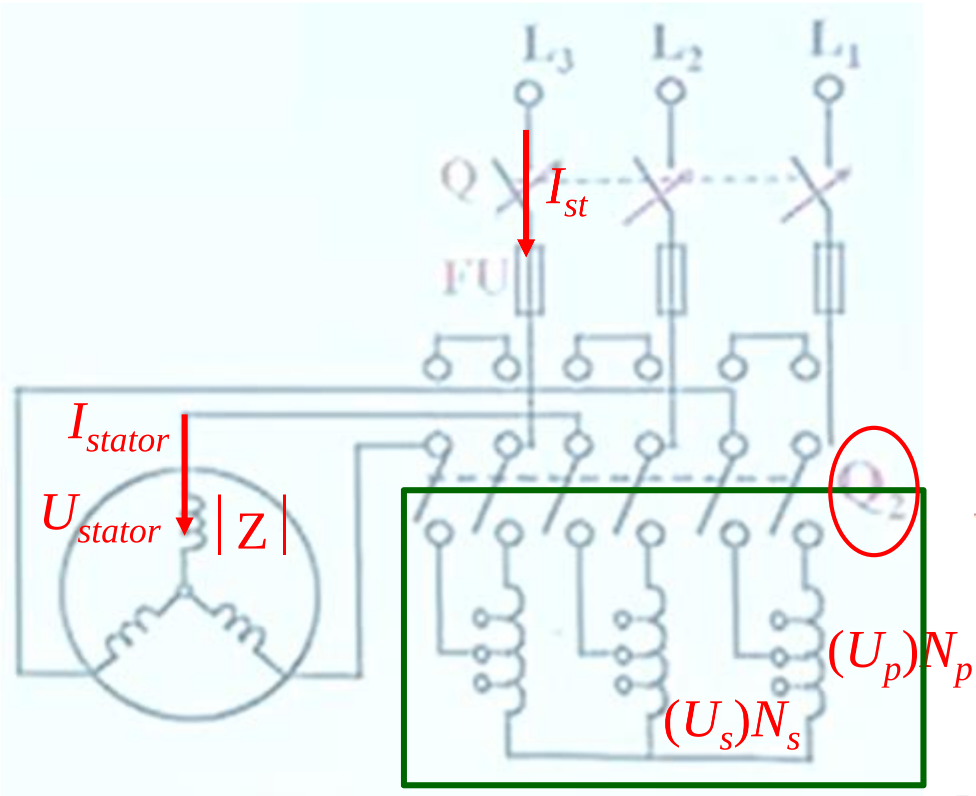


$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}} \qquad T = \frac{K \cdot R_2 \cdot U_1^2}{\frac{R_2^2}{s} + s \cdot X_{\sigma 2\max}^2}$$



Ip
Single Core
Series Winding
(Np - Ns)
Secondary
Tapping Point
Is = Ip + I'
Vp
Np
Common
Winding
I'
Vs
Ns

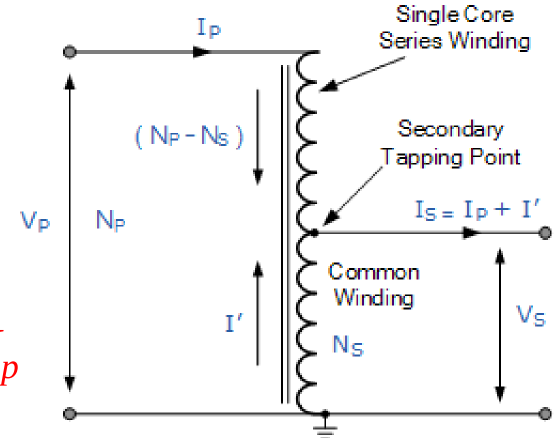
Use auto-transformer to start up the asynchronous motor



Normal operation Q_2 is connected up

$$U_{stator} = U_p \quad I_{st} = I_{stator} = \frac{U_p}{|Z|}$$

Start-up Q_2 is connected down



$$Define: \frac{N_p}{N_s} = K > 1$$

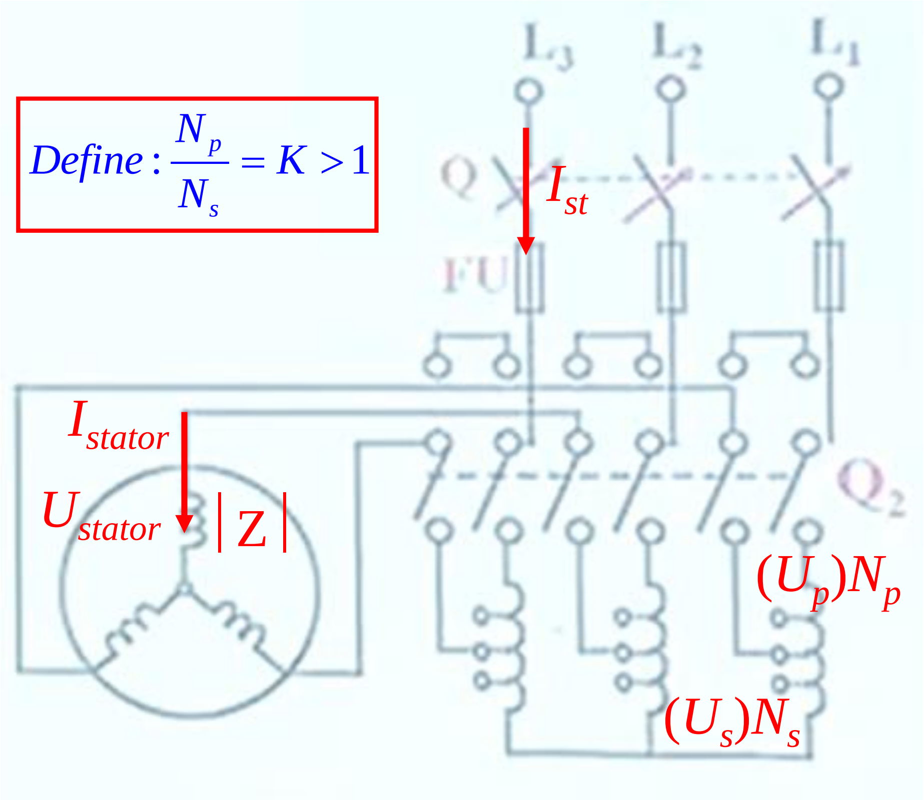
$$U_{stator} = U_s = \frac{N_s}{N_P} \cdot U_p = \frac{U_p}{K} < U_p$$

$$I_{st} = \frac{N_s}{N_P} \cdot I_{stator} = \frac{N_s}{N_P} \cdot \frac{U_s}{|Z|} = \frac{N_s}{N_P} \cdot \frac{N_s}{N_P} \cdot \frac{U_p}{|Z|} = \left(\frac{N_s}{N_P}\right)^2 \frac{U_p}{|Z|}$$

$$I_{st} = \frac{1}{K^2} \frac{U_p}{|Z|}$$

Application: Require the stator winding is connected by Y structure in normal case

Use auto-transformer to start up the asynchronous motor



$$Define: \frac{N_p}{N_s} = K > 1$$

Normal operation (Q_2 is connected up)

$$U_{stator} = U_p \qquad I_{st} = I_{stator} = \frac{U_p}{|Z|}$$

Start-up (Q_2 is connected down)

$$U_{stator} = \frac{1}{K} U_p < U_p \qquad I_{st} = \frac{1}{K^2}\frac{U_p}{|Z|}$$

$$U_{stator\_start} = \frac{1}{K} \cdot U_{stator\_normal} \qquad I_{st\_start} = \frac{1}{K^2} I_{st\_normal}$$

$$T \propto U_{stator}^2$$

$$T_{start} = \frac{1}{K^2} \cdot T_{normal} \qquad I_{st\_start} < I_{st\_normal}$$

Application: Require the stator winding is connected by Y structure in normal case

Limitation: Start up current is reduced

Advantage: Start up current is reduced

Example 2: For a three phase asynchronous motor, if it is started directly, its start torque T_{st} = 200 N·m, its start up current I_{st} = 50 A. Its load torque is 150 N·m and its maximum permitted start up current is 40 A. If an auto-transformer, whose turn ratio of secondary winding to the primary winding is 0.5, is utilized to start up this asynchronous motor, can it be successful?

$$T_{st\_\mathrm{AT}} = (0.5)^2 \cdot T_{st} = 0.25 \cdot 200 = 50 N \cdot m < 150 N \cdot m$$

$$I_{st\_\mathrm{AT}} = (0.5)^2 \cdot I_{st} = 0.25 \cdot 50 = 12.5\ A < 40\ A$$

Can not start at normal load torque

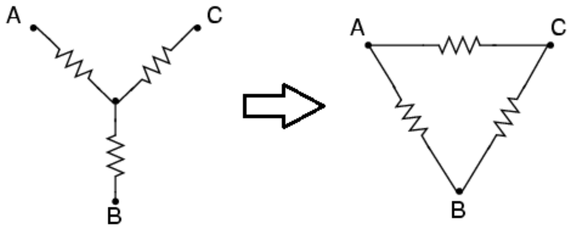
Typical start-up methods of the asynchronous motor

~~Method I~~: Connect to the grid and star-up the asynchronous motor directly

Do nothing

Small power asynchronous motor: Power < 20 or 30 kW

Method II: Y-Δ Changing structure of the stator to start up the asynchronous motor



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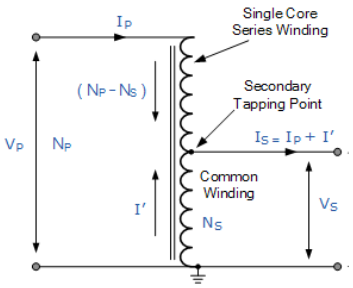
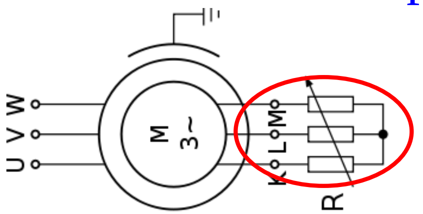
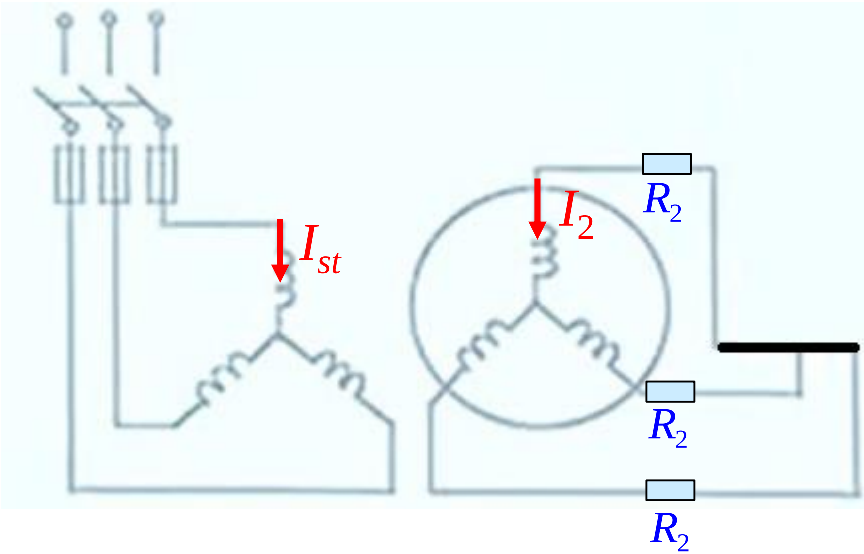


Method IV: Increase the rotor resistor to star up the asynchronous motor



$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}} \qquad T = \frac{K \cdot R_2 \cdot U_1^2}{\frac{R_2^2}{s} + s \cdot X_{\sigma 2\max}^2}$$

Increase the rotor resistor to star up the asynchronous motor



$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}} \qquad T = \frac{K \cdot R_2 \cdot U_1^2}{\frac{R_2^2}{s} + s \cdot X_{\sigma 2\max}^2}$$

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\% \Longrightarrow s = 1$$

$$n = 0$$

R_2 affects both T and I_2

If R_2 is increased

$$I_{st} = I_2\big|_{s=1} = \frac{E_{2\max}}{\sqrt{R_2^2 + \left(X_{\sigma 2\max}\right)^2}}$$

$$R_2 \nearrow \Longrightarrow I_{st} \searrow$$

$$T_{st} = T\big|_{s=1} = \frac{K \cdot R_2 \cdot U_1^2}{R_2^2 + X_{\sigma 2\max}^2} = \frac{K \cdot U_1^2}{R_2 + \frac{X_{\sigma 2\max}^2}{R_2}}$$

$if\ R_2 < X_{\sigma 2\max}$

$$R_2 \nearrow \Longrightarrow T_{st} \nearrow$$

$if\ R_2 \geq X_{\sigma 2\max}$

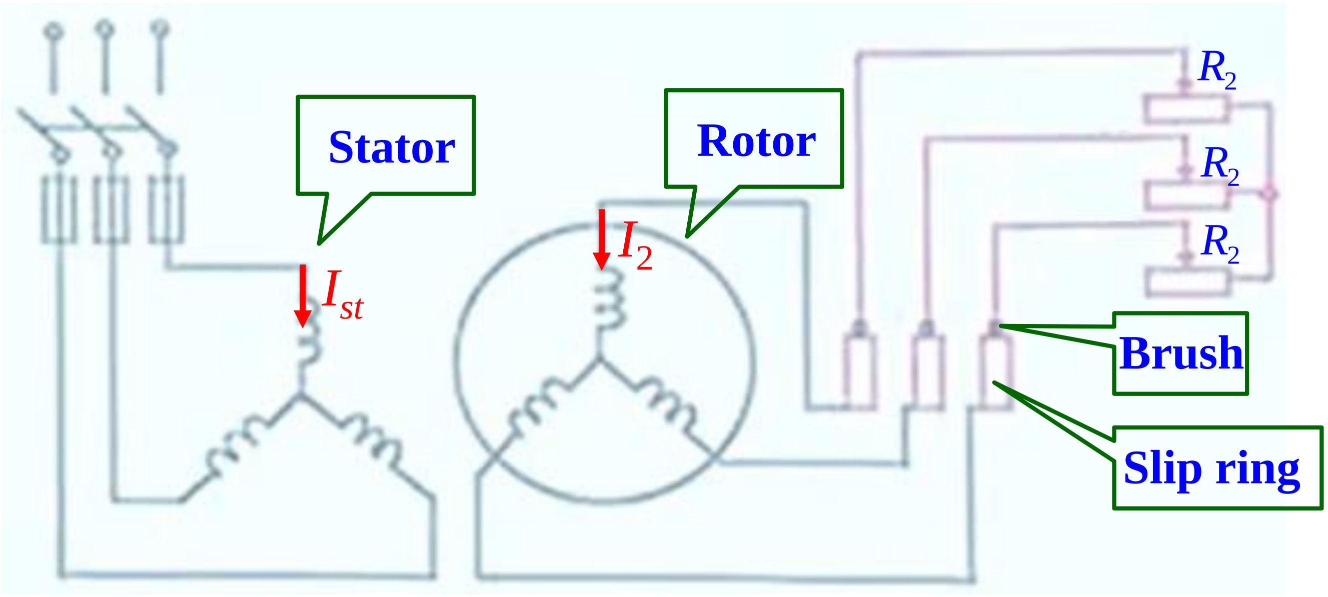
$$R_2 \nearrow \Longrightarrow T_{st} \searrow$$

Try to increase R_2, what will happen to the T_{st} and I_{st}?

If increases R_2 and make $R_2 < X_{\delta 2max}$, then we can get smaller I_{st} and larger T_{st} at the same time.

How to increase the resistor of the rotor windings R_2 ?

Add additional brush, slip ring and resistor to increase the equivalent rotor winding resistor R_2

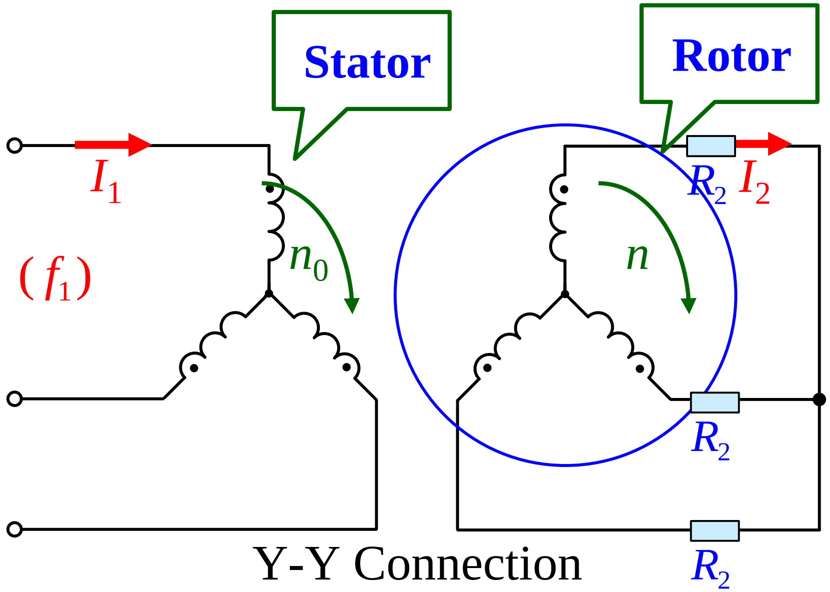


START-UP AND CONTROL OF THE ASYNCHRONOUS MOTOR

[24/03/2020]

- How to start-up an asynchronous motor
- How to control the rotor speed of an asynchronous motor

Typical speed control methods of the asynchronous motor



- Slip ratio s

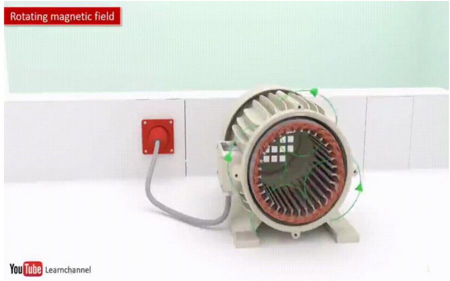
$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$n = (1 - s) n_o$$

$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

We can change f_1, P and s to regulate the rotor speed n.

- Speed of the magnetic field n_0
- Speed of the rotor n



$$n_o = \frac{60 \cdot f_1}{P}$$

f_1: frequency of U_1

P: Pole-pairs of the asynchronous motor

Typical speed control methods of the asynchronous motor

$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

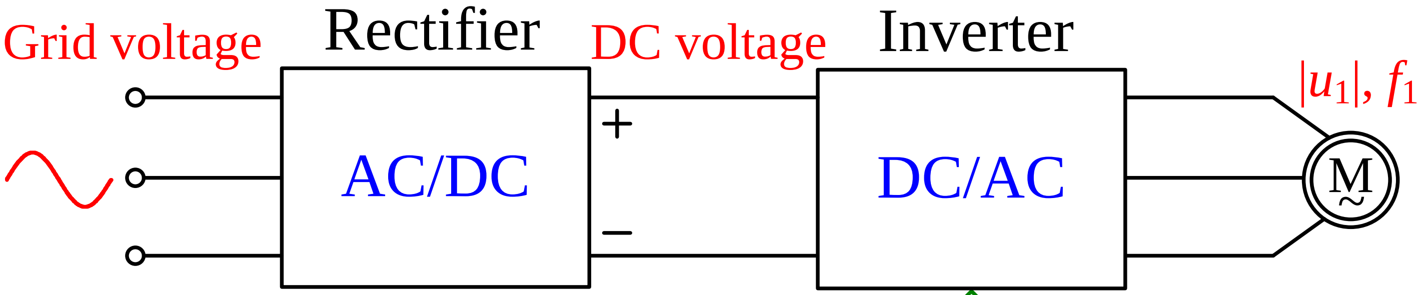
- Change the frequency (f_1) of the voltage of the stator winding
- Change the pole-pairs (P) of the asynchronous motor
- Change the slip ratio (s) of the asynchronous motor

Typical speed control methods of the asynchronous motor

$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

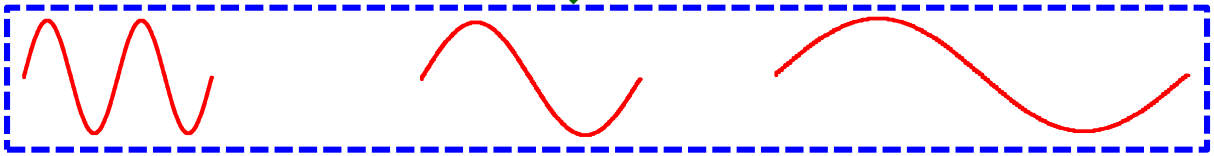
- Change the frequency (f_1) of the voltage of the stator winding
- Change the pole-pairs (P) of the asynchronous motor
- Change the slip ratio (s) of the asynchronous motor

Change stator voltage frequency to regulate the rotor speed of the asynchronous motor



Control the amplitude and frequency of its output voltage u_1, which is also the motor stator voltage

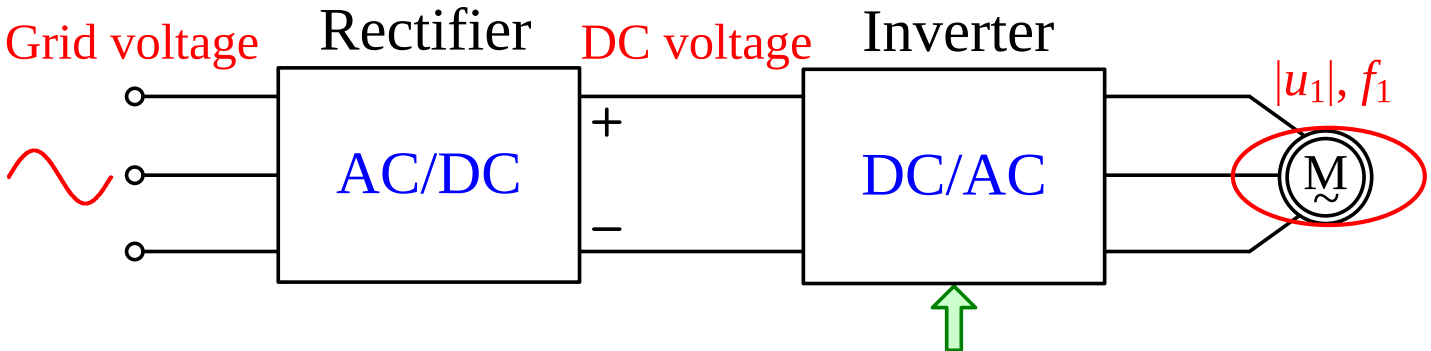
Function of the inverter



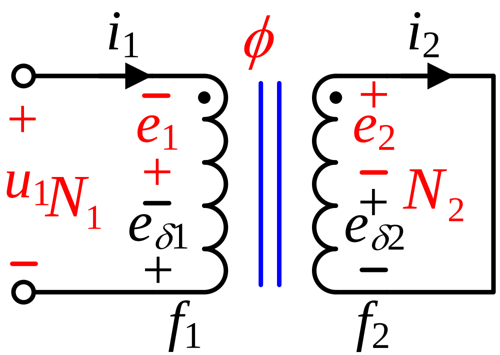
$$n = (1-s)\cdot\frac{60\cdot f_1}{P}$$

Change f_1

Question 1: can f_1 increase to infinite?



Control the amplitude and frequency of its output voltage u_1, which is also the motor stator voltage

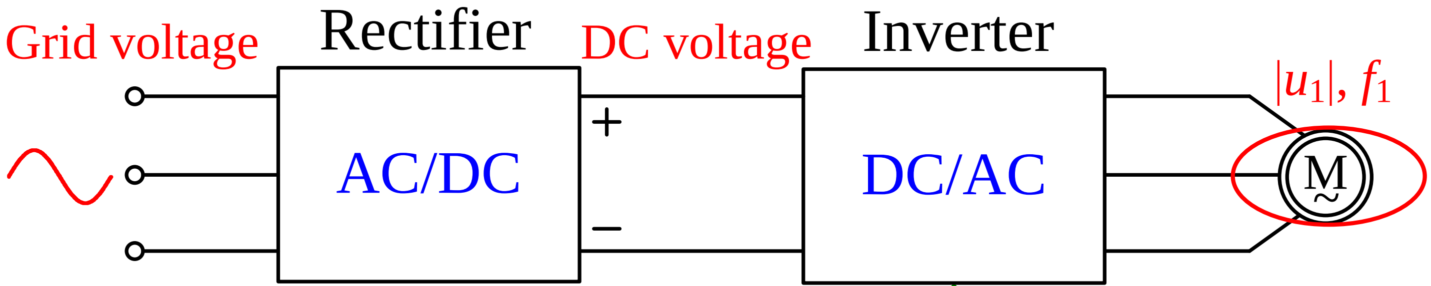


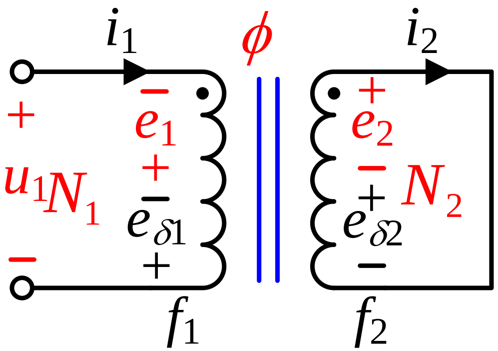
Answer: No, if f_1 is increased, the flux is decreased, and the torque will become smaller.

$$\phi \approx \frac{U_1}{4.44 \cdot N_1 \cdot f_1} \Longrightarrow f_1 \uparrow \rightarrow \phi \downarrow \Longrightarrow T = K_T \cdot \phi \cdot I_2 \cdot \cos\theta \downarrow$$

Motor cannot work well

Question 2: How to keep the flux constant when f_1 increased?





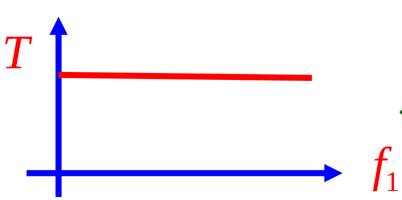
Control the amplitude and frequency of its output voltage u_1, which is also the motor stator voltage

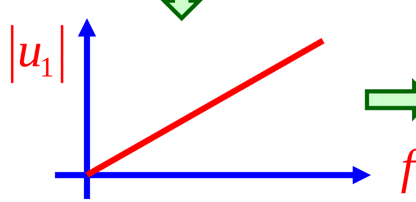
$$\phi \approx \frac{|u_1|}{4.44 \cdot N_1 \cdot f_1}$$

if $\frac{|u_1|}{f_1}$ *is constant when* f_1 *is increased*

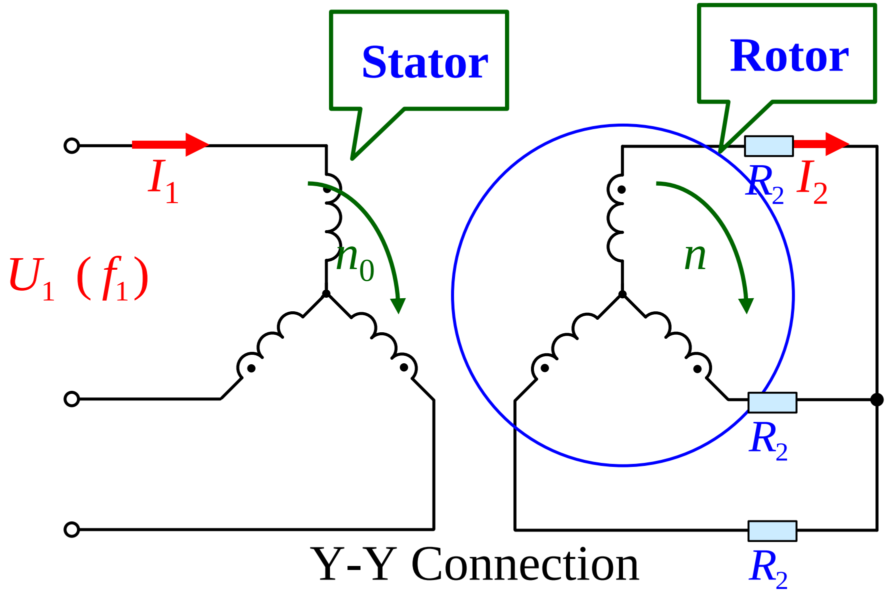
Flux is constant

$$T = K_T \cdot \phi \cdot I_2 \cdot \cos\theta$$





Question 3: can f_1 increase to infinite even if $|u_1|/f_1$ is constant?



if $\dfrac{|u_1|}{f_1}$ *is constant when* f_1 *is increased*

if f_1 *is increased to infinite*

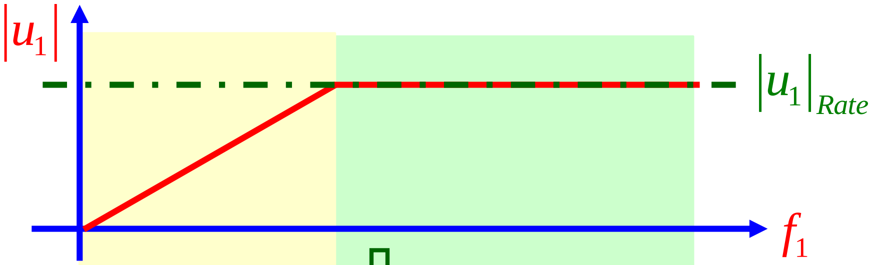
⇩

$|u_1| = \infty \gg$ *Rated stator voltage*

⇩

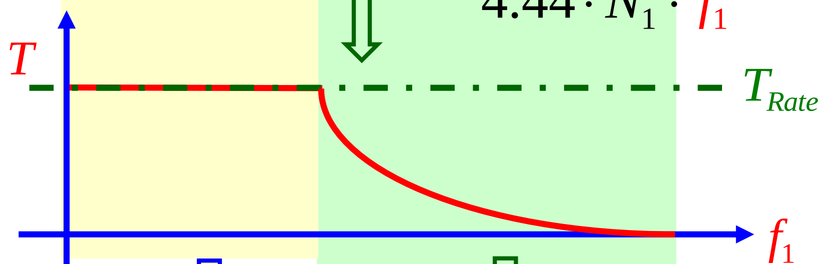
Asynchronous motor will be broken

The right relationship between $|u_1|$ and f_1, and its impact on torque T



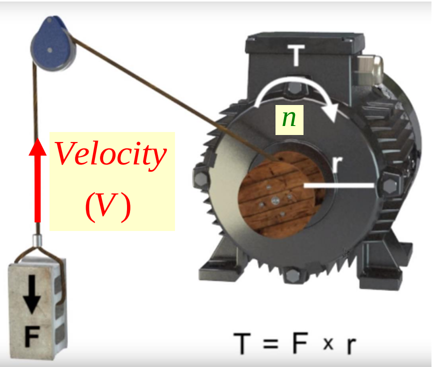
$$T = K_T \cdot \phi \cdot I_2 \cdot \cos\theta$$

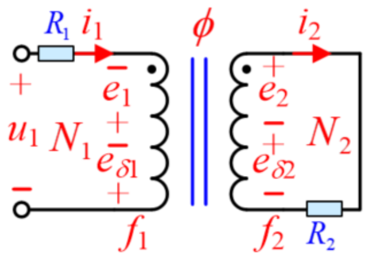
$$\phi \approx \frac{|u_1|}{4.44 \cdot N_1 \cdot f_1}$$



Constant Torque region

Constant Power region





$$Power = F \cdot Velocity$$

T=F×r→F=T/r

$$Velocity = 2\pi n \cdot r$$

$$Power = \frac{T}{r} \cdot 2\pi n \cdot r = T \cdot 2\pi n$$

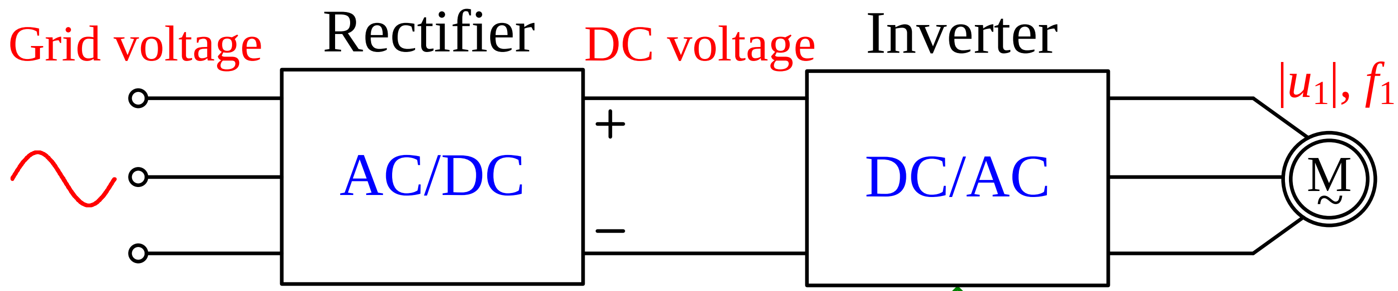
$$Power \approx T \cdot 2\pi f_1$$

$$T = K_T \cdot \phi \cdot I_2 \cdot \cos\theta \qquad \phi \approx \frac{|u_1|}{4.44 \cdot N_1 \cdot f_1}$$

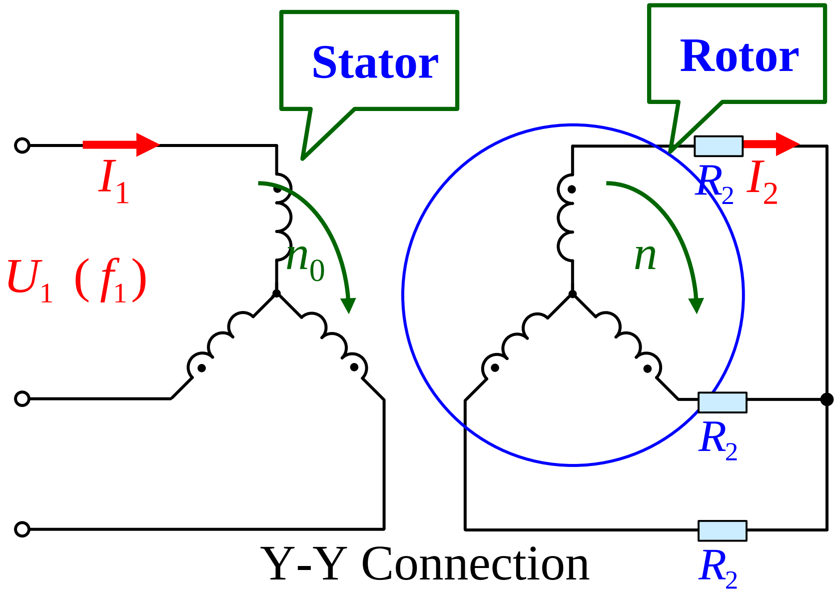
$$Power \approx K_T \frac{|u_1|}{4.44 \cdot N_1 \cdot \cancel{f_1}} I_2 \cos\theta 2\pi \cdot \cancel{f_1}$$

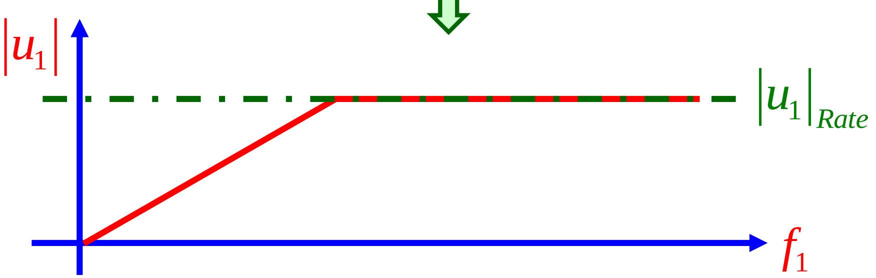
$\boxed{\textit{Power} \text{ is proportional to } |u_1|}$

The right method to change the stator voltage frequency to regulate the rotor speed of the asynchronous motor

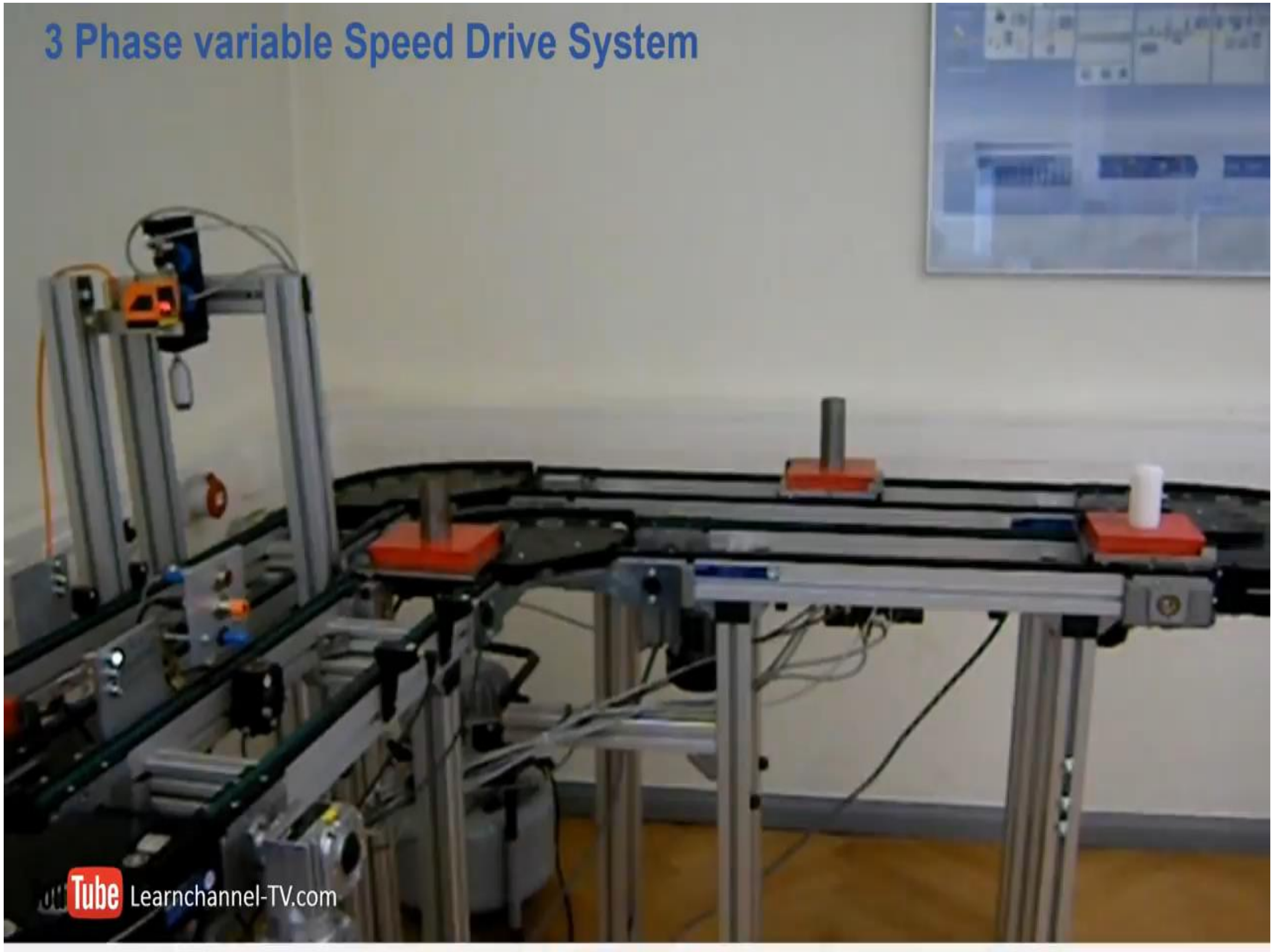


Control the amplitude and frequency of its output voltage u_1, which is also the motor stator voltage





Video: how a variable speed drive system work? (simple introduction)



Typical speed control methods of the asynchronous motor

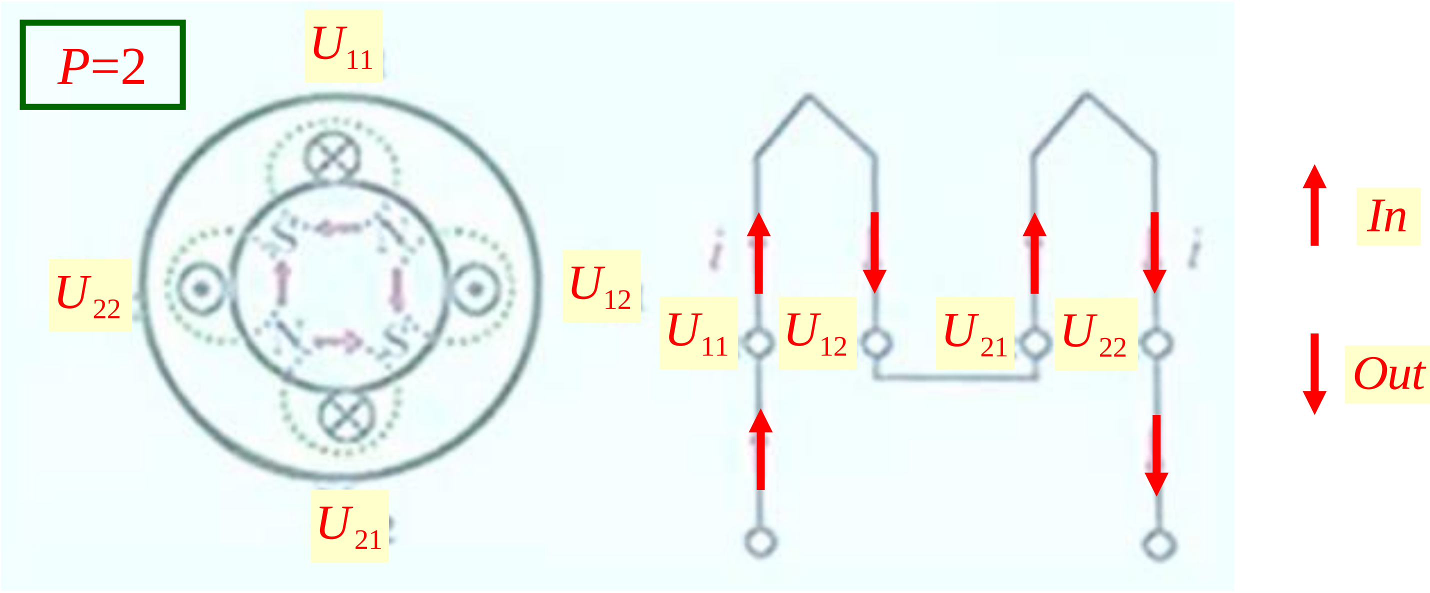
$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

- Change the frequency (f_1) of the voltage of the stator winding
- Change the pole-pairs (P) of the asynchronous motor
- Change the slip ratio (s) of the asynchronous motor

Change the pole-pairs to regulate the rotor speed of the asynchronous motor

$$n = (1-s)\cdot\frac{60\cdot f_1}{P}$$

P: pole-pairs, which is determined by the connection of the stator windings



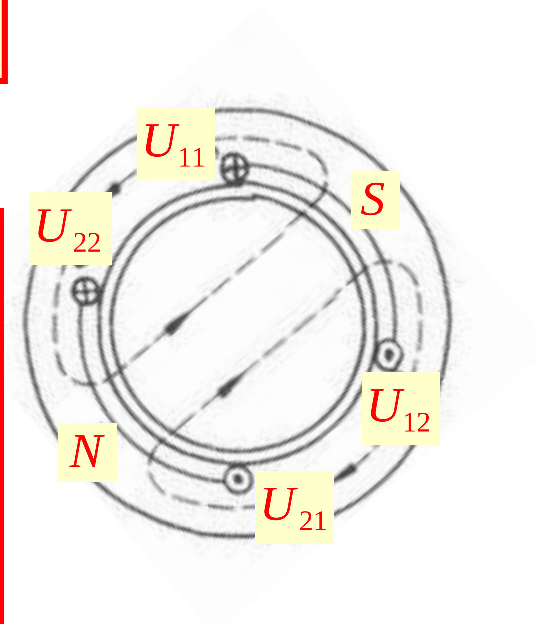
Change the pole-pairs to regulate the rotor speed of the asynchronous motor

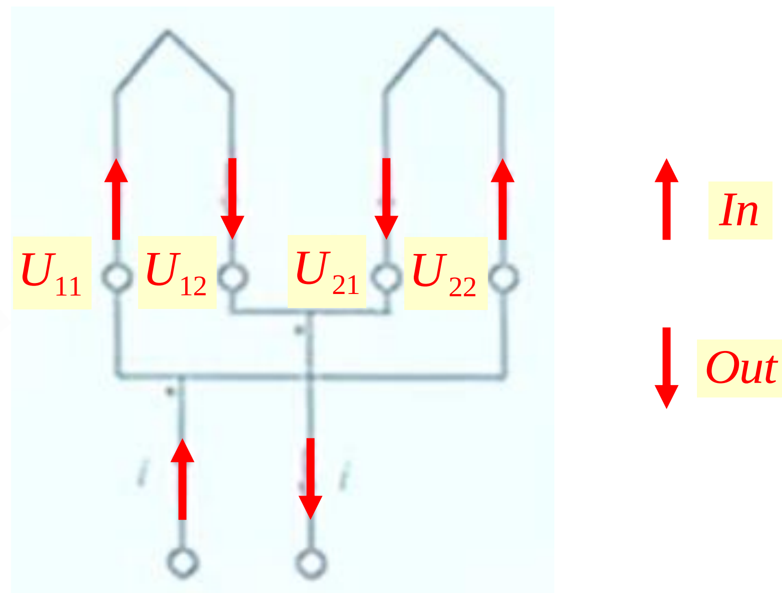
$$n = (1-s)\cdot\frac{60\cdot f_1}{P}$$

Change the connection structure of the stator winding can change P

P: pole-pairs, which is determined by the connection of the stator windings

P only can be discontinued changed, such as 1, 2, 3, 4, ….; cannot be changed smoothly.





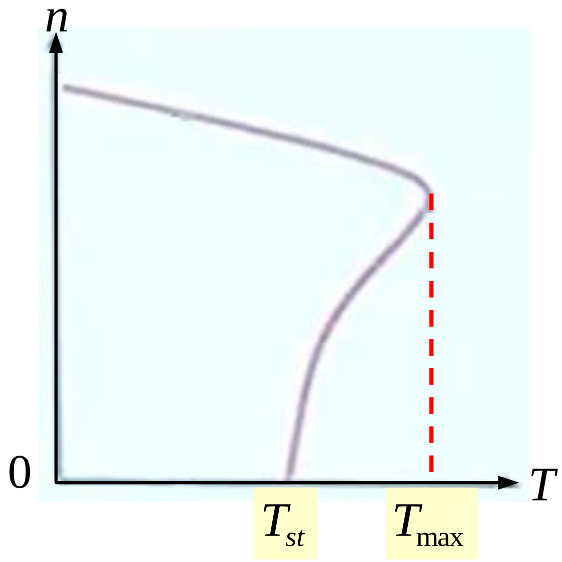
P=1

Typical speed control methods of the asynchronous motor

$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

- Change the frequency (f_1) of the voltage of the stator winding
- Change the pole-pairs (P) of the asynchronous motor
- Change the slip ratio (s) of the asynchronous motor

Review the n-T curve and the impact of R_2 on the n-T curve



$$T = K \cdot \frac{s \cdot R_2}{R_2^2 + (sX_{\sigma 2\max})^2} \cdot U_1^2$$

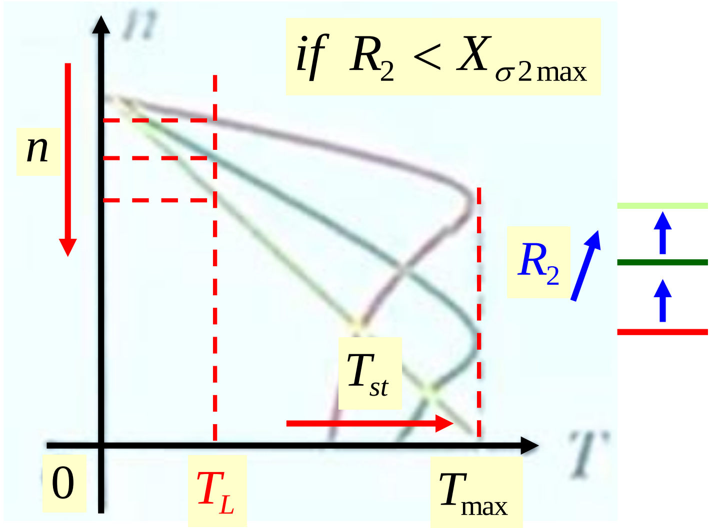
$$T_{st} = T\big|_{s=1} = \frac{K \cdot R_2 \cdot U_1^2}{R_2^2 + X_{\sigma 2\max}^2} = \frac{K \cdot U_1^2}{R_2 + \frac{X_{\sigma 2\max}^2}{R_2}}$$

if $R_2 < X_{\sigma 2\max}$

$R_2 \nearrow \Longrightarrow T_{st} \nearrow$

if $R_2 \geq X_{\sigma 2\max}$

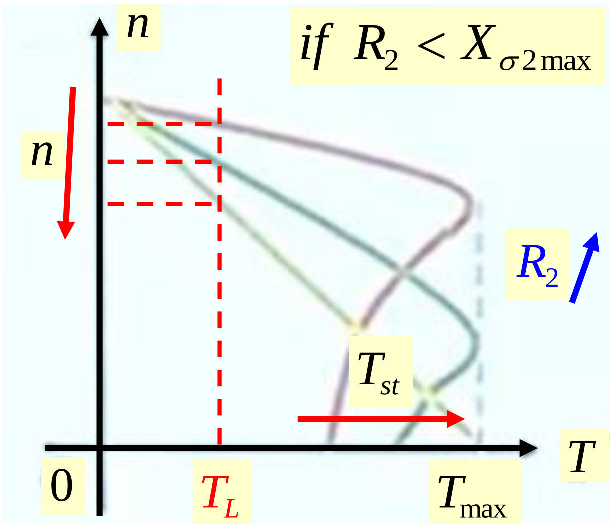
$R_2 \nearrow \Longrightarrow T_{st} \searrow$

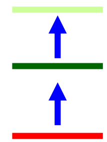


$$T_{\max} = \frac{K \cdot U_1^2}{2X_{\sigma 2\max}}$$

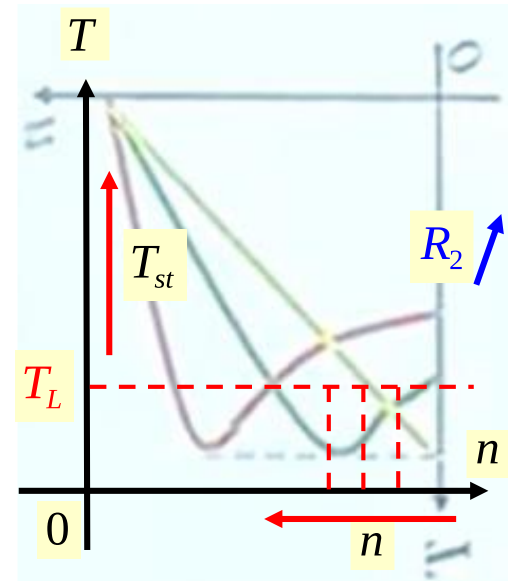
T_{max} is not affected by R_2.

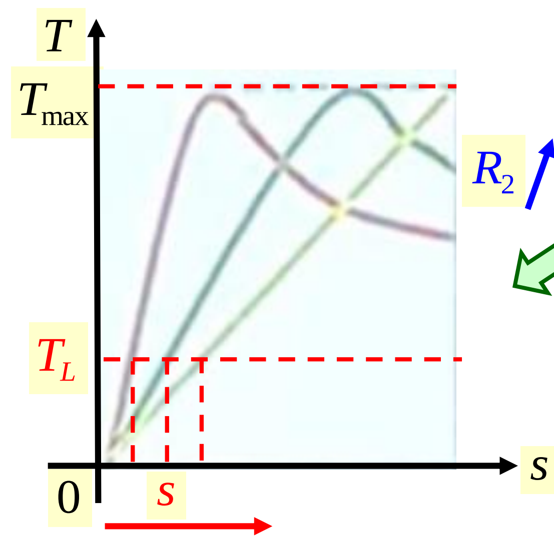
Change R_2 can change the slip ratio





Exchange X and Y axis





$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$s \nearrow \; \longrightarrow \; n \searrow$

$s \searrow \; \longrightarrow \; n \nearrow$

$if \;\; R_2 < X_{\sigma 2\max}$

R_2 increase, s increases

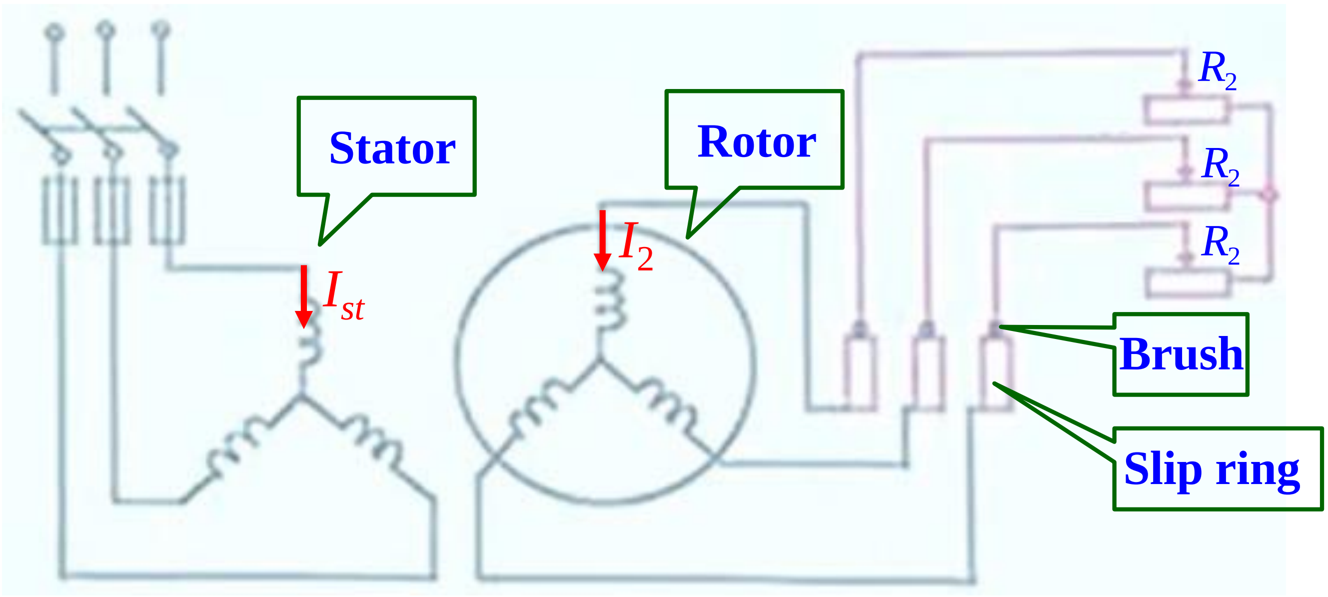
$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

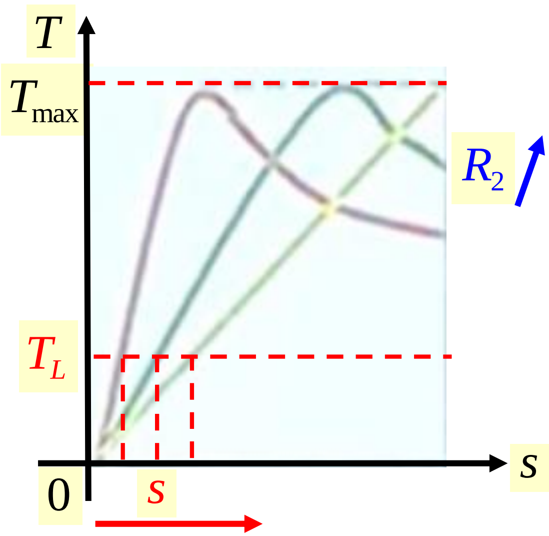
Change the slip ratio s to regulate the rotor speed n via changing R_2

$if\ R_2 < X_{\sigma 2\max}$

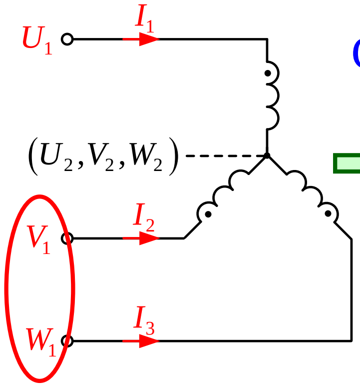
R_2 increase, s increases

$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

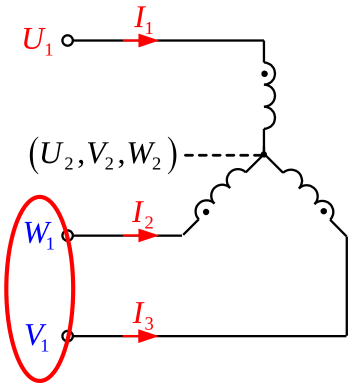


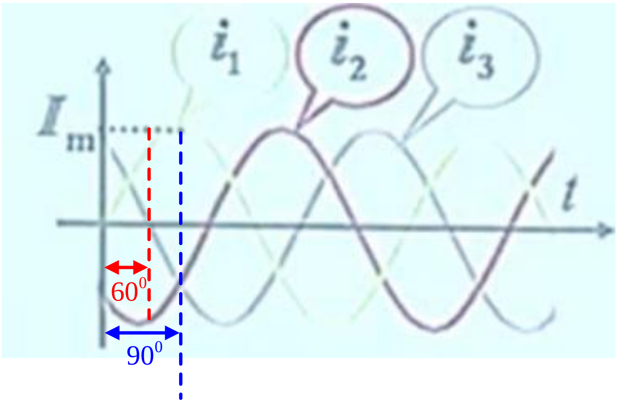


Open topic: how to brake an asynchronous motor?

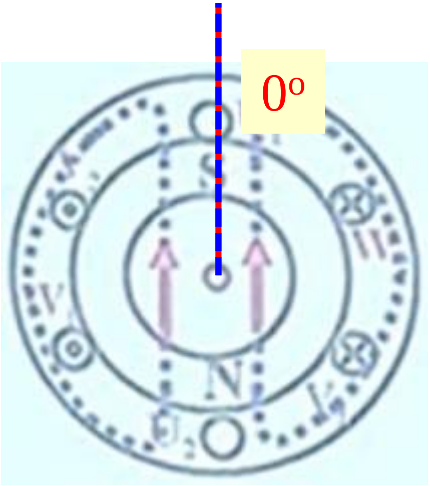


Change the position of W_1 and V_1

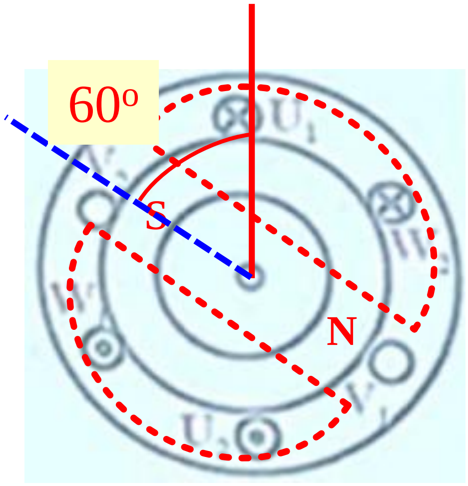




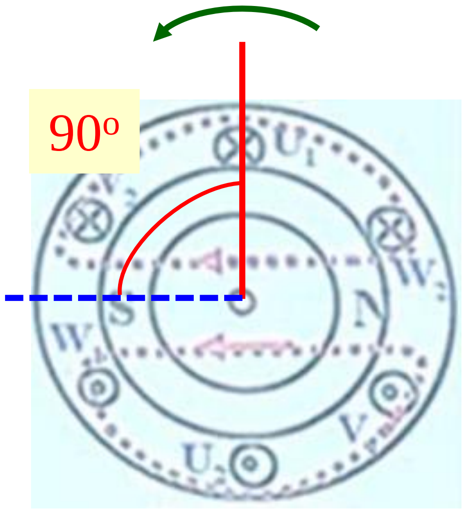
Rotated direction is changed → n_o



ωt = 0º

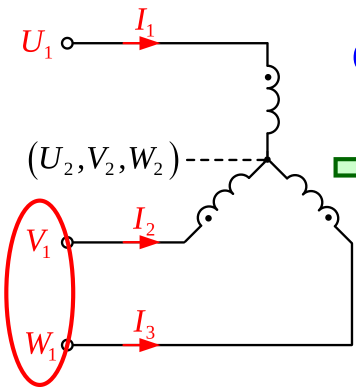


ωt = 60º

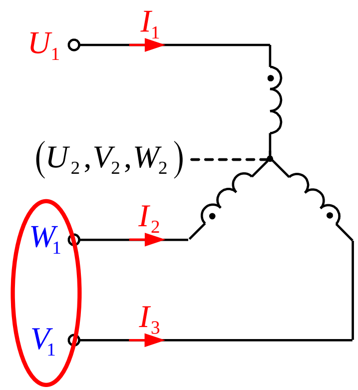


ωt = 90º

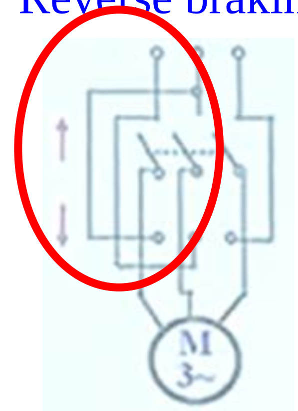
Open topic: how to brake an asynchronous motor?



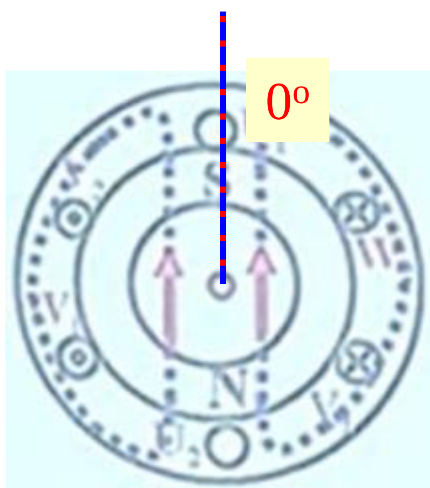
Change the position of W_1 and V_1



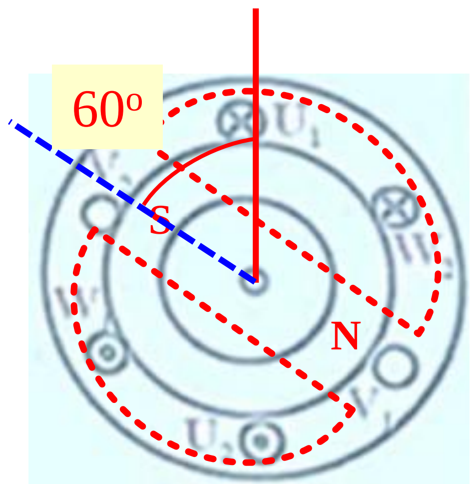
Reverse braking



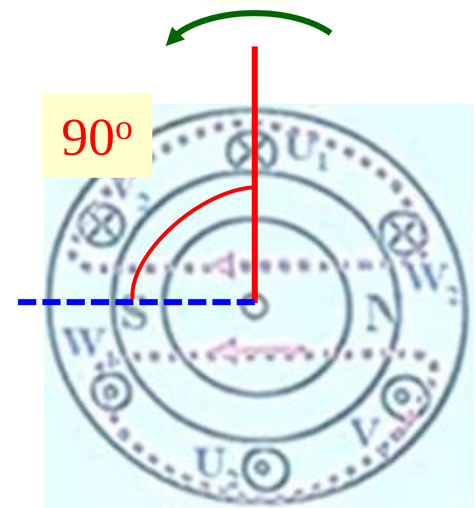
Rotated direction is changed ⟹ n_o



$\omega t = 0^o$



$\omega t = 60^o$



$\omega t = 90^o$

Review of today's topic

- What is the problem when we start up an asynchronous motor?
- Understand the operation principle of the different start-up methods.
- Understand the characteristics of the different start-up methods.
- How to control the rotor speed of the asynchronous motor?
- Understand the limitations of the above control methods.

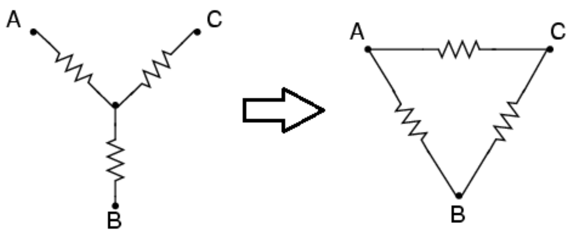
Typical start-up methods of the asynchronous motor

Method I: Connect to the grid and star-up the asynchronous motor directly

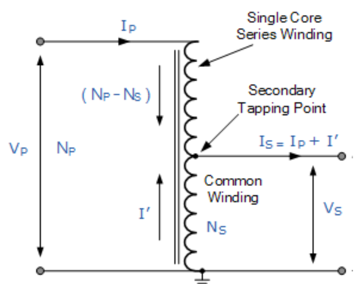
Do nothing

Small power asynchronous motor:
Power < 20 or 30 kW

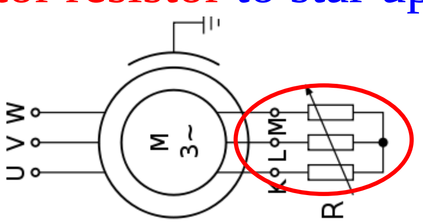
Method II: Y-Δ Changing structure of the stator to start up the asynchronous motor



Method III: Use auto-transformer to start up the asynchronous motor



Method IV: Increase the rotor resistor to star up the asynchronous motor



Typical speed control methods of the asynchronous motor

$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

- Change the frequency (f_1) of the voltage of the stator winding
- Change the pole-pairs (P) of the asynchronous motor
- Change the slip ratio (s) of the asynchronous motor

START-UP AND CONTROL OF THE ASYNCHRONOUS MOTOR

[24/03/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

END OF TOPIC

Important Notes on Quiz

There will be **one** quiz for the AC motor drives part at 31/03/2020:

- Quiz (10 marks): Topics to be tested covered **topics 1 to 4**;
- To answer a few compulsory questions within **60 minutes**;
- It is a **closed-book** Quiz;
- Student much present **ID (with photo)** for taking attendance;
- Zero mark will be given for **absentees** without valid reasons;
- Absentees must write in to the tutor through email within **THE SAME DAY OR EARLER** of Quiz to request a make-up (Failure to do so will result in a zero mark).

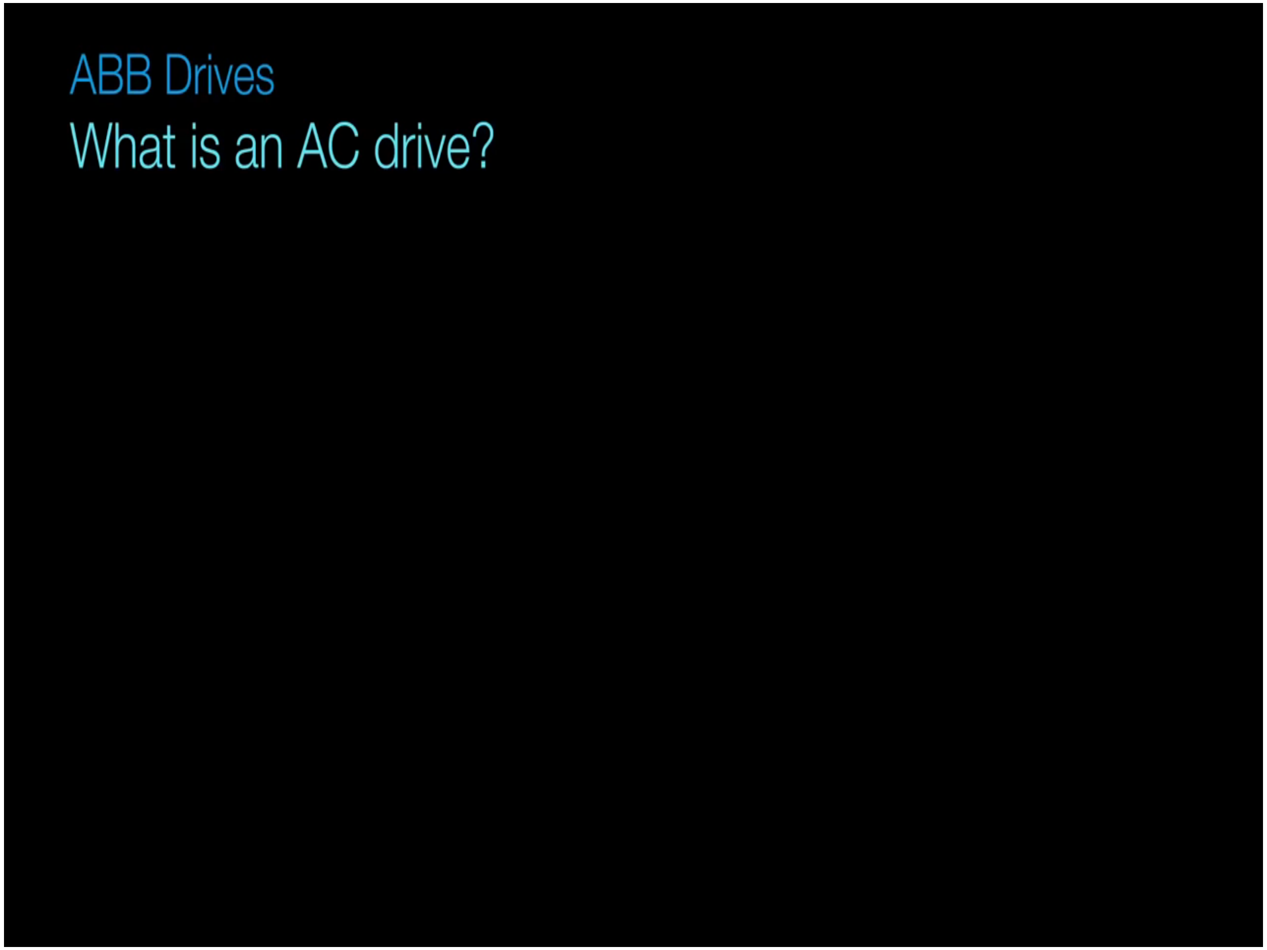
OPERATION PRINCIPLE OF THE RECTIFIER AND INVERTER

[31/03/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

- Three phase diode bridge rectifier
- Operation principle of the inverter

Video: the function of the motor drive system

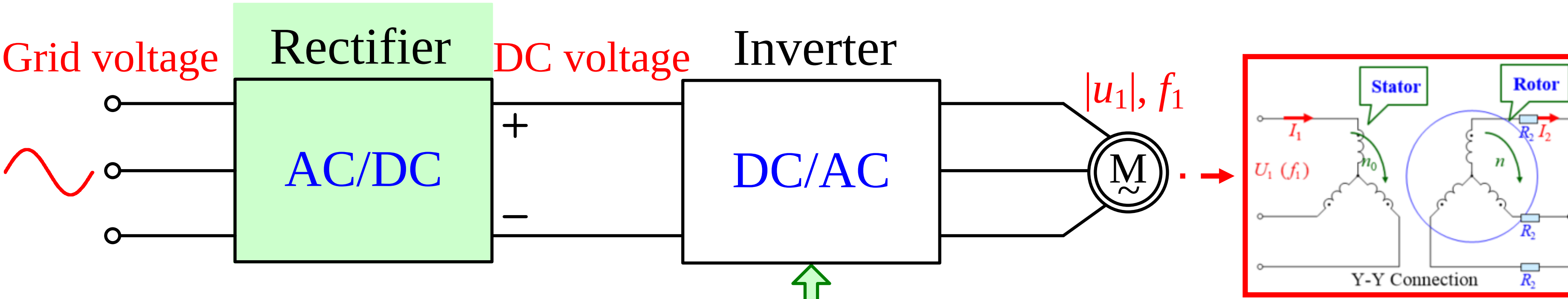


OPERATION PRINCIPLE OF THE RECTIFIER AND INVERTER

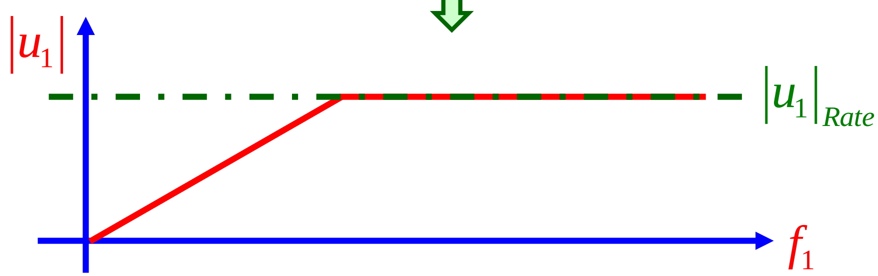
[31/03/2020]

- Three phase diode bridge rectifier
- Operation principle of the inverter

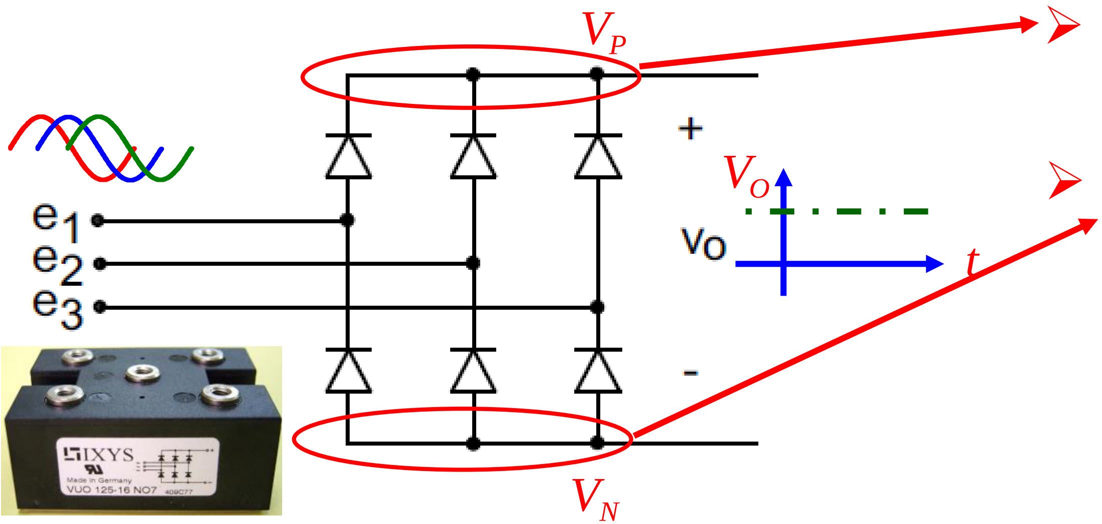
Review: the drive circuit of the asynchronous motor



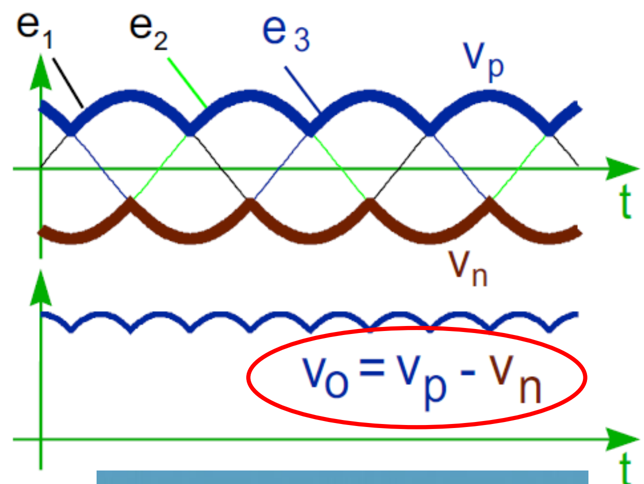
Control the amplitude and frequency of its output voltage u_1, which is also the motor stator voltage



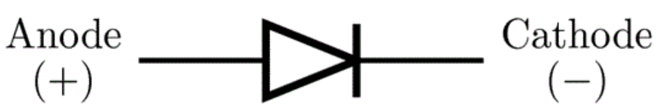
Three phase diode bridge rectifier



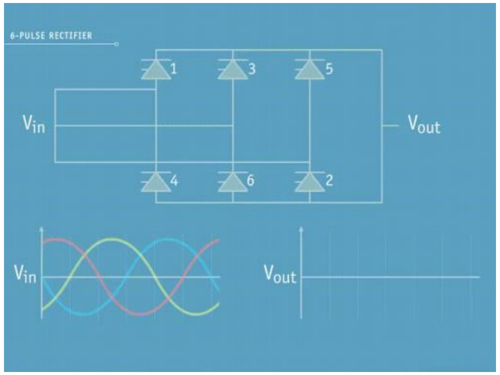
- V_p is always equal to the maximum voltage among e_1, e_2 and e_3.
- V_N is always equal to the minimum voltage among e_1, e_2 and e_3.



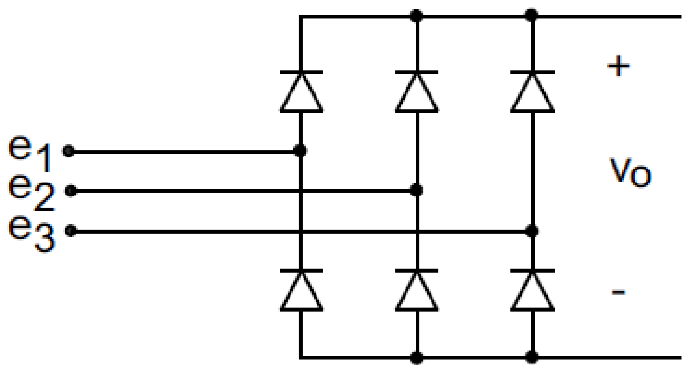
Basic function: transfer three phase AC voltage to DC voltage

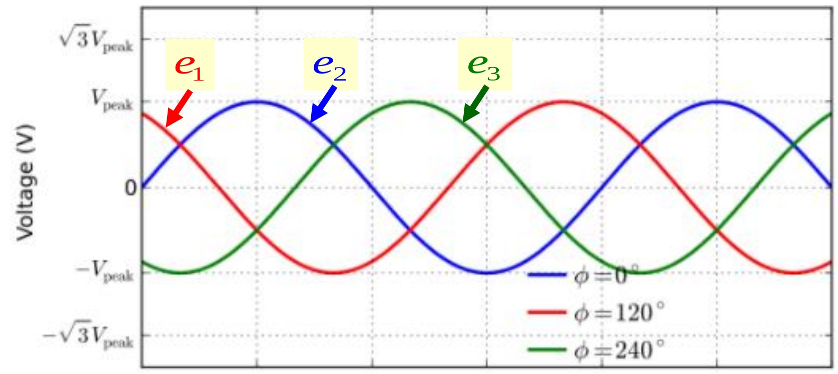


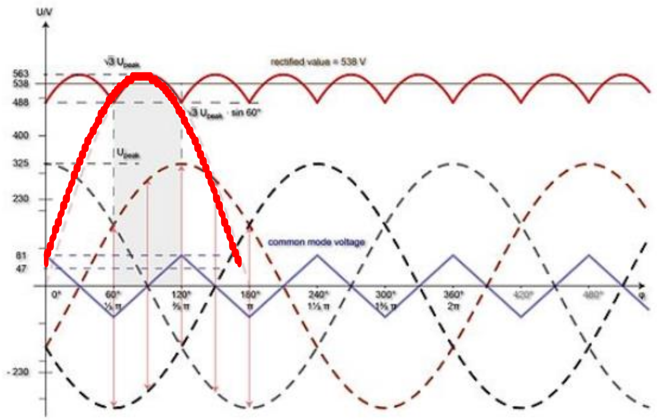
- If Anode voltage > Cathode voltage, the diode is turned on
- If Anode voltage < Cathode voltage, the diode is blocked

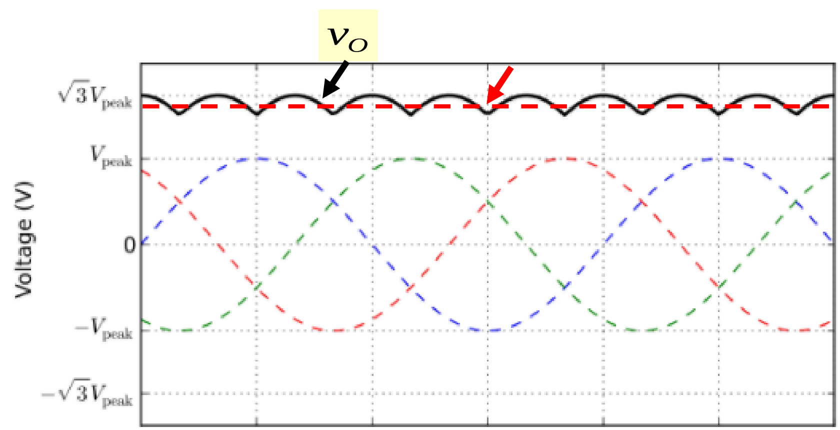


Relationship between the grid voltage and the DC output voltage of the rectifier





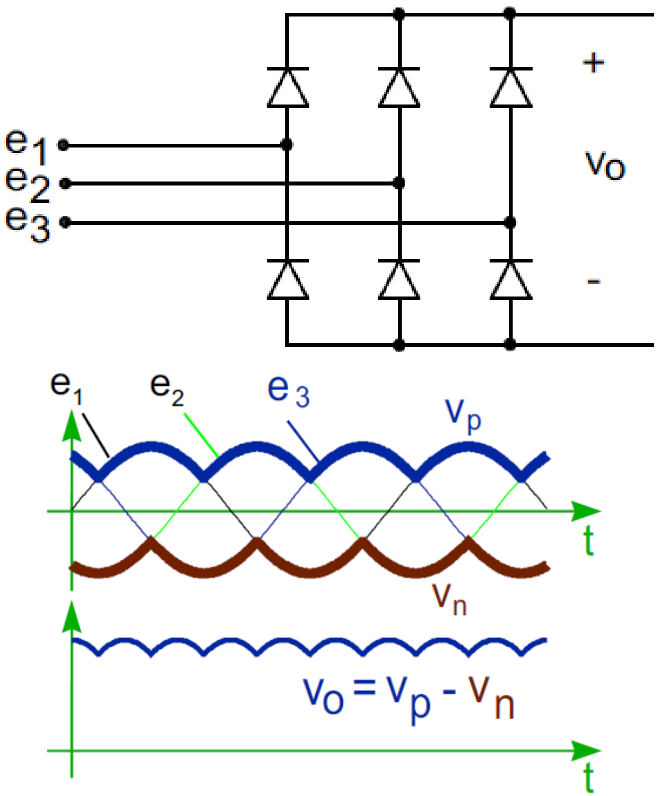




$$V_{dc} = V_{av} = \frac{1}{\frac{1}{3}\pi}\int_{60^\circ}^{120^\circ} \sqrt{3}\cdot V_{peak}\cdot \sin\varphi \cdot d\varphi = \frac{3\cdot\sqrt{3}\cdot V_{peak}}{\pi}\cdot(-\cos 120^\circ + \cos 60^\circ) = \frac{3\cdot\sqrt{3}\cdot V_{peak}}{\pi}\cdot\left[-\left(-\frac{1}{2}\right)+\frac{1}{2}\right] = \frac{3\cdot\sqrt{3}\cdot V_{peak}}{\pi}$$

$$V_{dc} = \frac{3\cdot\sqrt{3}\cdot\sqrt{2}\cdot e_{1LN}}{\pi} \approx 2.34 e_{1LN}$$

Example 1: For a three phase diode bridge rectifier, if its input is connected to the grid (230 V AC, 50 Hz), how many volts is the output voltage of the three phase diode bridge rectifier?



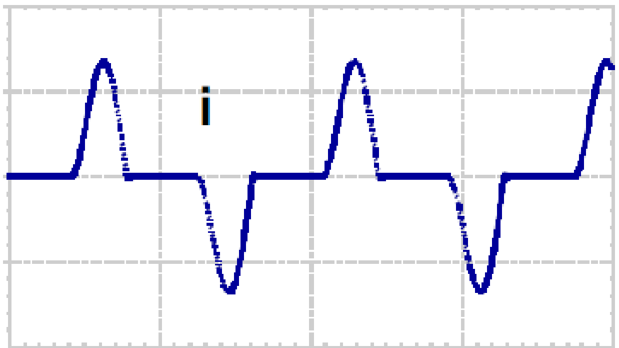
$$e_{1LN} = e_{2LN} = e_{3LN} = 230V\ AC$$

$$V_{dc} \approx 2.34 e_{1LN}$$

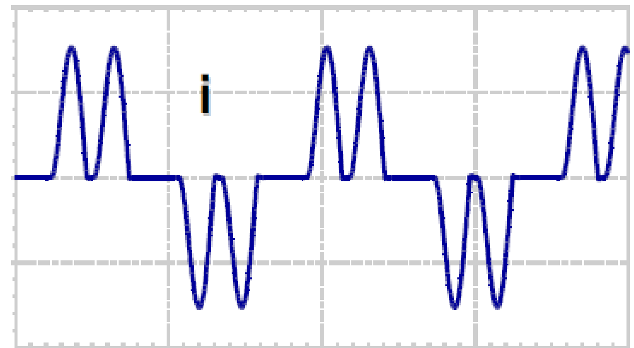
$$V_{dc} \approx 538.2V\ DC$$

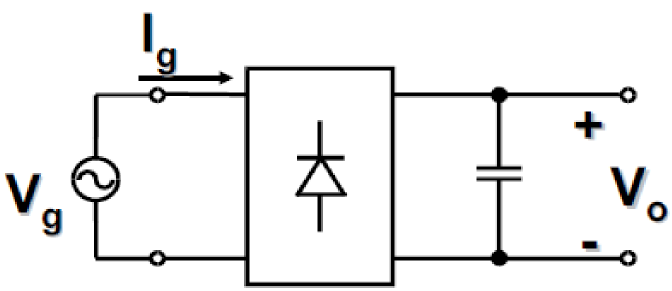
Limitation of the diode bridge rectifier: large harmonic components in the input current

THD ≅ 90%

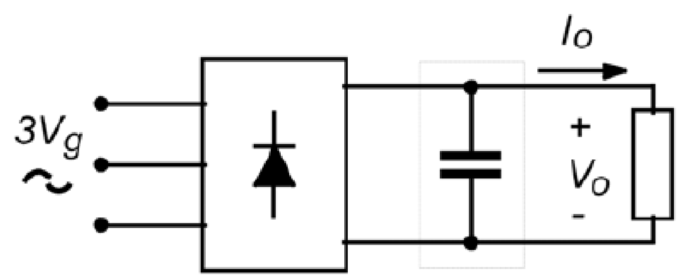


THD ≅ 80%





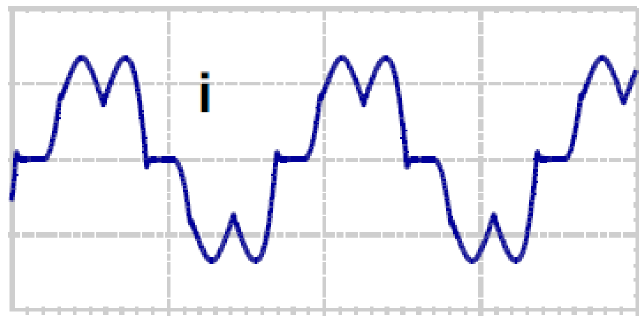
Single-phase rectifier

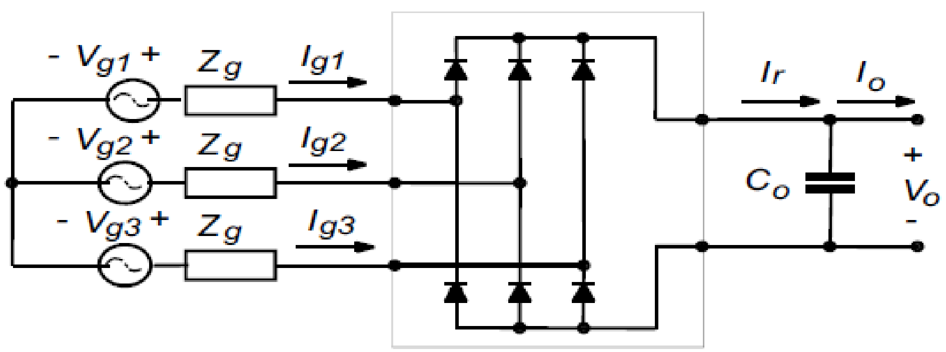


Three-phase rectifier

Limitation of the diode bridge rectifier: large harmonic components in the input current

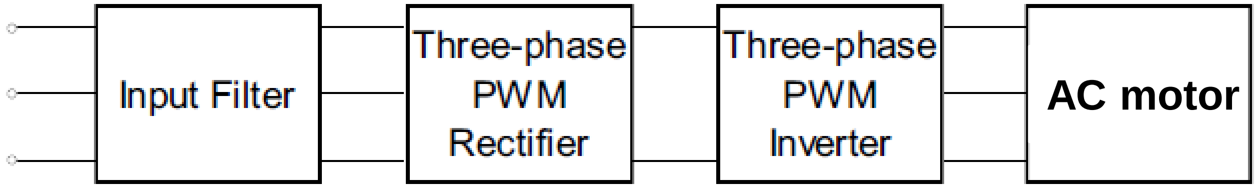
THD ≅ 40%

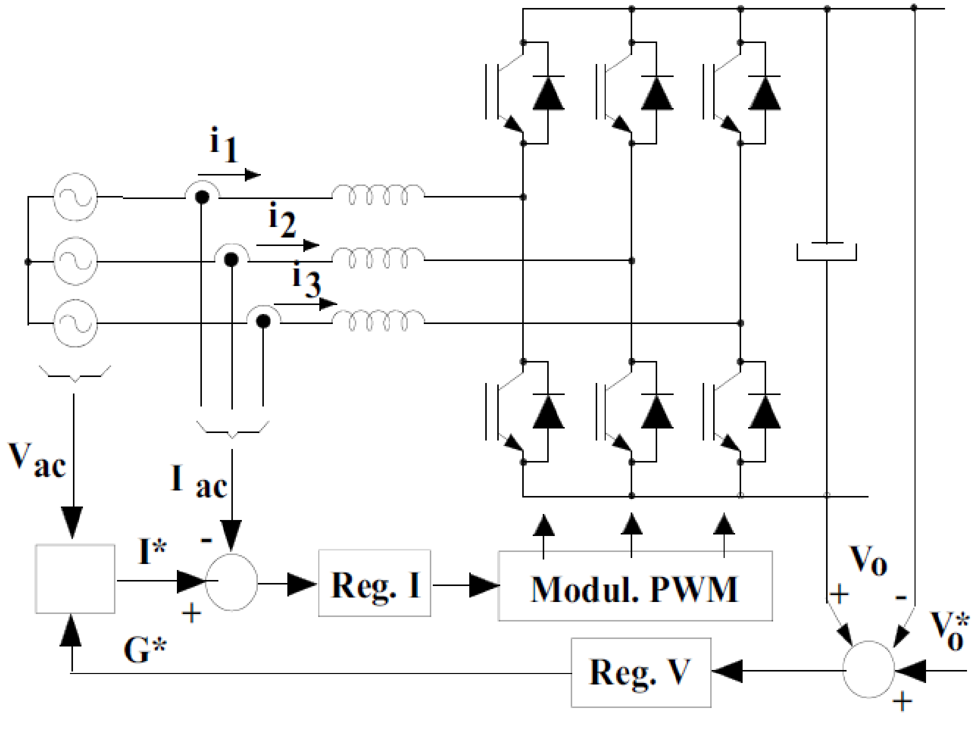




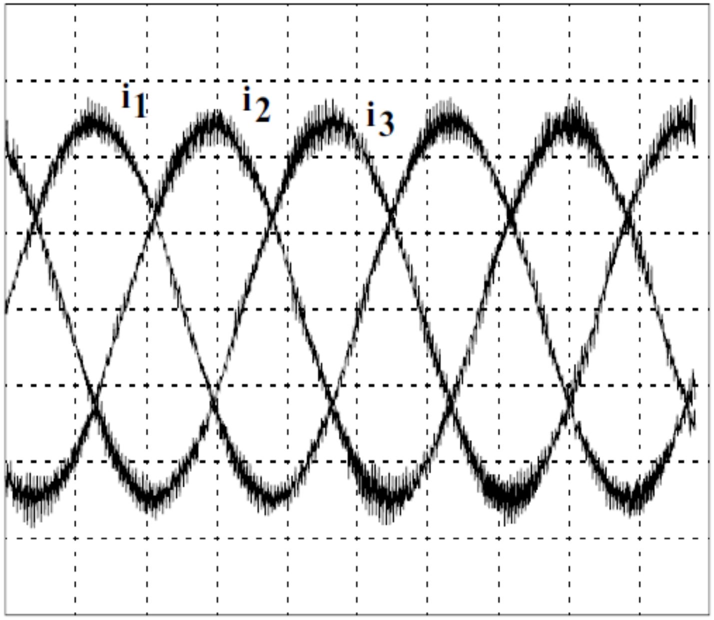
Three-phase rectifier with inductive filter

Knowledge extension: PWM rectifier





Control and circuit diagram of the PWM rectifier



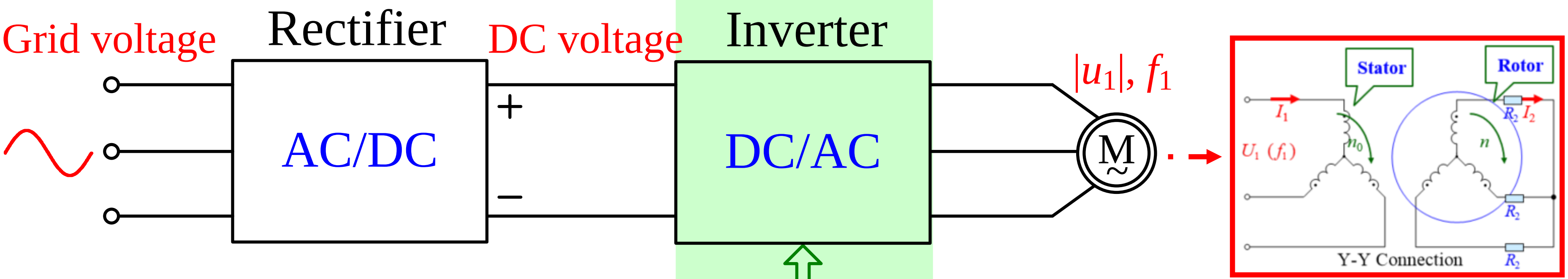
Sinusoidal input current and unity power factor

OPERATION PRINCIPLE OF THE RECTIFIER AND INVERTER

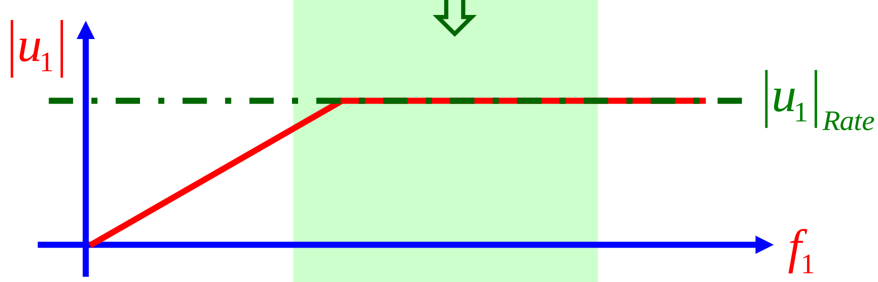
[31/03/2020]

- Three phase diode bridge rectifier
- Operation principle of the inverter

Review: the drive circuit of the asynchronous motor



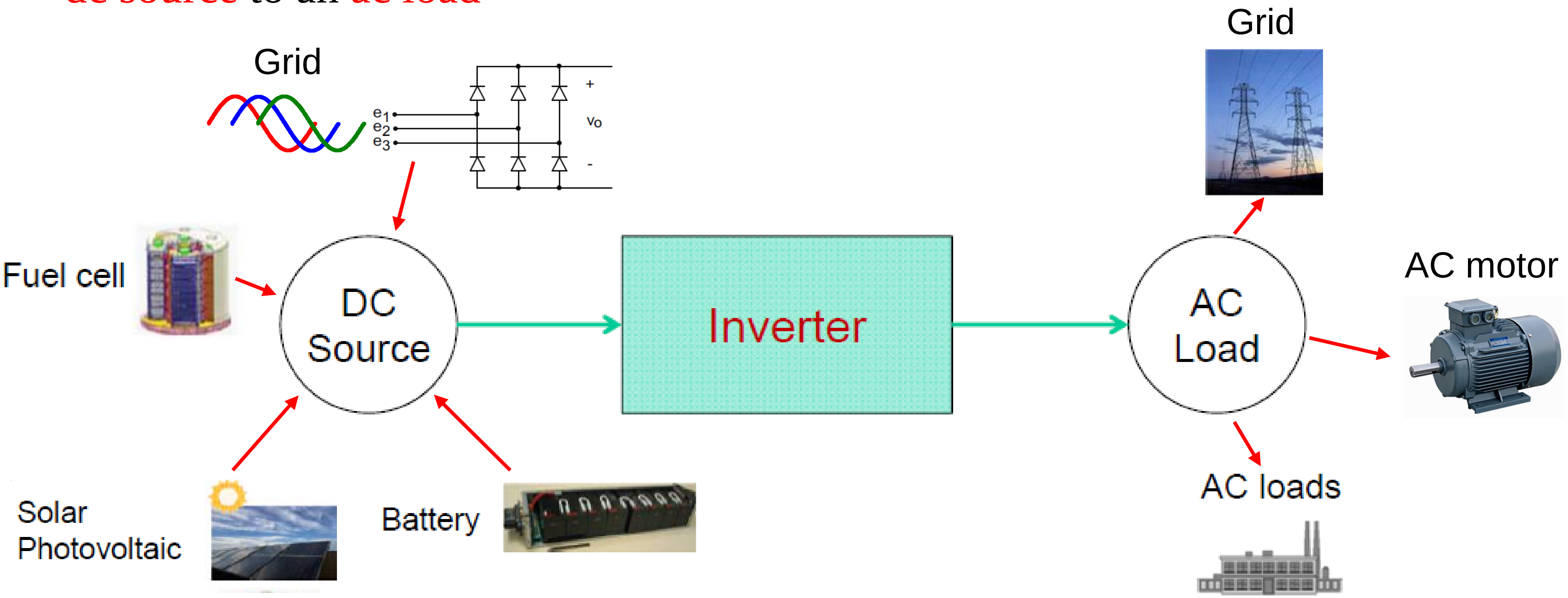
Control the amplitude and frequency of its output voltage u_1, which is also the motor stator voltage



Inverter basics: Definition of the inverter

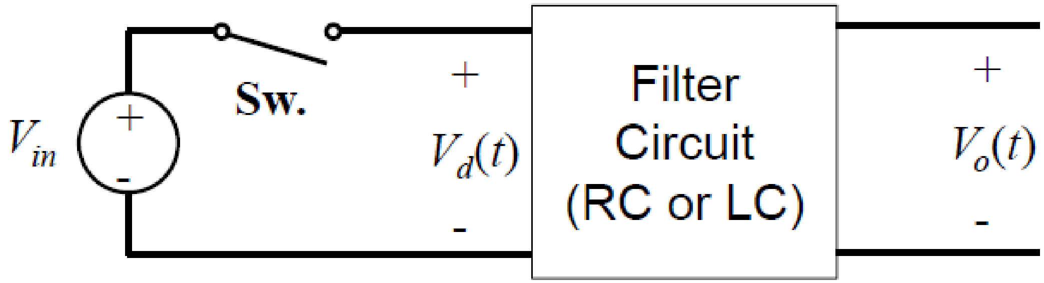
- A device used to convert direct current into alternating current – Merriam-Webster Dictionary.

- More precisely: inverter is to convert or transfer power from a dc source to an ac load

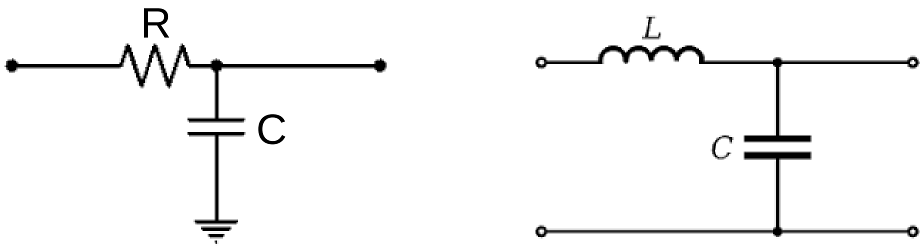


BEFORE STUDY THE OPERATION OF THE INVERTER, LET US REVISIT THE DC TO DC CONVERTER.

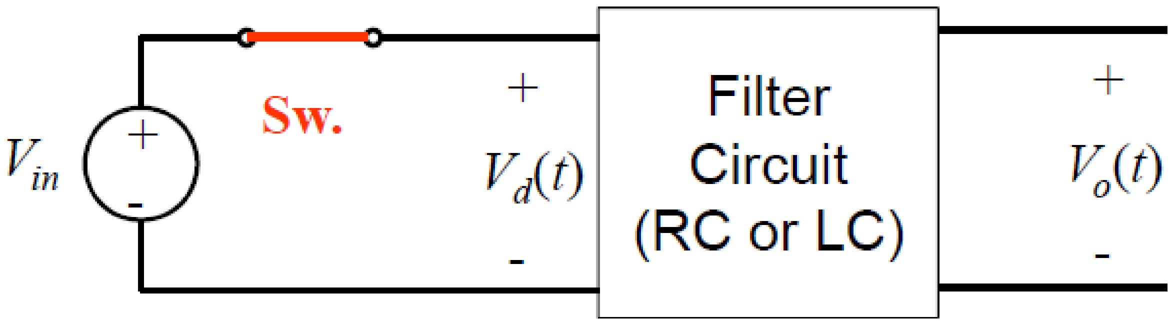
Consider a simple switching circuit that converts DC to DC

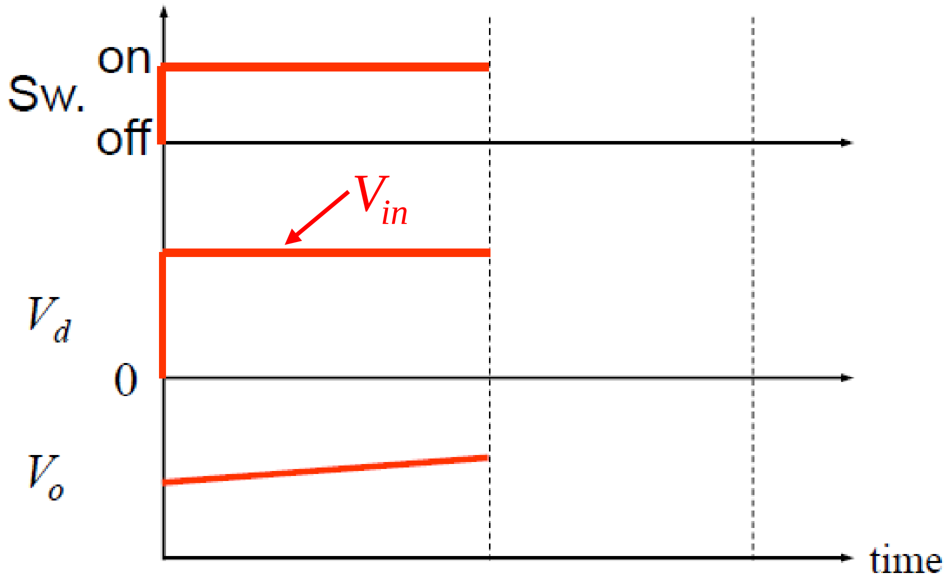


- ✓ V_{in}: Input voltage source
- ✓ V_d: An intermediate output voltage after the switcher
- ✓ V_o: Output voltage
- ✓ *Sw.*: Semiconductor switch with on and off operation
- ✓ Filter circuit: Typically passive *LC* circuit to smooth the output

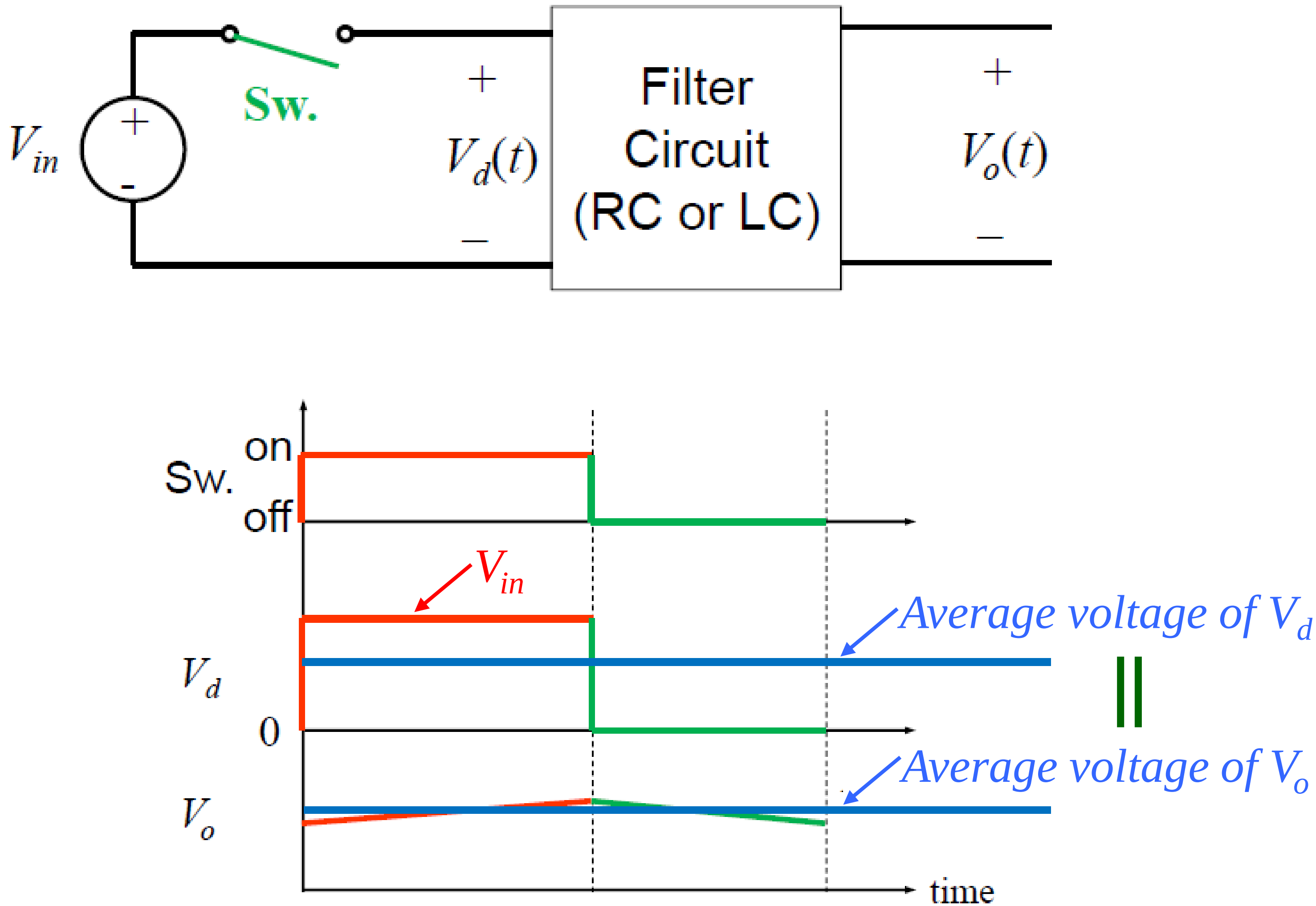


Switcher turn on

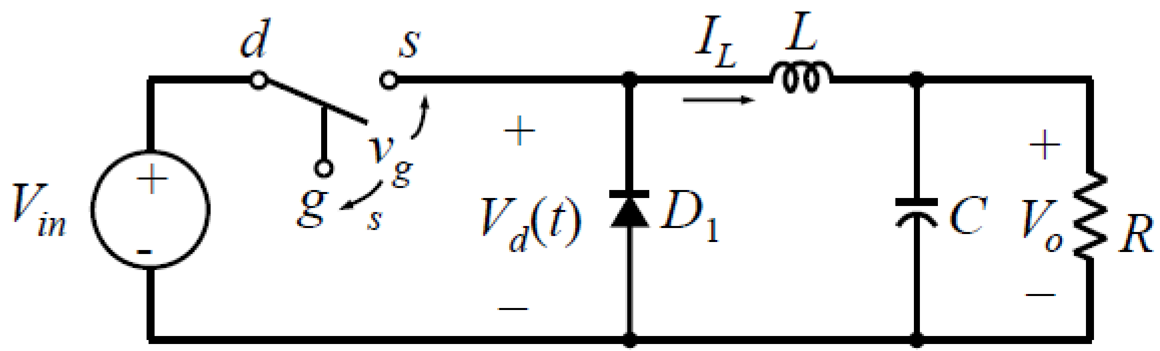


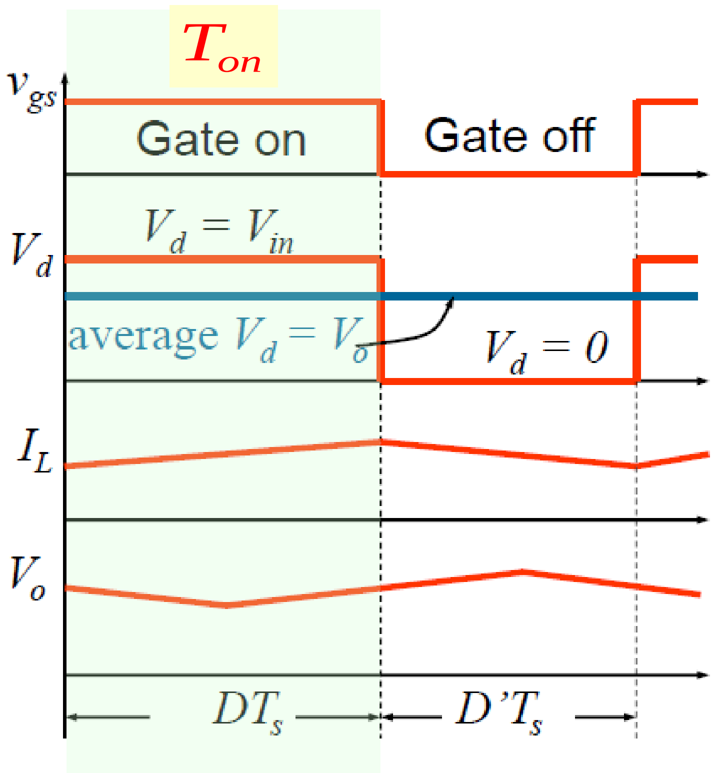


Switcher turn off



Complete DC-DC buck converter circuit





Average output voltage:

$$\bar{V}_o = D \cdot V_{in}$$

Where $D=T_{on}/T_s$ is the duty ratio.

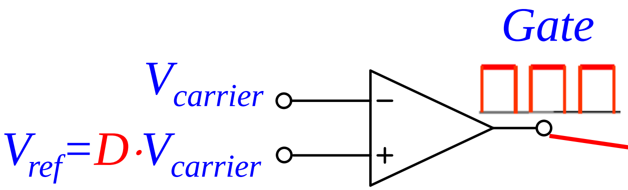
Because $D < 1$, V_o is always less than V_{in}

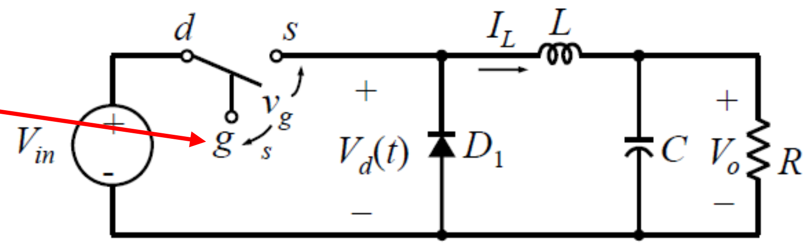
→ buck converting

T_s: switching period (unit: s) = $1/f_s$

f_s: switching frequency (unit: Hz)

How the gate signal generated for the switcher?



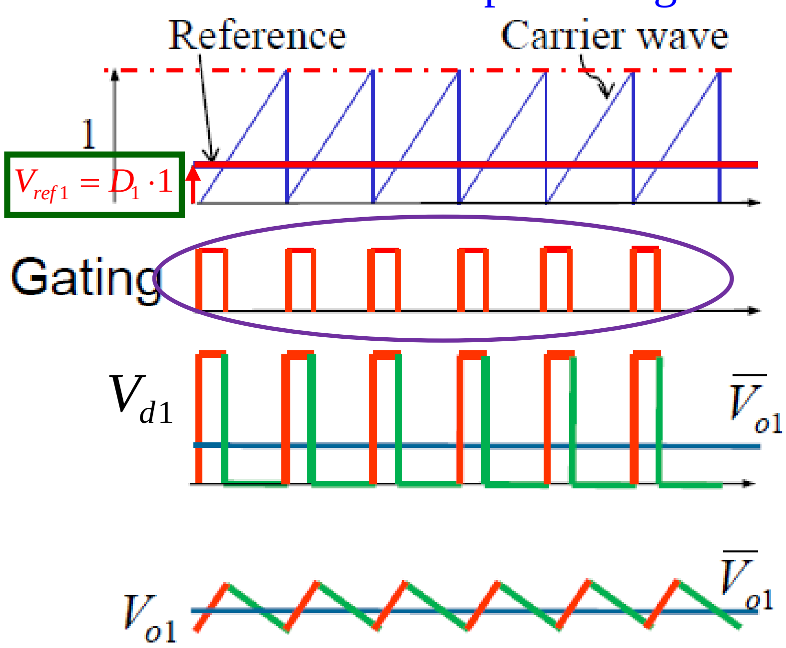


$$\bar{V}_o = D \cdot V_{in}$$

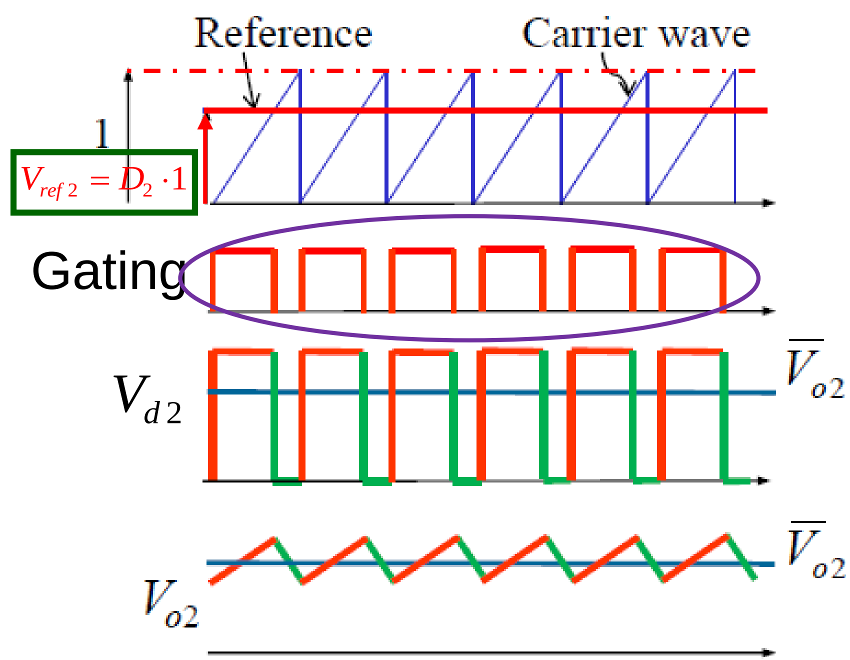
If $V_{ref} \geq V_{carrier}$, Gate=1

If $V_{ref} < V_{carrier}$, Gate=0

Get a small output voltage



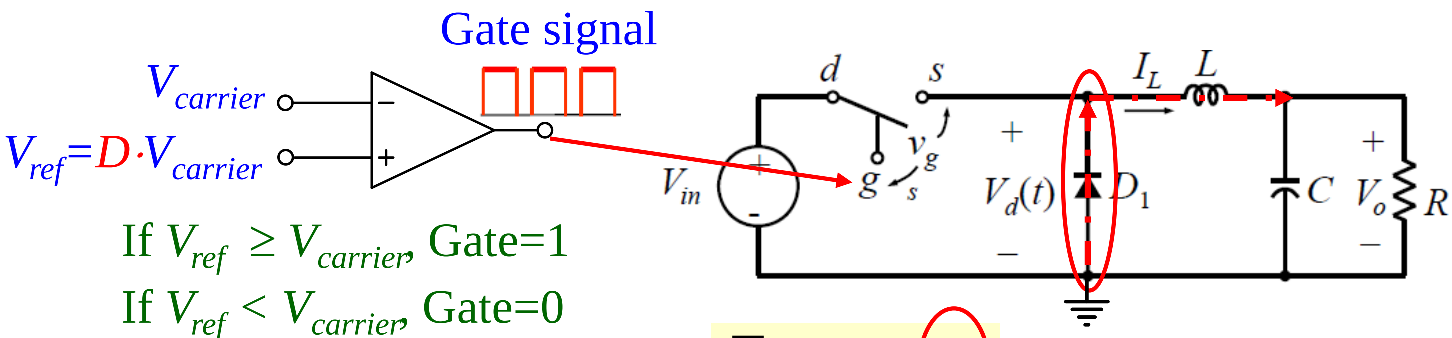
Get a large output voltage



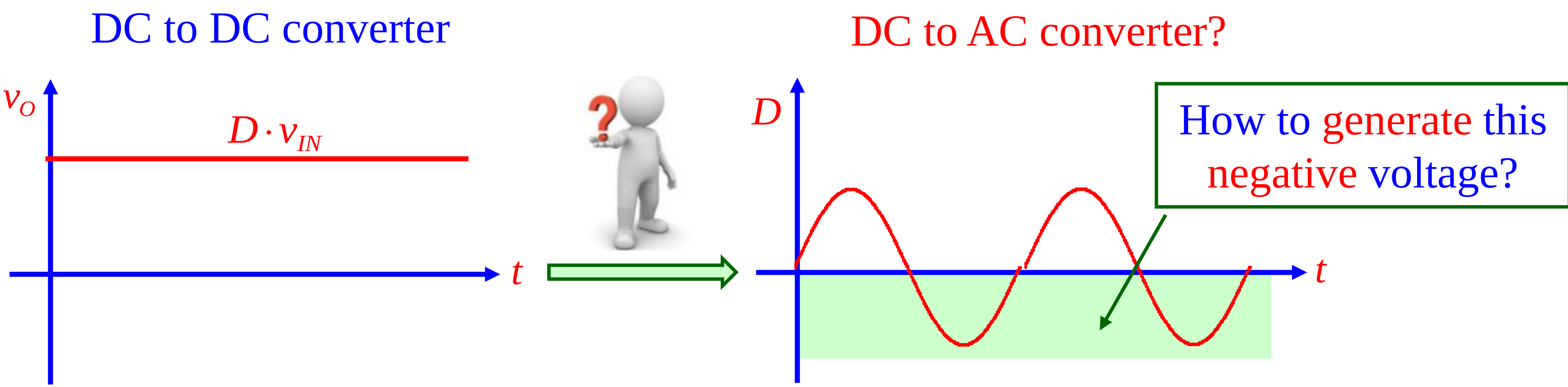
Average output voltage: $\bar{V}_{o1} = D_1 \cdot V_{in}$

$\bar{V}_{o2} = D_2 \cdot V_{in}$

Question: Can we change the duty cycle to a sinusoidal AC waveforms ?

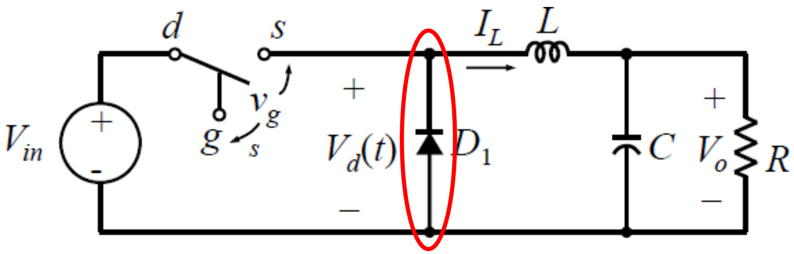


$$\bar{V}_o = D \cdot V_{in}$$ → DC voltage

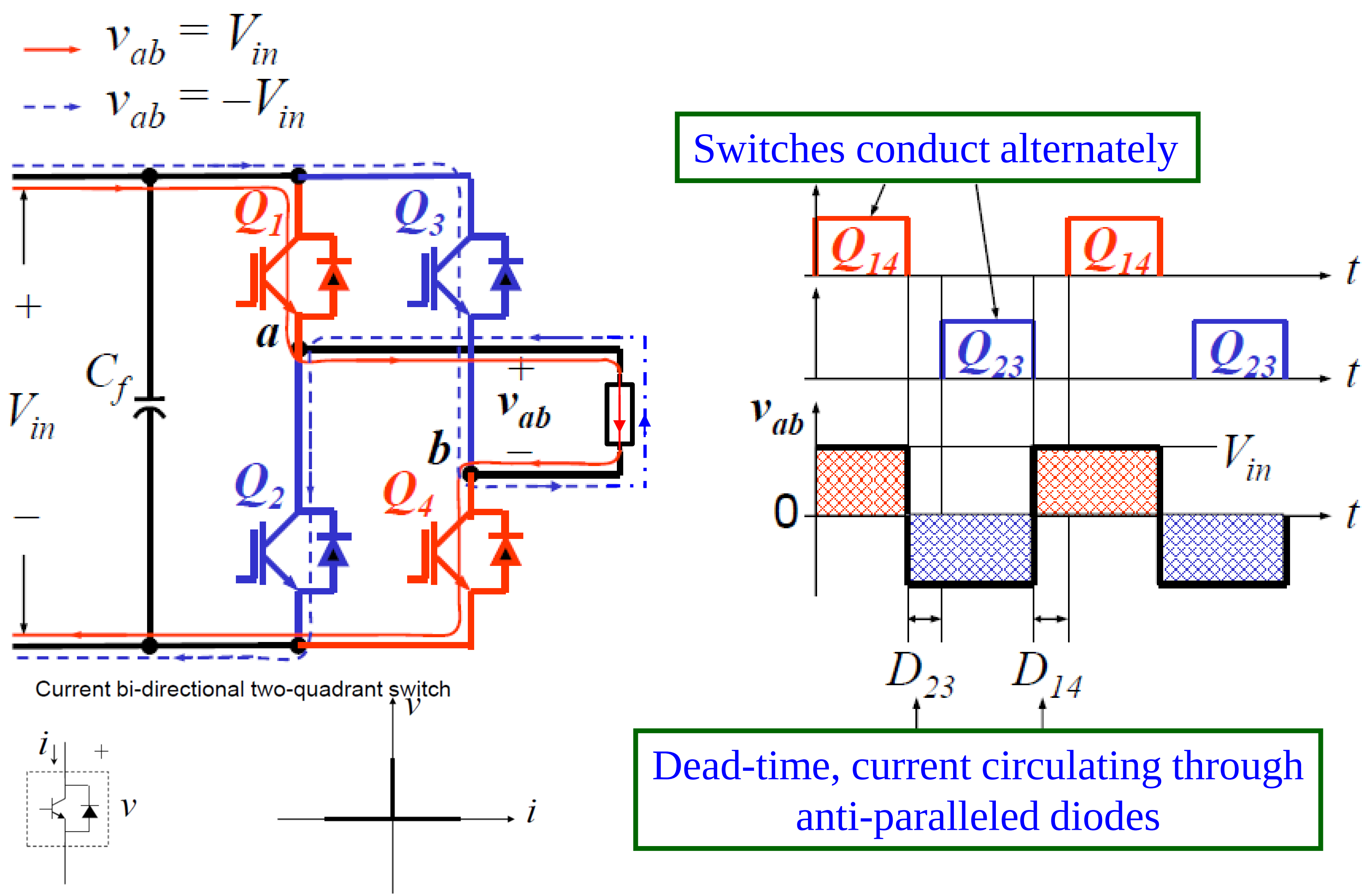


If V_o is negative, the current will flow from the ground to V_o through D_1, and make V_o clamped to 0 V. Therefore, V_o cannot be smaller than 0 V in this buck converter

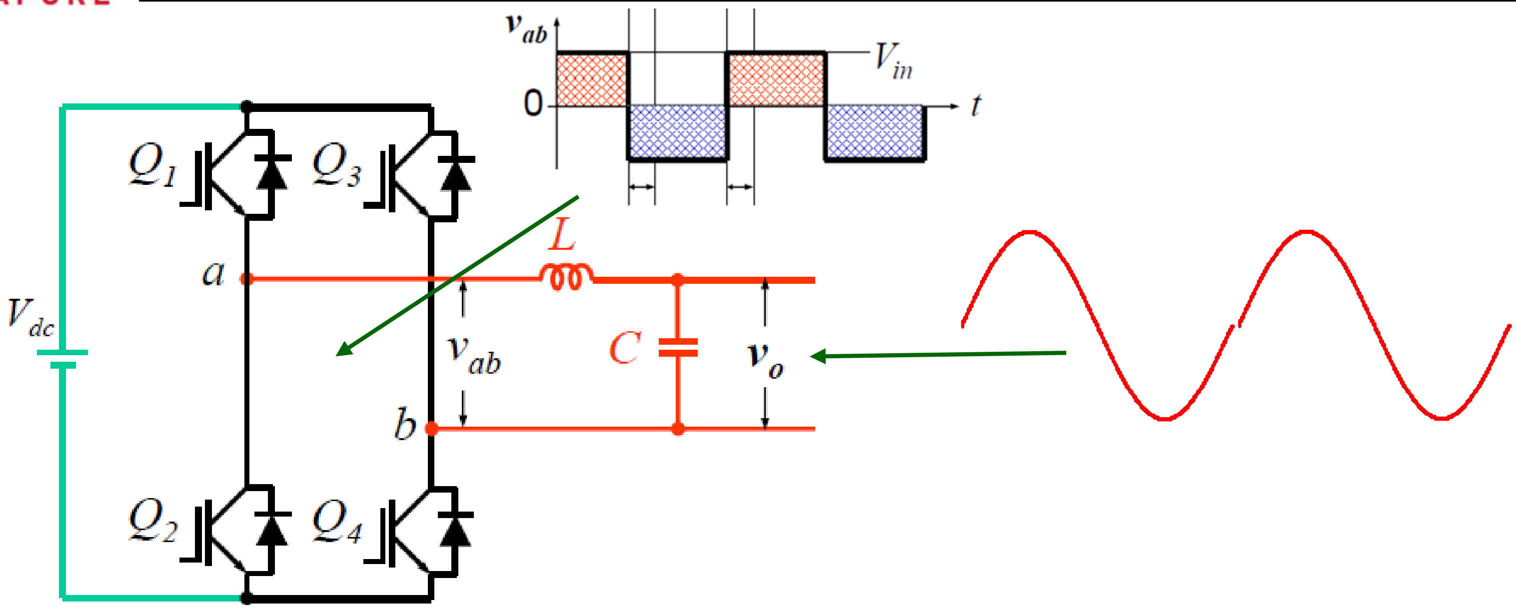
LET US COME BACK TO THE INVERTER



Full bridge circuit can generate both positive and negative voltages

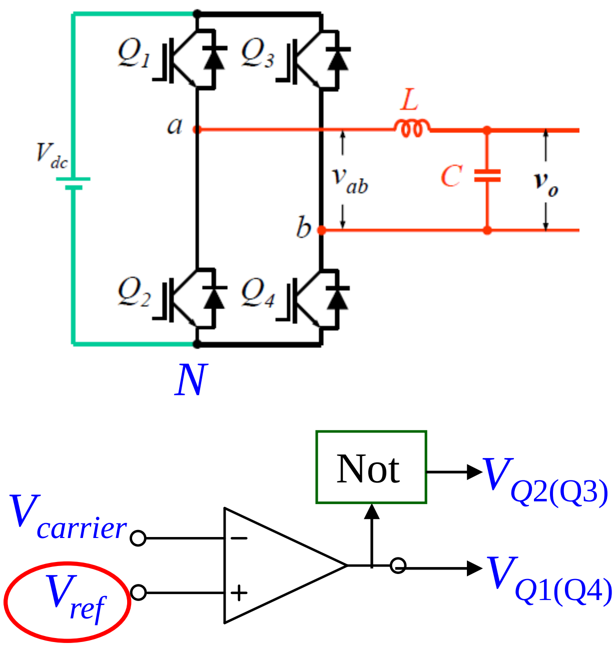


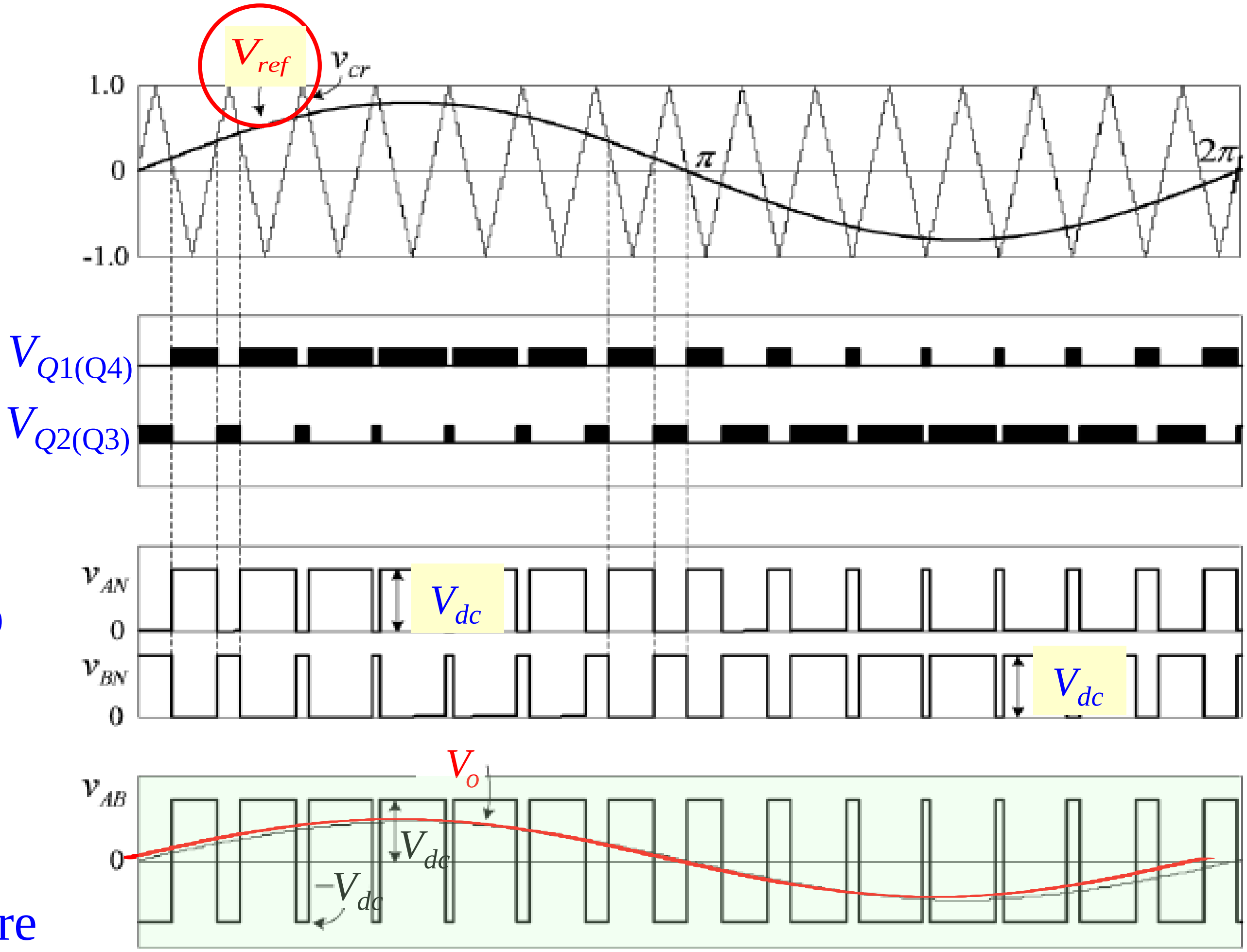
Single phase DC/AC inverter



- Q_1-Q_2 and Q_3-Q_4 pairs are switched complementarily.
- The total average output voltage v_o = average(v_{ab}).
- Output across a and b looks like a square wave. Adding LC circuit to smooth out the waveform to be sinusoidal.

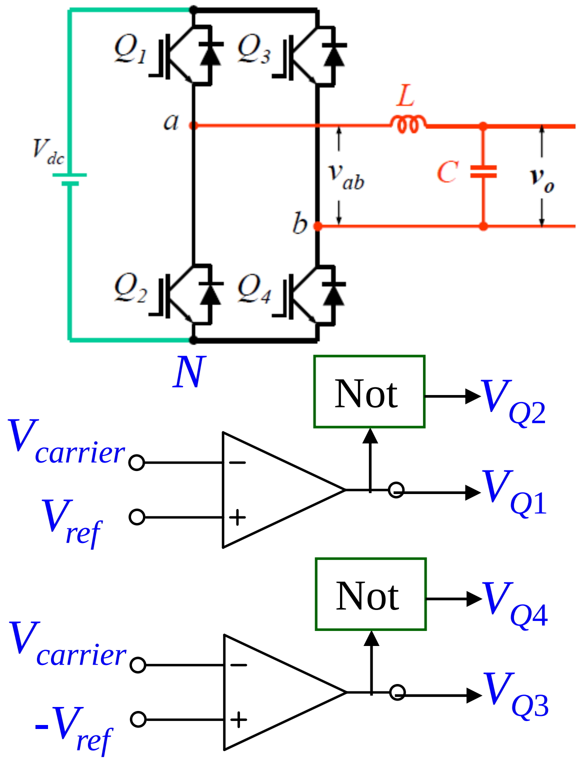
Bipolar modulation of the single phase DC/AC inverter

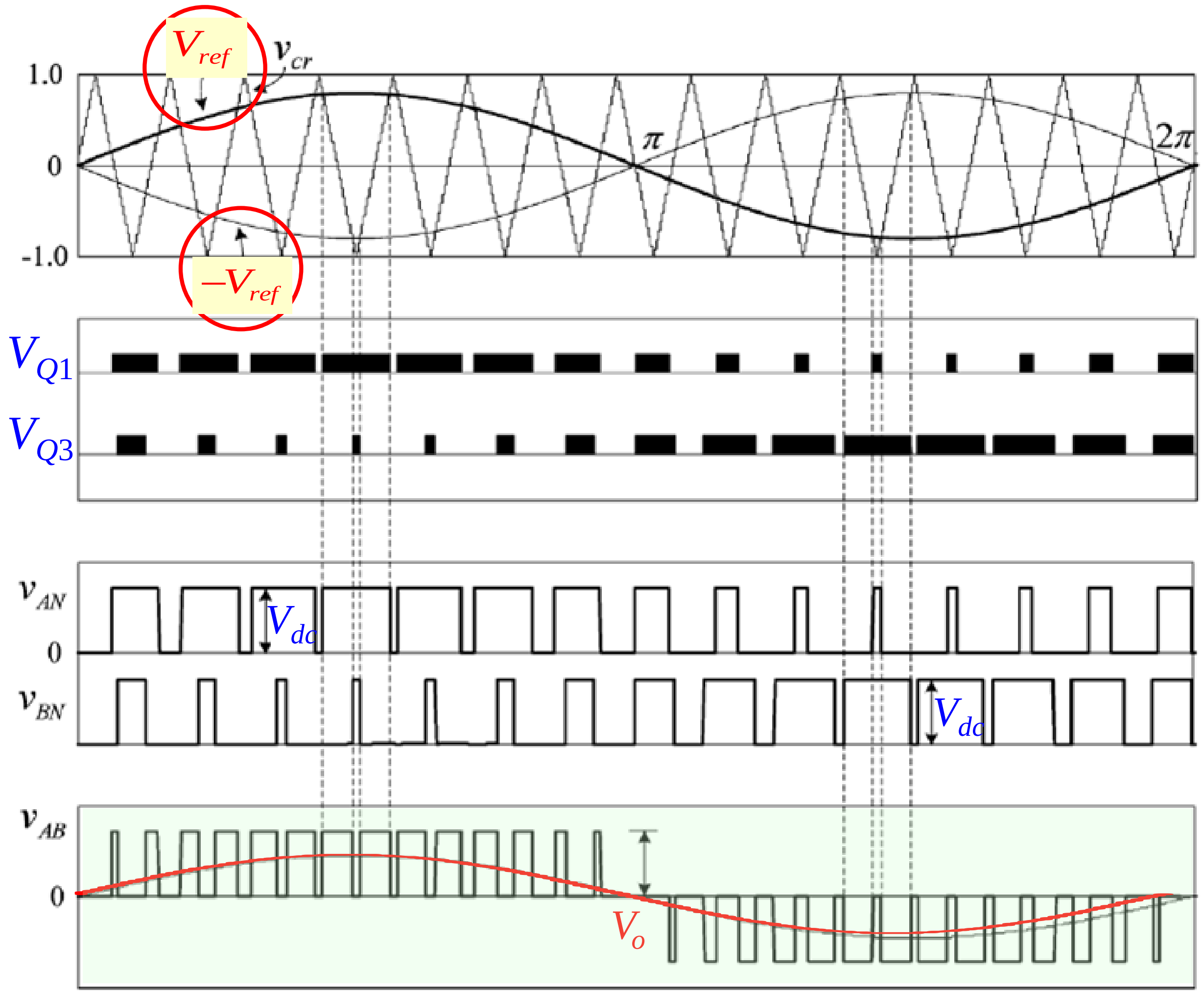




- V_{Q1}-V_{Q4} are the gating signal for Q_1-Q_4.
- Q_1-Q_2 and Q_3-Q_4 pairs are switched complementarily.

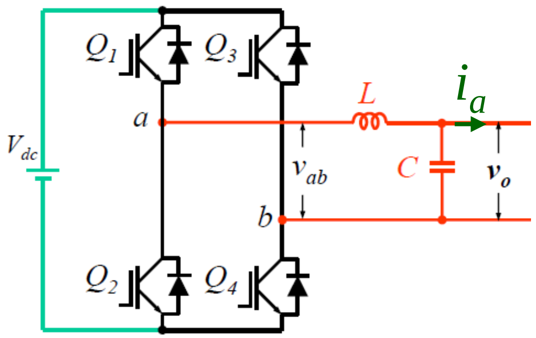
Unipolar modulation of the single phase DC/AC inverter





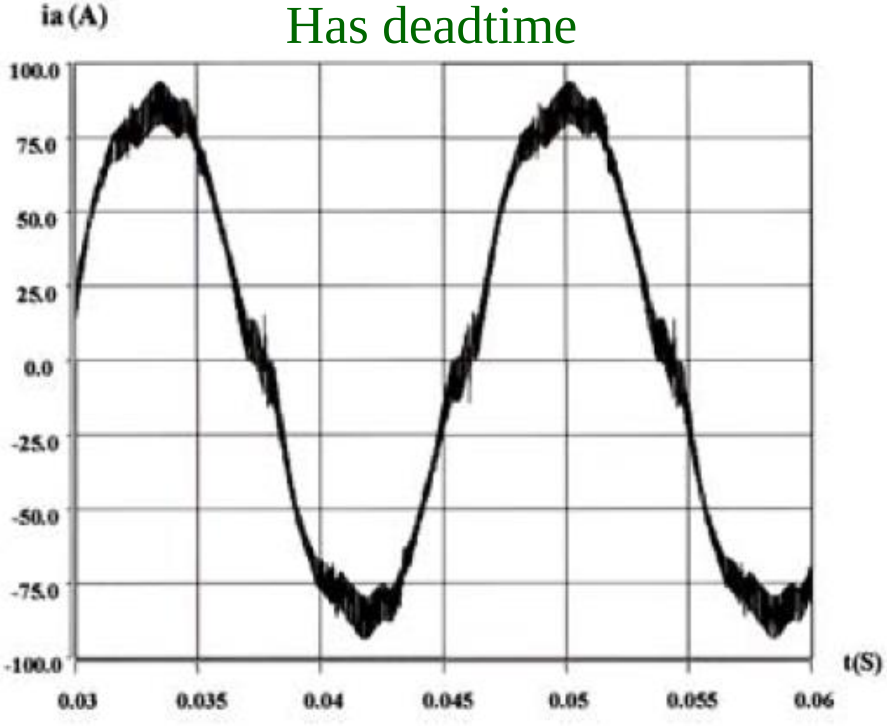
- V_{Q1}-V_{Q4} are the gating signal for Q_1-Q_4.
- Q_1-Q_2 and Q_3-Q_4 pairs are switched complementarily.

Deadtime issues of the inverters

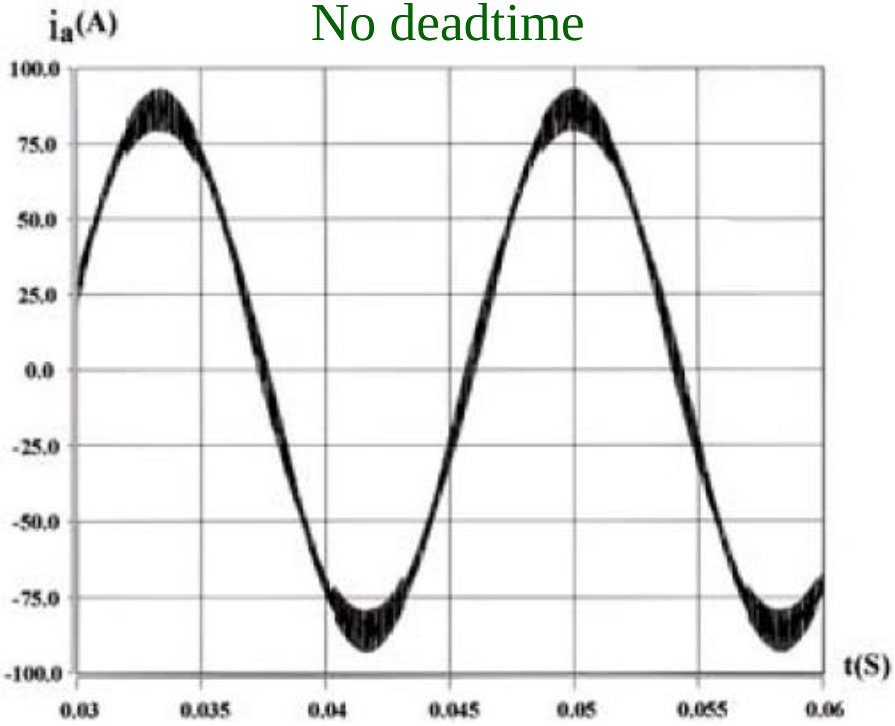


T_{sw}=50μs (20kHz), $T_{deadtime}$=4 μs, inverter control its output current: i_a

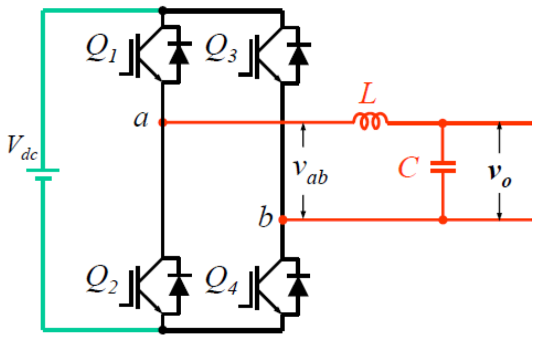
Has deadtime



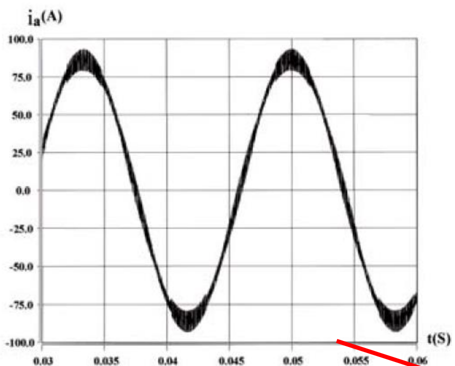
No deadtime



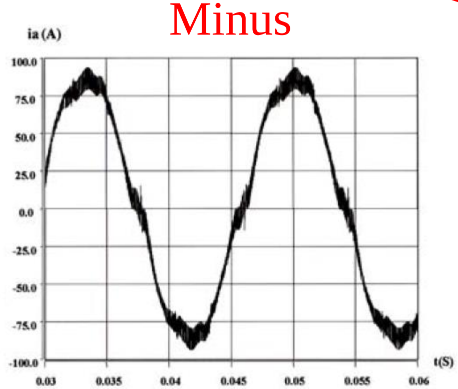
Extension knowledge: Deadtime compensation of the inverters

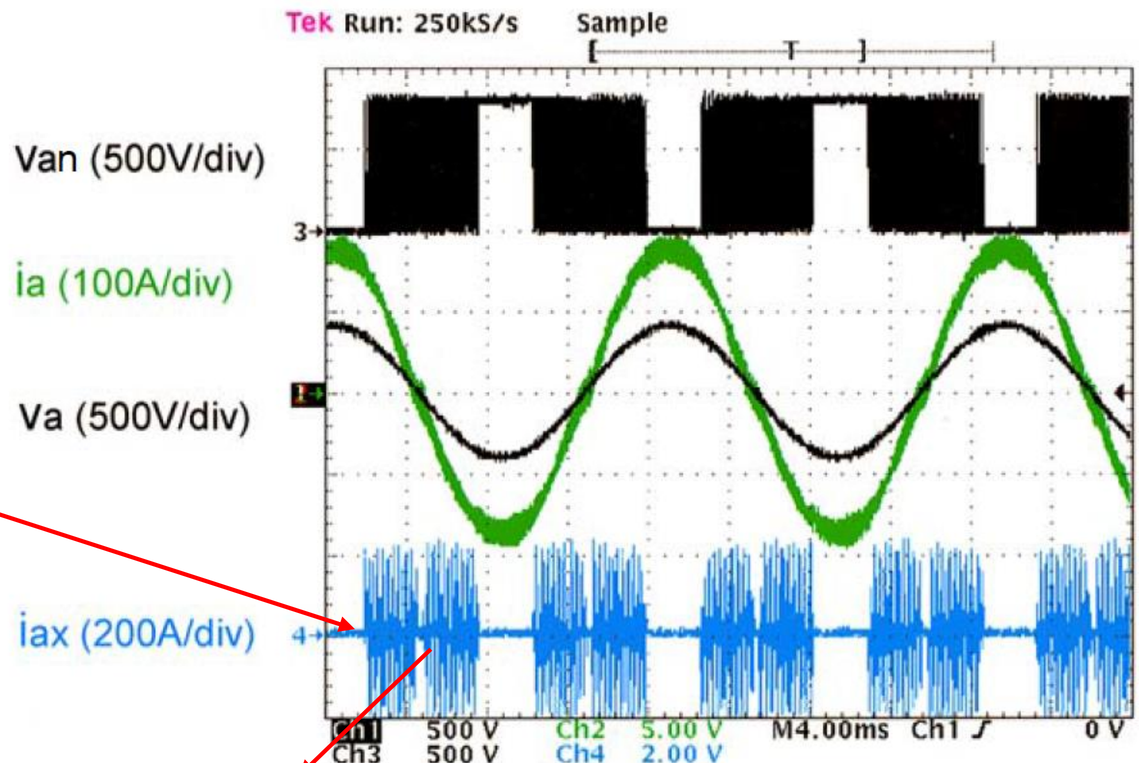


T_{sw}=50μs (20 kHz), $T_{deadtime}$=4 μs, inverter control its output current: i_a



Minus

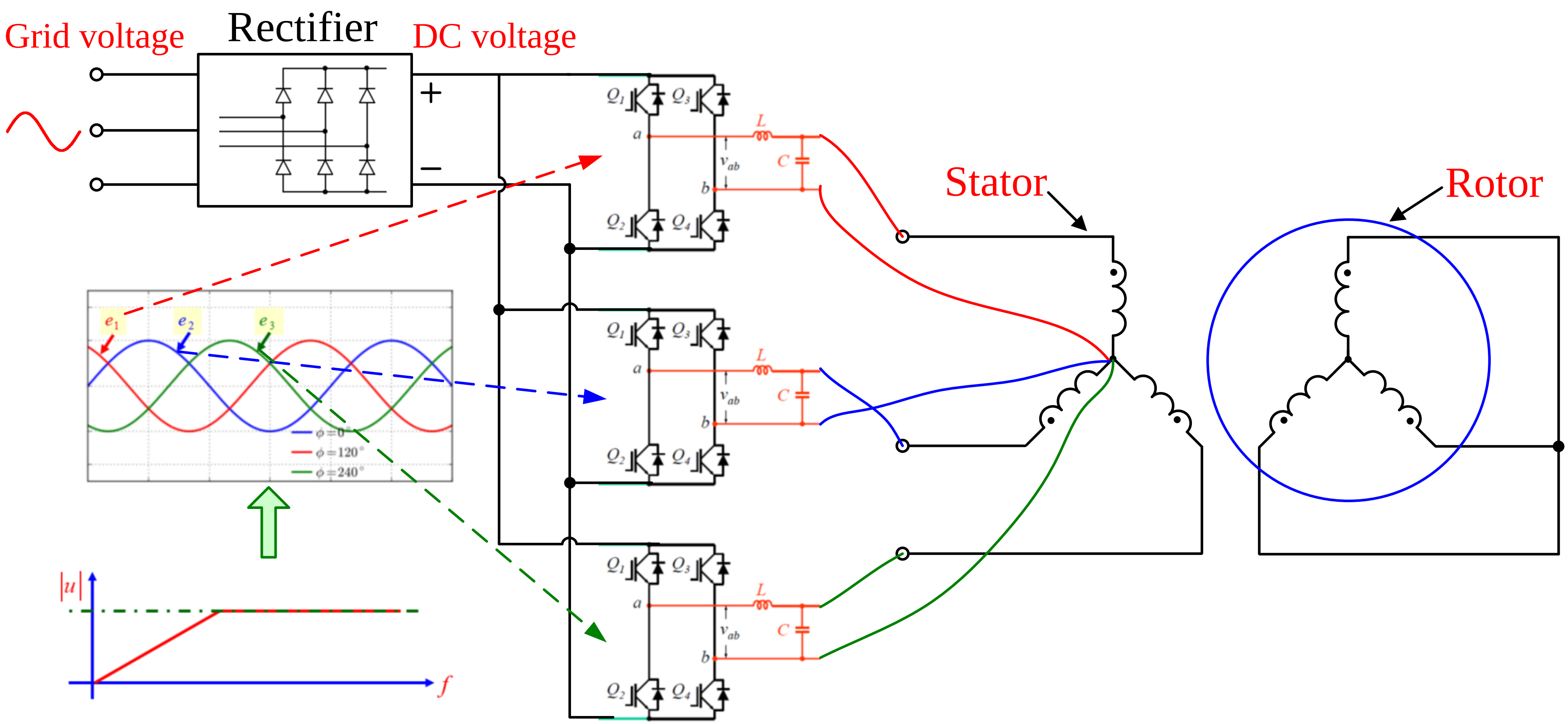




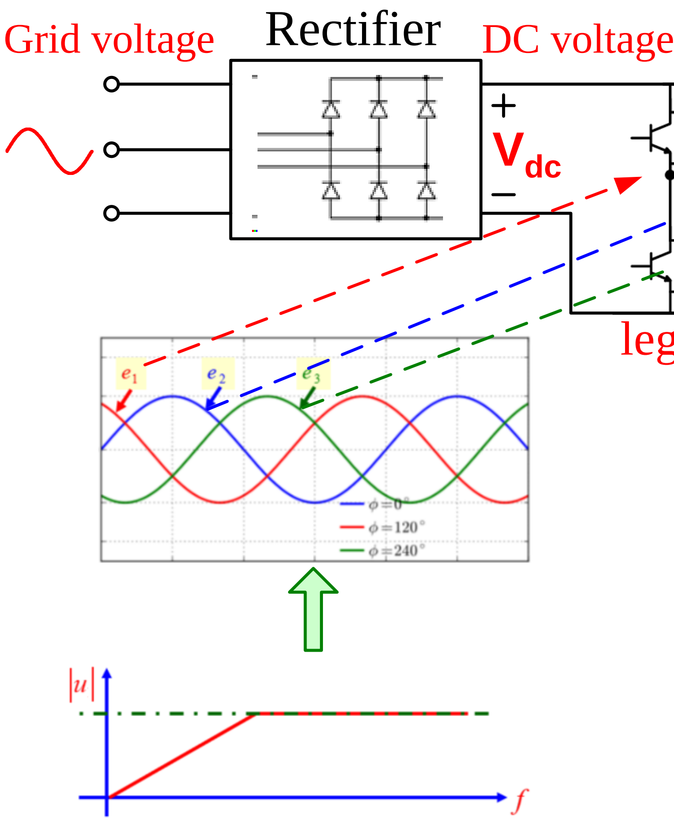
Add this waveform to the current reference to compensate the deadtime impact

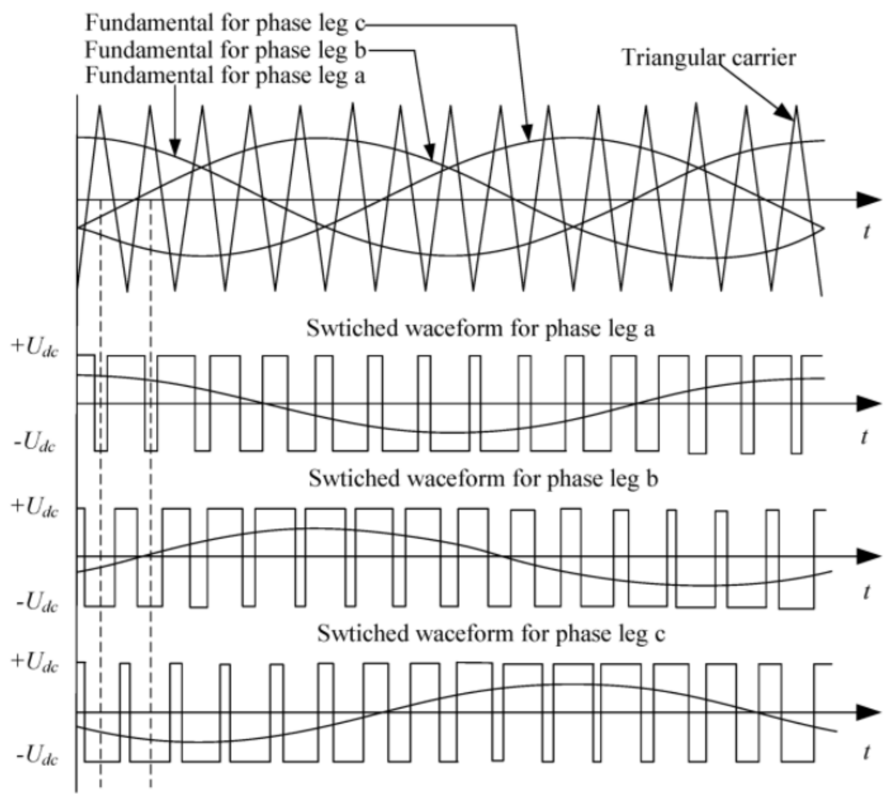
Review the operation principle of the single phase DC/AC inverter (unipolar modulation for example)

A simple way to apply the inverter to the three phase asynchronous motor drive

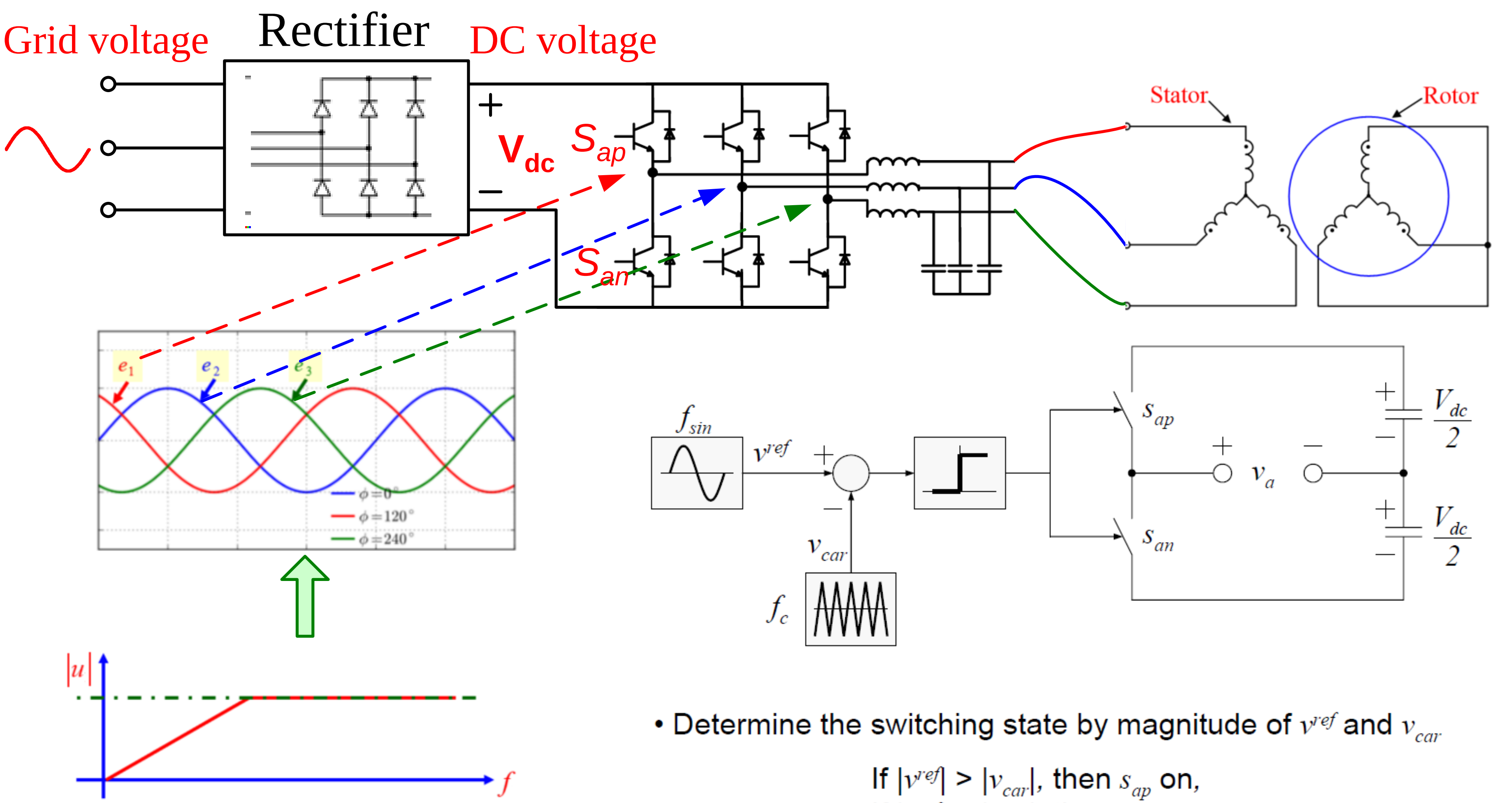


A simple way to apply the inverter to the three phase asynchronous motor drive





Three phase inverter is actually equivalent to 3 single phase half bridge inverters

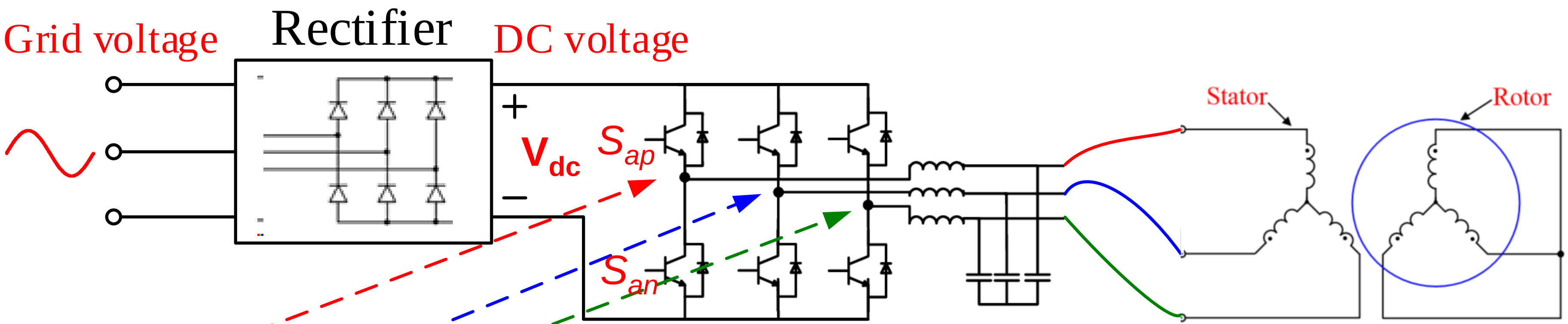


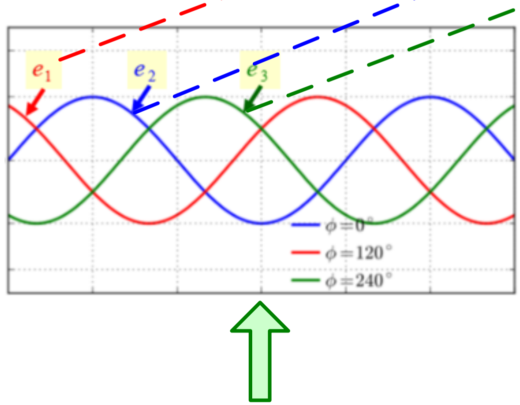
- Determine the switching state by magnitude of v^{ref} and v_{car}

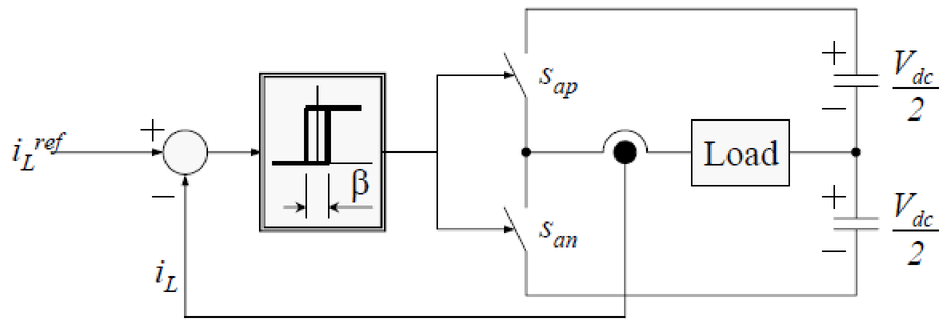
  If $|v^{ref}| > |v_{car}|$, then s_{ap} on,
  If $|v^{ref}| < |v_{car}|$, then s_{an} on

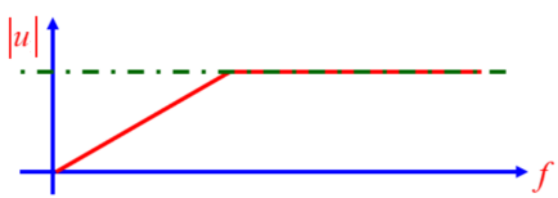
- Switching frequency is the same as carrier wave *frequency*, f_c

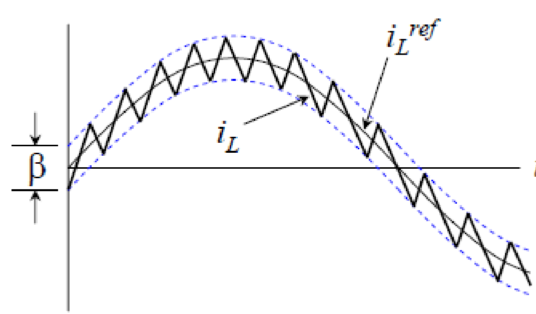
Extension knowledge: Hysteresis control of the inverter











If $i_L^{ref} - \frac{\beta}{2} > i_L$, then s_{ap} on,

If $i_L^{ref} + \frac{\beta}{2} < i_L$, then s_{an} on

- Switching frequency is varying in one switching cycle.

Sometimes the motor drive is much more expensive than the AC motor

ATV320D15N4B - Variable Speed Drive, Altivar Machine ATV320 Series, Three Phase, 15 kW, 380 to 500 Vac NEW

Image is for illustrative purposes only. Please refer to product description.

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Synmot 15kw 70nm AC Permanent Magnet Synchronous Servo Motor

FOB Price: **US $ 324-600** / Piece

Min. Order: **1 Piece**

Application: Engine	Speed: Variable Speed
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Zhejiang Synmot Electrical Technology Co., Ltd.

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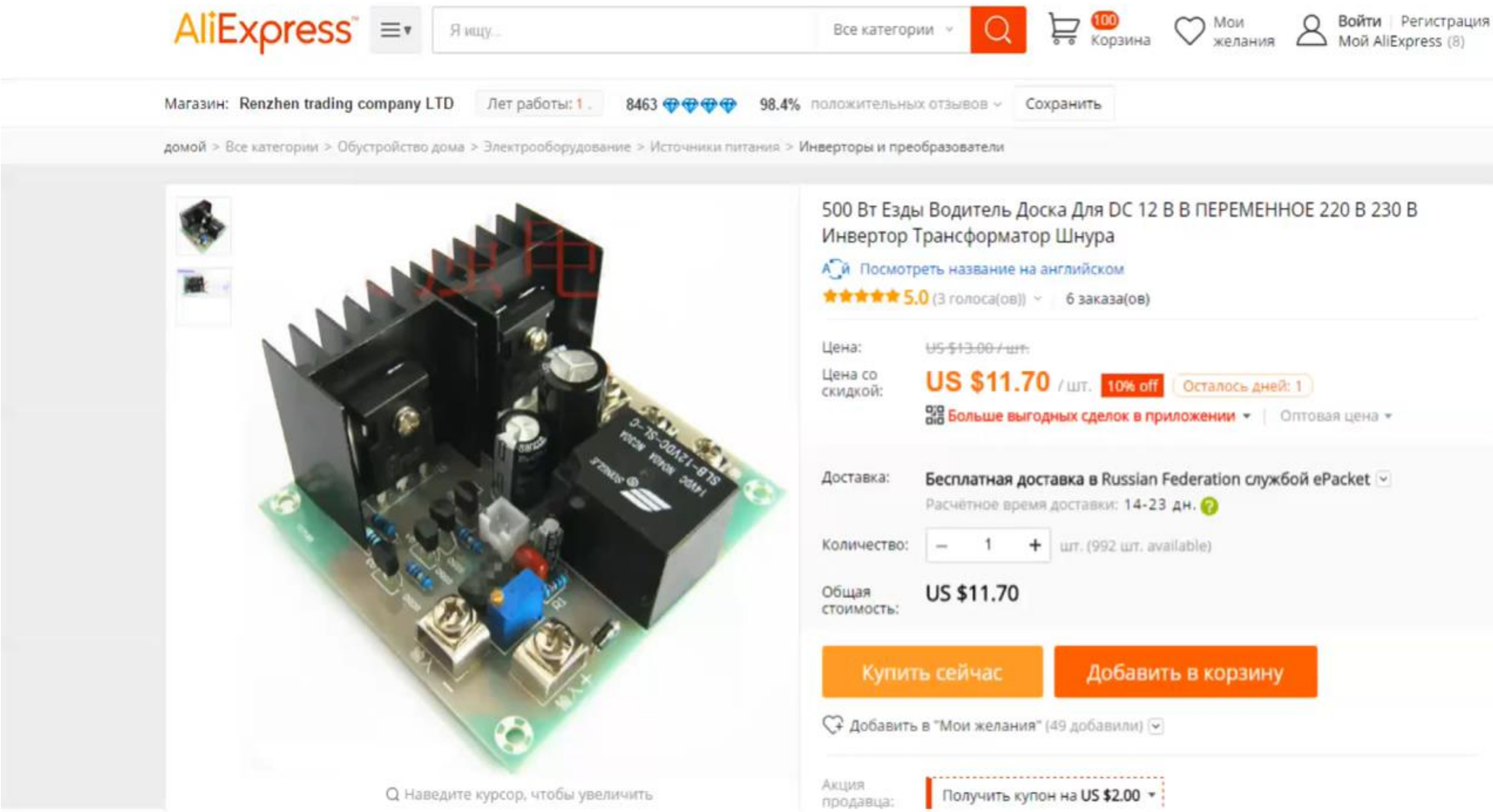
Contact Now Inquiry Basket Leave a message.

We can DIY inverter by ourselves



Review of today's topic

- What is roles of the rectifier and inverter in the control system of the asynchronous motor?
- Understand the operation principle of the rectifier.
- Understand the operation principle of the inverter.
- Understand the modulation methods of the inverter.
- Understand the impact of the deadtime on the inverter.

OPERATION PRINCIPLE OF THE RECTIFIER AND INVERTER

[31/03/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

END OF TOPIC

- **10 marks**;
- **60 minutes: 08:25 PM to 09:25 PM**;
- **Closed-book** Quiz;
- Student much present **ID (with photo)** for taking attendance;
- Sit separately and **there is at least one seat** between two people;
- Do not forget to **write your name and ID** on the test paper;
- If you finish the quiz and **want to leave first**, please **put up the hand** to let me know.

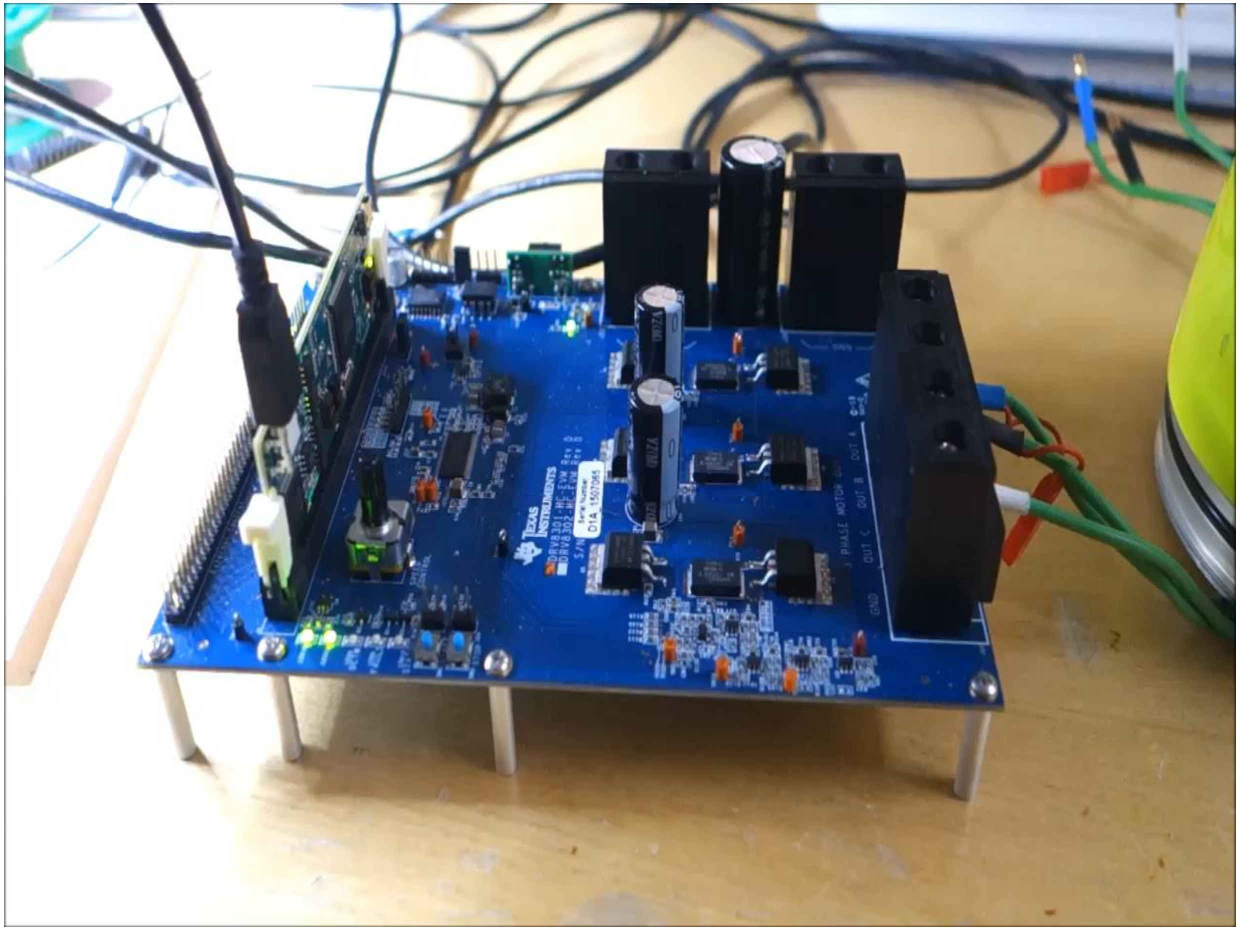
FIELD-ORIENTED CONTROL OF THE ASYNCHRONOUS MOTOR

[07/04/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

- Coupling problem when control asynchronous motor
- How to solve the coupling problem?
- Transformation from ABC to dq frames
- Field oriented control (FOC)

Video: Real results of FOC control



FIELD-ORIENTED CONTROL OF THE ASYNCHRONOUS MOTOR

[07/04/2020]

- Coupling problem when control asynchronous motor
- How to solve the coupling problem?
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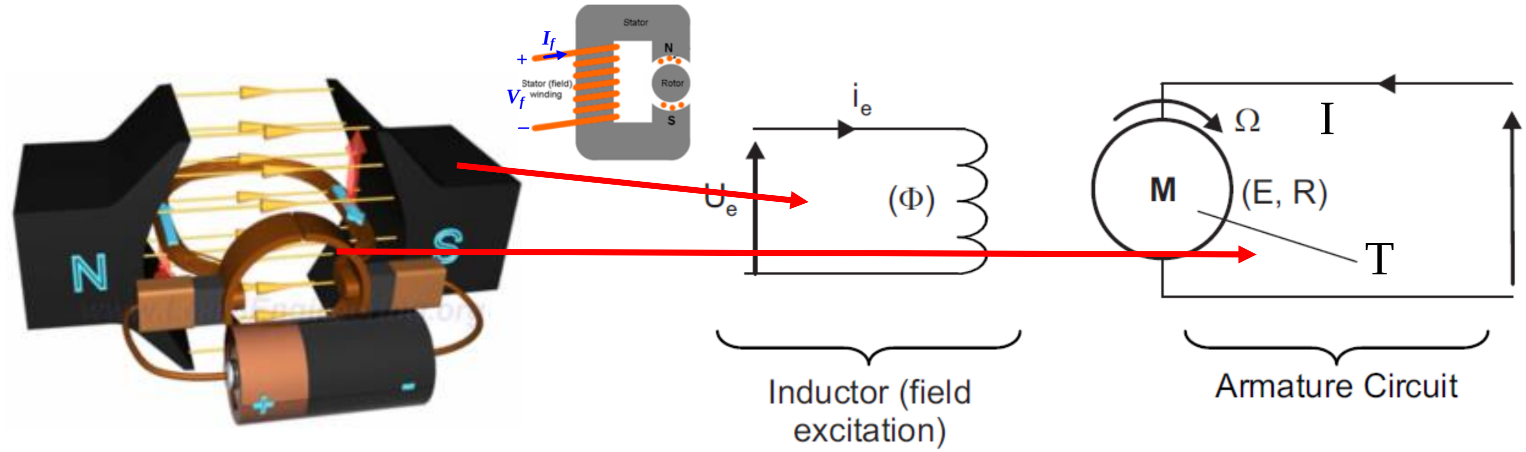
- Field oriented control (FOC)

Recall: control of the DC motor



$T = K.\Phi.I$
$E = K.\Phi.\Omega$
$\Phi = f(I_e)$

Separate control of flux (ϕ) and torque (T):

a) The current through the field windings determines the amount of the flux ϕ;

b) The current through the rotor windings determines the amount of torque T generated.

Recall: torque balance equation of the DC motor:

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

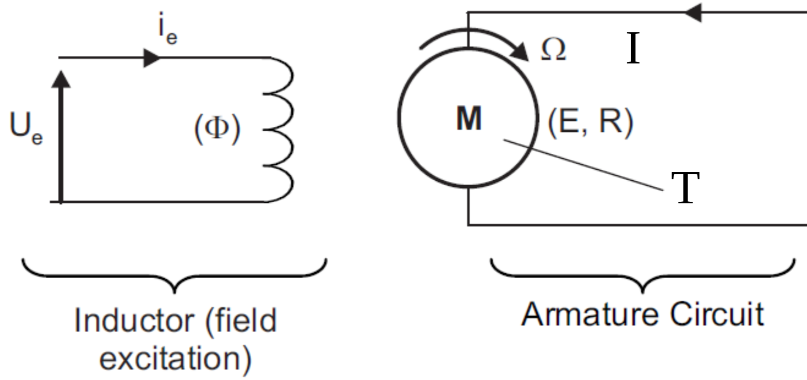
Control T can control the ω_r

ω_r: rotor angle speed (Final control target)

T: Magnetic torque (Control T is equal to control ω_r)

T_L: load torque (determined by the load, cannot be controlled)

Recall: control of the DC motor



T = K.Φ.I
E = K.Φ.Ω
$\Phi = f(I_e)$

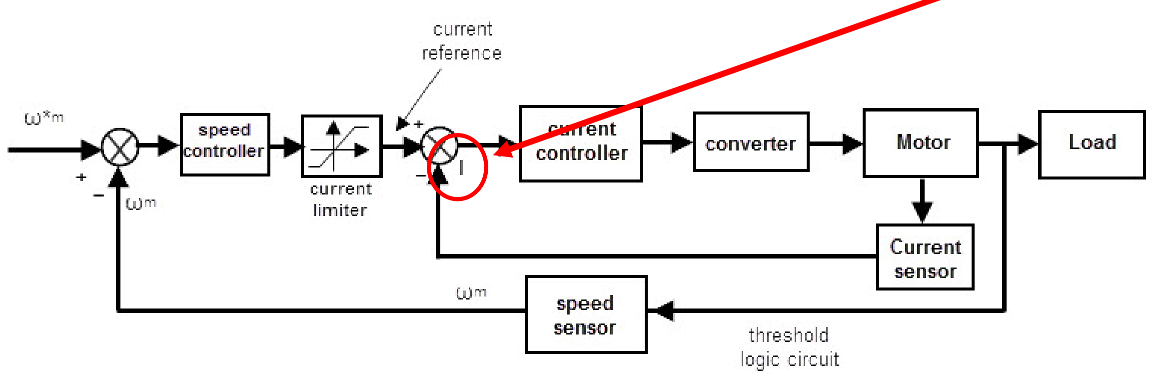
Control T is equal to control ω_r

$$T = K\phi I$$

ϕ and I are decoupled

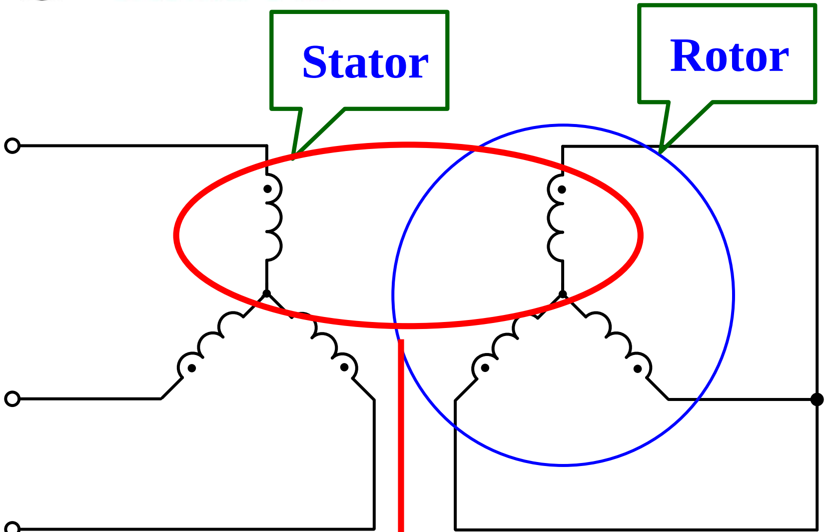
If ϕ is controlled constant

We only need to control I to regulate T and reach the purpose of regulating ω_r



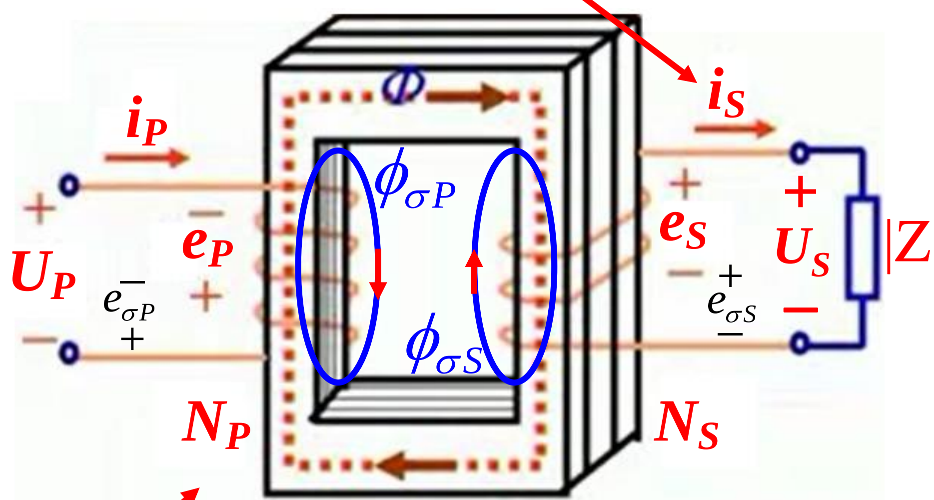
Easy

Coupling problem of the asynchronous motor control

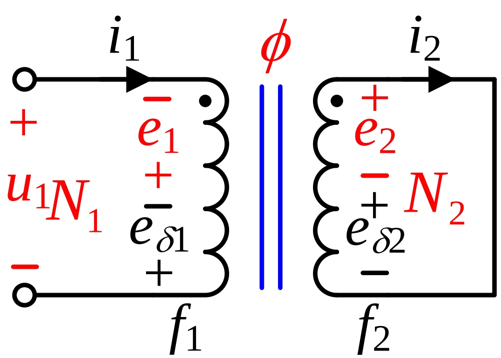


Y-Y Connection

$$T = K_T \cdot \phi \cdot I_2 \cdot \cos\theta$$



Each phase of the asynchronous motor



ϕ and I_2 are affected with each other through the magnetic filed

Difficult

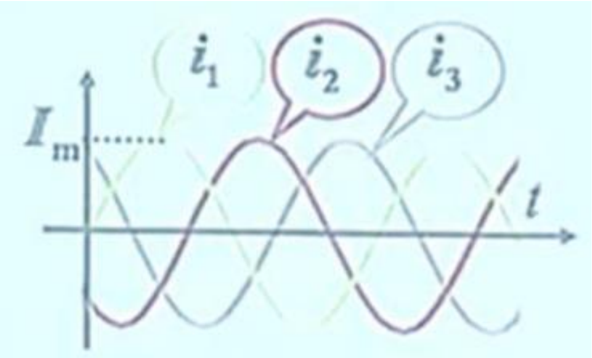
We cannot control T via only controlling ϕ or I_2 (they are coupled)

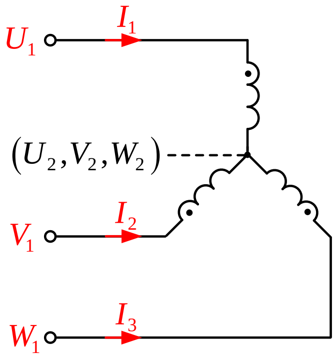
FIELD-ORIENTED CONTROL OF THE ASYNCHRONOUS MOTOR

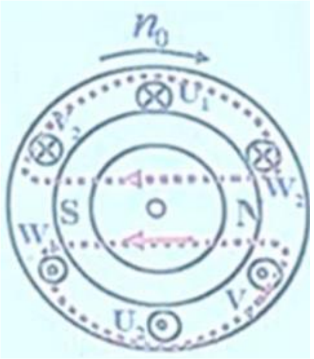
[07/04/2020]

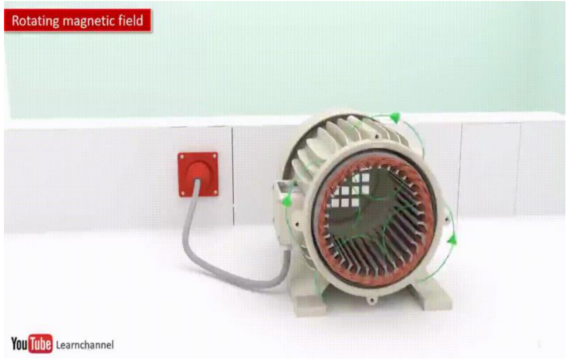
- Coupling problem of when control asynchronous motor
- How to solve the coupling problem?
- Transformation from ABC to dq frames
- Field oriented control (FOC)

Revisit the rotated principle of the asynchronous motor



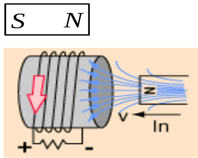


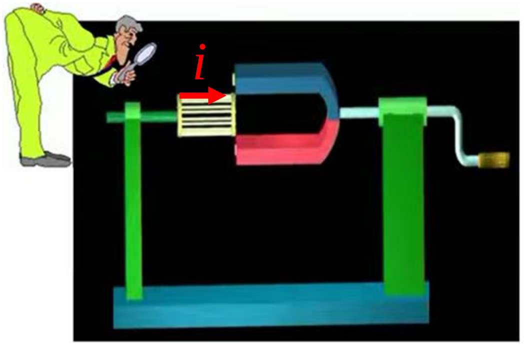




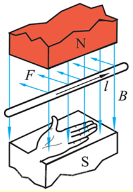
Three phase AC currents generate rotated magnetic field

Lenz's Law



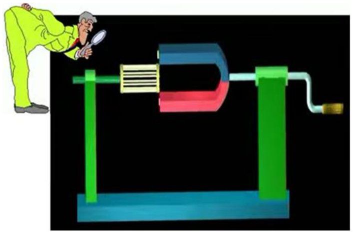


Induce current is generated in the rotor windings to stop its flux change



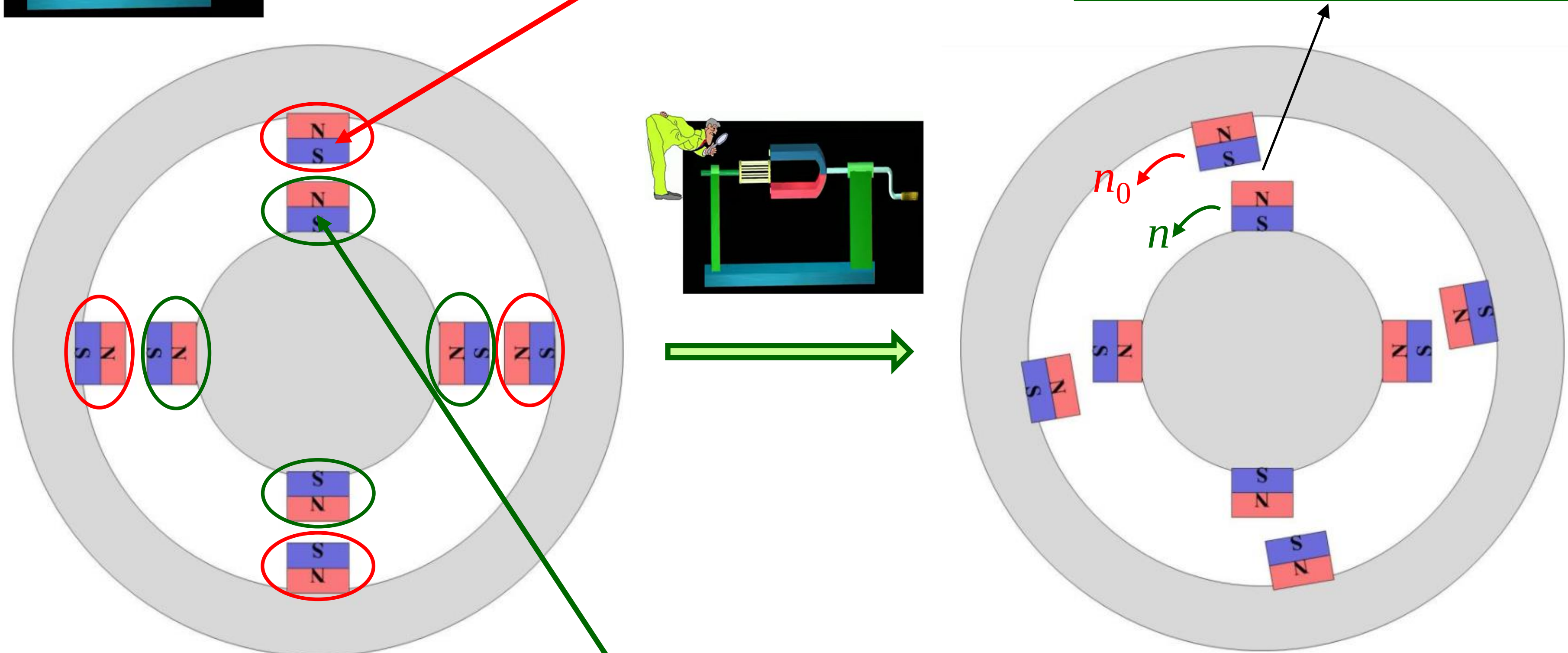
Electromagnetic force is generated to make the rotor windings follow the rotated magnetic field

A simple way to understand rotated principle of the asynchronous motor



Magnetic field generated by the stator current

Electromagnetic torque (T) to let the rotor follow the stator magnetic field



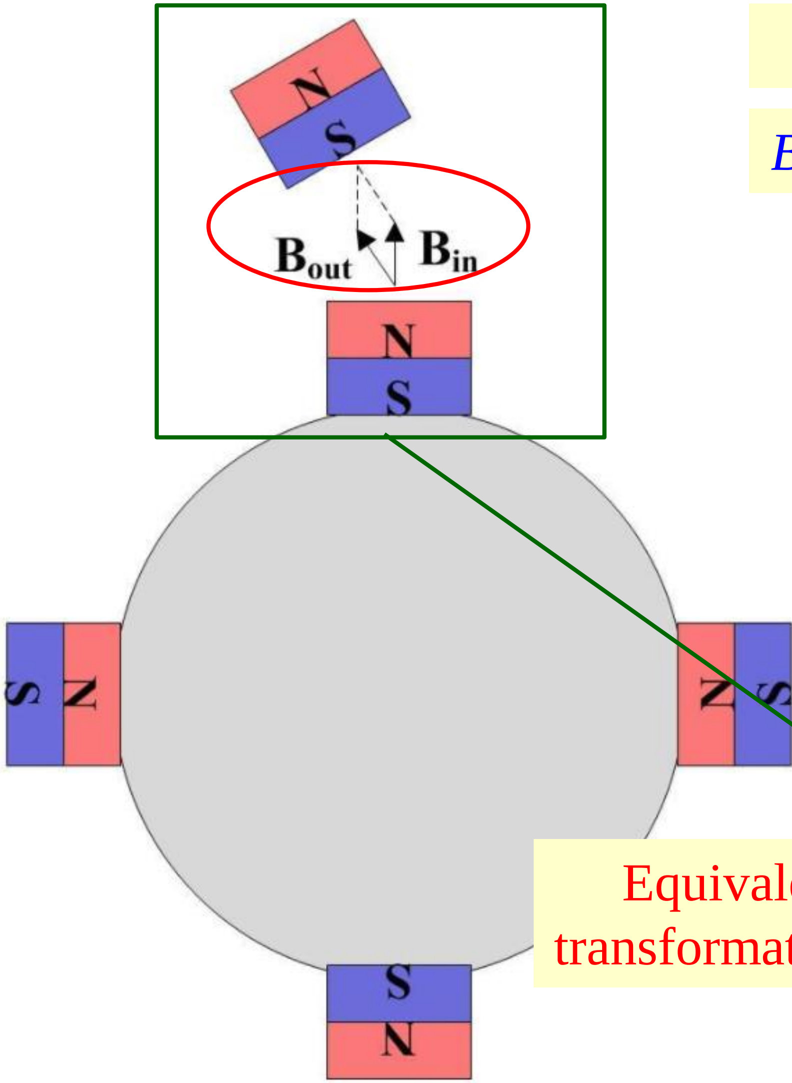
Induced rotor magnetic field

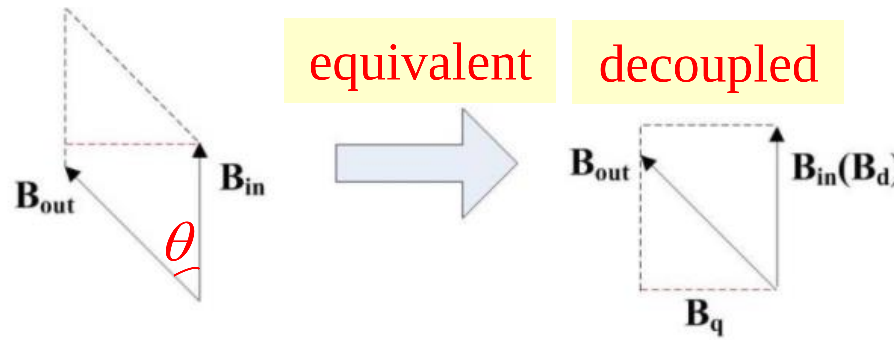
A simple and straight method to control the rotor follow the rotated stator magnetic field

B_{in}: Strength of the induced rotor magnetic field

B_{out}: Strength of the stator magnetic field

Torque: $T = B_{in} \times B_{out} = |B_{in}| \cdot |B_{out}| \cdot \sin\theta$



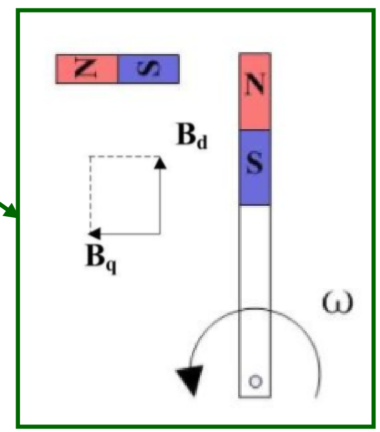


equivalent

decoupled

B_d and B_q are decoupled

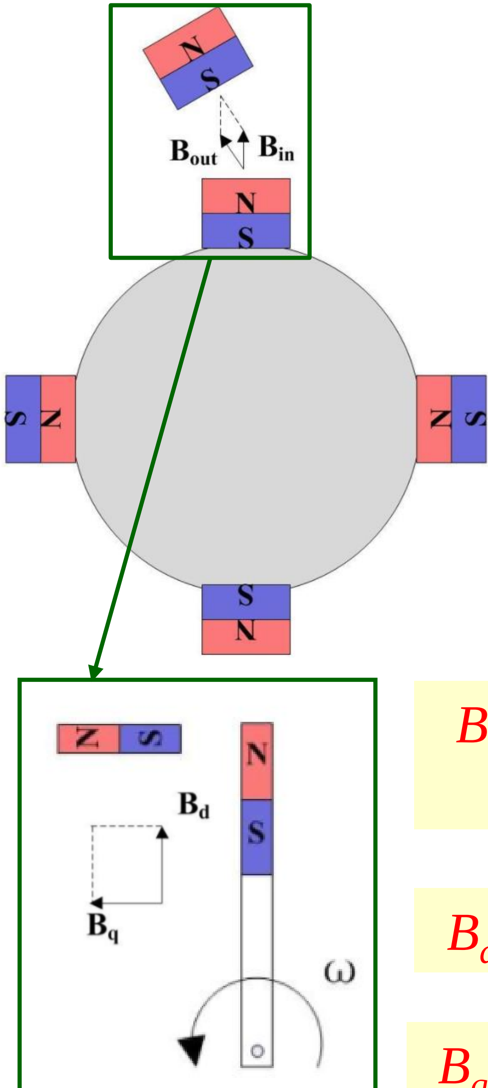
Equivalent transformation to

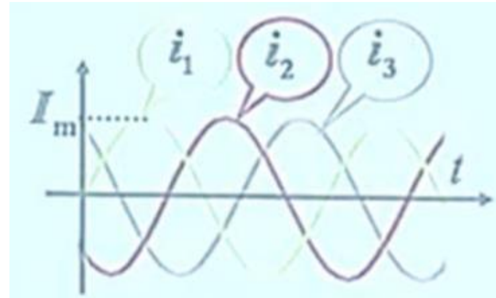


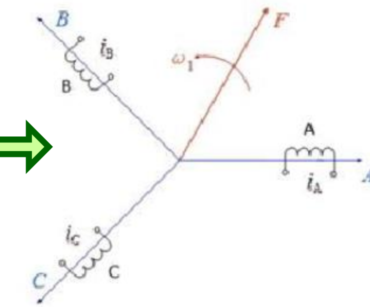
B_d: Only for ϕ

B_q: Only for T

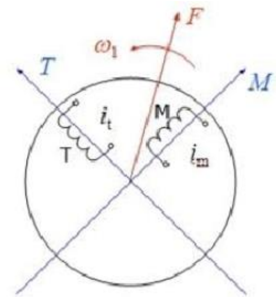
Concept of the field oriented control (FOC)







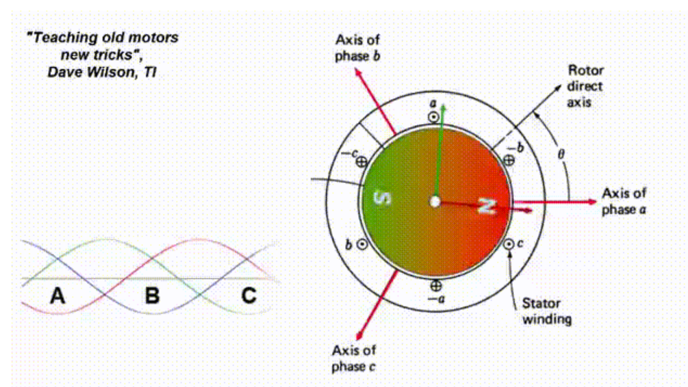
ABC→dq



B_d and B_q are decoupled

B_d: Only for ϕ

B_q: Only for T



Concept of the Field oriented control

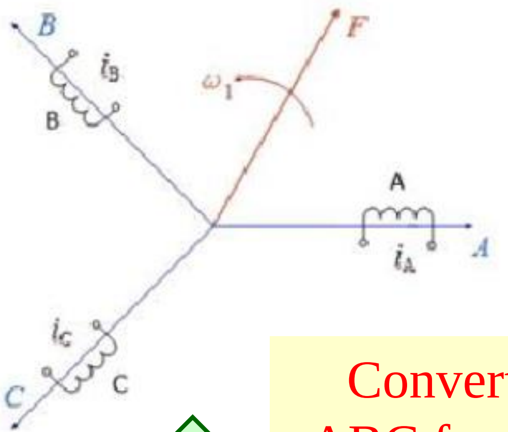
FIELD-ORIENTED CONTROL OF THE ASYNCHRONOUS MOTOR

[07/04/2020]

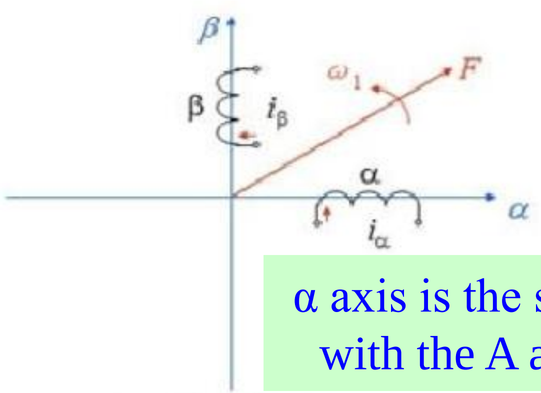
- Coupling problem of when control asynchronous motor
- How to solve the coupling problem?
- Transformation from ABC to dq frames
- Field oriented control (FOC)

ABC frame to dq frame

(Inverse) Clarke transformation

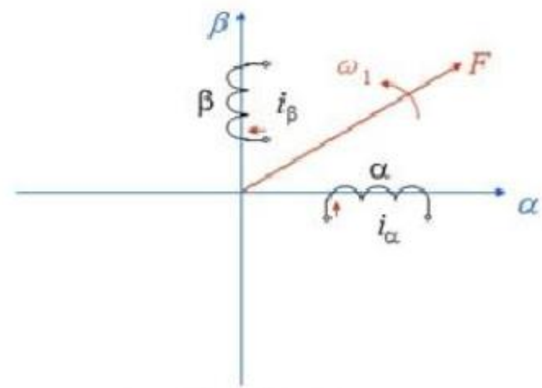


Convert ABC frame to stationary αβ frame



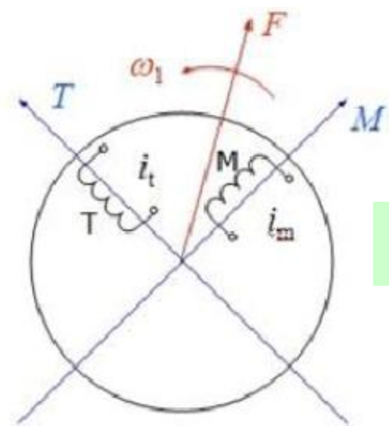
α axis is the same with the A axis

(Inverse) Park transformation



Vertical with the rotor flux

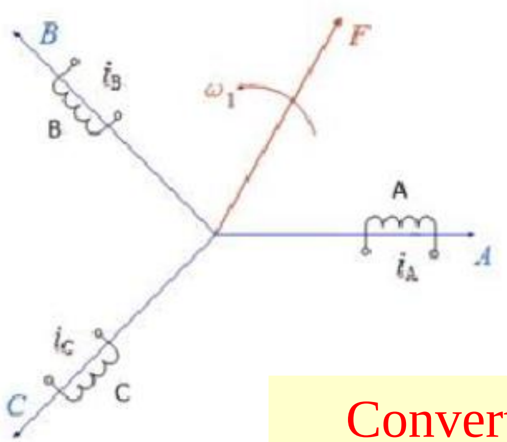
Convert stationary αβ frame to rotated dq frame



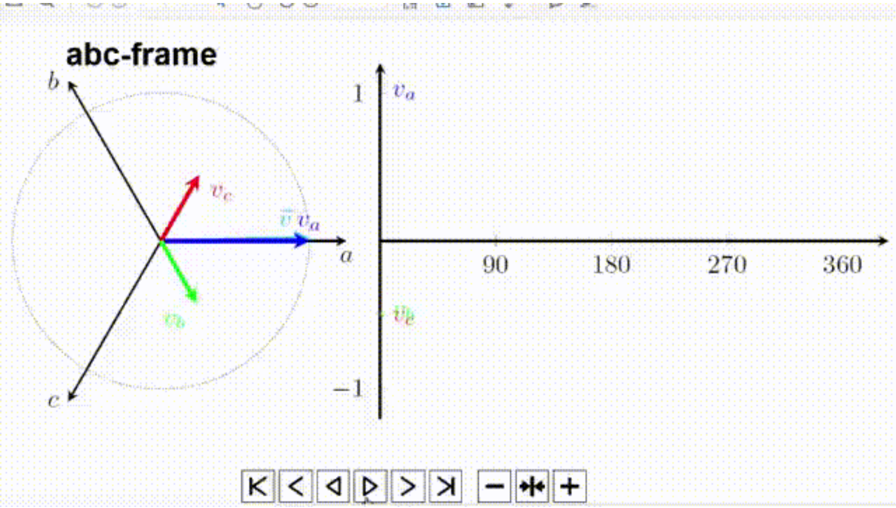
Rotor flux

CLARKE TRANSFORMATION

ABC frame to αβ frame: Clarke transformation

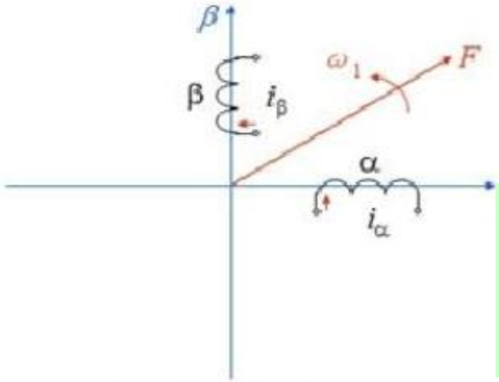


Convert ABC frame to stationary αβ frame

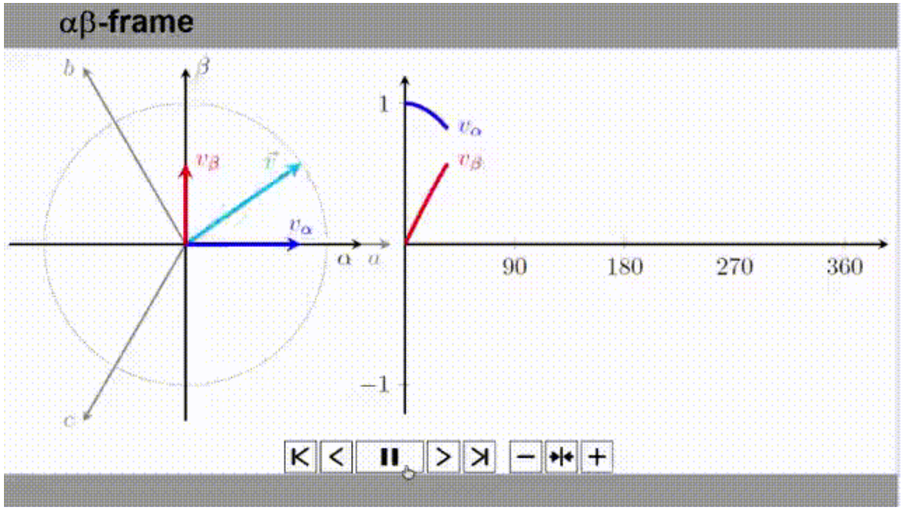


The amplitude of phase voltage is the same

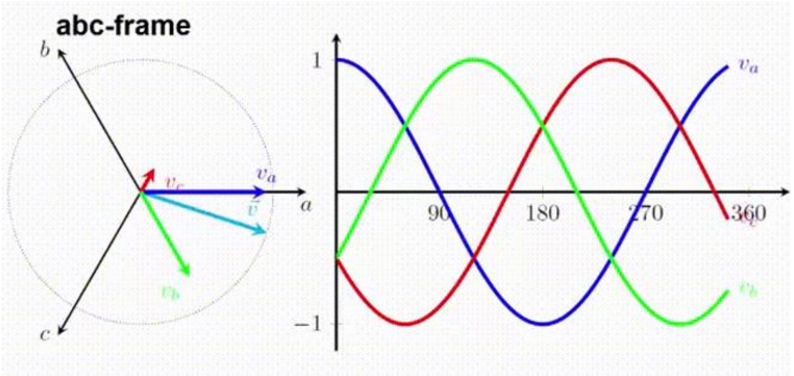
Clarke transformation



α axis is the same with the a axis



Derivation of the Clarke transformation



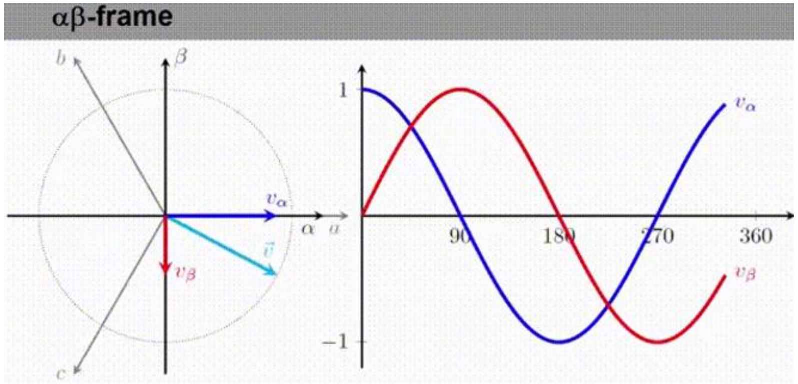
$$u_A = U_m \cos(\omega t)$$

$$u_B = U_m \cos(\omega t - 120^0)$$

$$u_c = U_m \cos(\omega t + 120^0)$$

Clarke transformation

The amplitude of phase voltage is the same

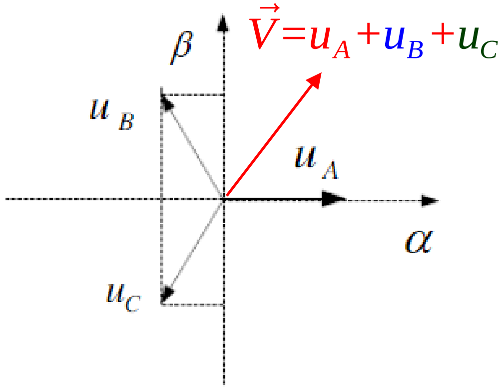


$$u_\alpha = U_m \cos(\omega t)$$

$$u_B = U_m \sin(\omega t)$$

$$\boxed{\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = [?] \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}}$$

Derivation of the Clarke transformation



$$u_A=U_m\cos(\omega t)$$

$$u_B=U_m\cos\left(\omega t-120^0\right)$$

$$u_c=U_m\cos\left(\omega t-120^0\right)$$

$$\sin\alpha+\sin\beta=2\sin\frac{\alpha+\beta}{2}\cos\frac{\alpha-\beta}{2}$$

$$\sin\alpha-\sin\beta=2\cos\frac{\alpha+\beta}{2}\sin\frac{\alpha-\beta}{2}$$

$$\cos\alpha+\cos\beta=2\cos\frac{\alpha+\beta}{2}\cos\frac{\alpha-\beta}{2}$$

$$\cos\alpha-\cos\beta=-2\sin\frac{\alpha+\beta}{2}\sin\frac{\alpha-\beta}{2}$$

u_α is the projection of $\vec{V}$ on the α axis:

$$u_\alpha=k\left(u_A+u_B\cos120^0+u_C\cos240^0\right)$$

$$=k\left(u_A-\frac{1}{2}u_B-\frac{1}{2}u_C\right)\boxed{=\frac{3}{2}kU_m\cos\omega t}$$

u_β is the projection of $\vec{V}$ on the β axis:

$$u_\beta=k\left(0\cdot u_A+u_B\sin120^0+u_C\sin240^0\right)$$

$$=k\left(0\cdot u_A+\frac{\sqrt{3}}{2}u_B-\frac{\sqrt{3}}{2}u_C\right)$$

k is the projection coefficient

$$u_\alpha=k\left(u_A-\frac{1}{2}u_B-\frac{1}{2}u_C\right)$$

$$=k\left[U_m\cos\omega t-\frac{1}{2}U_m\cos\left(\omega t-120^0\right)-\frac{1}{2}U_m\cos\left(\omega t+120^0\right)\right]$$

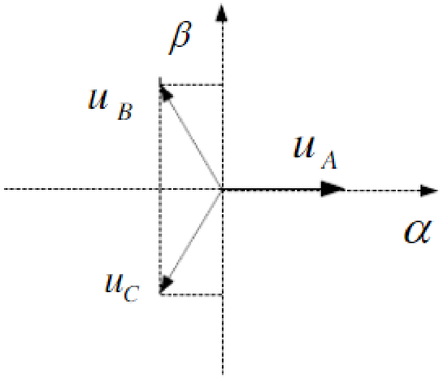
$$=kU_m\left\{\cos\omega t-\frac{1}{2}\left[\cos\left(\omega t-120^0\right)+\cos\left(\omega t+120^0\right)\right]\right\}$$

$$=kU_m\left[\cos\omega t-\frac{1}{2}\cdot2\cos\omega t\cdot\cos\left(-120^0\right)\right]$$

$$=kU_m\left(\cos\omega t+\frac{1}{2}\cos\omega t\right)$$

$$=\frac{3}{2}kU_m\cos\omega t$$

Derivation of the Clarke transformation



$$u_A = U_m \cos(\omega t)$$

$$u_B = U_m \cos(\omega t - 120^0)$$

$$u_c = U_m \cos(\omega t - 120^0)$$

$$\sin\alpha + \sin\beta = 2\sin\frac{\alpha+\beta}{2}\cos\frac{\alpha-\beta}{2}$$

$$\sin\alpha - \sin\beta = 2\cos\frac{\alpha+\beta}{2}\sin\frac{\alpha-\beta}{2}$$

$$\cos\alpha + \cos\beta = 2\cos\frac{\alpha+\beta}{2}\cos\frac{\alpha-\beta}{2}$$

$$\cos\alpha - \cos\beta = -2\sin\frac{\alpha+\beta}{2}\sin\frac{\alpha-\beta}{2}$$

u_α is the projection of $\vec{V}$ on the α axis:

$$u_\alpha = k\left(u_A + u_B\cos 120^0 + u_C\cos 240^0\right)$$

$$= k\left(u_A - \frac{1}{2}u_B - \frac{1}{2}u_C\right)$$

u_β is the projection of $\vec{V}$ on the β axis:

$$u_\beta = k\left(0\cdot u_A + u_B\sin 120^0 + u_C\sin 240^0\right)$$

$$= k\left(0\cdot u_A + \frac{\sqrt{3}}{2}u_B - \frac{\sqrt{3}}{2}u_C\right) = \frac{3}{2}kU_m\sin\omega t$$

k is the projection coefficient

$$u_\alpha = k\left(0\cdot u_A + \frac{\sqrt{3}}{2}u_B - \frac{\sqrt{3}}{2}u_C\right)$$

$$= k\left[0 + \frac{\sqrt{3}}{2}U_m\cos(\omega t - 120^0) - \frac{\sqrt{3}}{2}U_m\cos(\omega t + 120^0)\right]$$

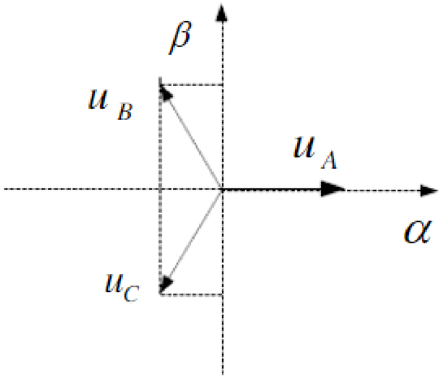
$$= kU_m\left\{0 + \frac{\sqrt{3}}{2}\left[\cos(\omega t - 120^0) - \cos(\omega t + 120^0)\right]\right\}$$

$$= kU_m\left[0 - \frac{\sqrt{3}}{2}\cdot 2\sin\omega t\cdot\sin(-120^0)\right]$$

$$= kU_m\left(0 + \frac{\sqrt{3}}{2}\cdot 2\sin\omega t\,\frac{\sqrt{3}}{2}\right)$$

$$= \frac{3}{2}kU_m\sin\omega t$$

Derivation of the Clarke transformation



$$u_A = U_m \cos(\omega t)$$

$$u_B = U_m \cos\left(\omega t - 120^0\right)$$

$$u_c = U_m \cos\left(\omega t - 120^0\right)$$

Clarke transformation

$$u_\alpha = U_m \cos(\omega t)$$

$$u_B = U_m \sin(\omega t)$$

u_α is the projection of $\vec{V}$ on the α axis:

$$u_\alpha = k\left(u_A + u_B \cos 120^0 + u_C \cos 240^0\right)$$

$$= k\left(u_A - \frac{1}{2}u_B - \frac{1}{2}u_C\right) = \frac{3}{2}kU_m \cos\omega t$$

u_β is the projection of $\vec{V}$ on the β axis:

$$u_\beta = k\left(0 \cdot u_A + u_B \sin 120^0 + u_C \sin 240^0\right)$$

$$= k\left(0 \cdot u_A + \frac{\sqrt{3}}{2}u_B - \frac{\sqrt{3}}{2}u_C\right) = \frac{3}{2}kU_m \sin\omega t$$

k is the projection coefficient

$$u_\alpha = \frac{3}{2}kU_m \cos\omega t$$

$$u_\beta = \frac{3}{2}kU_m \sin\omega t$$

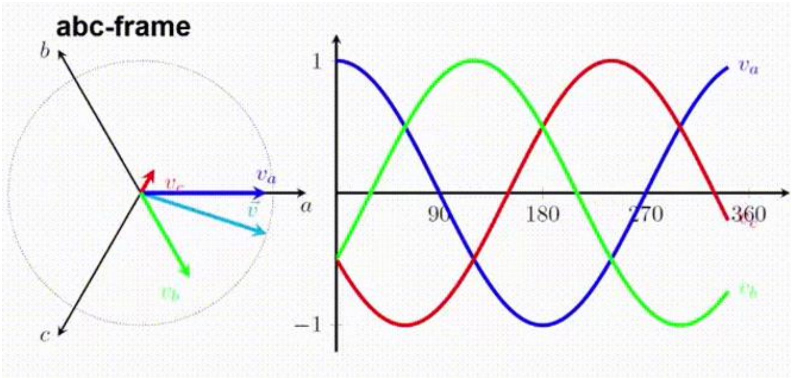
$$\boxed{\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = [?]\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}}$$

$$k = \frac{2}{3}$$

$$u_\alpha = \frac{2}{3}\left(u_A - \frac{1}{2}u_B - \frac{1}{2}u_C\right)$$

$$u_\beta = \frac{2}{3}\left(0 \cdot u_A + \frac{\sqrt{3}}{2}u_B - \frac{\sqrt{3}}{2}u_C\right)$$

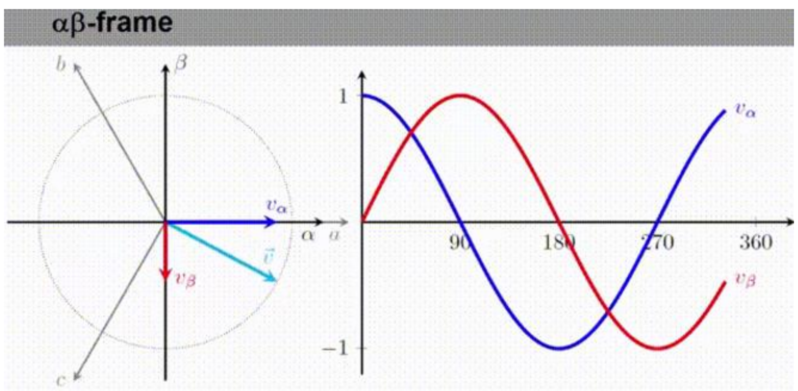
ABC frame to αβ frame: Clarke transformation



$$u_\alpha = \frac{2}{3}\left(u_A - \frac{1}{2}u_B - \frac{1}{2}u_C\right)$$

$$u_\beta = \frac{2}{3}\left(0 \cdot u_A + \frac{\sqrt{3}}{2}u_B - \frac{\sqrt{3}}{2}u_C\right)$$

Clarke transformation

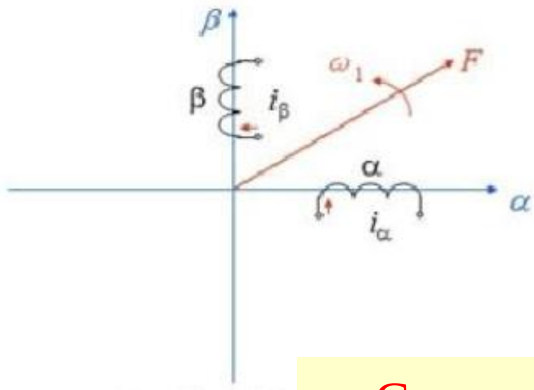


$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

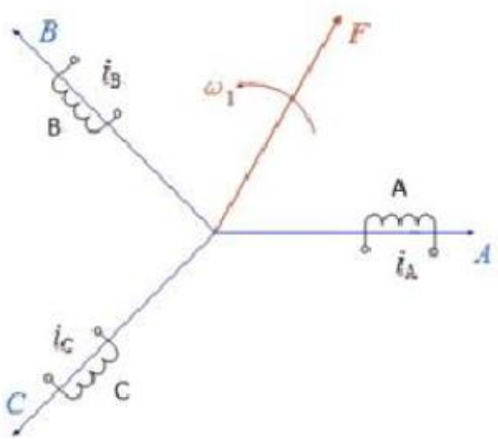
Clarke transformation

INVERSE CLARKE TRANSFORMATION

αβ frame to ABC frame: Inverse Clarke transformation



Convert stationary αβ frame to ABC frame



$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \left(\frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\right)^{-1}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Inverse Clarke transformation

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Summary: (Inverse) Clarke transformation

$$u_\alpha = \frac{2}{3}\left(u_A - \frac{1}{2}u_B - \frac{1}{2}u_C\right)$$

$$u_\beta = \frac{2}{3}\left(0\cdot u_A + \frac{\sqrt{3}}{2}u_B - \frac{\sqrt{3}}{2}u_C\right)$$

Clarke transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \left(\frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\right)^{-1}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Inverse Clarke transformation

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

(Inverse) Park transformation

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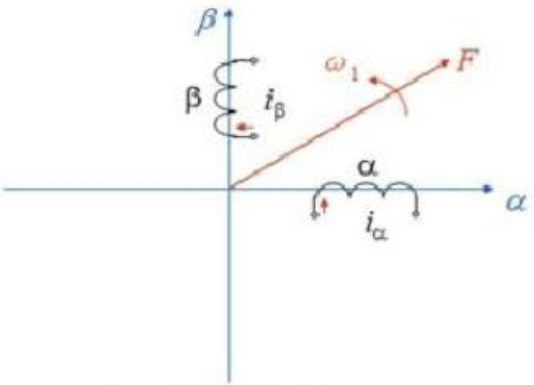
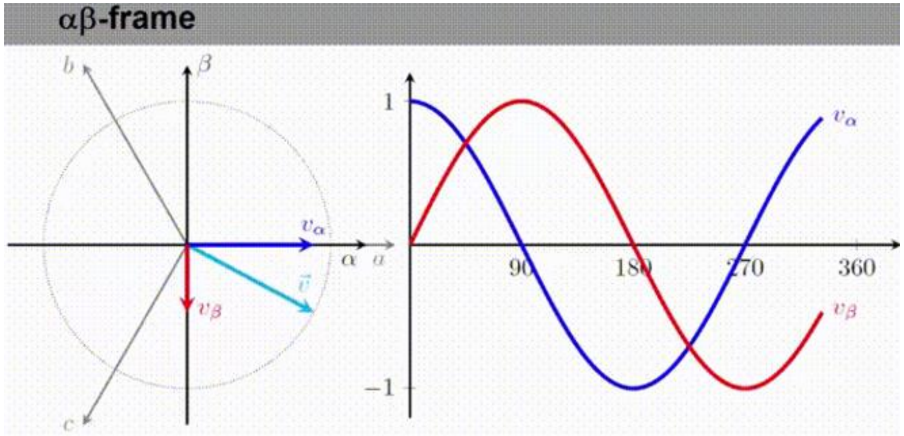
αβ frame to dq frame: Park transformation

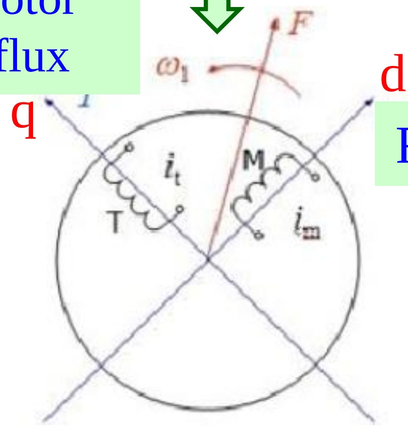




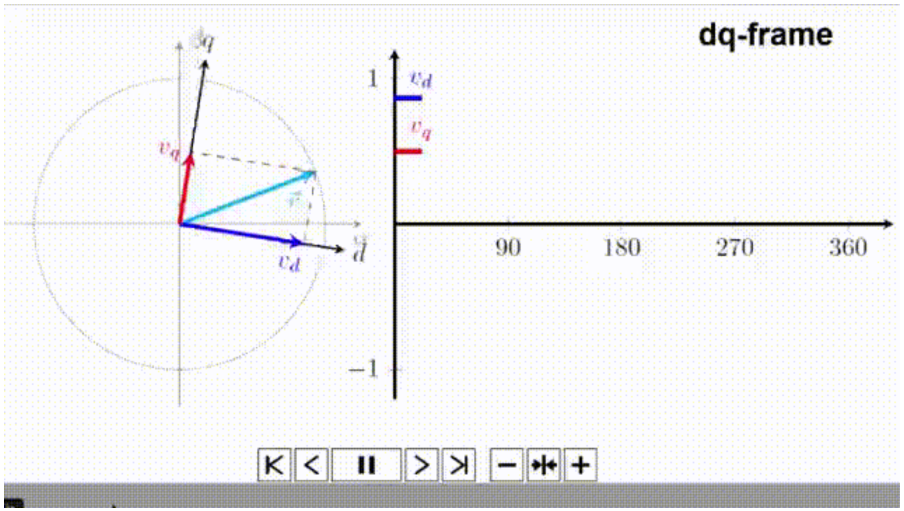
Convert stationary αβ frame to rotated dq frame

Park transformation

Vertical with the rotor flux



Rotor flux

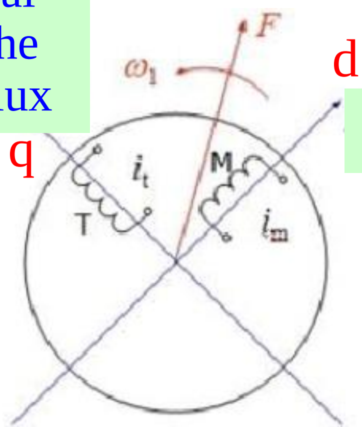


dq frame to αβ frame: Inverse Park transformation

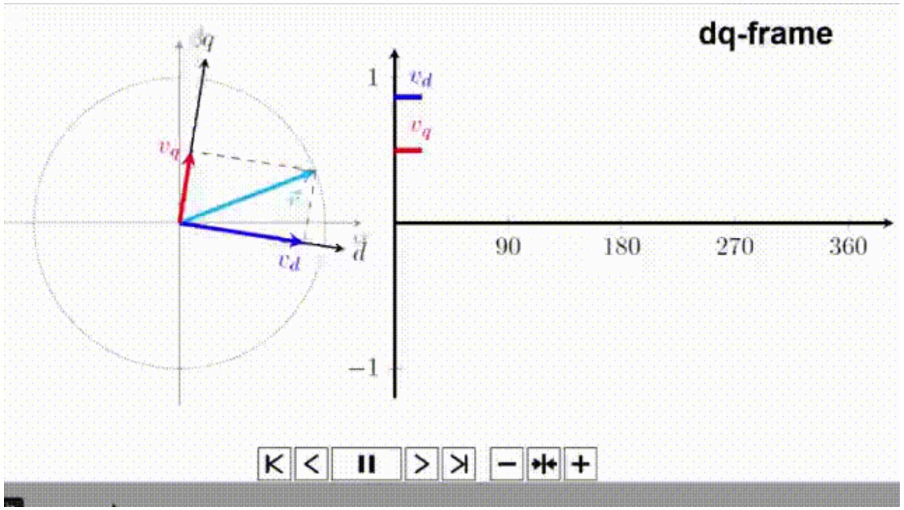
Vertical with the rotor flux

q

d

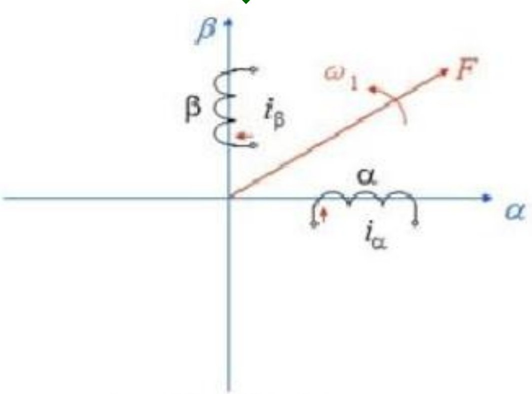


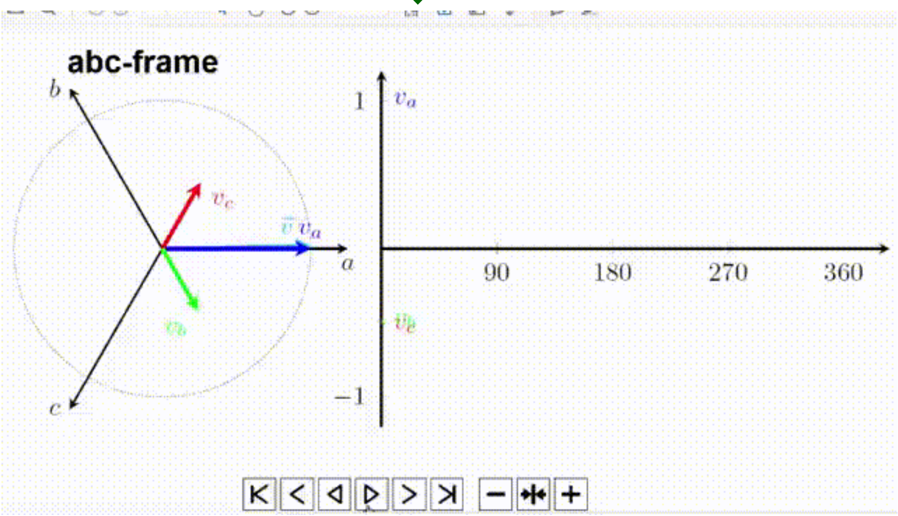
Rotor flux



Convert rotated dq frame to stationary αβ frame

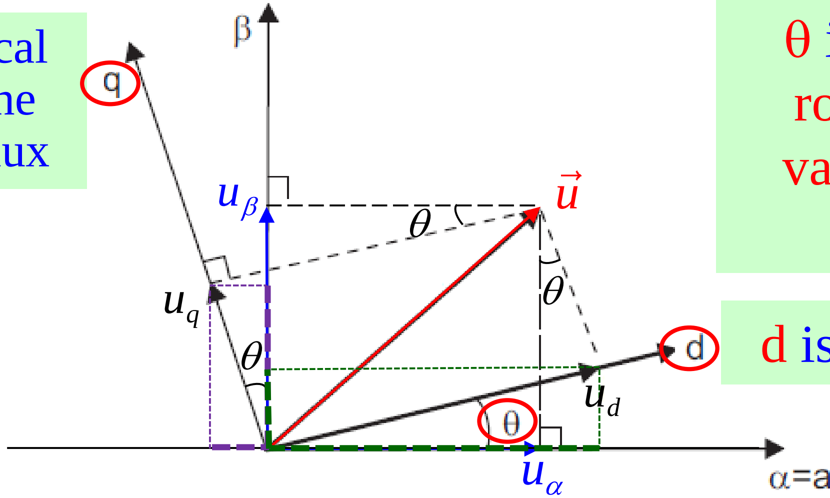
Inverse Park transformation





Derivation of the Park & inverse Park transformation

q vertical with the rotor flux



θ is the angle between the rotor flux and a axis, it is variable due to the rotated rotor

d is along with the rotor flux

$$u_\alpha = u_d \cos\theta - u_q \sin\theta$$

$$u_\beta = u_d \sin\theta + u_q \cos\theta$$

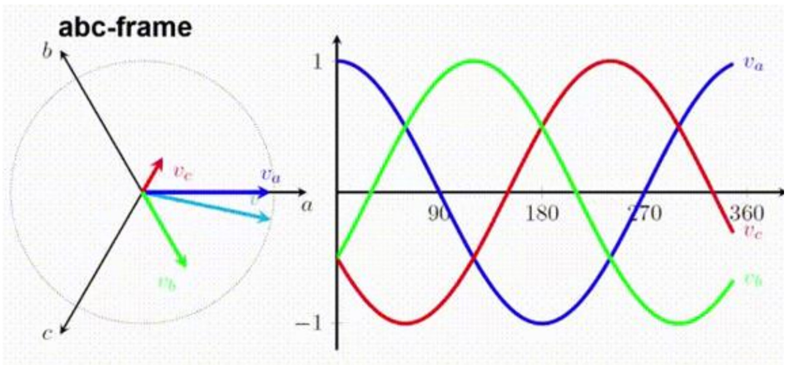
Inverse park transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} \Longrightarrow \begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}^{-1} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Park transformation

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

From ABC frame to dq frame



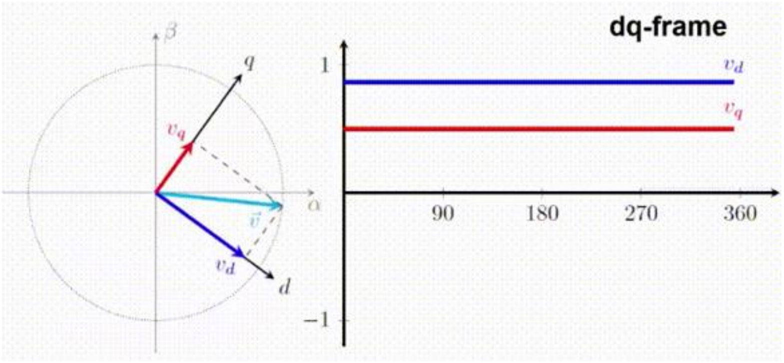
Convert ABC frame to stationary αβ frame

Convert stationary αβ frame to rotated dq frame

Convert stationary ABC frame to rotated dq frame

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$



$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

From ABC frame to dq frame

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$\Downarrow$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\frac{1}{2}\cos\theta + \frac{\sqrt{3}}{2}\sin\theta & -\frac{1}{2}\cos\theta - \frac{\sqrt{3}}{2}\sin\theta \\ -\sin\theta & \frac{1}{2}\sin\theta + \frac{\sqrt{3}}{2}\cos\theta & \frac{1}{2}\sin\theta - \frac{\sqrt{3}}{2}\cos\theta \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

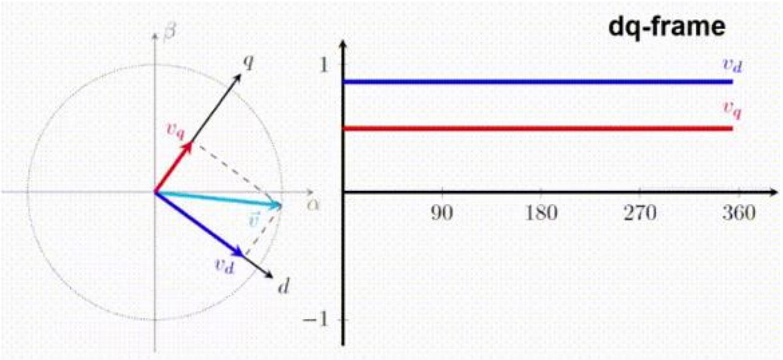
$$\sin(\alpha+\beta) = \sin\alpha\cos\beta + \cos\alpha\sin\beta$$
$$\sin(\alpha-\beta) = \sin\alpha\cos\beta - \cos\alpha\sin\beta$$
$$\cos(\alpha+\beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$$
$$\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$

$$\cos\left(\pm 120^0\right) = -\frac{1}{2}$$
$$\sin 120^0 = \frac{\sqrt{3}}{2}$$

$$\Downarrow$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - 120^0\right) & \cos\left(\theta + 120^0\right) \\ -\sin\theta & -\sin\left(\theta - 120^0\right) & -\sin\left(\theta + 120^0\right) \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

From dq frame to ABC frame

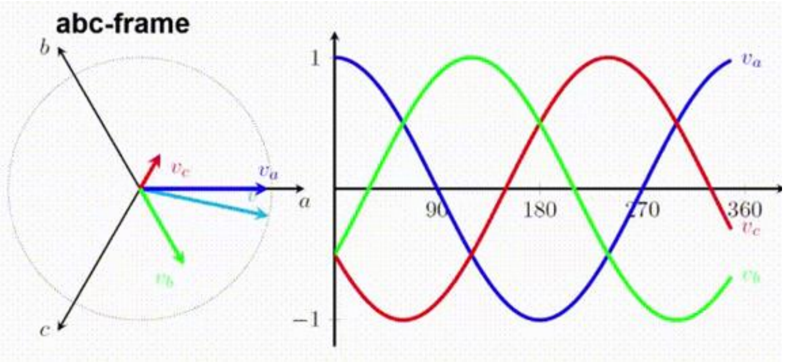


Convert rotated dq frame to stationary αβ frame

Convert stationary αβ frame to ABC frame

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \quad \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

Convert rotated dq frame to stationary ABC frame



$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

From dq frame to ABC frame

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

$$\Downarrow$$

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ -\frac{1}{2}\cos\theta + \frac{\sqrt{3}}{2}\sin\theta & \frac{1}{2}\sin\theta + \frac{\sqrt{3}}{2}\cos\theta \\ -\frac{1}{2}\cos\theta - \frac{\sqrt{3}}{2}\sin\theta & \frac{1}{2}\sin\theta - \frac{\sqrt{3}}{2}\cos\theta \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

$$\sin(\alpha+\beta) = \sin\alpha\cos\beta + \cos\alpha\sin\beta$$
$$\sin(\alpha-\beta) = \sin\alpha\cos\beta - \cos\alpha\sin\beta$$
$$\cos(\alpha+\beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$$
$$\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$

$$\cos\left(\pm 120^0\right) = -\frac{1}{2}$$
$$\sin 120^0 = \frac{\sqrt{3}}{2}$$

$$\Downarrow$$

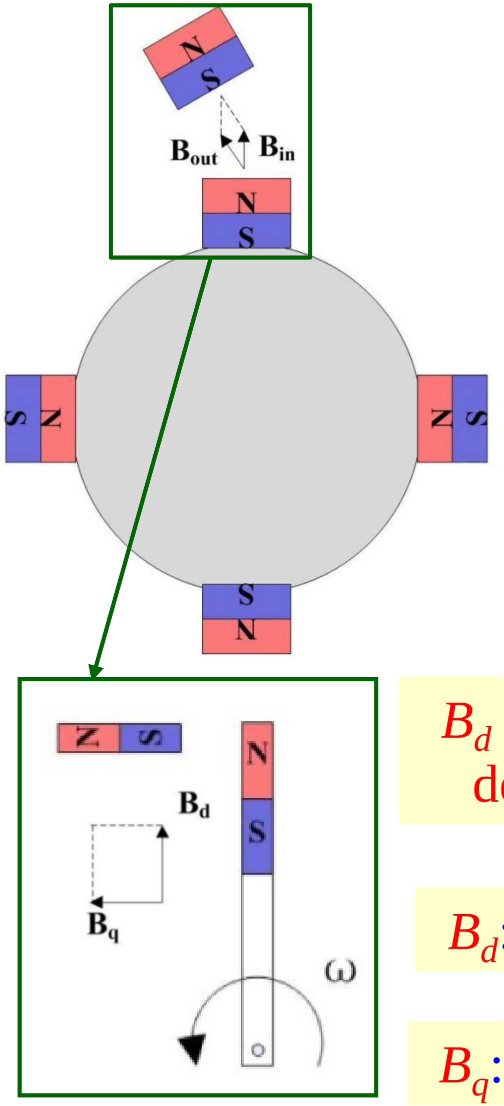
$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta - 120^0\right) & -\sin\left(\theta - 120^0\right) \\ \cos\left(\theta + 120^0\right) & -\sin\left(\theta + 120^0\right) \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

FIELD-ORIENTED CONTROL OF THE ASYNCHRONOUS MOTOR

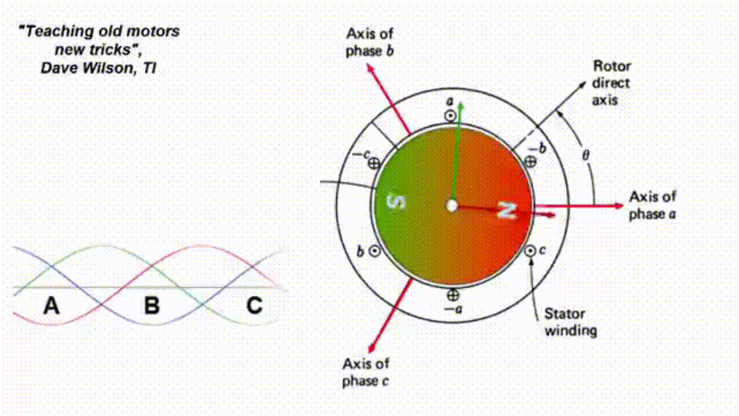
[07/04/2020]

- Coupling problem of when control asynchronous motor
- How to solve the coupling problem?
- Transformation from ABC to dq frames
- Field oriented control (FOC)

What is a field oriented control (FOC)?



ABC→dq



Field oriented control

B_d and B_q are decoupled

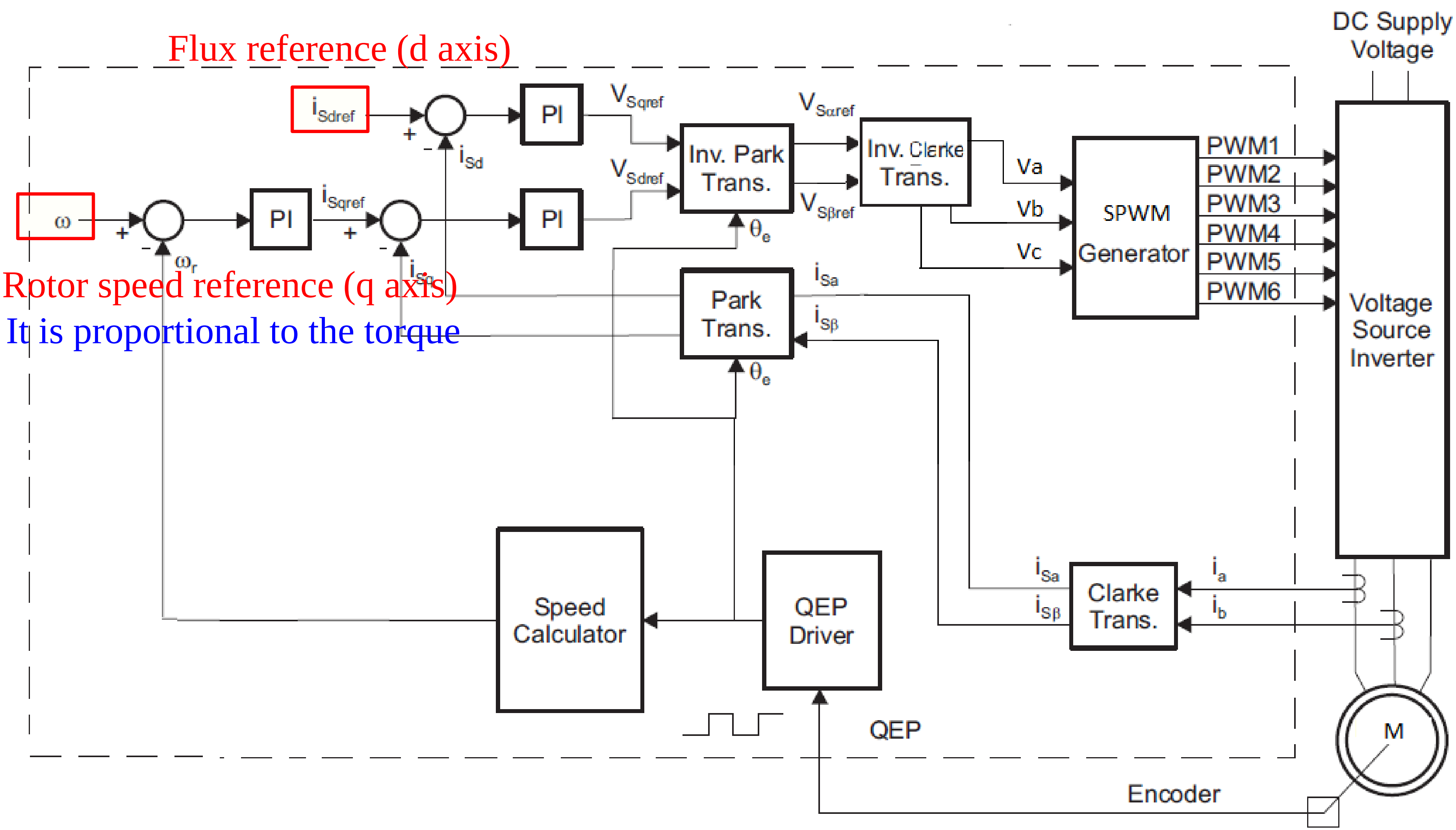
B_d: Only for ϕ

B_q: Only for T

Field-oriented control (FOC), is a control method in which the stator currents/voltages of a three-phase AC electric motor are identified as two orthogonal components that can be visualized with a vector. One component defines the magnetic flux of the motor, the other one refers to the torque.

Control block of the field oriented control (FOC)

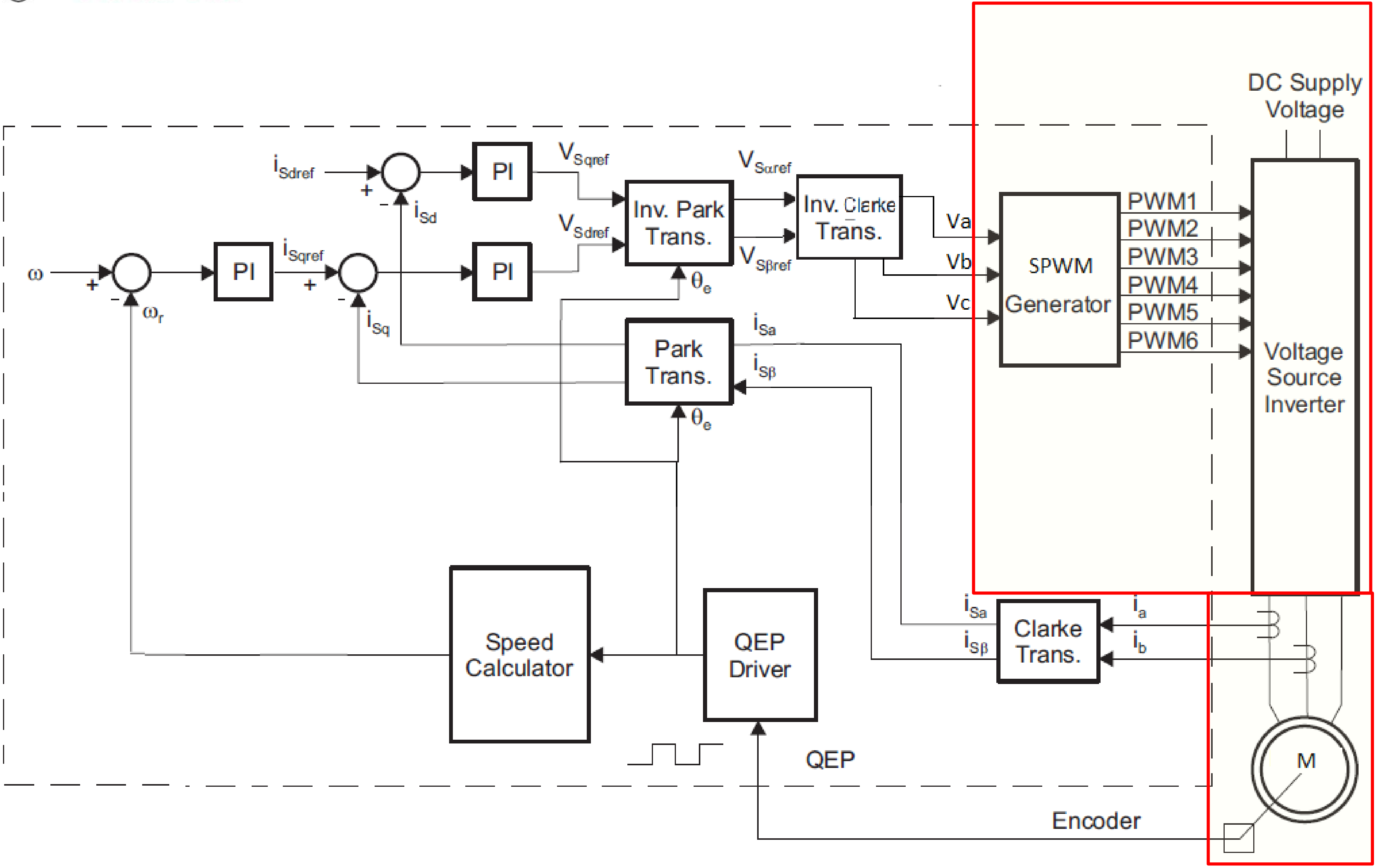
Flux reference (d axis)



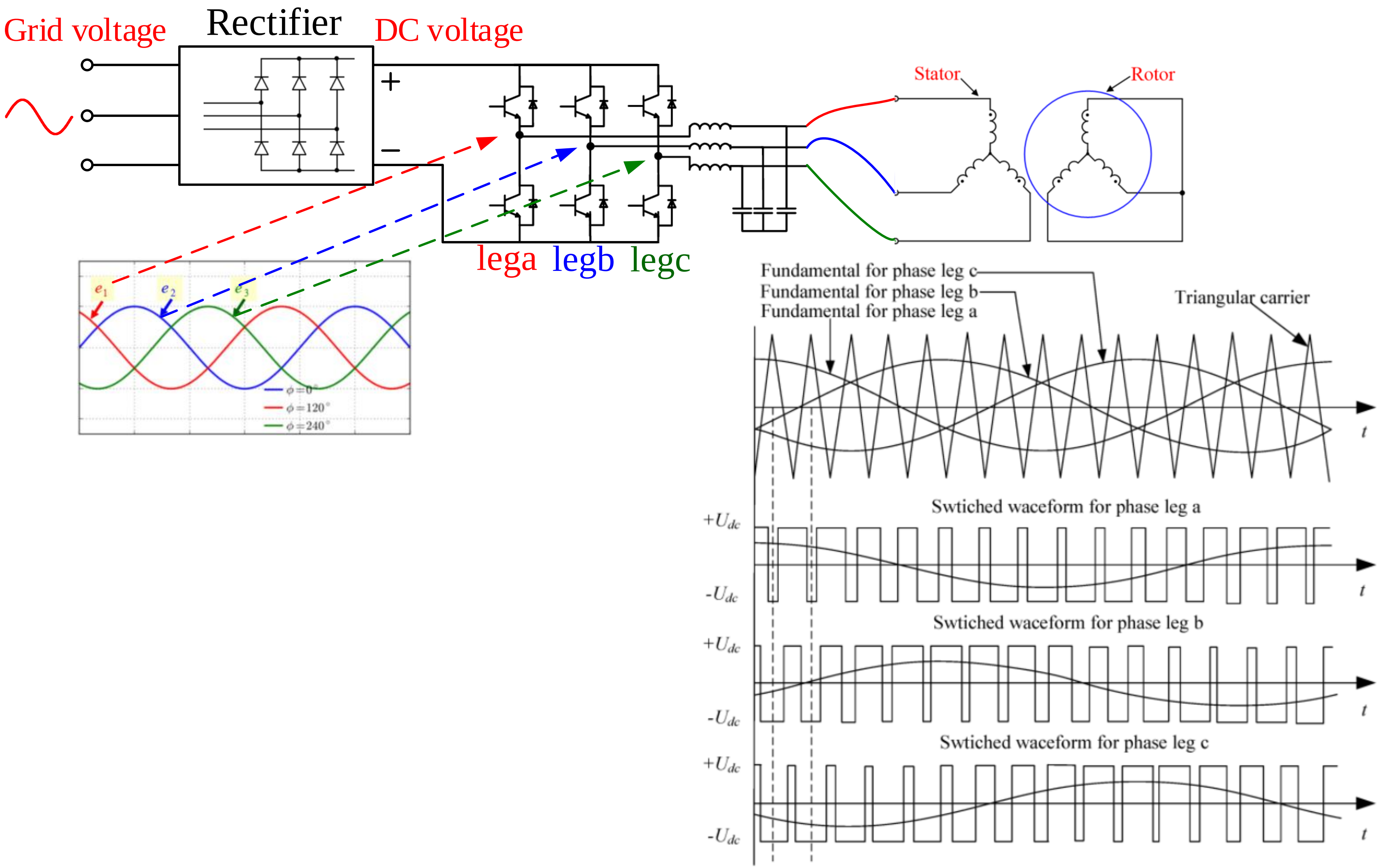
Rotor speed reference (q axis)

It is proportional to the torque

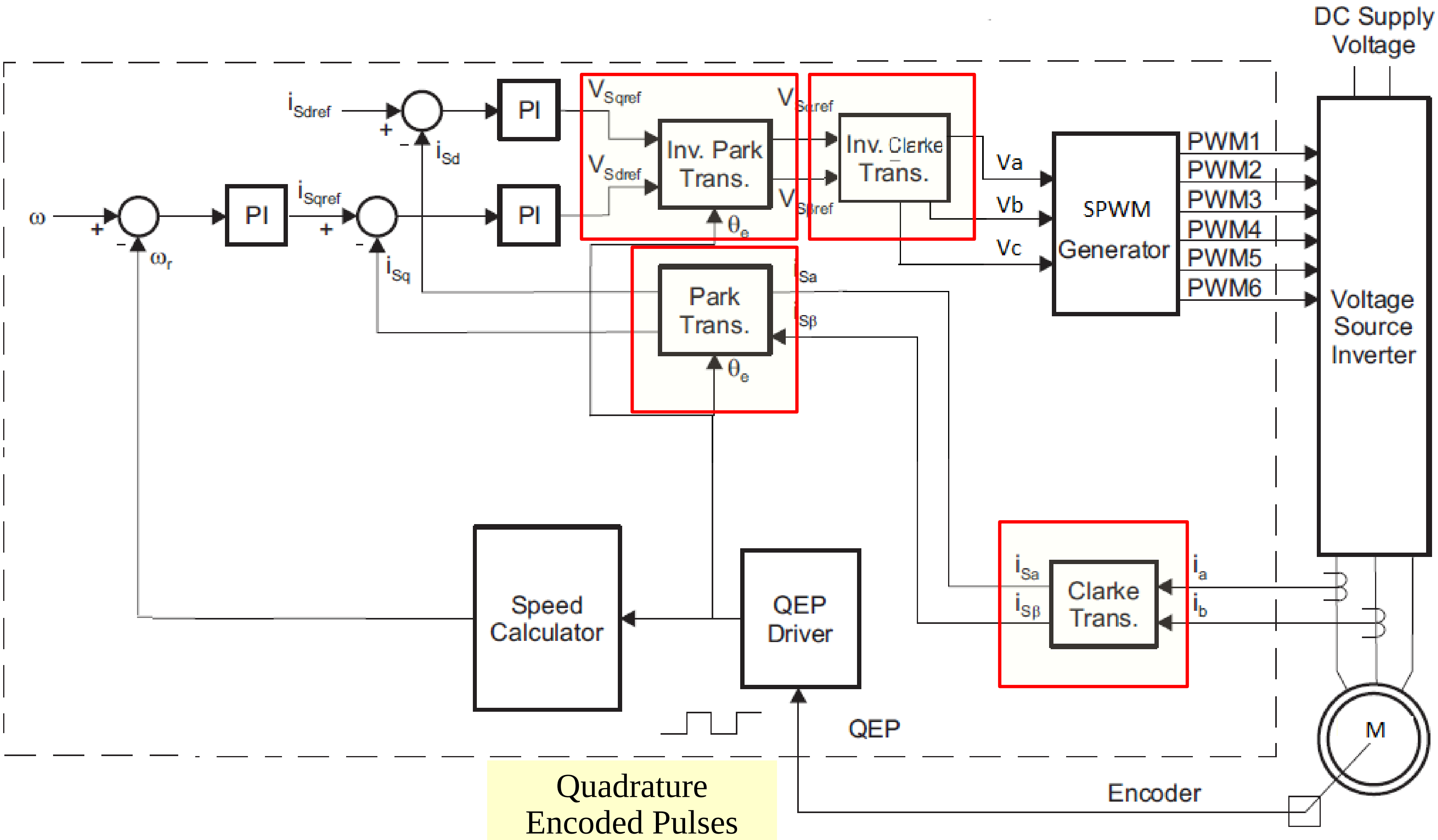
Motor and inverter parts



Recall the inverter part and its modulation



(Inverse) Clarke & Park transformation



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Recall the (inverse) Clarke & Park transformation

Clarke transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

Inverse Clarke transformation

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Park transformation

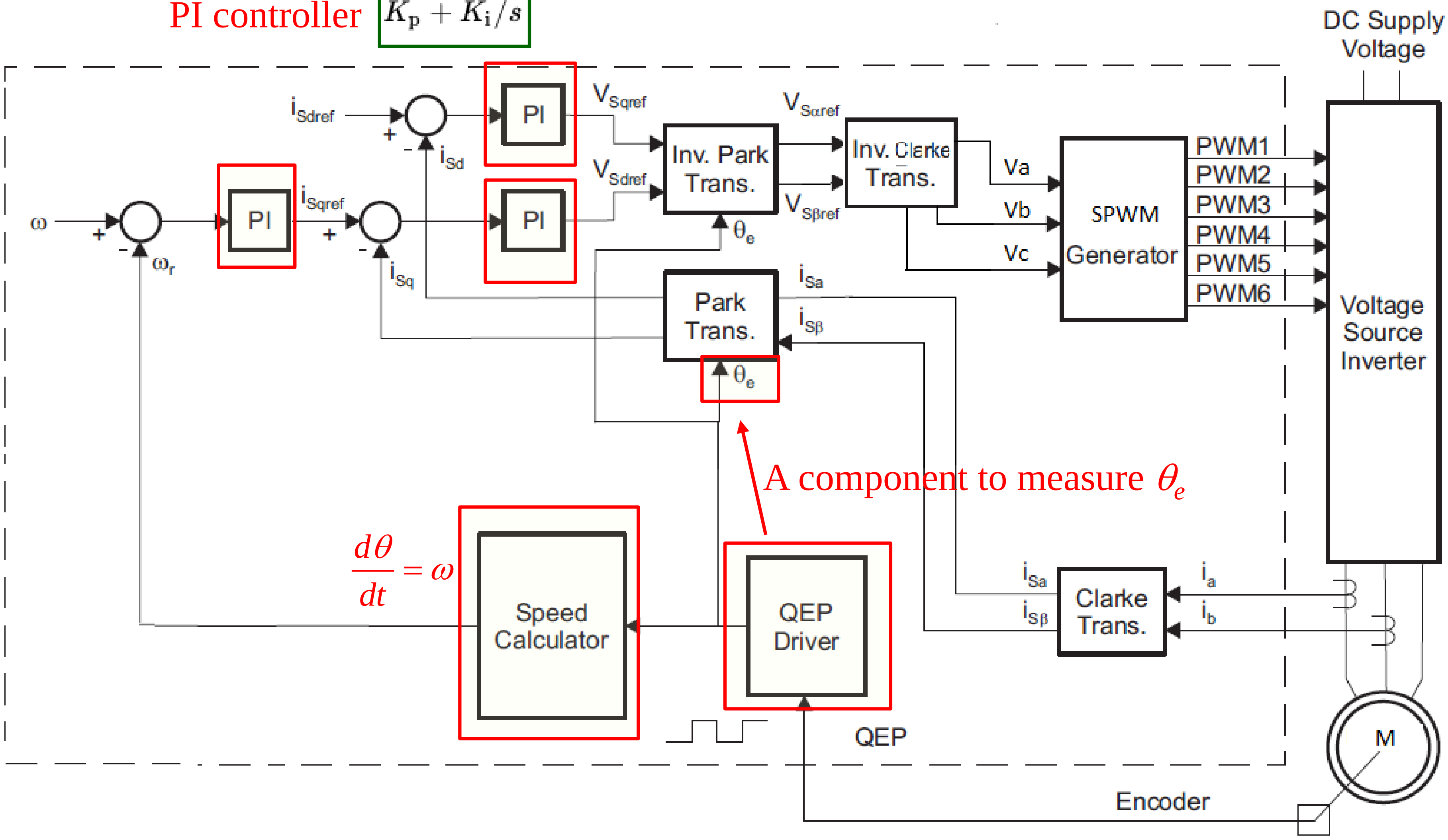
$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}^{-1}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Inverse Park transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

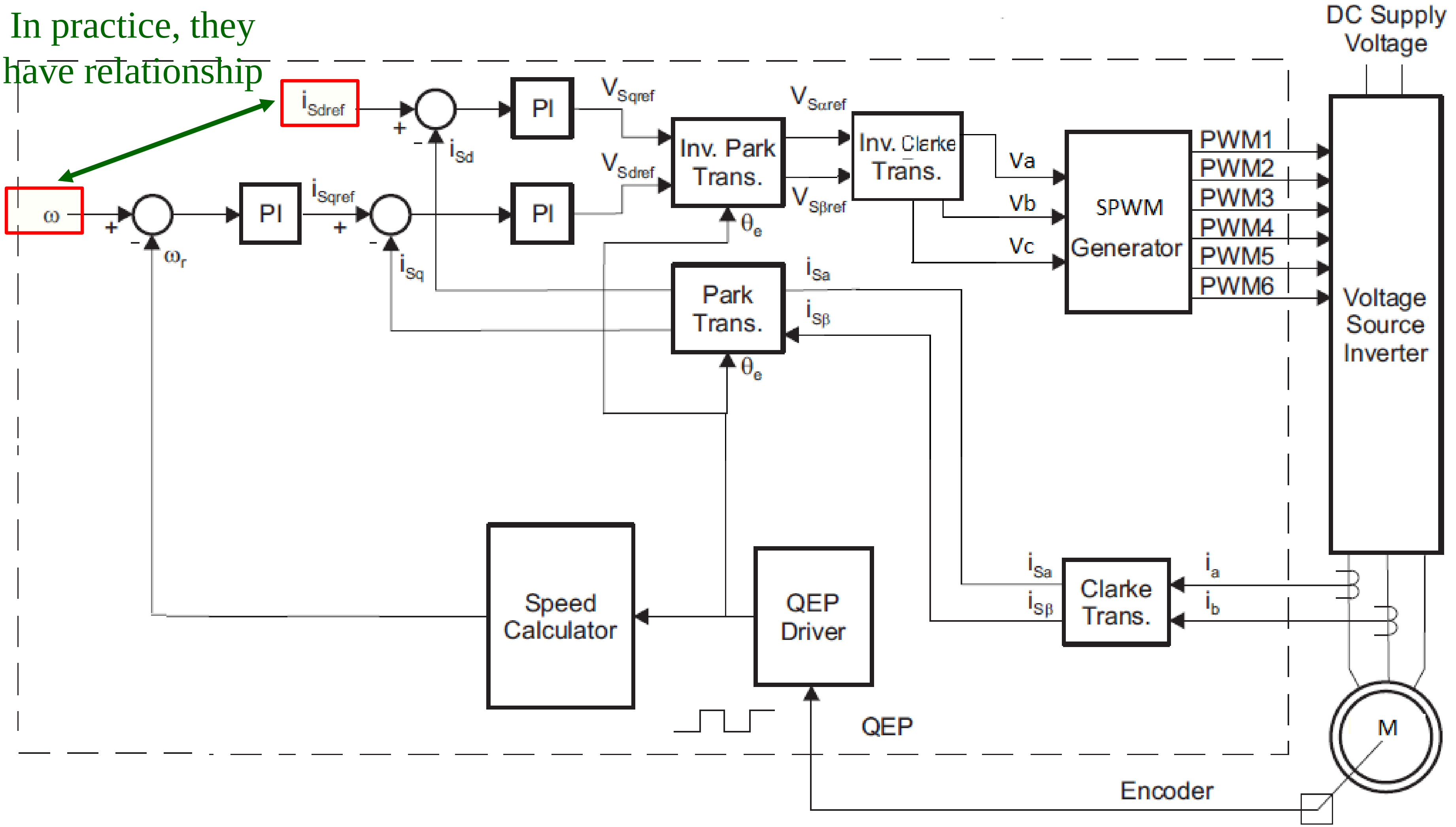
Speed sensor and PI controller

PI controller $K_p + K_i/s$



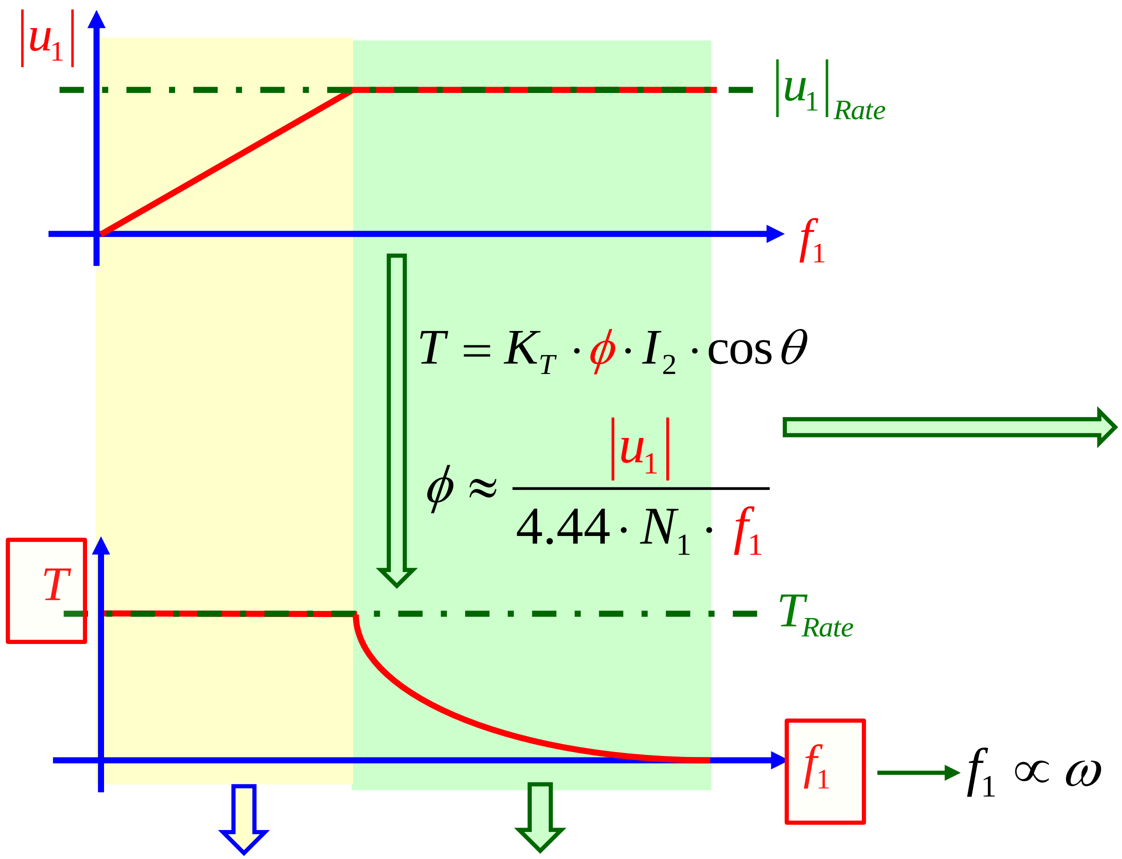
Practical issues of the FOC

In practice, they have relationship



Recall: the relationship between the motor speed and flux

- The motor cannot exceed its rated voltage

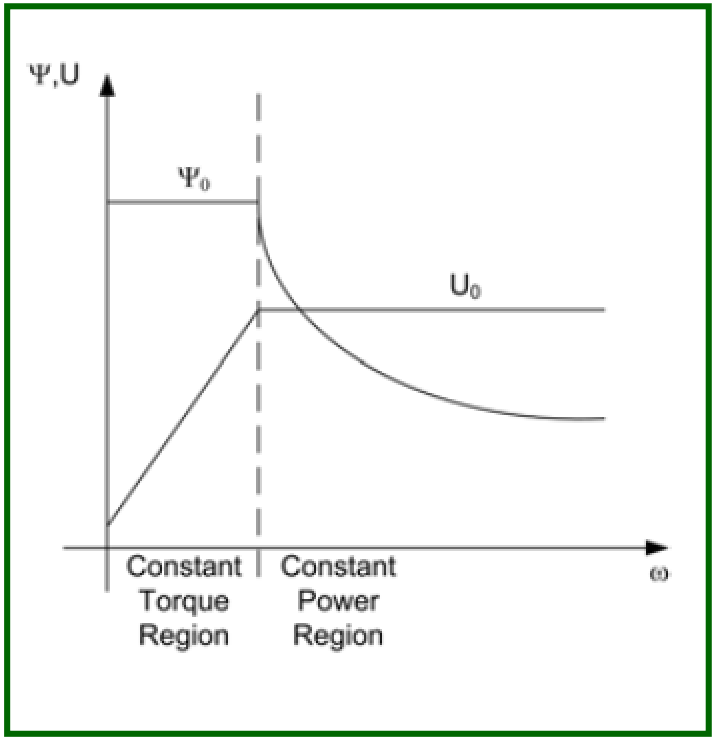


$$T = K_T \cdot \phi \cdot I_2 \cdot \cos\theta$$

$$\phi \approx \frac{|u_1|}{4.44 \cdot N_1 \cdot f_1}$$

Constant torque region

Constant power region



Review of today's topic

- Challenge of the asynchronous motor control compared to the DC motor control.
- Understand the physical concept of the coupling solution.
- Understand the Clarke transformation and its inverse transformation.
- Understand the Park transformation and its inverse transformation.
- Understand the concept of the field oriented control (FOC).
- Understand the FOC control of the asynchronous motor .

FIELD-ORIENTED CONTROL OF THE ASYNCHRONOUS MOTOR

[07/04/2020]

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END OF TOPIC

Example 1: Calculate the synchronous speed of a three phase asynchronous motor which having 10 poles and connected to a 50 Hz source:

Solutions:

a) $\boxed{P = 5}$

b) $$\boxed{n_s = \frac{60f}{P} = \frac{60 \cdot 50}{5} = 600(rpm)}$$

Example 2: A 6 poles asynchronous motor is excited by a three phase, 60 Hz source. If the rotor speed is 1140 rpm, calculate the slip ratio.

Solutions:

a) $\boxed{P = 3}$

b) $$\boxed{n_s = \frac{60f}{P} = \frac{60 \cdot 60}{3} = 1200\,(rpm)}$$

c) $$\boxed{s = \frac{n_s - n}{n_s} = \frac{1200 - 1140}{1200} = 0.05 = 5\%}$$

Example 3: The 6-poles, wound-rotor induction motor is excited by a three phase, 60 Hz source. Calculate the frequency of the rotor current under the following conditions:

a) At standstill condition;

b) Motor turning at 500 rpm at the same direction as the rotated magnetic field;

c) Motor turning at 500 rpm in the opposite direction to the rotated magnetic field;

d) Motor turning at 2000 rpm at the same direction as the rotated magnetic field.

Solutions:

$$\boxed{P = 3} \qquad \boxed{n_s = \frac{60f}{P} = \frac{60 \cdot 60}{3} = 1200(rpm)}$$

Example 3: The 6-pole, wound-rotor induction motor is excited by a three phase, 60 Hz source. Calculate the frequency of the rotor current under the following conditions:

a) At standstill condition;

b) Motor turning at 500 rpm at the same direction as the rotated magnetic field;

c) Motor turning at 500 rpm in the opposite direction to the rotated magnetic field;

d) Motor turning at 2000 rpm at the same direction as the rotated magnetic field.

Solutions:

a) $\boxed{n = 0(rpm)}$

$$\boxed{s = \frac{n_s - n}{n_s} = \frac{1200 - 0}{1200} = 1}$$

$$\boxed{f_r = s \cdot f = 1 \cdot 60 = 60(Hz)}$$

Example 3: The 6-pole, wound-rotor induction motor is excited by a three phase, 60 Hz source. Calculate the frequency of the rotor current under the following conditions:

a) At standstill condition;

b) Motor turning at 500 rpm at the same direction as the rotated magnetic field;

c) Motor turning at 500 rpm in the opposite direction to the rotated magnetic field;

d) Motor turning at 2000 rpm at the same direction as the rotated magnetic field.

Solutions:

b) $\boxed{n = 500(rpm)}$

$$\boxed{s = \frac{n_s - n}{n_s} = \frac{1200 - 500}{1200} = 0.583} \quad \boxed{f_r = s \cdot f = 0.583 \cdot 60 = 35(Hz)}$$

Example 3: The 6-pole, wound-rotor induction motor is excited by a three phase, 60 Hz source. Calculate the frequency of the rotor current under the following conditions:

a) At standstill condition;

b) Motor turning at 500 rpm at the same direction as the rotated magnetic field;

c) Motor turning at 500 rpm in the opposite direction to the rotated magnetic field;

d) Motor turning at 2000 rpm at the same direction as the rotated magnetic field.

Solutions:

c) $\boxed{n = -500(rpm)}$ (s>1 means motor is operating as a brake)

$$\boxed{s = \frac{n_s - n}{n_s} = \frac{1200-(\text{-}500)}{1200} = 1.417}$$

$$\boxed{f_r = s \cdot f = 1.417 \cdot 60 = 85(Hz)}$$

Example 3: The 6-pole, wound-rotor induction motor is excited by a three phase, 60 Hz source. Calculate the frequency of the rotor current under the following conditions:

a) At standstill condition;

b) Motor turning at 500 rpm at the same direction as the rotated magnetic field;

c) Motor turning at 500 rpm in the opposite direction to the rotated magnetic field;

d) Motor turning at 2000 rpm at the same direction as the rotated magnetic field.

Solutions:

d) $\boxed{n = 2000(rpm)}$

(-40 Hz means that the phase sequence of the voltage induced in the rotor winding is revised)

$$\boxed{s = \frac{n_s - n}{n_s} = \frac{1200-(2000)}{1200} = -0.667}$$

$$\boxed{f_r = s \cdot f = -0.667 \cdot 60 = -40(Hz)}$$

SYNCHRONOUS MOTOR AND ITS CONTROL

[14/04/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

- Structure and working principle of the synchronous motor
- How to start the synchronous motor?
- Control of the synchronous motor

SYNCHRONOUS MOTOR AND ITS CONTROL

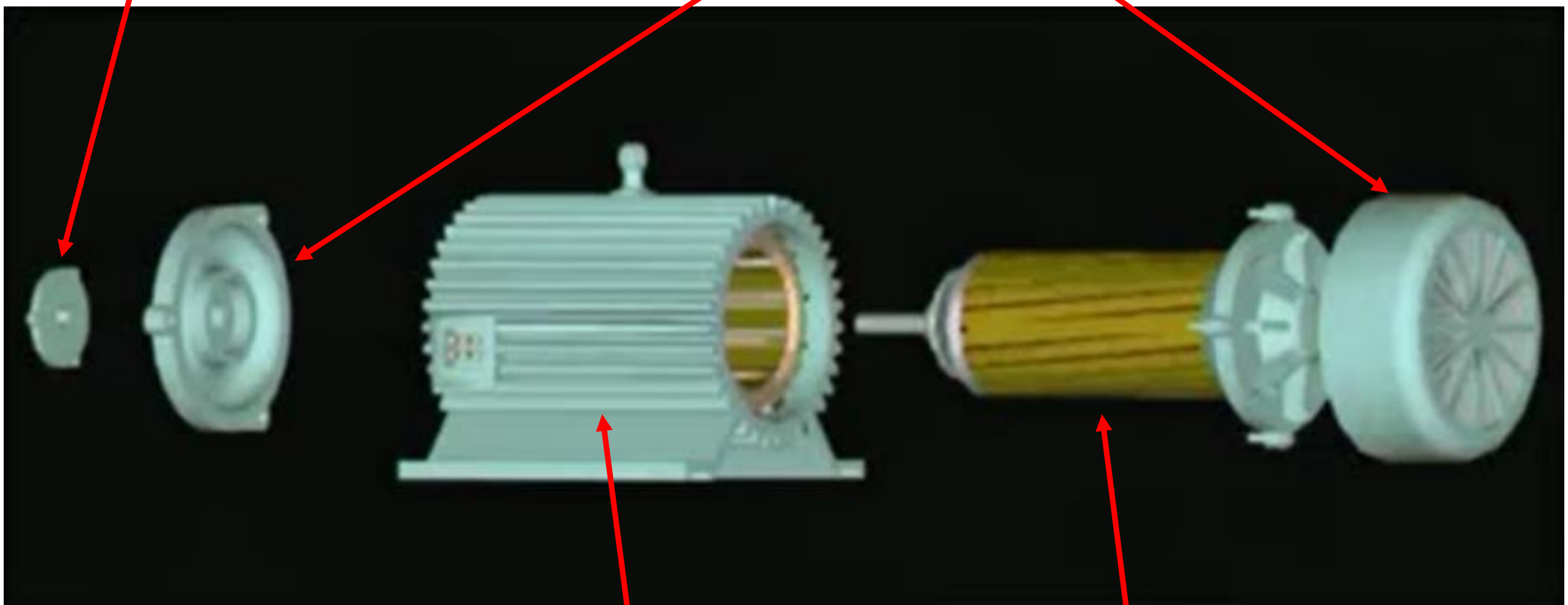
[14/04/2020]

- Structure and working principle of the synchronous motor
- How to start the synchronous motor?
- Control of the synchronous motor

Review the structure of the asynchronous motor

Bearing cap

End Bell

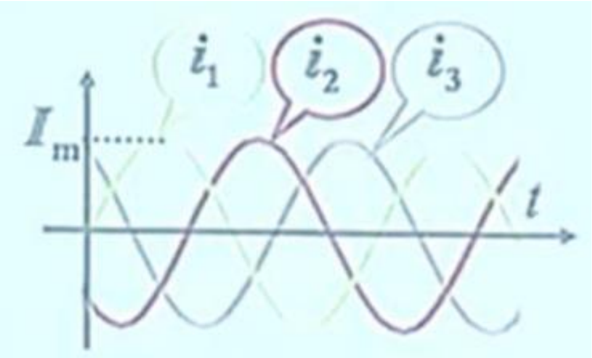


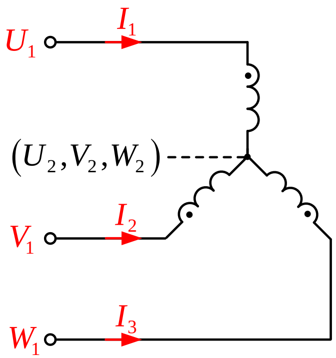
Main parts: Stator Rotor

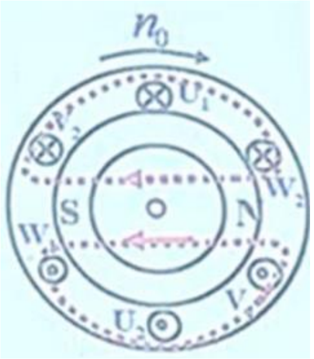
Cage rotor

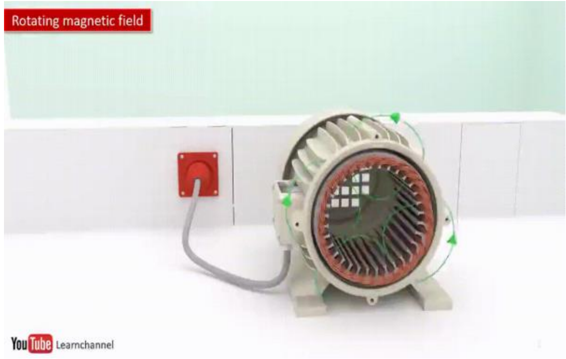
Wound rotor

Review the rotated principle of the asynchronous motor



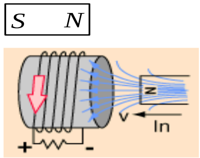


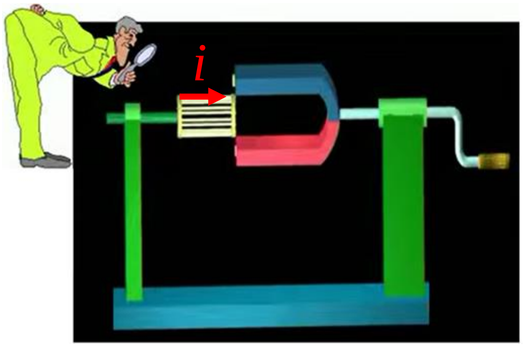




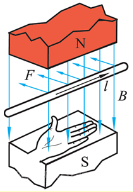
Three phase AC currents generate rotated magnetic field

Lenz's Law



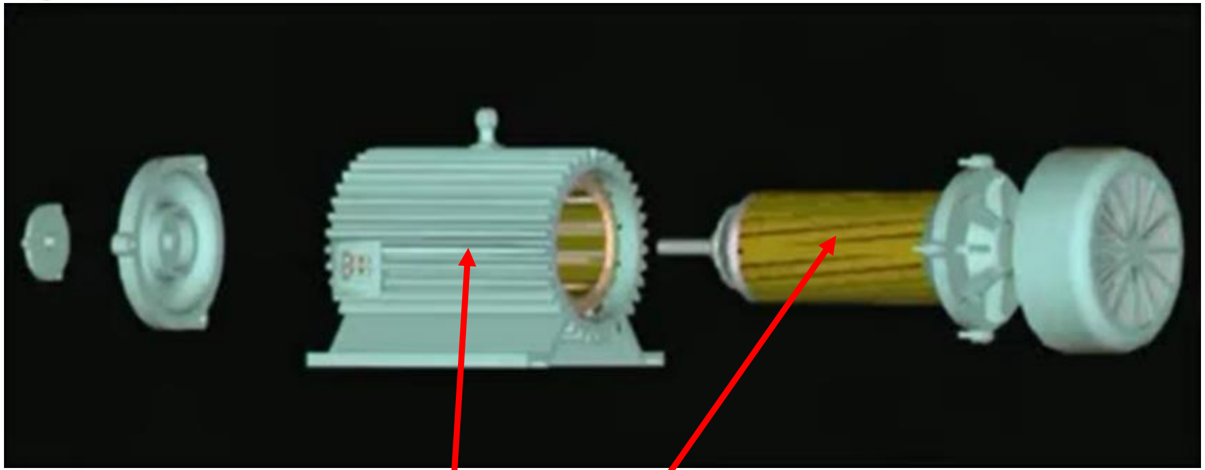


Induce current is generated in the rotor windings to stop its flux change



Electromagnetic force is generated to make the rotor windings follow the rotated magnetic field

Review the rotated speed of the asynchronous motor



$$n=(1-s)n_o$$

$$n_o = \frac{60f}{P} \quad (rpm)$$

The rotor is cage/wound rotor, whose magnetic field only can be induced by the stator magnetic field

$\boxed{n < n_o}$ ← asynchronous motor

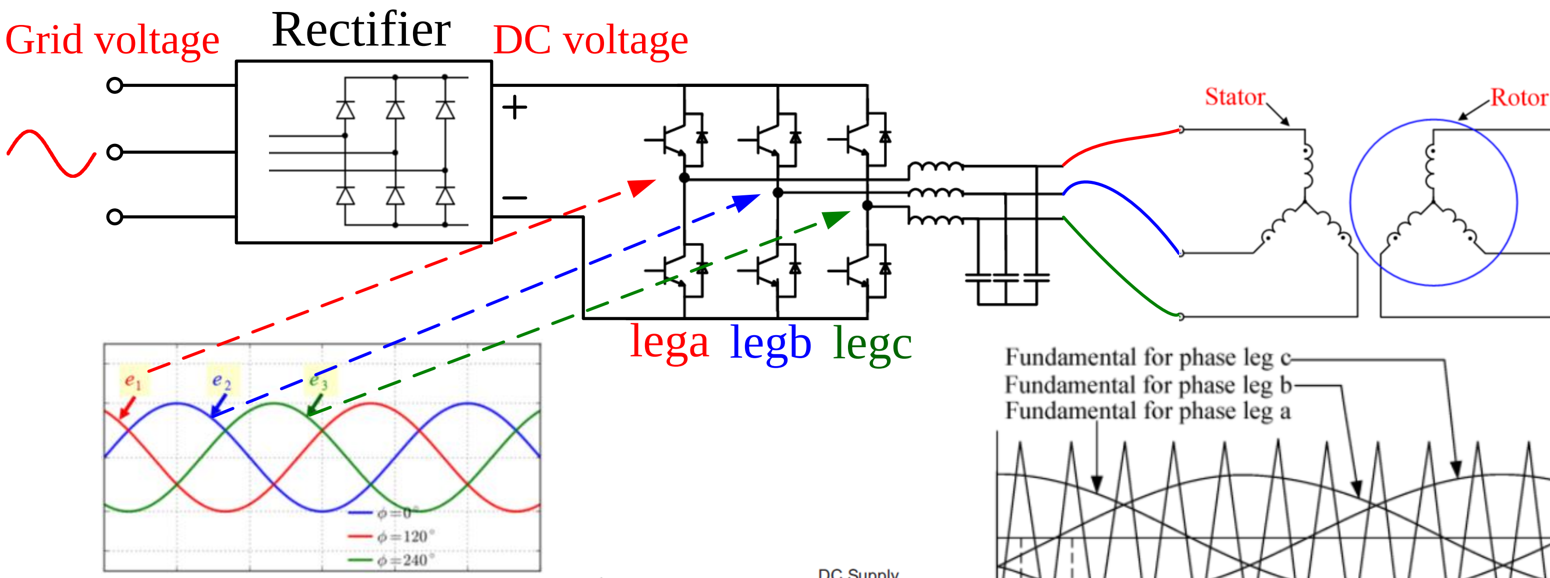
- Rotated speed of the magnetic field n_0
- Rotated speed of the rotor n

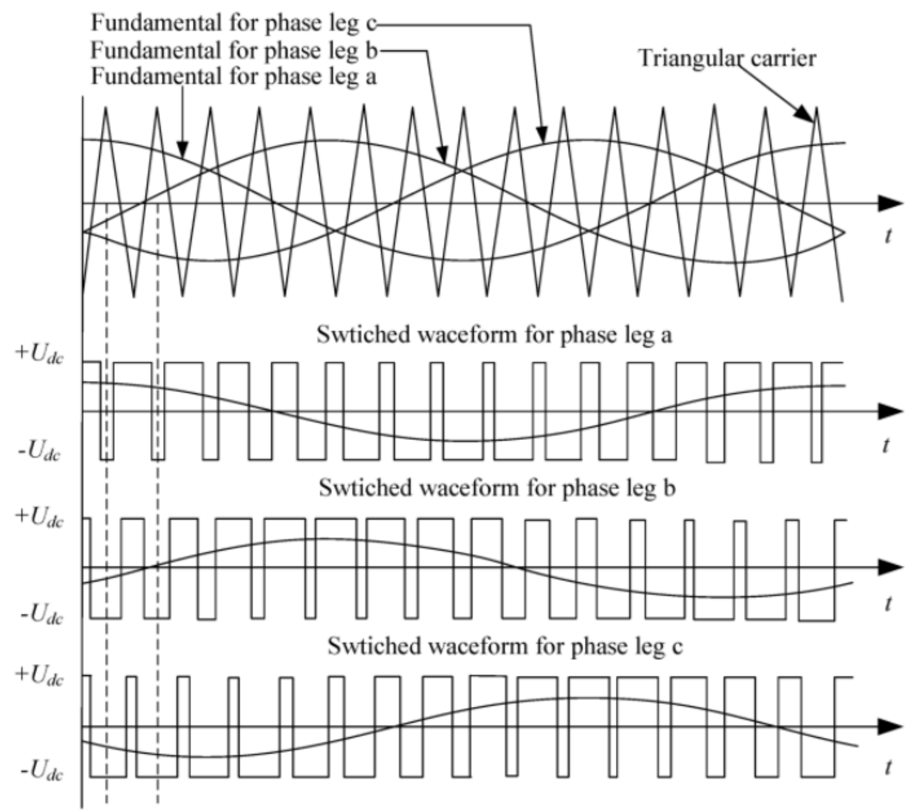
- Rotated frequency of the magnetic field f
- Pole-pairs of the asynchronous motor P
- Slip ratio: s

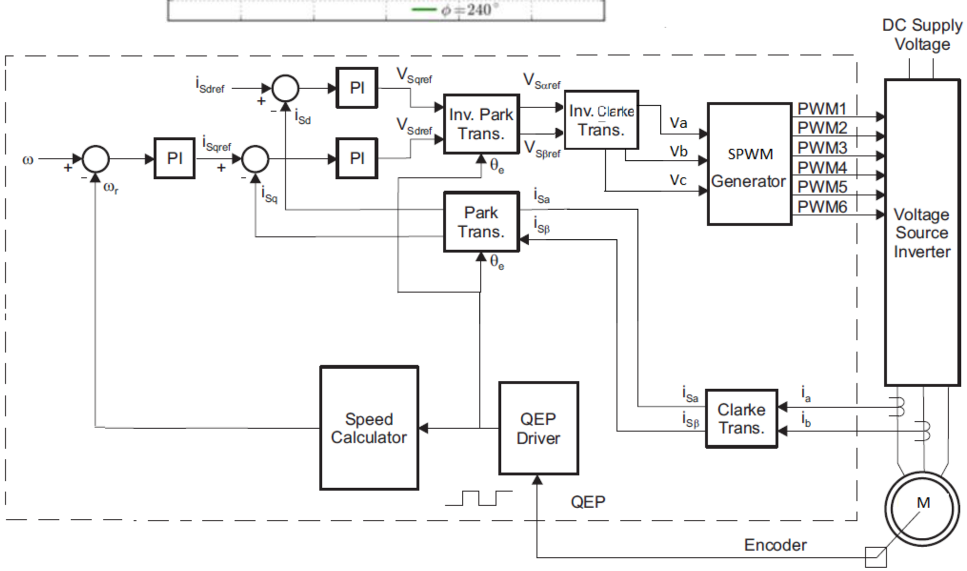
$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

Difficult to control the rotor speed of the asynchronous motor

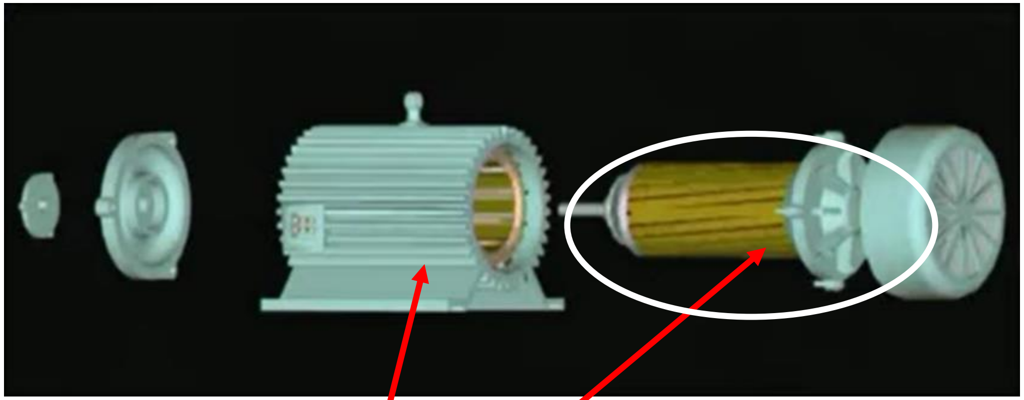
Recall the inverter part and its modulation





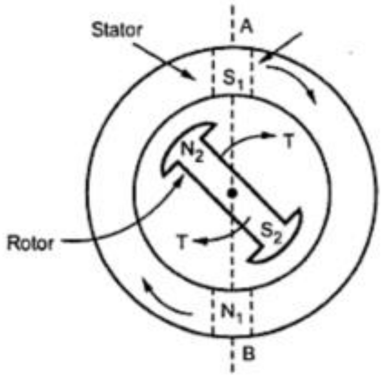


Motivation of the synchronous motor



Why not make the rotor generate the rotor magnetic field by its self? Then, $n = n_o$

Stator & rotor magnetic field (independent)



The rotor is cage/wound rotor, whose magnetic field only can be induced by the stator magnetic field

$n < n_o$

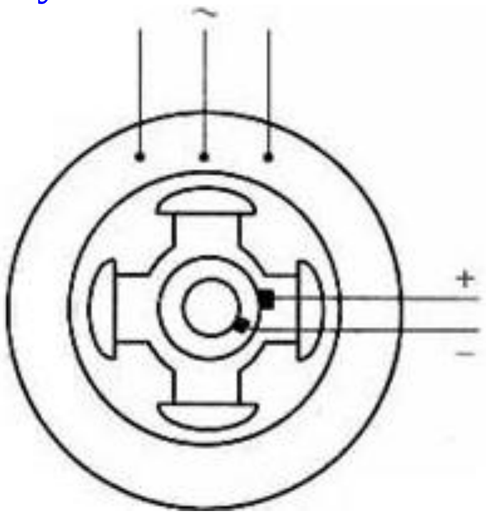
Asynchronous motor

- Same polarity repel with each other
- Opposite polarity attract with each other

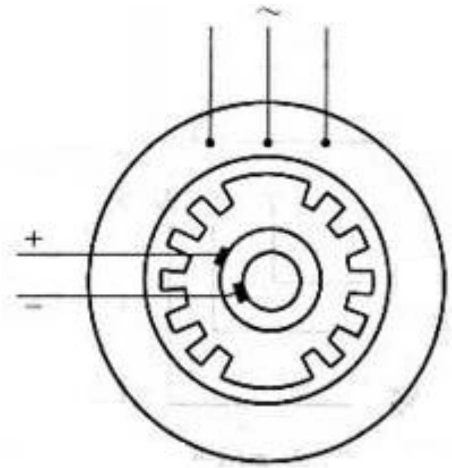
$n = n_o$ → Synchronous motor

Typical types of the synchronous motor I: Using external excitation winding

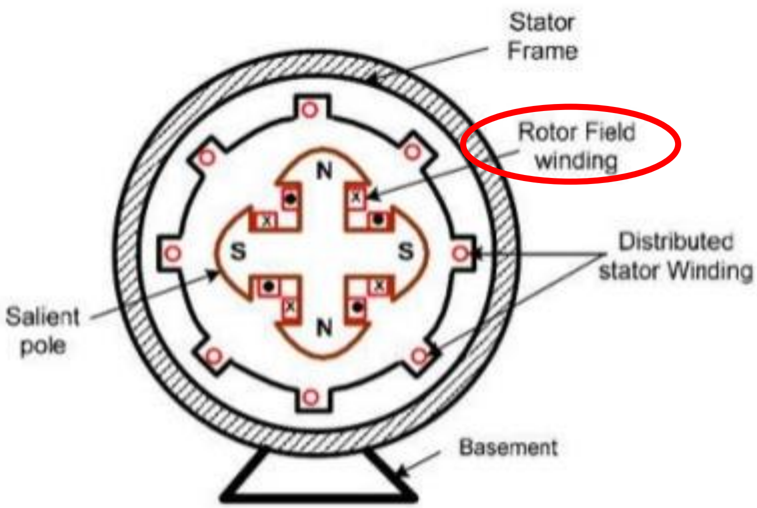
Salient pole synchronous motor

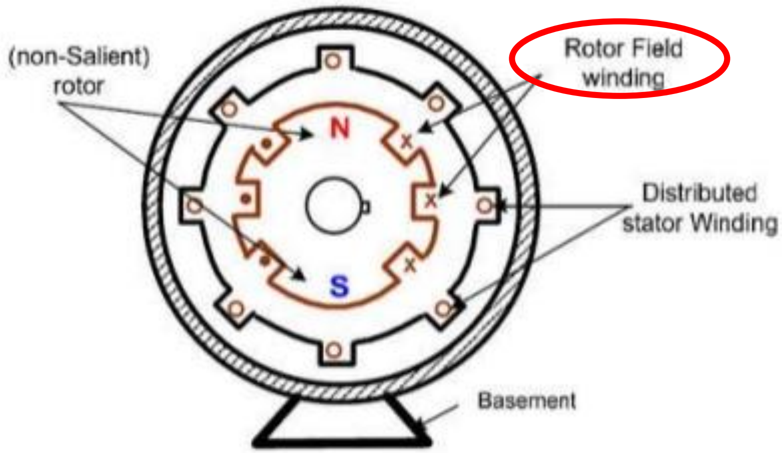


Non-salient pole synchronous motor



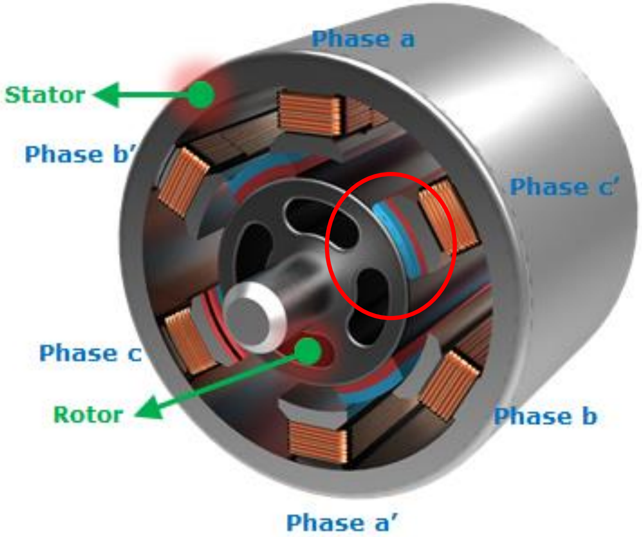
Like DC motor to use external excitation winding to make the rotor become a magnetic core

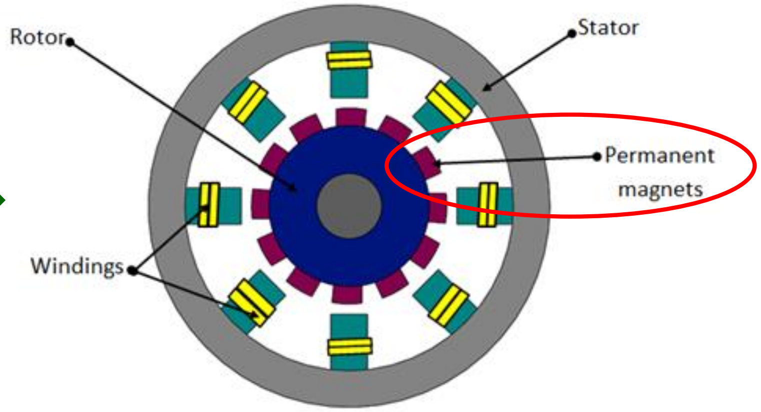


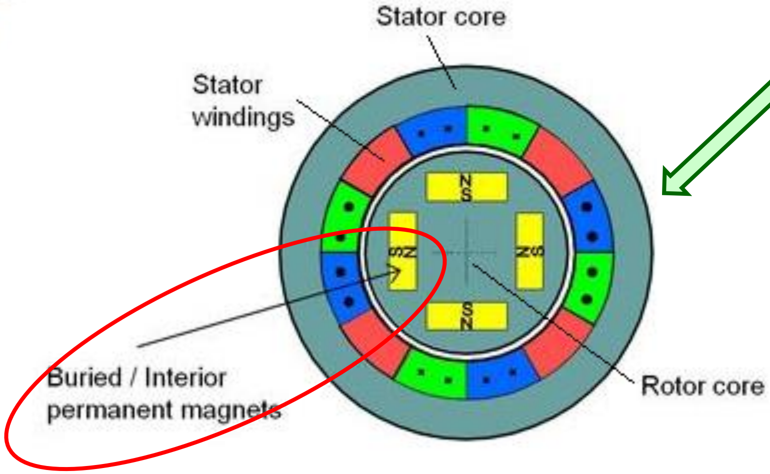


Typical types of the synchronous motor II: Permanent magnet synchronous motor (PMSM)

Using permanent magnet to generate the rotor magnetic field directly







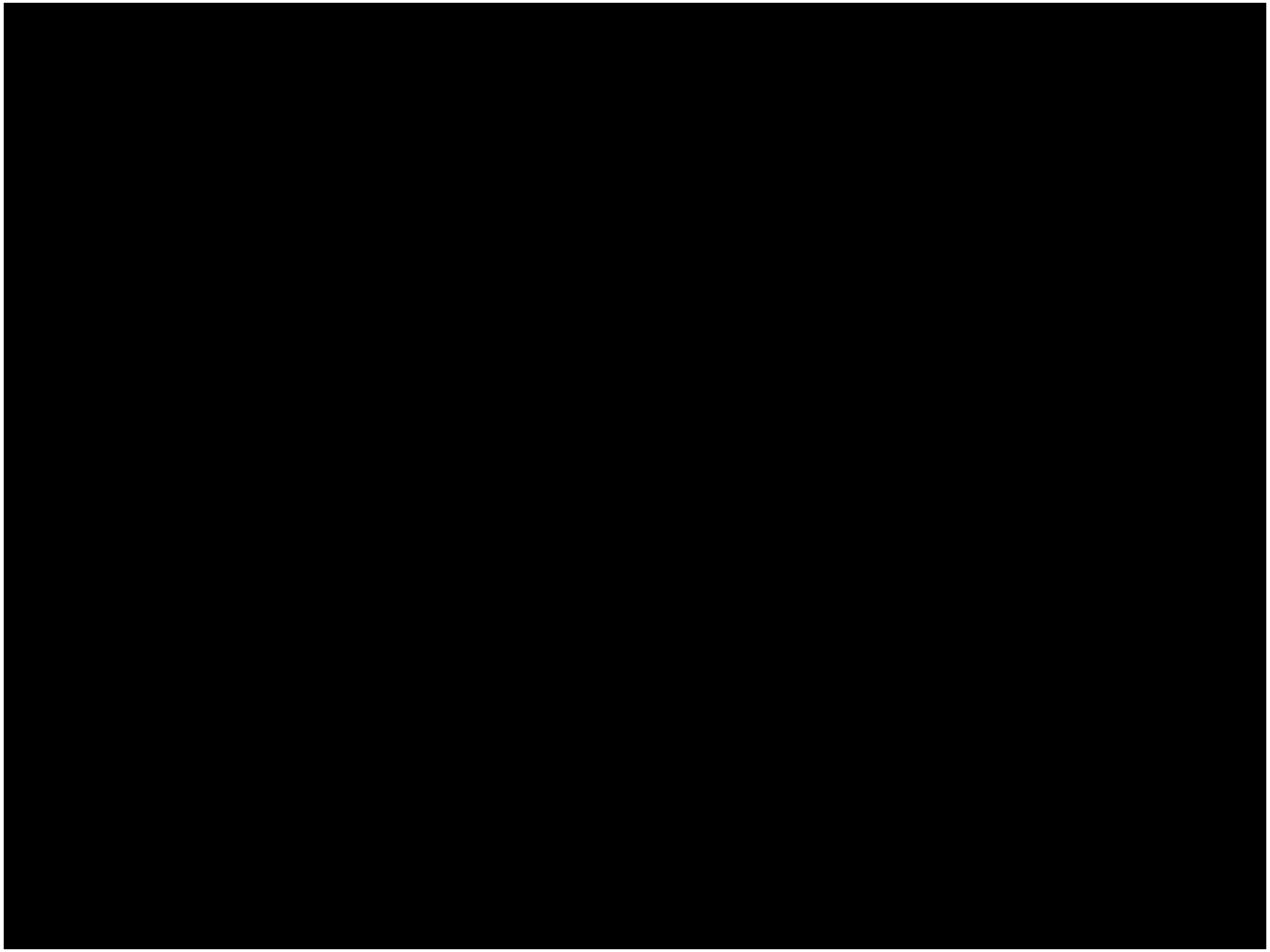
Ferrite / Ceramic

Alnico

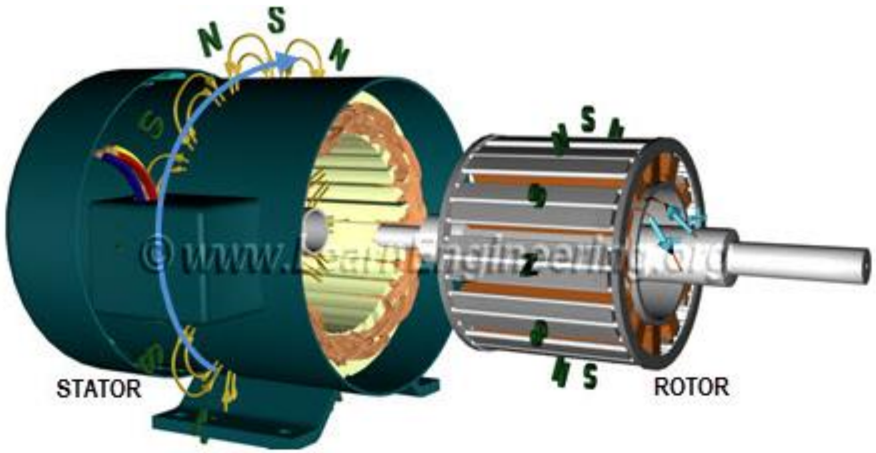
Cobalt

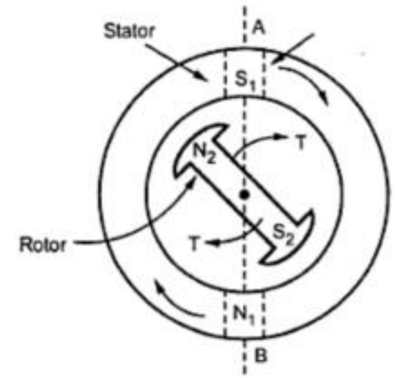
Flexible Rubber Magnet

Video: how to make magnets?



Rotor speed of the synchronous motors





$n = n_o$

Synchronous motor

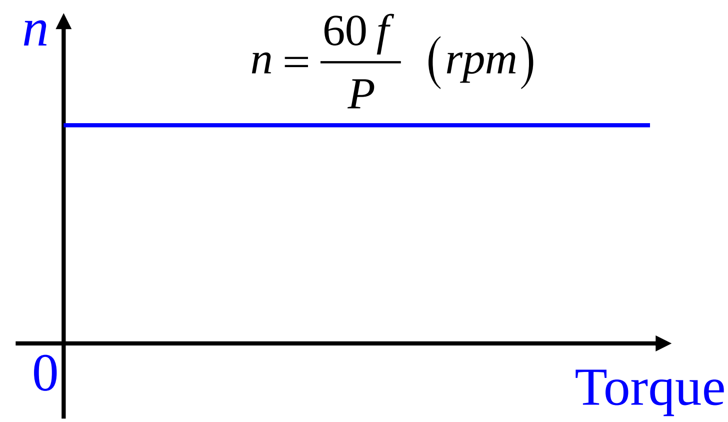
$$n_o = \frac{60f}{P} \quad (rpm)$$

$$n = \frac{60f}{P} \quad (rpm)$$

Rotated frequency of the magnetic field

Minutes

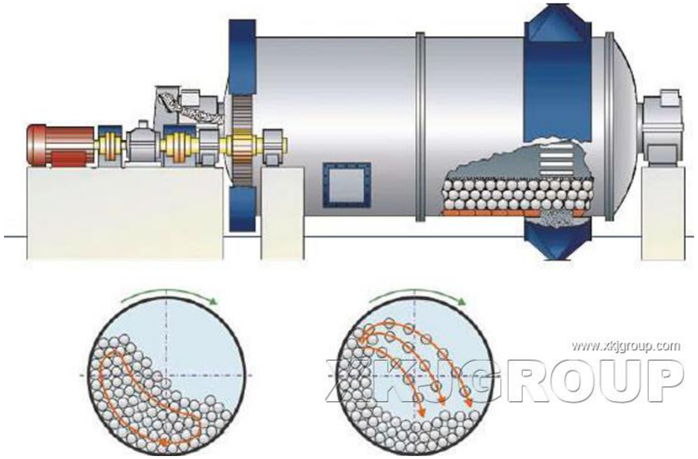
Pole-pairs



Constant and only determined by f ---(Advantages)

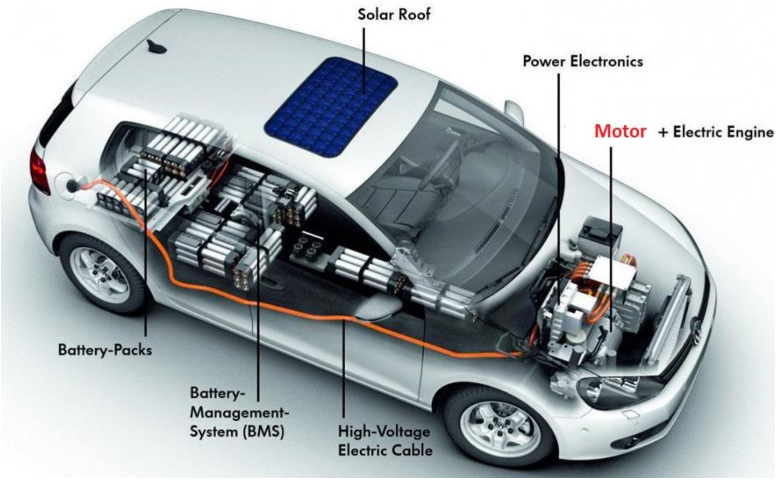
Application of synchronous motors

Ball mill in a mine ore process



Compressor drive in a petrochemical plant

Electrical vehicle



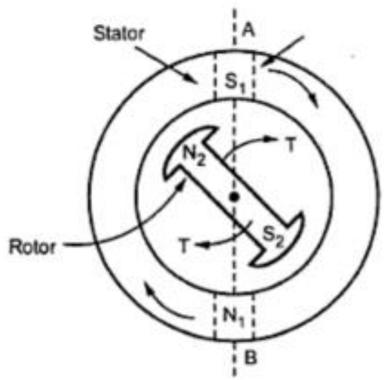
Video: how to DIY a synchronous motors

SYNCHRONOUS MOTOR AND ITS CONTROL

[14/04/2020]

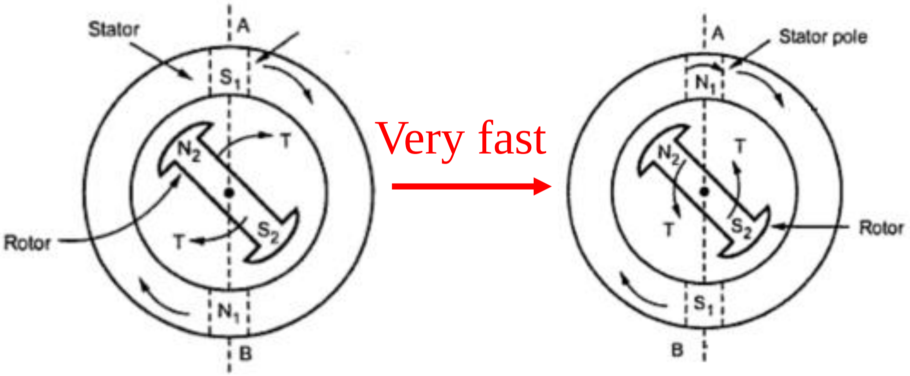
- Structure and working principle of the synchronous motor
- How to start the synchronous motor?
- Control of the synchronous motor

Self-starting problem of synchronous motors



- Same polarity repel with each other
- Opposite polarity attract with each other

$n = n_o$ → Synchronous motor

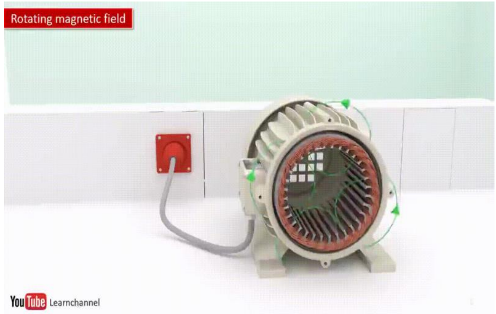


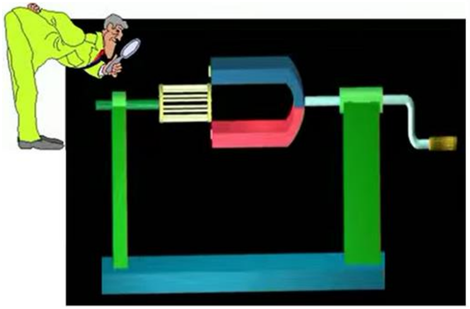
Problem: If the speed of the stator rotated magnetic field is very fast, the rotor magnet cannot follow it

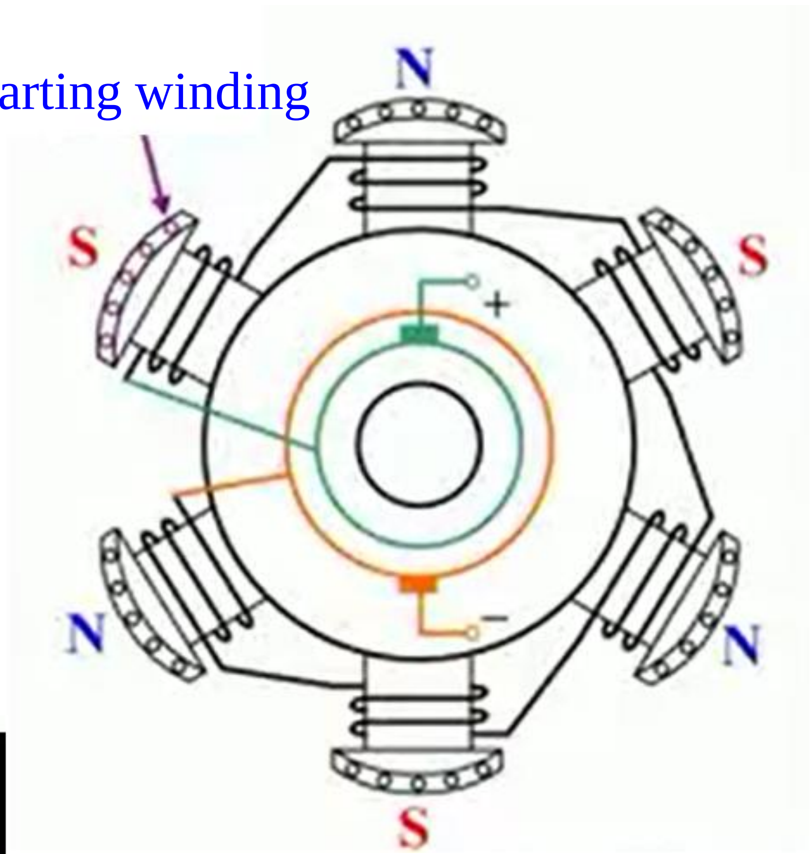
How to start the synchronous motor with external excitation winding?

Step1: do not give the power to the excitation winding

Starting winding has the same function with the rotor winding of the asynchronous motor, which generated induced magnetic field and follow the rotated stator magnetic field



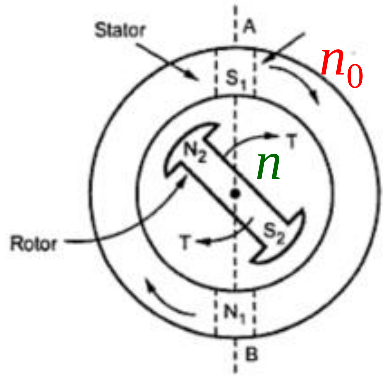


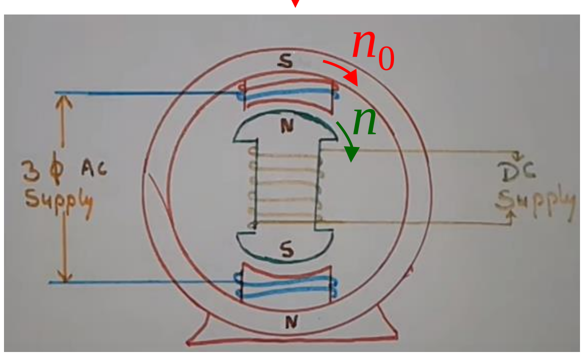


The synchronous motor start like an asynchronous motor!

How to start the synchronous motor with external excitation winding?

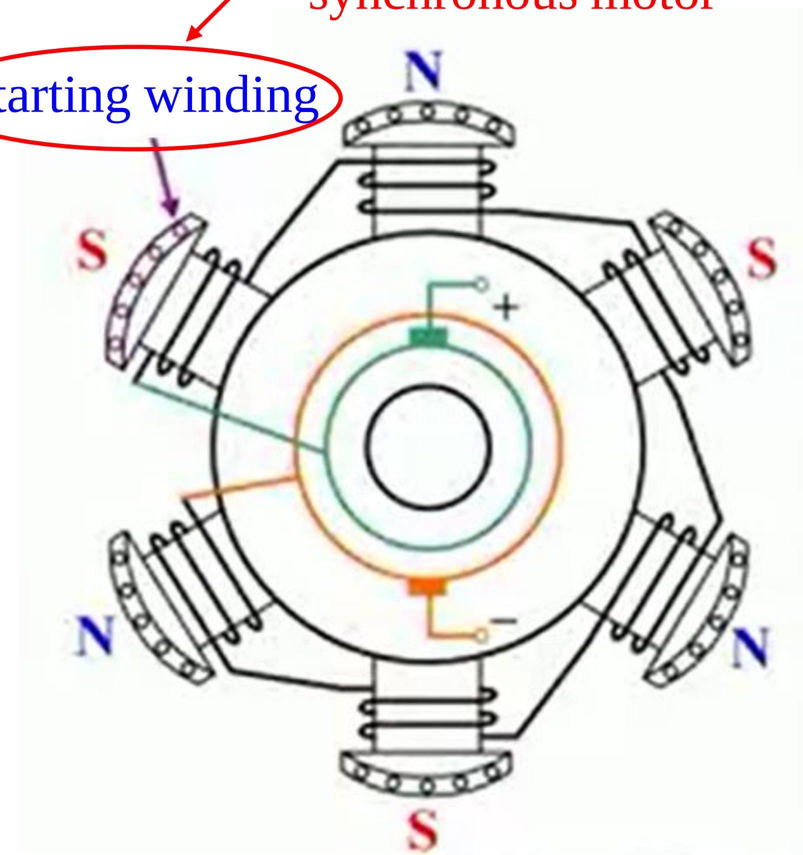
Step2: If the rotor speed is near the speed of the stator rotated magnetic field, give the power to the excitation winding to make the rotor become a magnetic core





No impact after starting the synchronous motor

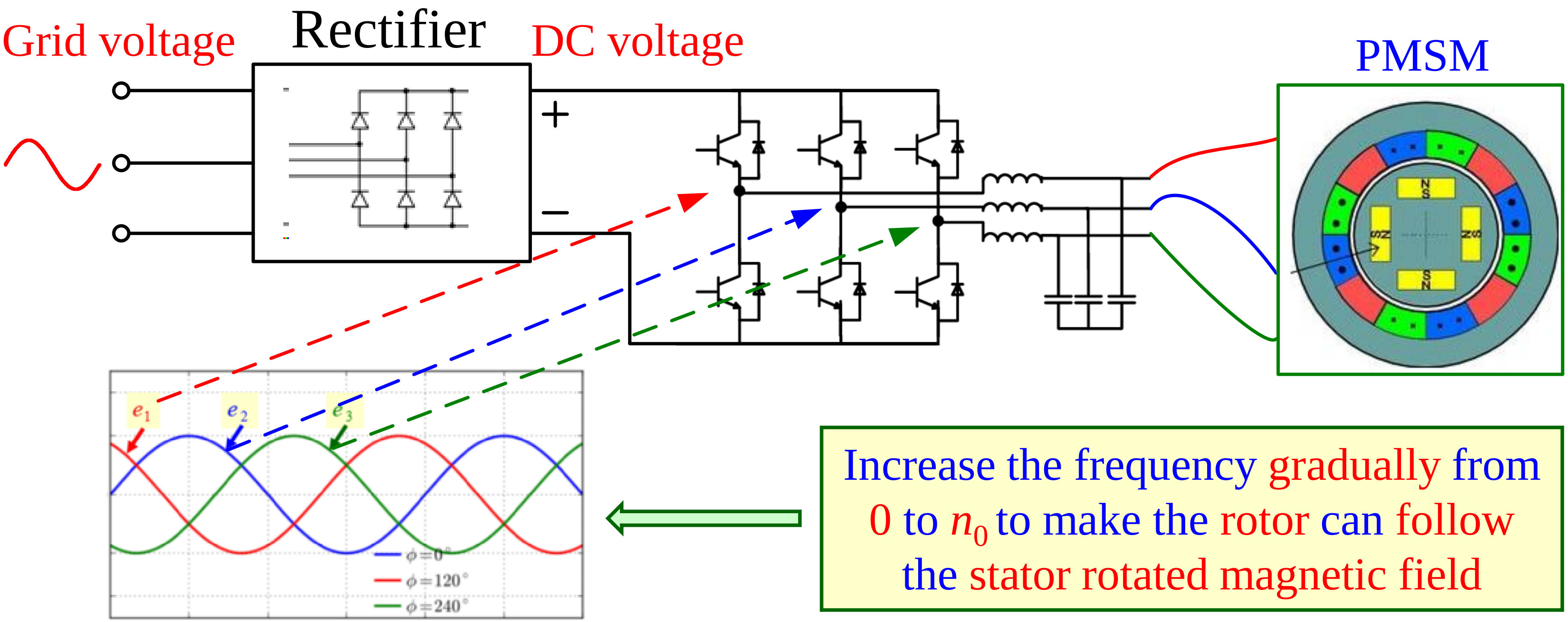
Starting winding



$n=n_o$

There is no current in the starting winding due to $n=n_0$

How to start the Permanent magnet synchronous motor?



Increase the frequency gradually from 0 to n_0 to make the rotor can follow the stator rotated magnetic field

Video: review the operation principle of the synchronous motor

www.LearnEngineering.org

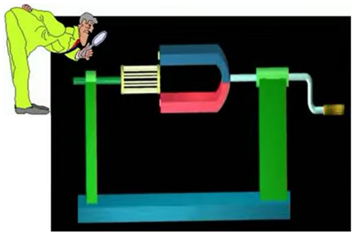
https://www.youtube.com/watch?v=Vk2jDXxZIhs

SYNCHRONOUS MOTOR AND ITS CONTROL

[14/04/2020]

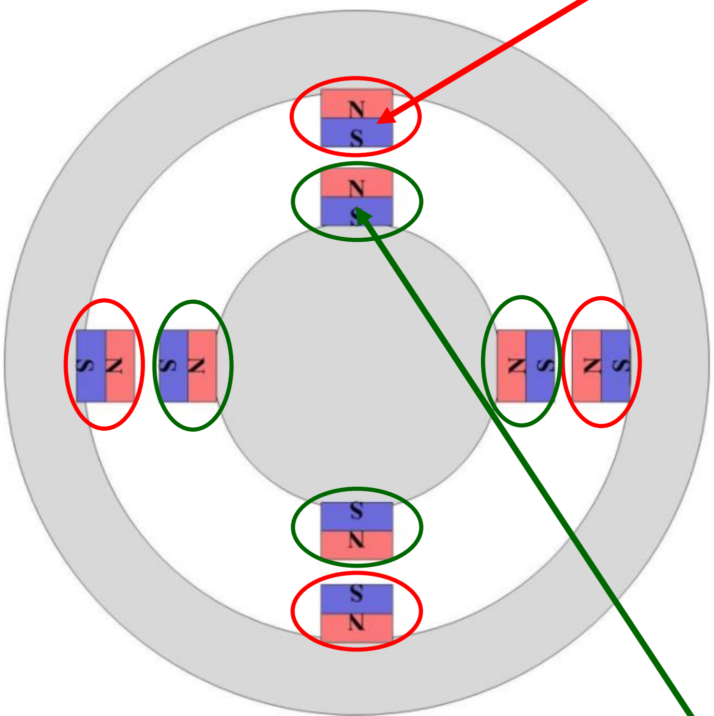
- Structure and working principle of the synchronous motor
- How to start the synchronous motor?
- Control of the synchronous motor

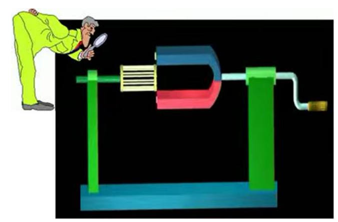
A simple way to understand rotated principle of the asynchronous motor

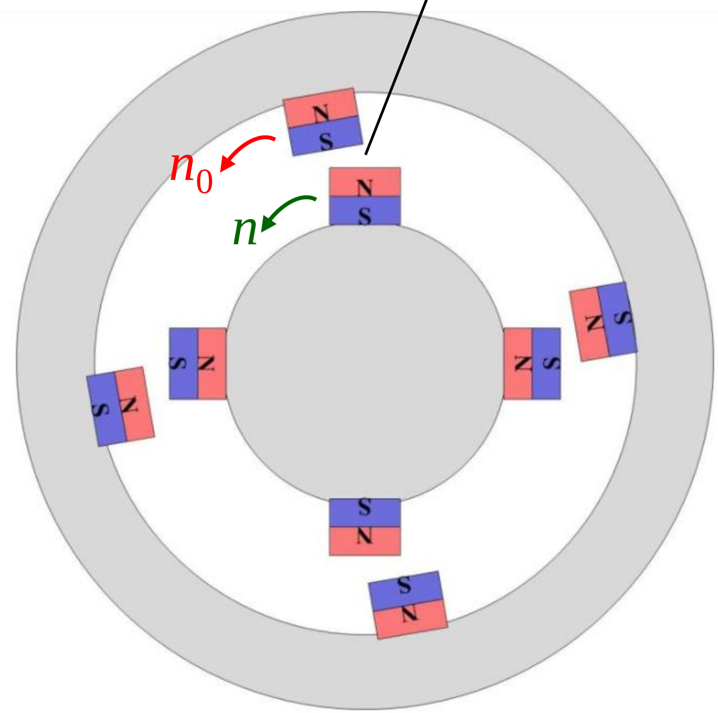


Magnetic field generated by the stator current

Electromagnetic torque (T) to let the rotor follow the stator magnetic field

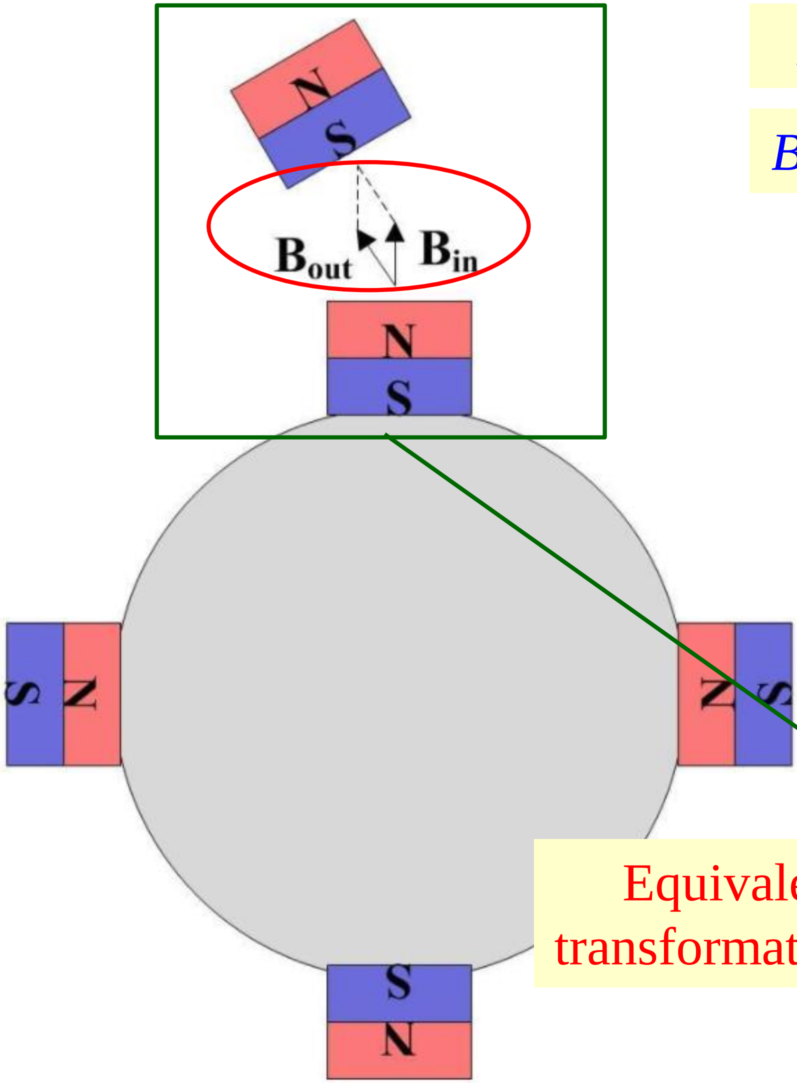






Induced rotor magnetic field

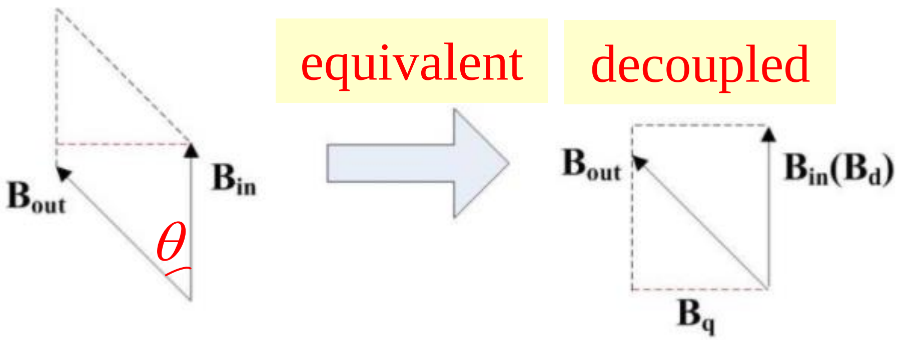
A simple and straight method to control the rotor follow the rotated stator magnetic field



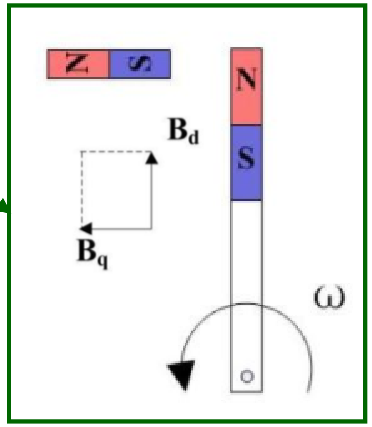
B_{in}: Strength of the induced rotor magnetic field

B_{out}: Strength of the stator magnetic field

Torque: $T = B_{in} \times B_{out} = |B_{in}| \cdot |B_{out}| \cdot \sin\theta$



Equivalent transformation to

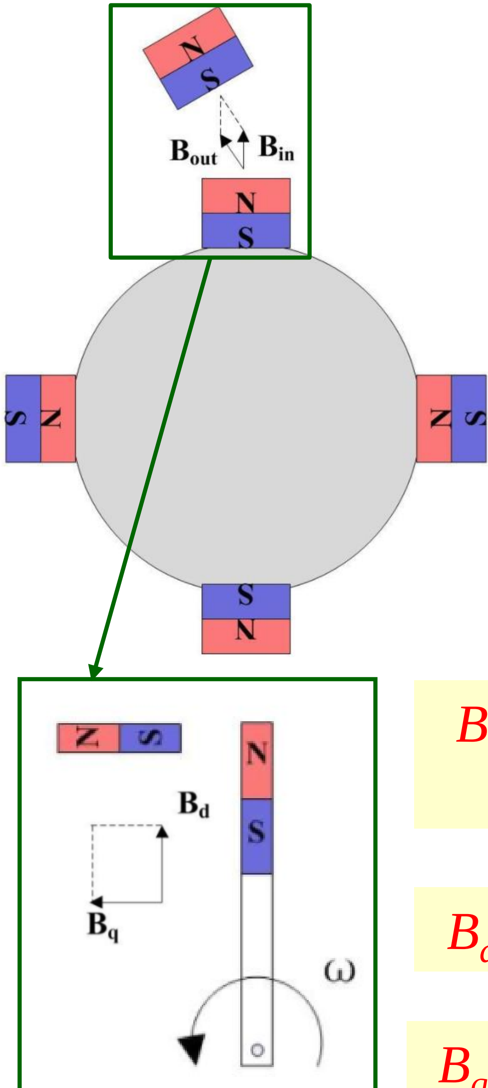


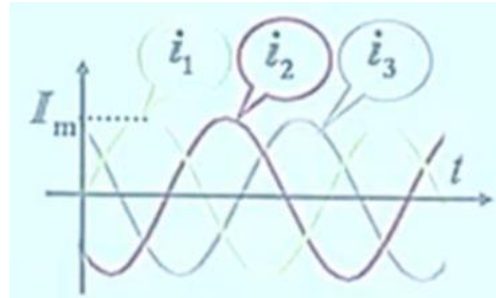
B_d and B_q are decoupled

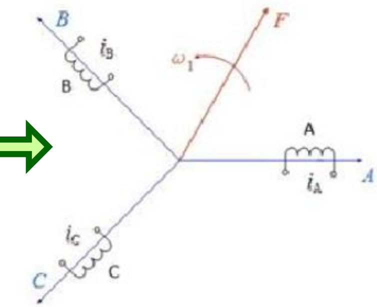
B_d: Only for ϕ

B_q: Only for T

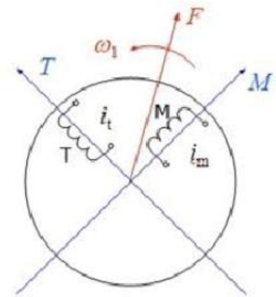
Concept of the field oriented control (FOC)







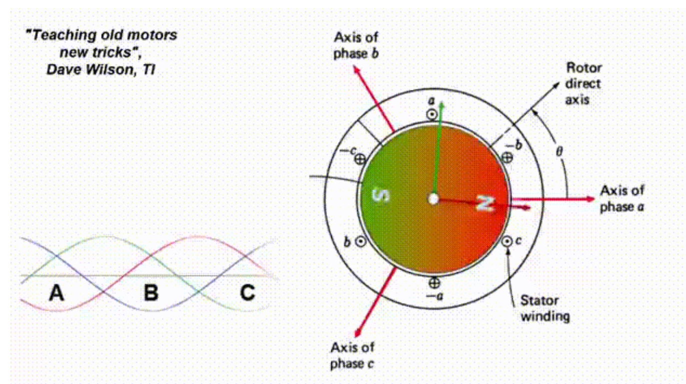
ABC→dq



B_d and B_q are decoupled

B_d: Only for ϕ

B_q: Only for T



Concept of the Field oriented control

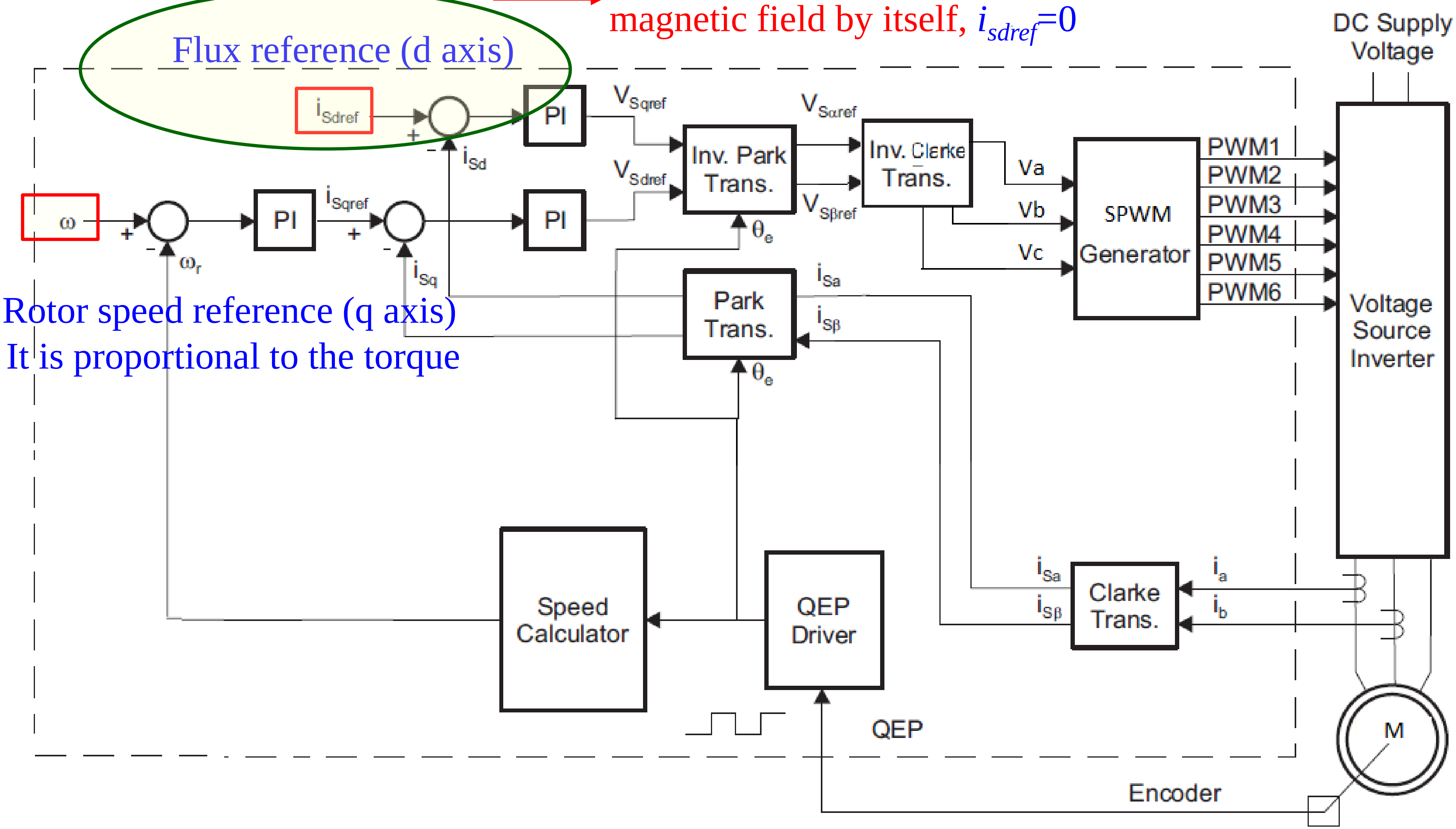
Field oriented control (FOC) also suitable and popular for the synchronous motor

Since the rotor generates rotor magnetic field by itself, $i_{sdref}=0$

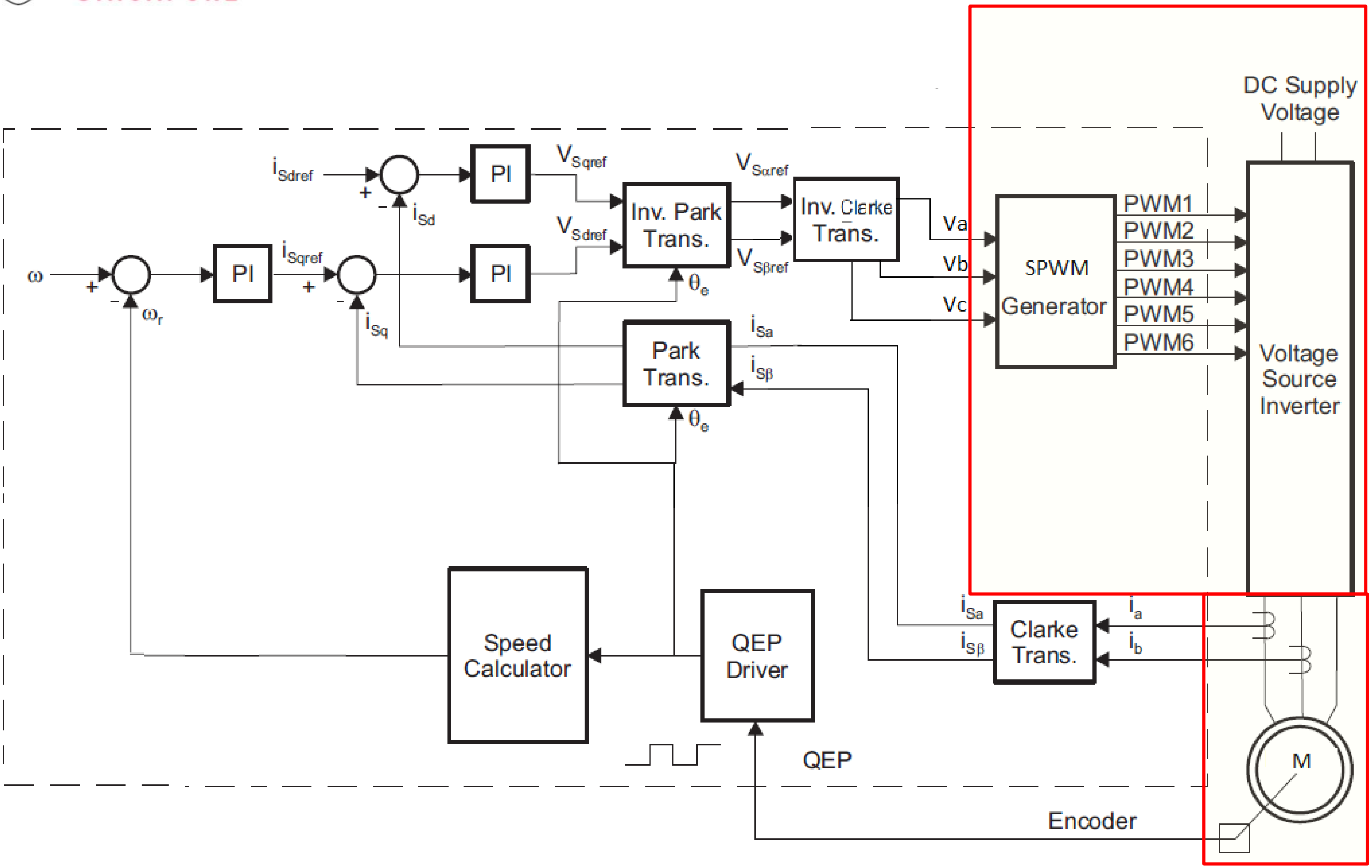
Flux reference (d axis)

Rotor speed reference (q axis)

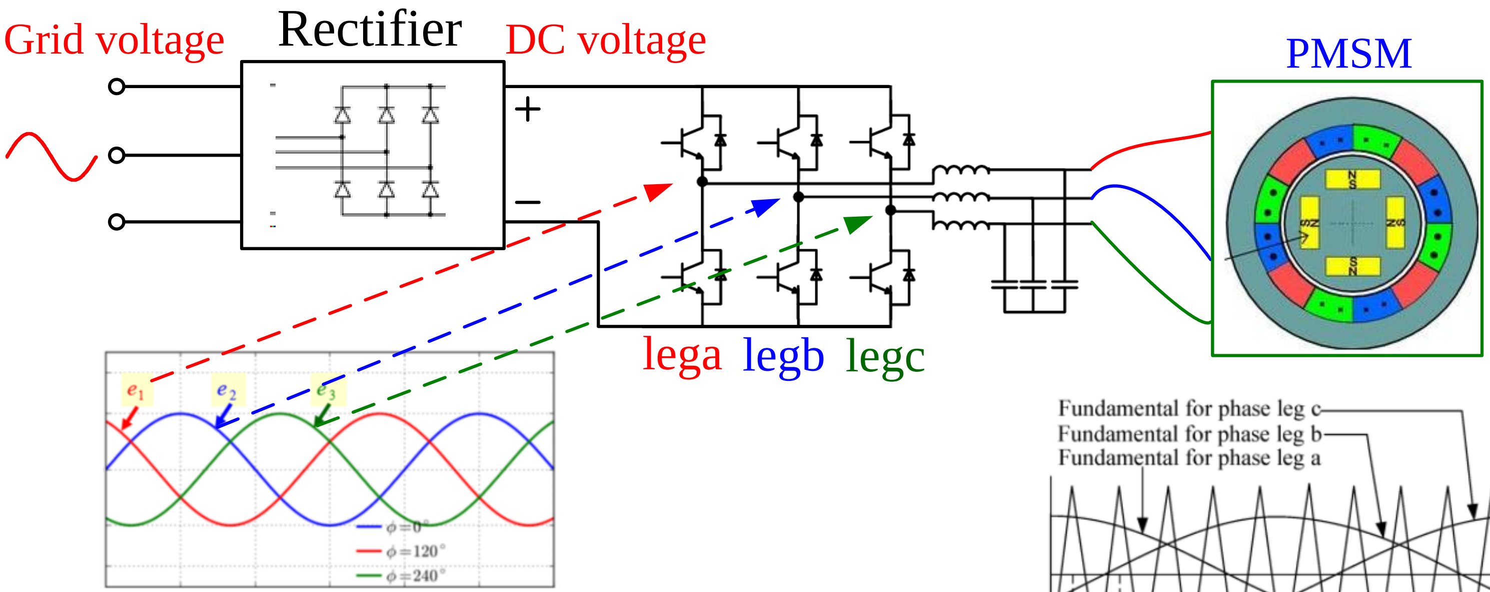
It is proportional to the torque

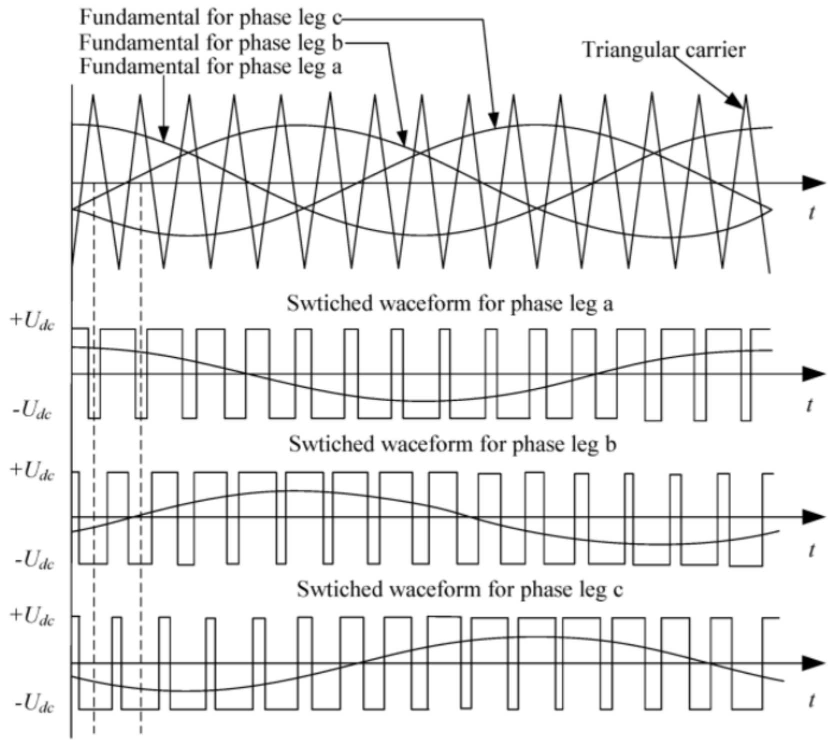


Motor and inverter parts

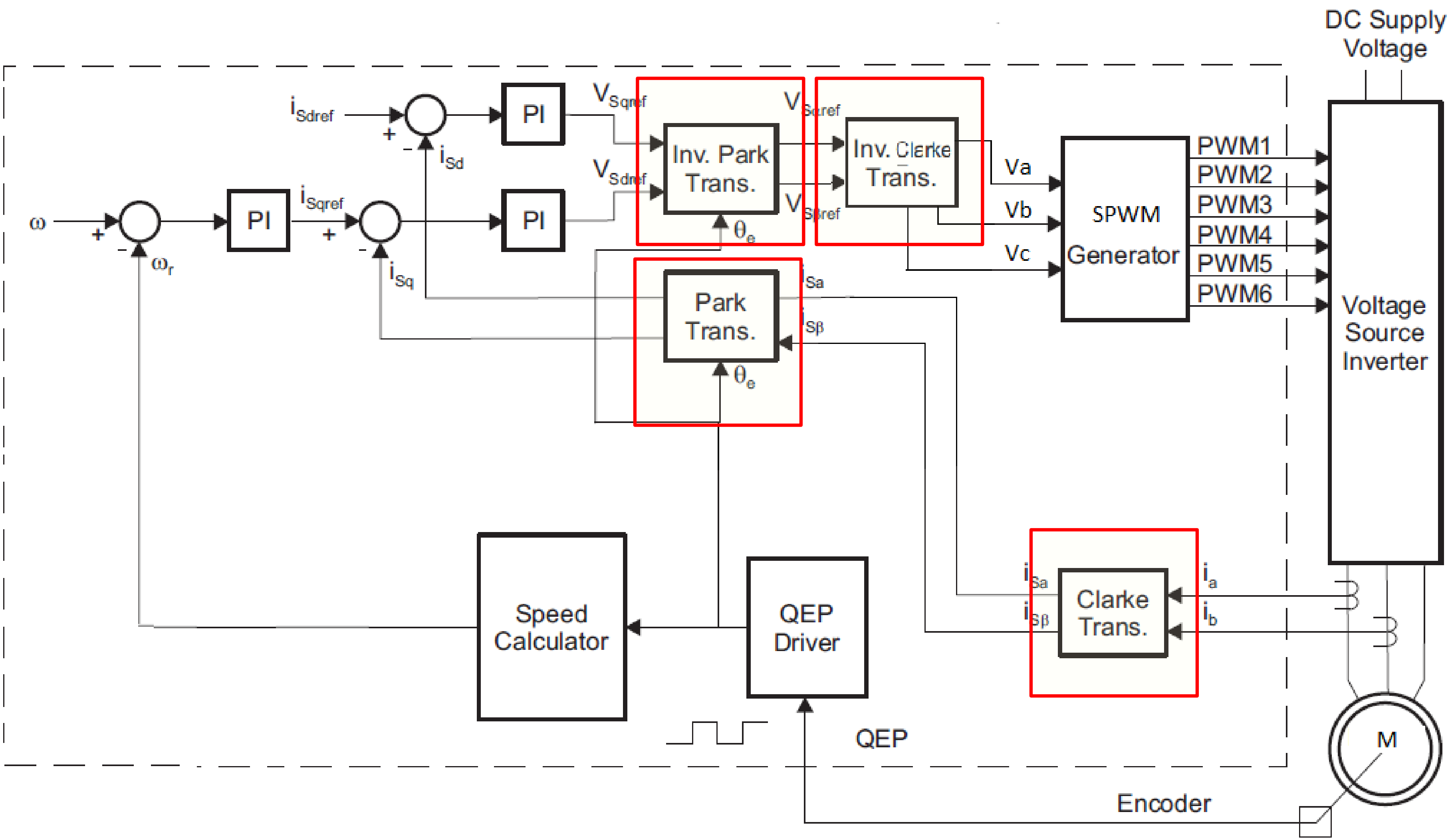


Recall the inverter part and its modulation





(Inverse) Clarke & Park transformation



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Recall the (inverse) Clarke & Park transformation

Clarke transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

Inverse Clarke transformation

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Park transformation

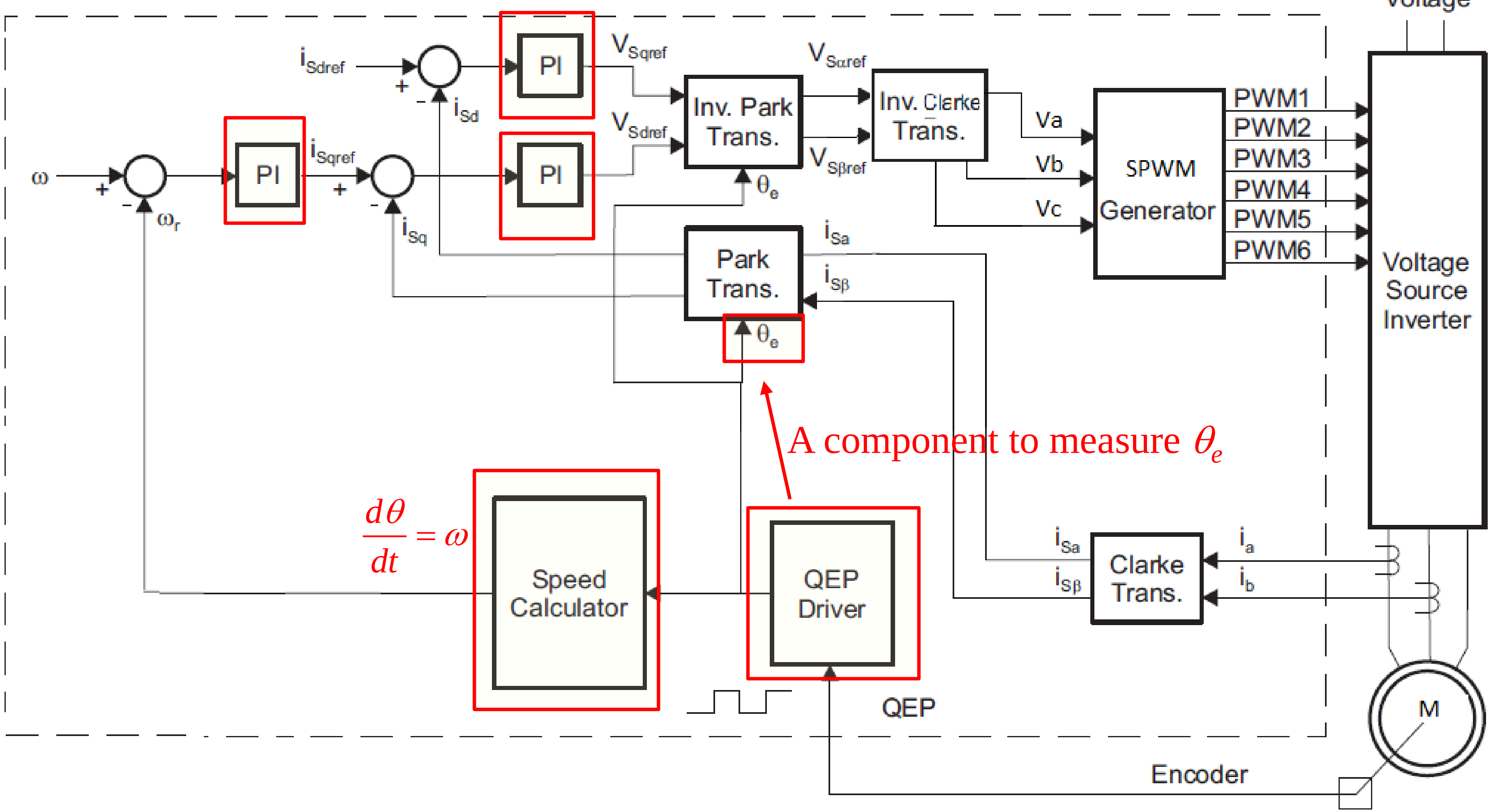
$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Inverse Park transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

Speed sensor and PI controller

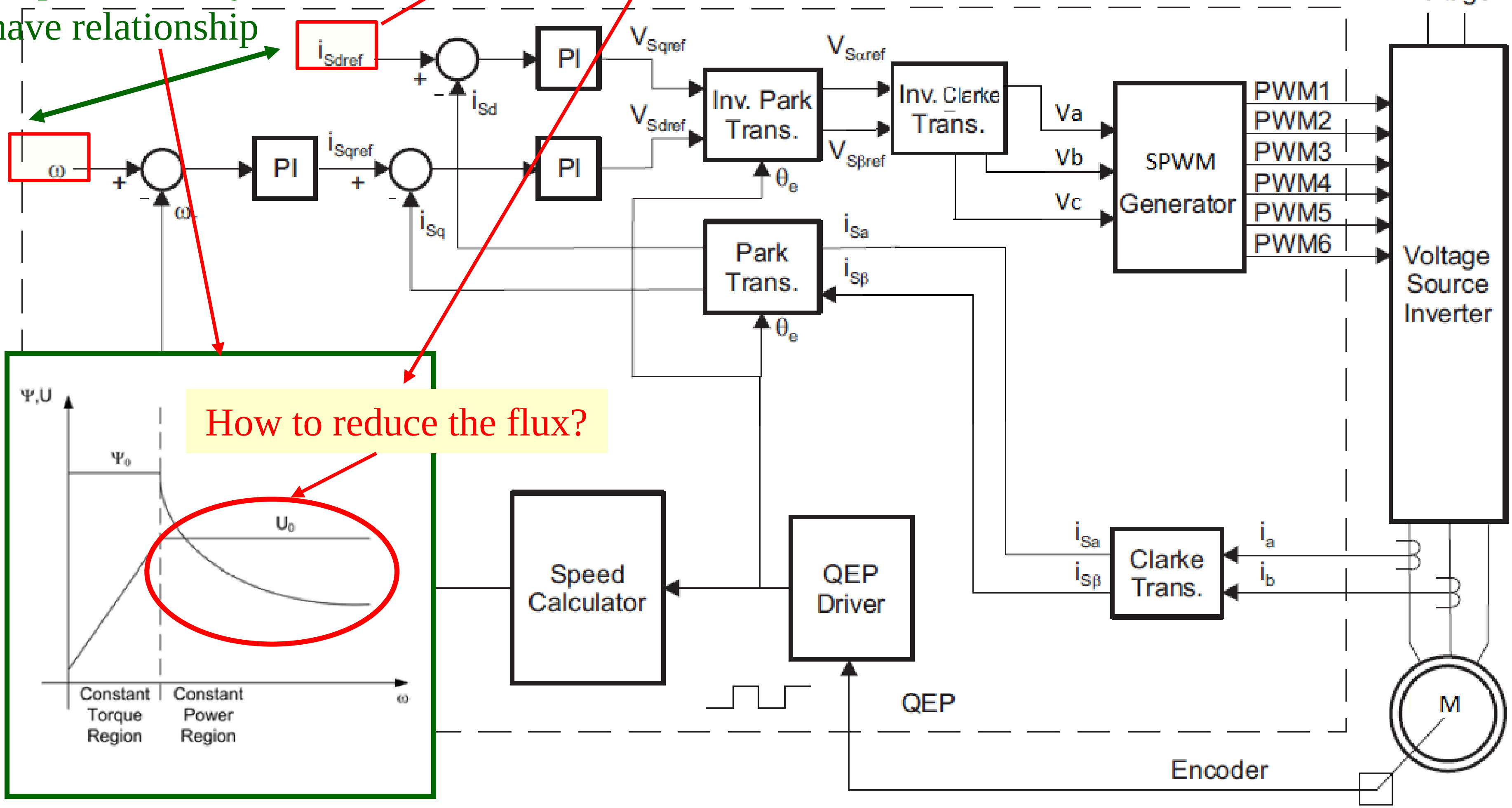
PI controller $K_p + K_i/s$



Problem of the FOC of the synchronous motor

Since the rotor generates rotor magnetic field by itself, $i_{sdref}=0$

In practice, they have relationship

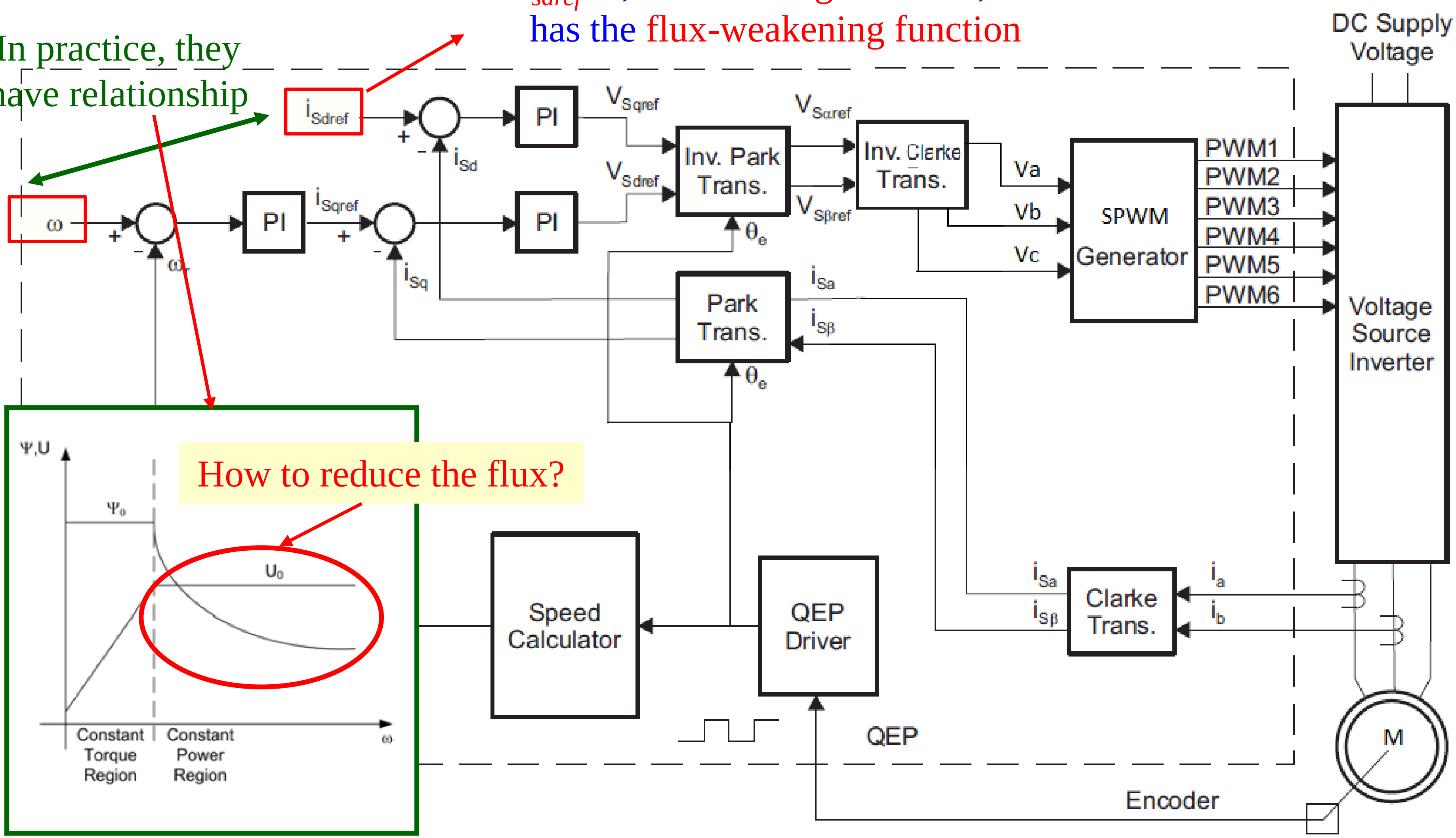


How to reduce the flux?

Flux-weakening control of the synchronous motor

Let $i_{sdref}<0$, it means negative flux, which has the flux-weakening function

In practice, they have relationship



Review of today's topic

- The difference between the synchronous motor and the asynchronous motor.
- Understand the different types of the synchronous motor.
- Start-up problem of the synchronous motor and its solution.
- Field oriented control method of the synchronous motor and its problem.
- Flux-weakening control of the synchronous motor.

SYNCHRONOUS MOTOR AND ITS CONTROL

[14/04/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

END OF TOPIC

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REVIEW THE KEY KNOWLEDGE POINTS OF THE AC MOTOR CONTROL PART

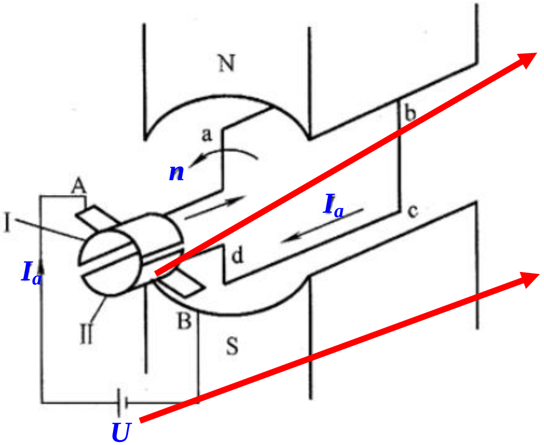
[14/04/2020]

Dr Xin Zhang: Jackzhang@ntu.edu.sg

Schedules

25/02/2019	Topic 1	• INTRODUCTION AND PRELIMINARY
10/03/2019	Topic 2	• OPERATION PRINCIPLE OF ASYNCHRONOUS MOTOR
17/03/2019	Topic 3	• CHARACTERISTICS OF ASYNCHRONOUS MOTOR
24/03/2019	Topic 4	• START-UP & CONTROL OF ASYNCHRONOUS MOTOR
31/03/2019	Topic 5	• PRINCIPLE OF RECTIFIER AND INVERTERS AND QUIZ
07/04/2019	Topic 6	• FIELD-ORIENTED CONTROL OF ASYNCHRONOUS MOTOR
14/04/2019	Topic 7	• SYNCHRONOUS MOTOR AND ITS CONTROL • REVIEW THE KNOWLEDGE POINTS OF AC MOTOR DRIVES

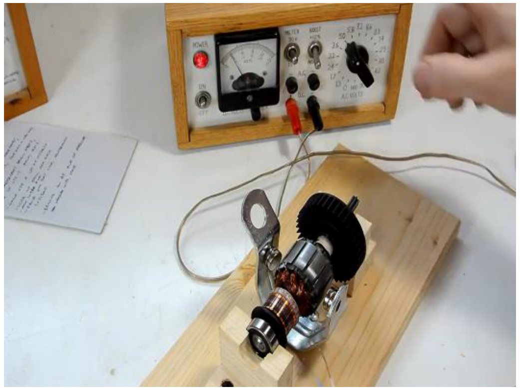
- The problem of the DC motor.
- The application of the AC motor.
- The application of right hand rule and left hand rule in the AC motor.
- The relationship between the transformer and the AC motor.

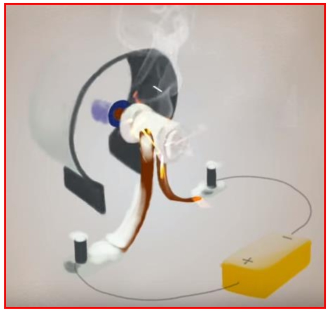


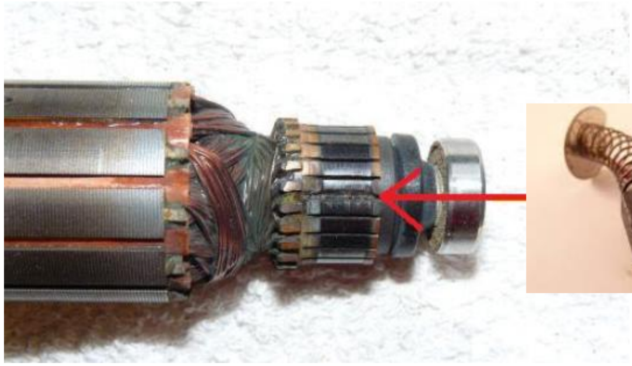
- The use of Brush DC motor could cause the maintenance problem and limits the power-rating and life-time of the DC motor
- Need DC voltage, however our real grid is AC voltage, for instance, 230V AC / 50 Hz at Singapore. So a special DC power supply is needed for DC motor.

Real DC motor speed control (need DC power supply)

Damaged DC motor carbon brush





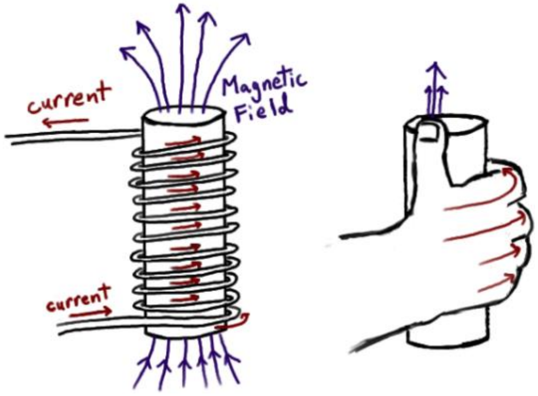


- Maximum power of DC motor is 500 kW @ rotate speed = 3000 rad/min
- Carbon brush need to be changed if it works more than 2000 hours.

Right Hand Rule I: simply shows how a current-carrying wire generates a magnetic field.

- If you point your thumb in the direction of the current, as shown, and let your fingers assume a curved position, the magnetic field circling around those wires flows in the direction in which your four fingers point.

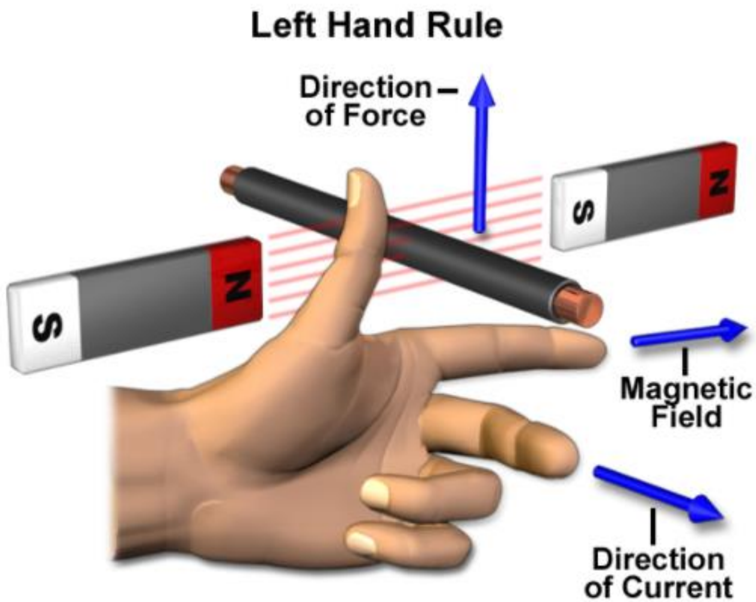
Ampere



Right Hand Rule II: Determine the direction of the magnetic field of an electro-magnet constructed by wrapping current carrying wire around an iron core.

- Magnetic field direction is in the same direction as the thumb when the right hand is wrapped around the core with the fingers pointing along the direction of the electric current.

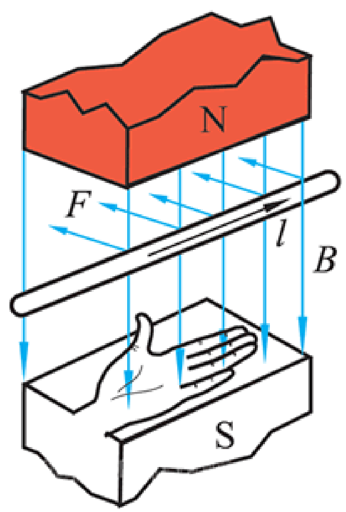
Left hand rule



Left Hand Rule: shows what happens when charged particles (such as electrons in a current) enter a magnetic field. You need to contort your left hand in an unnatural position for this rule, illustrated below:

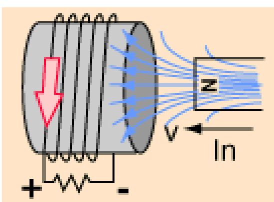
- Your index finger points in the direction of a magnetic field;
- Your middle finger, at a 90 degree angle to your index, points in the direction of the charged particle (as in an electrical current);
- Your extended thumb (forming an L with your index) points in the direction of the force exerted upon that particle.

John Ambrose Fleming

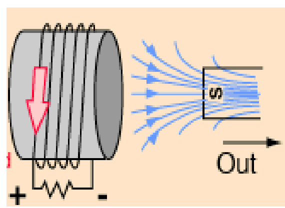


Lenz’s Law: the direction of the induced current is such that it opposes the change that causes it.

S N



S N



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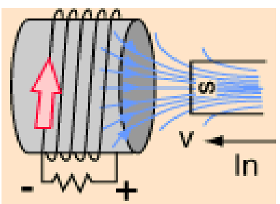

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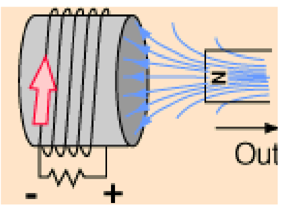


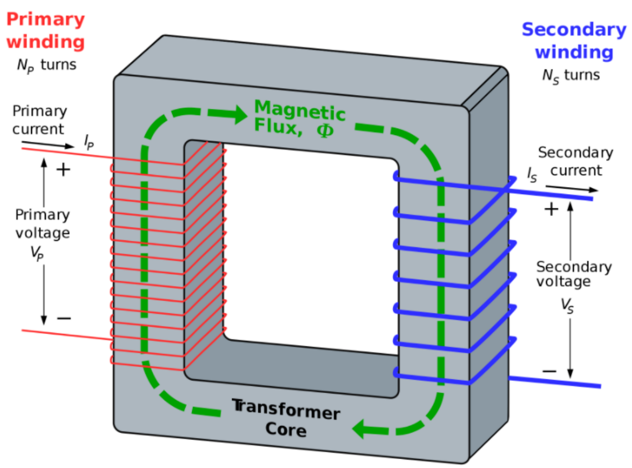
‘If you push a wire through a field the induced current makes a force that pushes back’

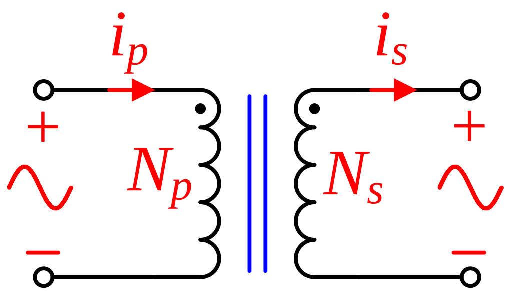
‘If a field is pointing one way and a conductor moves through it, then the induced current makes a field that points the opposite way’

Why we recall the transformer before learning AC motor?

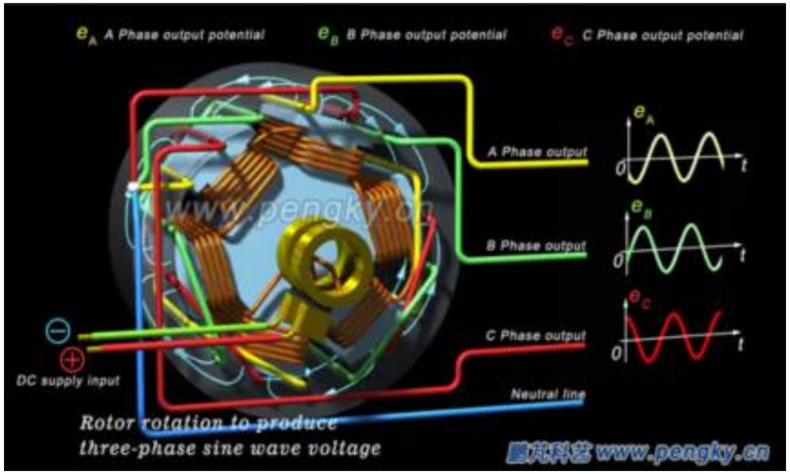
AC motor is essentially a rotated three phase transformer

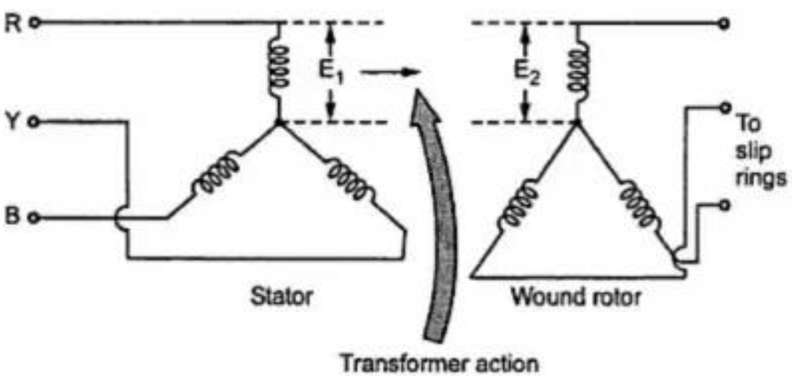
Basic transformer





Basic AC motor





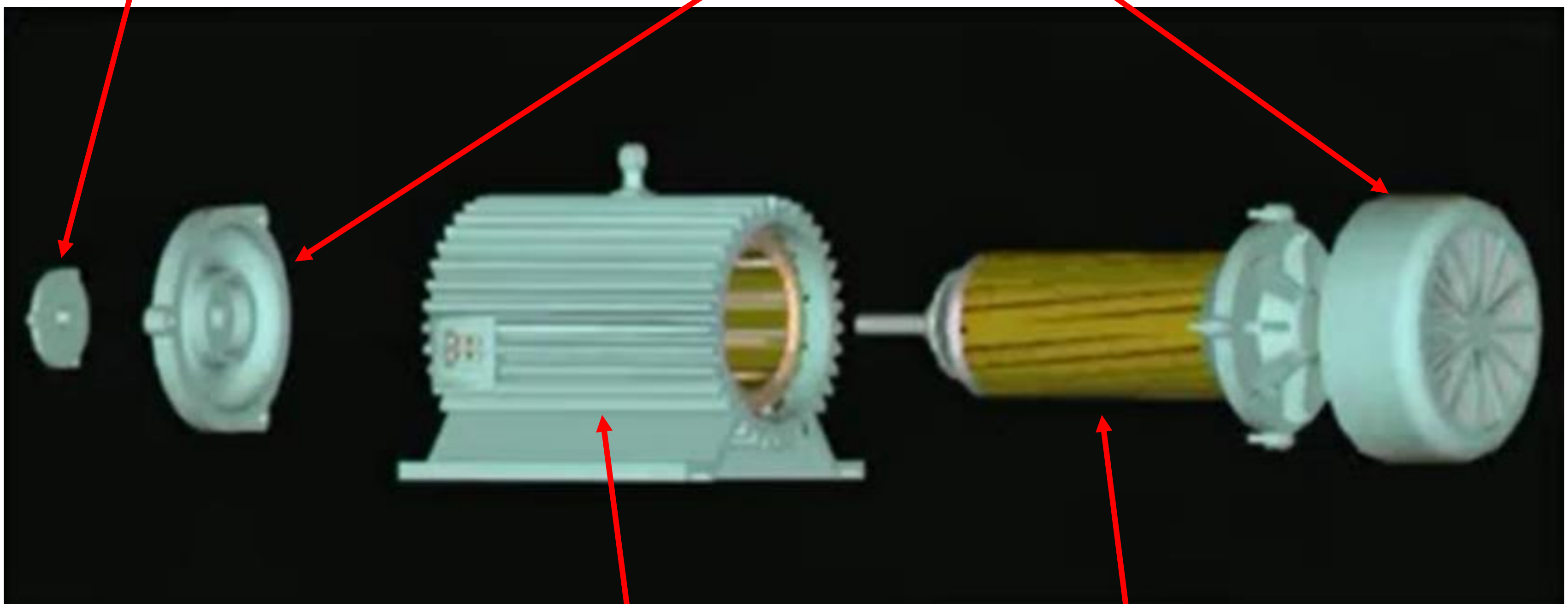
Key knowledge points at Topic 2

- Structure of the asynchronous motor.
- How to make an asynchronous motor rotate?
- Key parameters of the asynchronous motor.

Overview of the structure of the AC asynchronous motor

Bearing cap

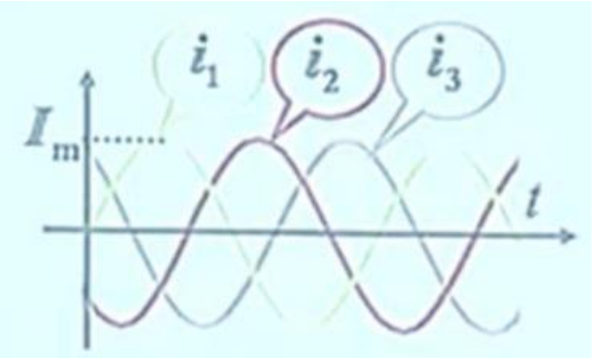
End Bell

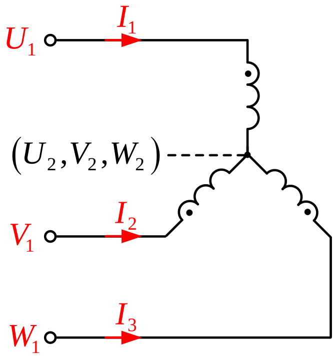


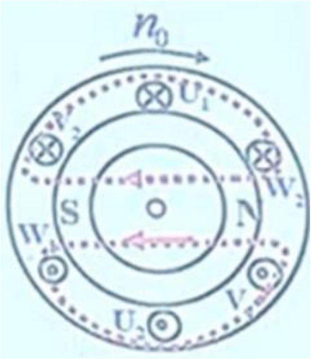
Main parts: Stator Rotor

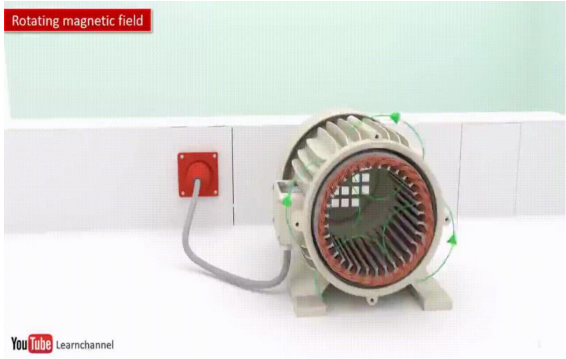
Rotor: Cage rotor / Wound rotor

Review the rotated principle of the asynchronous motor



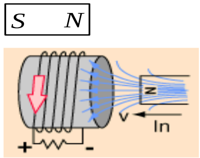


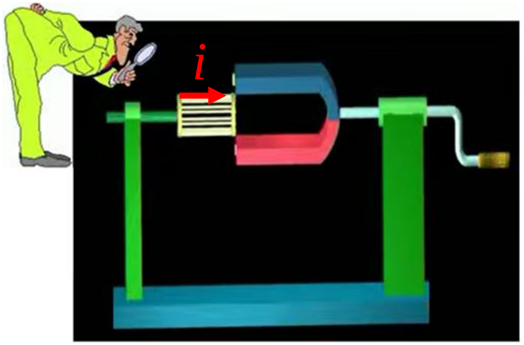




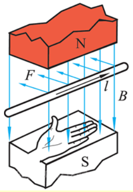
Three phase AC currents generate rotated magnetic field

Lenz's Law



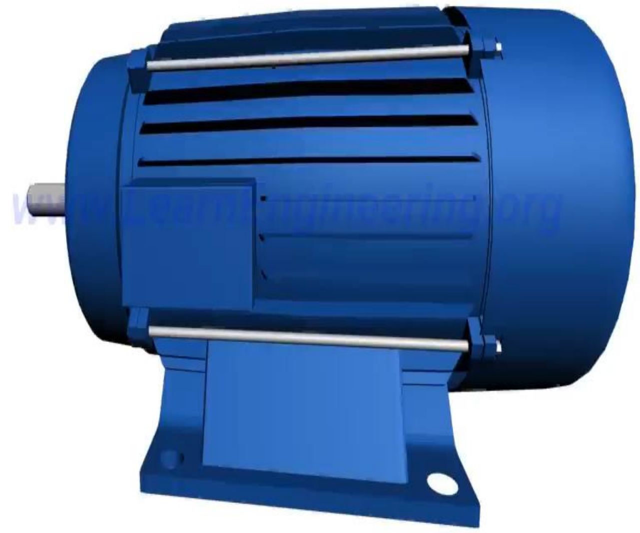


Induce current is generated in the rotor windings to stop its flux change



Electromagnetic force is generated to make the rotor windings follow the rotated magnetic field

Video: quick review of the operation principle of the three phase asynchronous motor



Special Thanks
Sajith K V

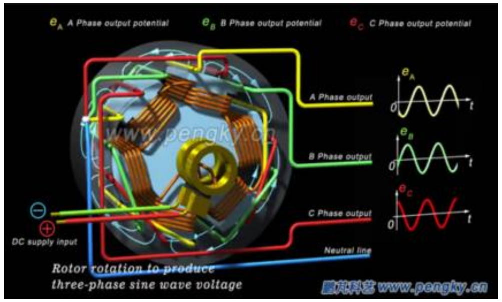
www.LearnEngineering.org

Key parameters of the asynchronous motor

- Pole-pairs of the asynchronous motor
- Rotated speed of the magnetic field of the asynchronous motor
- Slip ratio of the asynchronous motor

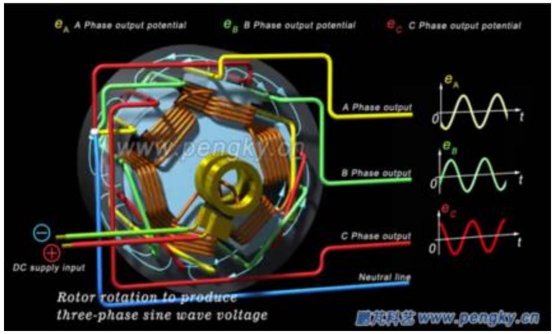
$$\boxed{n_o = \frac{60f}{P} \ (rpm)}$$

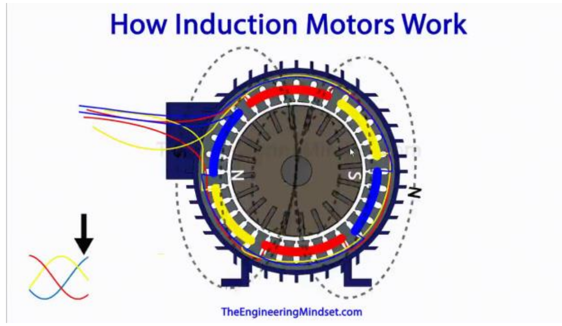
$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$



- The key equations of the asynchronous motor, such as the rotor current, rotor speed, stator magnetic field rotated speed, torque, etc.
- Understand the torque vs rotor speed curve.

Frequency of the rotor electromotive force (E_2): f_2



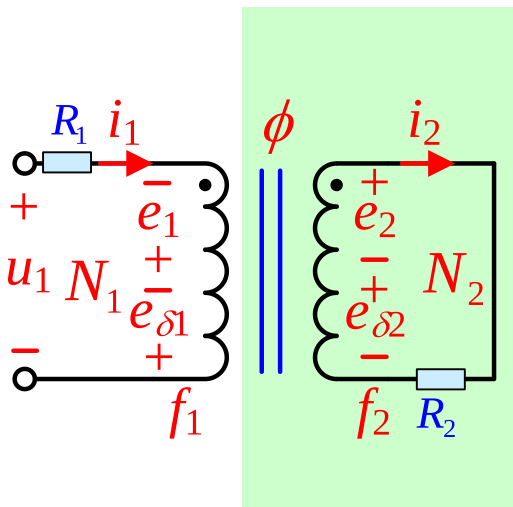


- Rotated speed of the magnetic field n_0
- Rotated speed of the rotor n

$$\boxed{n < n_o} \qquad \boxed{n = (1\text{-}s)\, n_o}$$

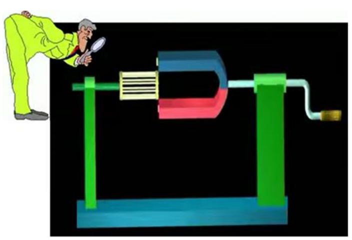
Slip ratio:

$$s = \left(\frac{n_0 - n}{n_0} \right) \times 100\%$$



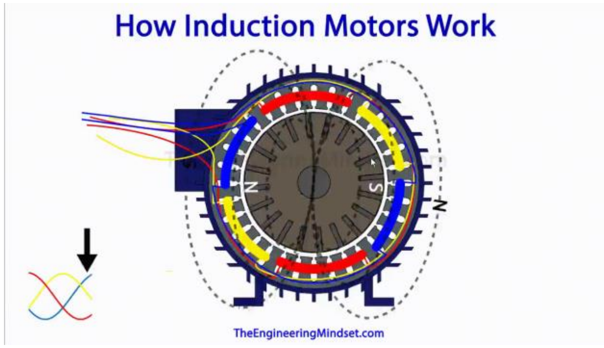
The speed difference between the rotated magnetic field and the rotated rotor generate the electromotive force E_2

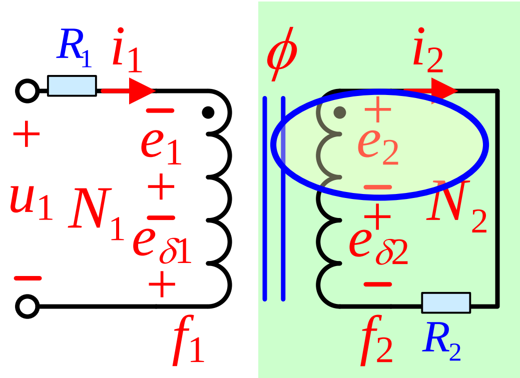
$$\boxed{\Delta n = \frac{60 \cdot f_2}{P}} \rightarrow \boxed{f_2 = \frac{P \cdot \Delta n}{60} = \frac{P \cdot (n_o\text{-}n)}{60}}$$



$$\boxed{f_2 = \frac{P\left(n_o\text{-}(1\text{-}s)\,n_o\right)}{60} = \frac{P \cdot s \cdot n_o}{60} = s \cdot \frac{P \cdot n_o}{60} = s \cdot f_1}$$

Characteristics of the rotor electromotive force E_2





$$E_2 = 4.44 \cdot N_2 \cdot f_2 \cdot \phi$$

$$f_2 = s \cdot f_1$$

$$E_2 = s \cdot 4.44 N_2 f_1 \phi$$

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$s \in [0,1]$$

$$E_{2\max} = 4.44 N_2 f_1 \phi$$ when $s=1$

Maximum E_2

$$\phi \approx \frac{U_1}{4.44 \cdot N_1 \cdot f_1}$$

When s=1?

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

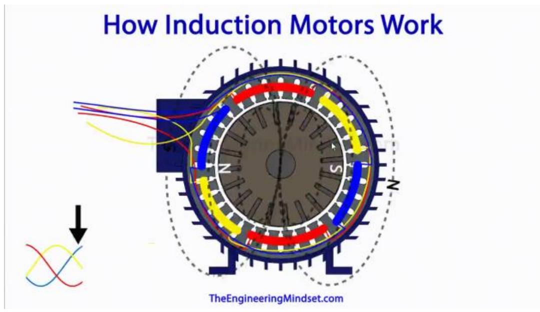
if $s = 1$?

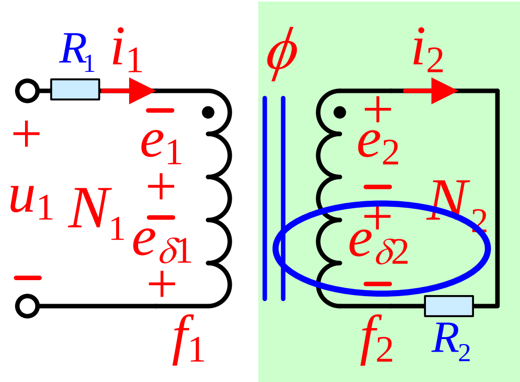
$$1 = \frac{n_0 - n}{n_0}$$

$$n = 0$$

The rotor is not rotated

Inductive reactance of the rotor winding $X_{\delta2}$





$$X_{\sigma2} = 2\pi f_2 L_{\sigma2}$$ Caused by leakage flux

$$\boxed{f_2 = s \cdot f_1}$$

$$X_{\sigma2} = s \cdot 2\pi f_1 L_{\sigma2}$$

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$\boxed{s \in [0,1]}$$

$$X_{\sigma2\max} = 2\pi f_1 L_{\sigma2}$$ *when s=1*

Maximum $X_{\delta2}$

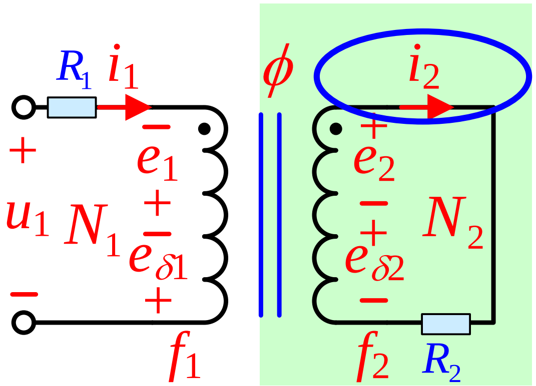
When s=1?

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$\boxed{s = 1}$$

$$\boxed{1 = \frac{n_0 - n}{n_0}} \Rightarrow \boxed{n = 0} \Rightarrow$$ The rotor is not rotated

Current of the rotor winding I_2



$$\left\{\begin{array}{ll} s=0 & I_2 = I_{2\min} = \dfrac{E_{2\max}}{\infty} = 0 \\ s=1 & I_2 = I_{2\max} = \dfrac{E_{2\max}}{\sqrt{R_2^2 + \left(X_{\sigma 2\max}\right)^2}} \end{array}\right.$$

$$\dot{E}_2 = R_2 \dot{I}_2 + \left(-\dot{E}_{\sigma 2}\right)$$

$$= R_2 \dot{I}_2 + j(2\pi f_2 L_{\sigma 2})\dot{I}_2$$

$$= R_2 \dot{I}_2 + jX_{\sigma 2}\dot{I}_2$$

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

$$\boxed{s \in [0,1]}$$

$$I_2 \propto s \Leftarrow$$

$$I_2 = \frac{E_{2\max}}{\sqrt{\dfrac{R_2^2}{s^2} + \left(X_{\sigma 2\max}\right)^2}}$$

$$I_2 = \frac{E_2}{\sqrt{R_2^2 + X_{\sigma 2}^2}}$$

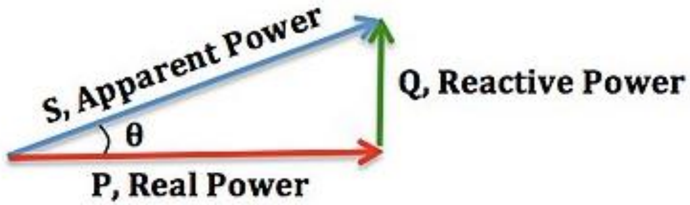
$$E_2 = s \cdot 4.44 N_2 f_1 \phi = s \cdot E_{2\max}$$

$$X_{\sigma 2} = s \cdot 2\pi f_1 L_{\sigma 2} = s \cdot X_{\sigma 2\max}$$

$$I_2 = \frac{s \cdot E_{2\max}}{\sqrt{R_2^2 + \left(s \cdot X_{\sigma 2\max}\right)^2}}$$

Power factor cosθ of the asynchronous motor

Definition of the power factor

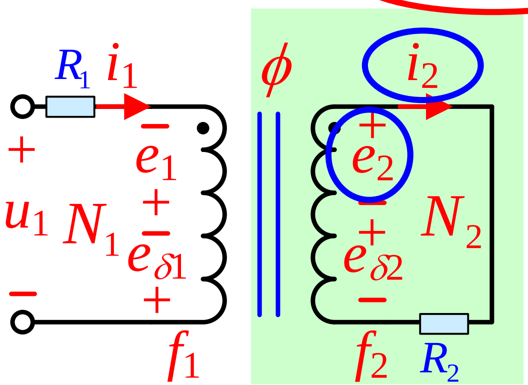


$$S = P + jQ$$

$$|S|^2 = P^2 + Q^2$$

$$|S| = \sqrt{P^2 + Q^2}$$

$$\cos\theta,\ \text{power factor} = \frac{P,\ \text{real power}}{|S|,\ \text{apparent power}}$$



$$\boxed{\dot{E}_2 = R_2 \dot{I}_2 + jX_{\sigma 2}\dot{I}_2}$$

$$S = \dot{E}_2 \cdot \dot{I}_2 = \left(R_2 \cdot I_2^2 + jX_{\sigma 2} I_2^2\right)$$

$$P = R_2 \cdot I_2^2 \qquad Q = X_{\sigma 2} I_2^2$$

$$\cos\theta = \frac{P}{|S|} = \frac{P}{\sqrt{P^2+Q^2}} = \frac{R_2 \cdot \cancel{I_2^2}}{\sqrt{\left(R_2 \cdot \cancel{I_2^2}\right)^2 + \left(X_{\sigma 2}\cancel{I_2^2}\right)^2}}$$

$$X_{\sigma 2} = sX_{\sigma 2\max}$$

$$\Rightarrow \cos\theta = \frac{R_2}{\sqrt{R_2^2 + \left(sX_{\sigma 2\max}\right)^2}} = \frac{1}{\sqrt{1 + \left(\frac{sX_{\sigma 2\max}}{R_2}\right)^2}}$$

If $sX_{\sigma 2\max} \gg R_2$

$$\boxed{\left(\frac{sX_{\sigma 2\max}}{R_2}\right)^2 \gg 1} \qquad \cos\theta \approx \frac{1}{\sqrt{\left(\frac{sX_{\sigma 2\max}}{R_2}\right)^2}} = \frac{R_2}{sX_{\sigma 2\max}}$$

If $sX_{\sigma 2\max} \ll R_2$

$$\boxed{\left(\frac{sX_{\sigma 2\max}}{R_2}\right)^2 \ll 1} \qquad \cos\theta \approx 1$$

The curve of rotor current I_2 and motor power factor $\cos\theta$

$$I_2 = \frac{E_{2\max}}{\sqrt{\frac{R_2^2}{s^2} + (X_{\sigma 2\max})^2}}$$

$s \nearrow \Longrightarrow I_2 \nearrow$

$s \searrow \Longrightarrow I_2 \searrow$

$\boxed{s \in [0,1]}$

$I_{2\min} = 0$

$$I_{2\max} = \frac{E_{2\max}}{\sqrt{R_2^2 + (X_{\sigma 2\max})^2}}$$

$$\cos\theta = \frac{R_2}{\sqrt{R_2^2 + (sX_{\sigma 2\max})^2}}$$

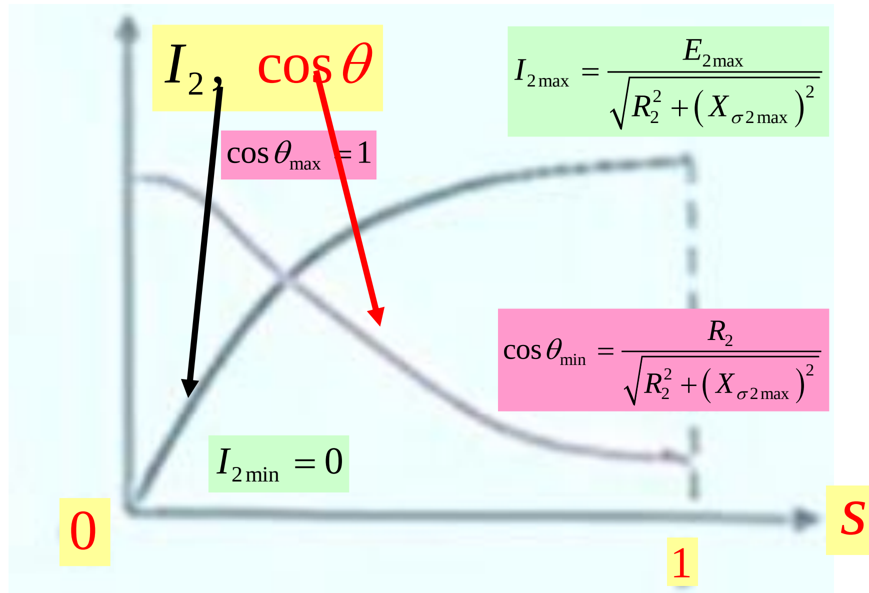
$s \nearrow \Longrightarrow \cos\theta \searrow$

$s \searrow \Longrightarrow \cos\theta \nearrow$

$\boxed{s \in [0,1]}$

$$\cos\theta_{\min} = \frac{R_2}{\sqrt{R_2^2 + (X_{\sigma 2\max})^2}}$$

$\cos\theta_{\max} = 1$



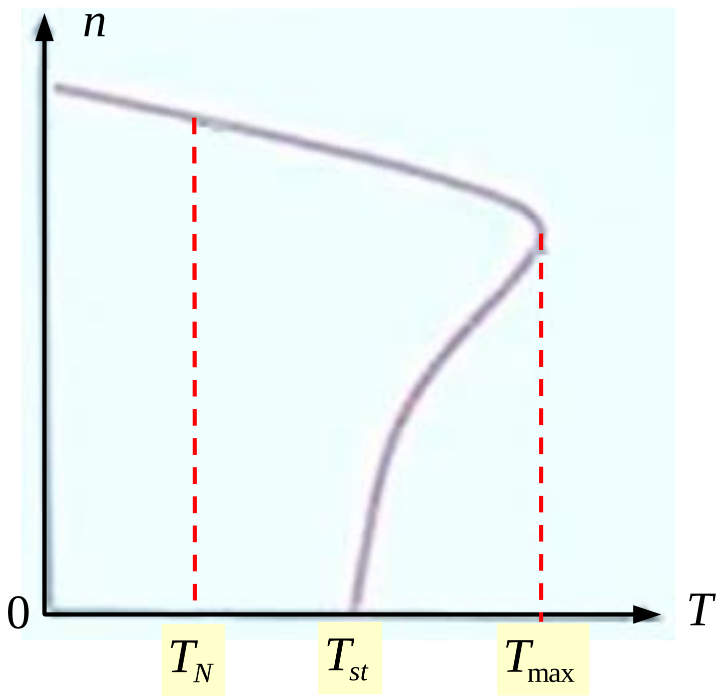
Both the rotor current I_2 and power factor $\cos\theta$ have great relationship with the slip ratio s

$$s = \left(\frac{n_0 - n}{n_0}\right) \times 100\%$$

Both the rotor current I_2 and power factor $\cos\theta$ have great relationship with the rotor speed n

Three typical torques of the asynchronous motor

Mechanical characteristics curve of the asynchronous motor



- Nominal torque T_N

  Torque of the asynchronous motor at nominal power

- Starting torque T_{st}

  Torque of the asynchronous motor when the motor is starting (n=0)

- Maximum torque T_{max}

  Torque of the asynchronous motor at maximum power

Key knowledge points at Topic 4

- How to start an asynchronous motor? Understand the different methods.
- How to control the speed of an asynchronous motor? Understand the different methods.

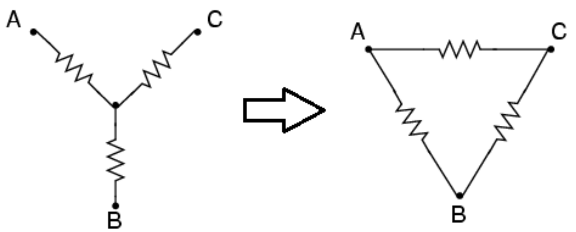
Typical start-up methods of the asynchronous motor

Method I: Connect to the grid and star-up the asynchronous motor directly

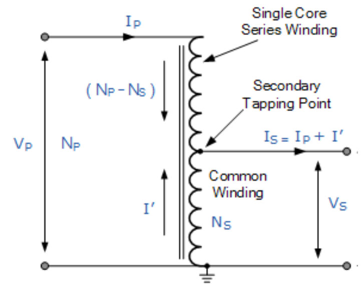
Do nothing

Small power asynchronous motor:
Power < 20 or 30 kW

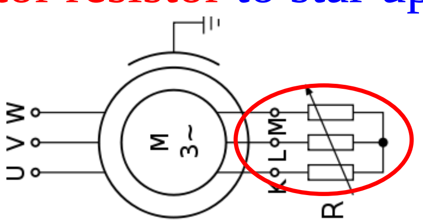
Method II: Y-Δ Changing structure of the stator to start up the asynchronous motor



Method III: Use auto-transformer to start up the asynchronous motor



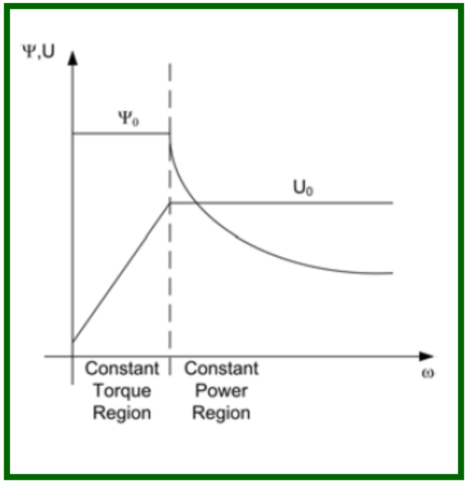
Method IV: Increase the rotor resistor to star up the asynchronous motor



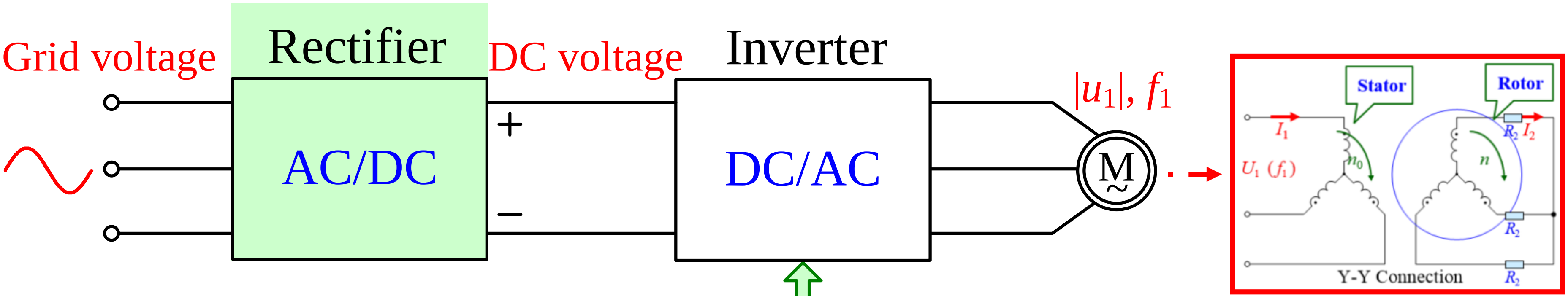
Typical speed control methods of the asynchronous motor

$$n = (1 - s) \cdot \frac{60 \cdot f_1}{P}$$

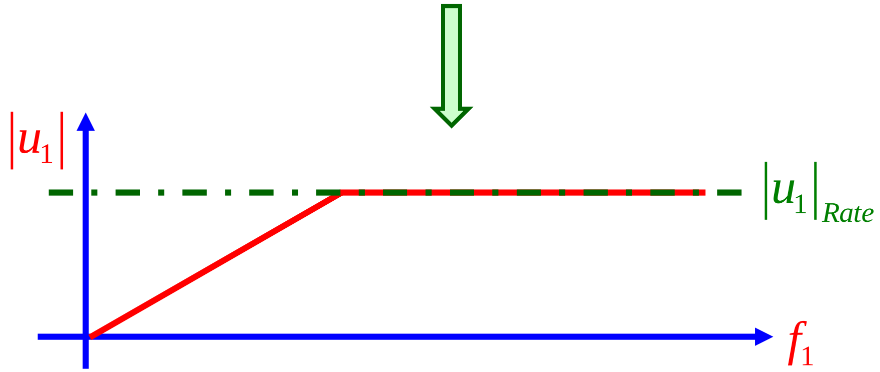
- Change the frequency (f_1) of the voltage of the stator winding
- Change the pole-pairs (P) of the asynchronous motor
- Change the slip ratio (s) of the asynchronous motor



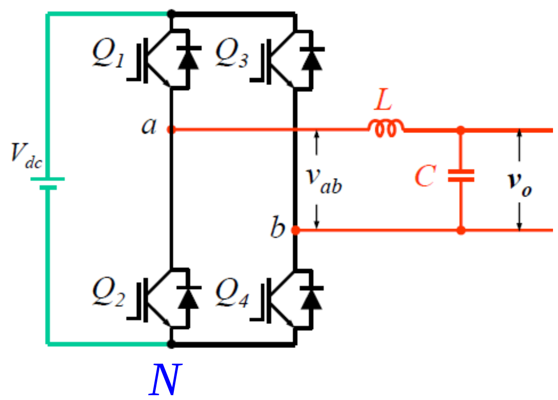
- Why we need rectifier and inverter to realize the real asynchronous motor control?
- Function of the rectifier and inverter.
- Modulation methods of the inverter.

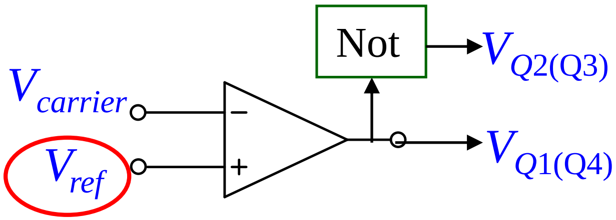


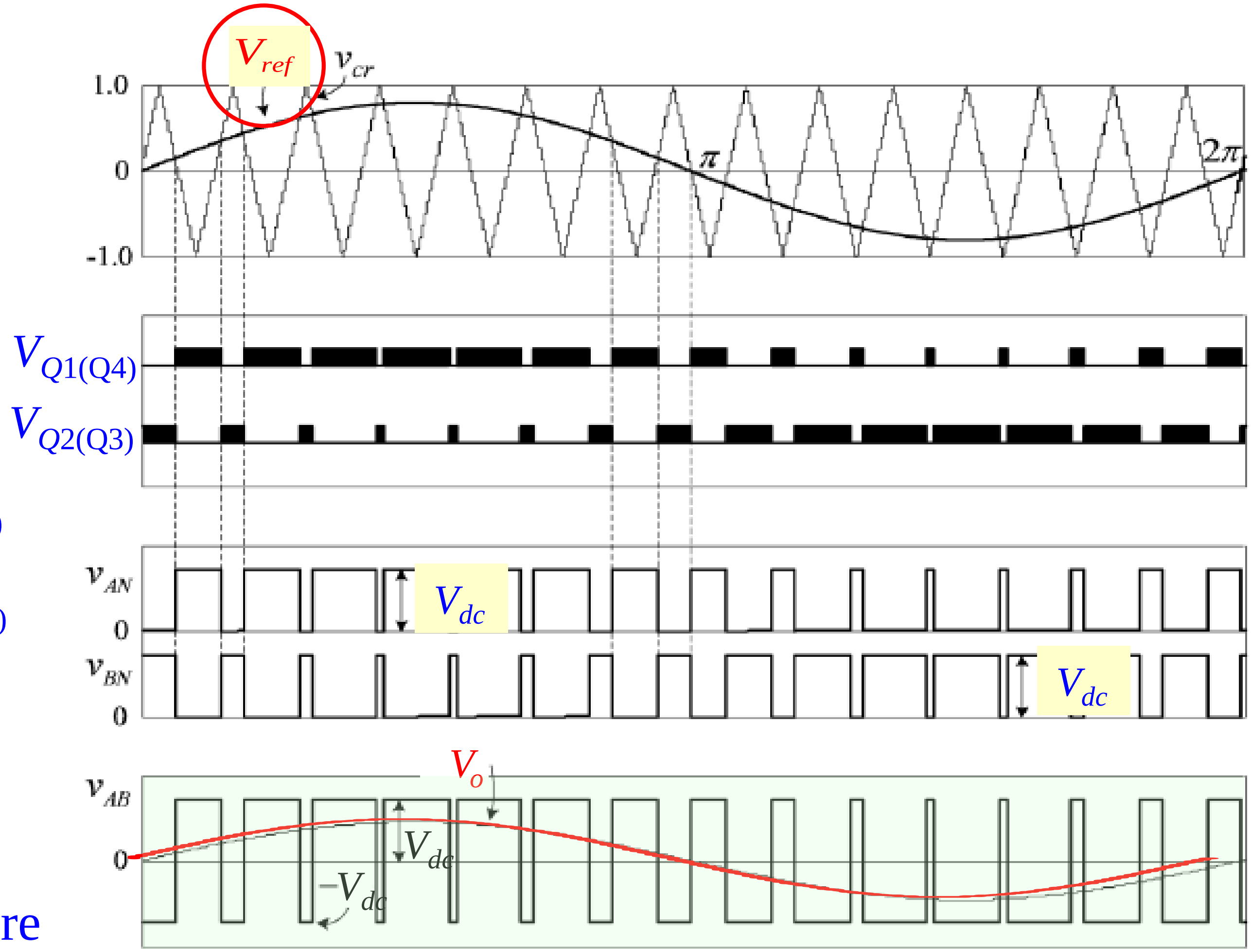
Control the amplitude and frequency of its output voltage u_1, which is also the motor stator voltage



Bipolar modulation of the single phase DC/AC inverter

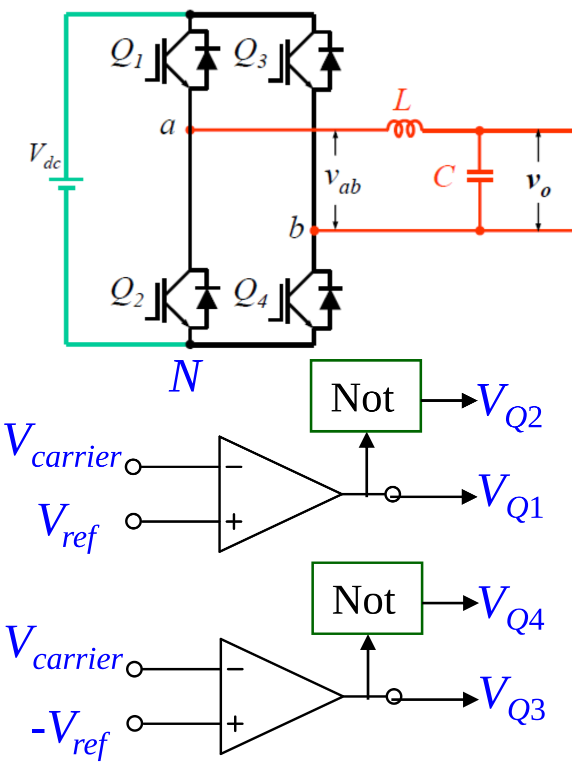


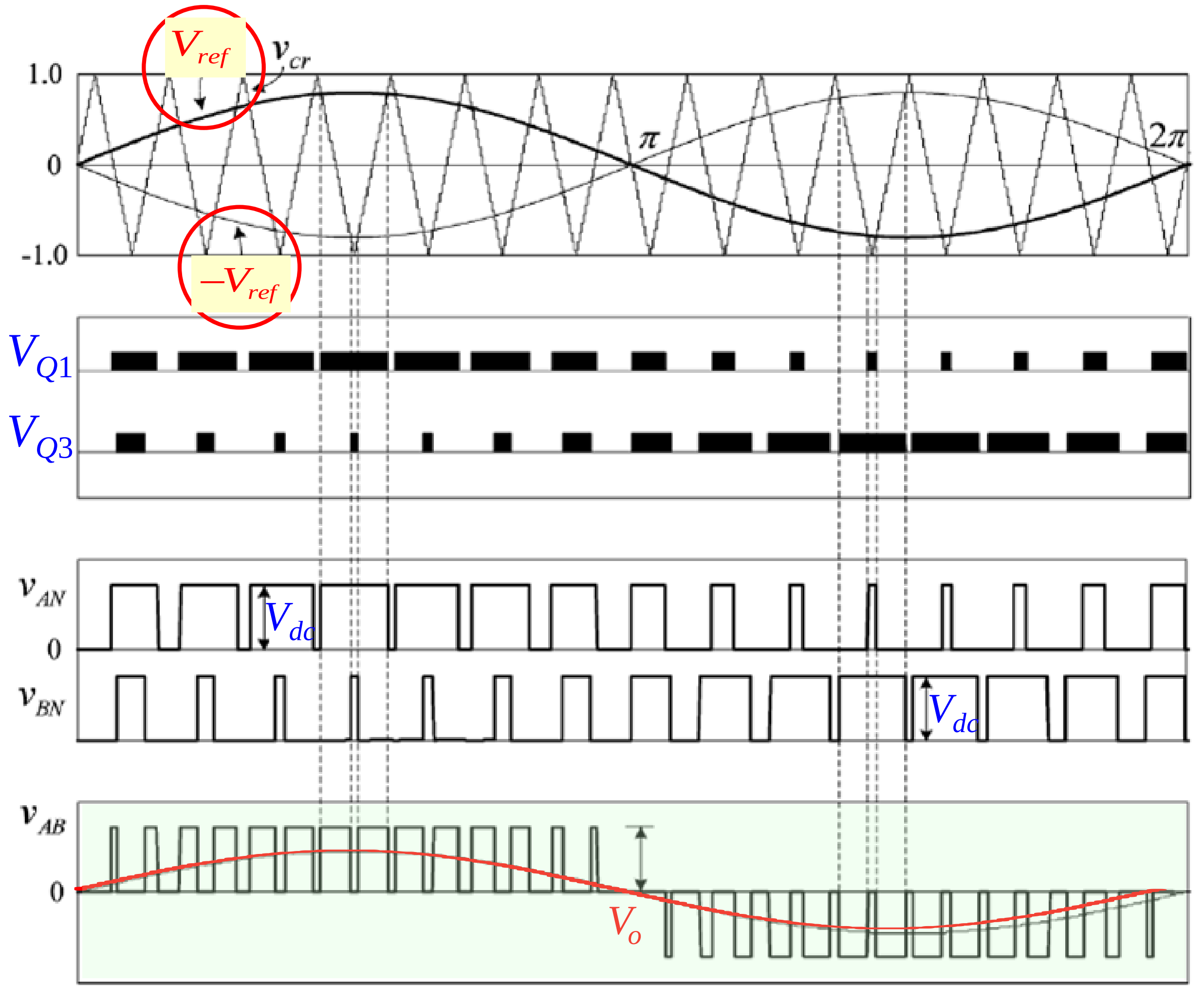




- V_{Q1}-V_{Q4} are the gating signal for Q_1-Q_4.
- Q_1-Q_2 and Q_3-Q_4 pairs are switched complementarily.

Unipolar modulation of the single phase DC/AC inverter





- V_{Q1}-V_{Q4} are the gating signal for Q_1-Q_4.
- Q_1-Q_2 and Q_3-Q_4 pairs are switched complementarily.

Key knowledge points at Topic 6

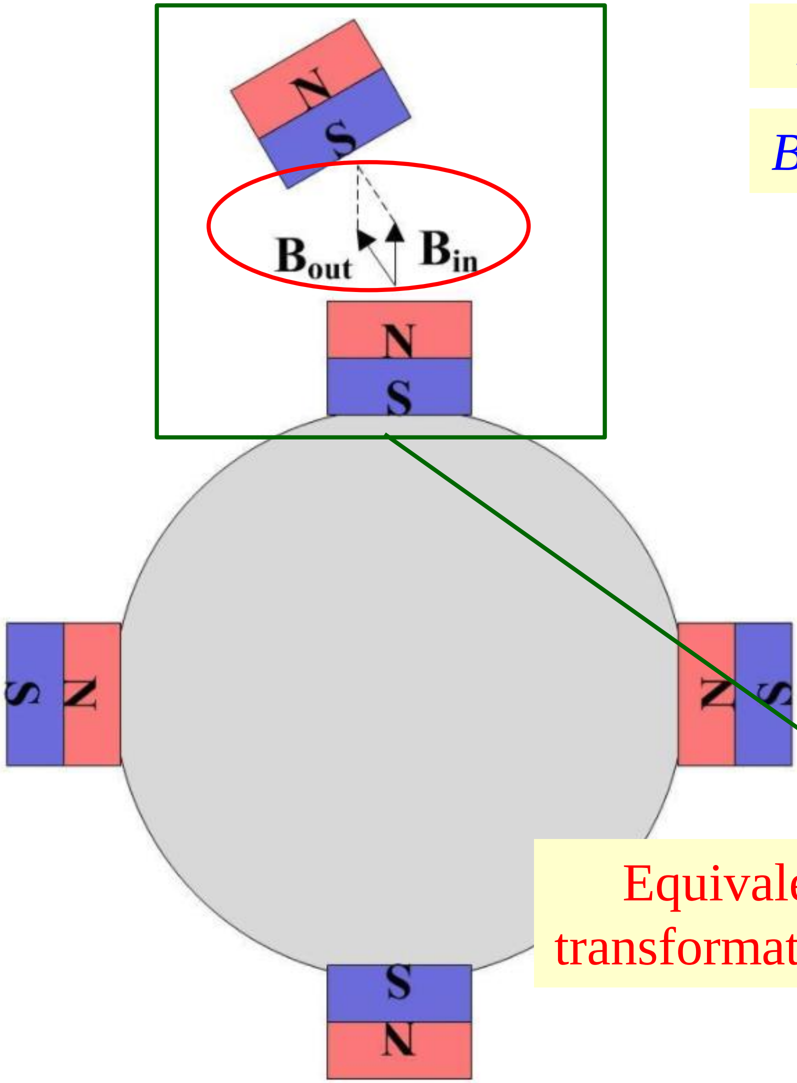
- Challenge of asynchronous motor control.
- Why we need to learn ABC to dq frames transformation? What is the benefit to the asynchronous motor control?
- Understand the (inverse) Clarke/Park transformation.
- Understand the FOC control of the asynchronous motor.

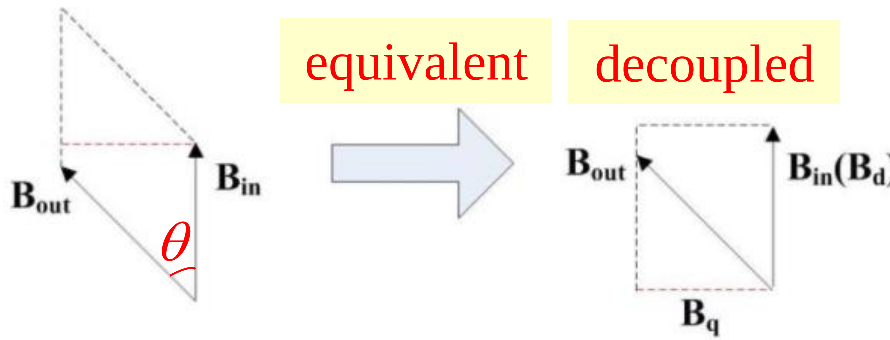
A simple and straight method to control the rotor follow the rotated stator magnetic field

B_{in}: Strength of the induced rotor magnetic field

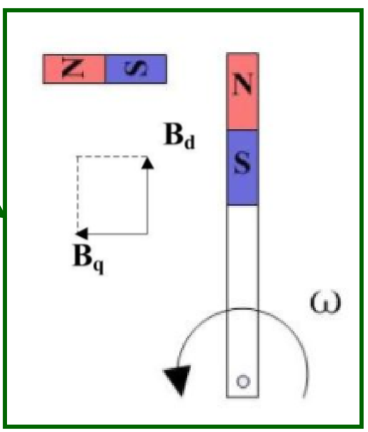
B_{out}: Strength of the stator magnetic field

Torque: $T = B_{in} \times B_{out} = |B_{in}| \cdot |B_{out}| \cdot \sin\theta$





Equivalent transformation to



B_d and B_q are decoupled

B_d: Only for ϕ

B_q: Only for T

Recall the (inverse) Clarke & Park transformation

Clarke transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

Inverse Clarke transformation

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Park transformation

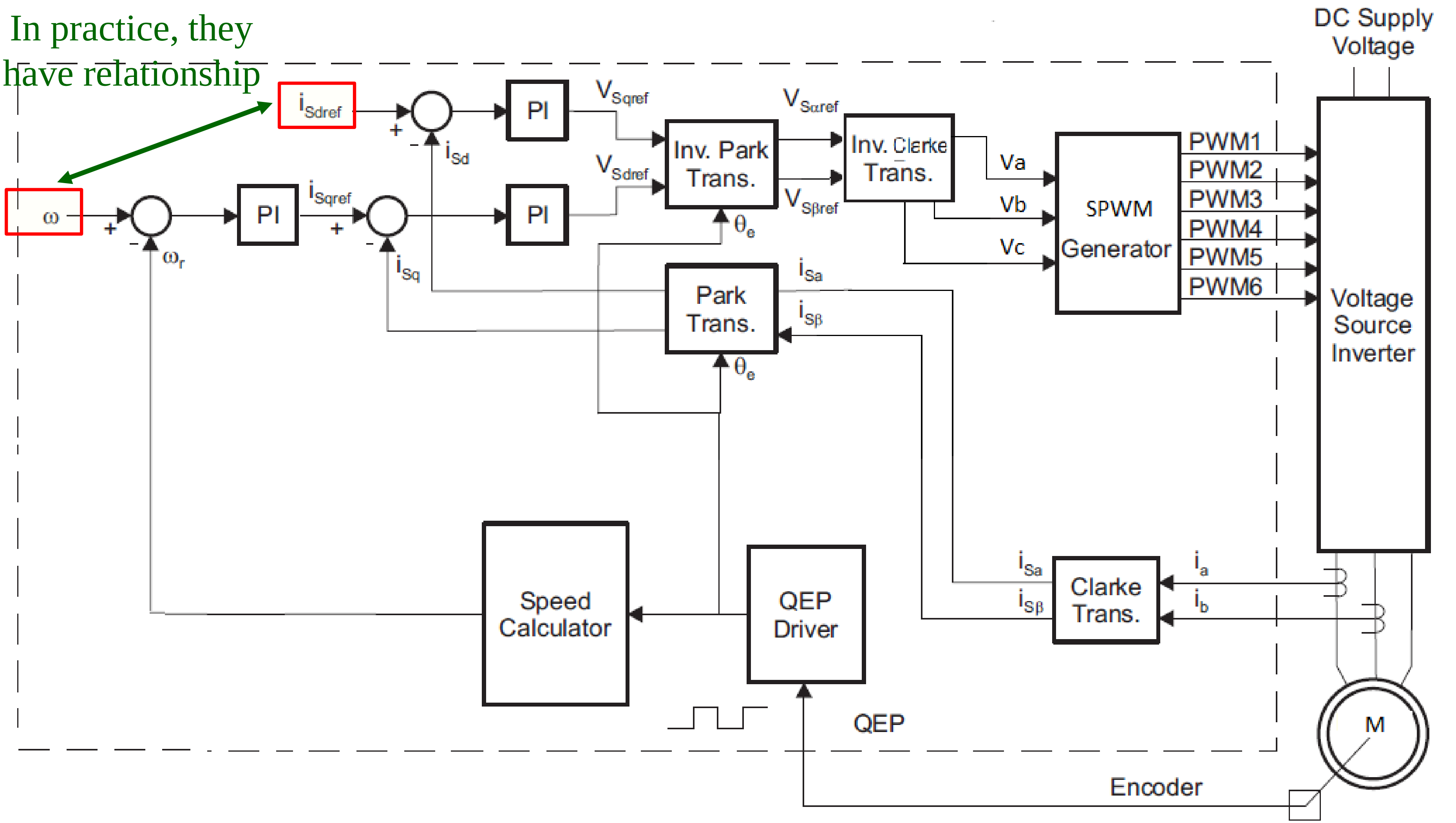
$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Inverse Park transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

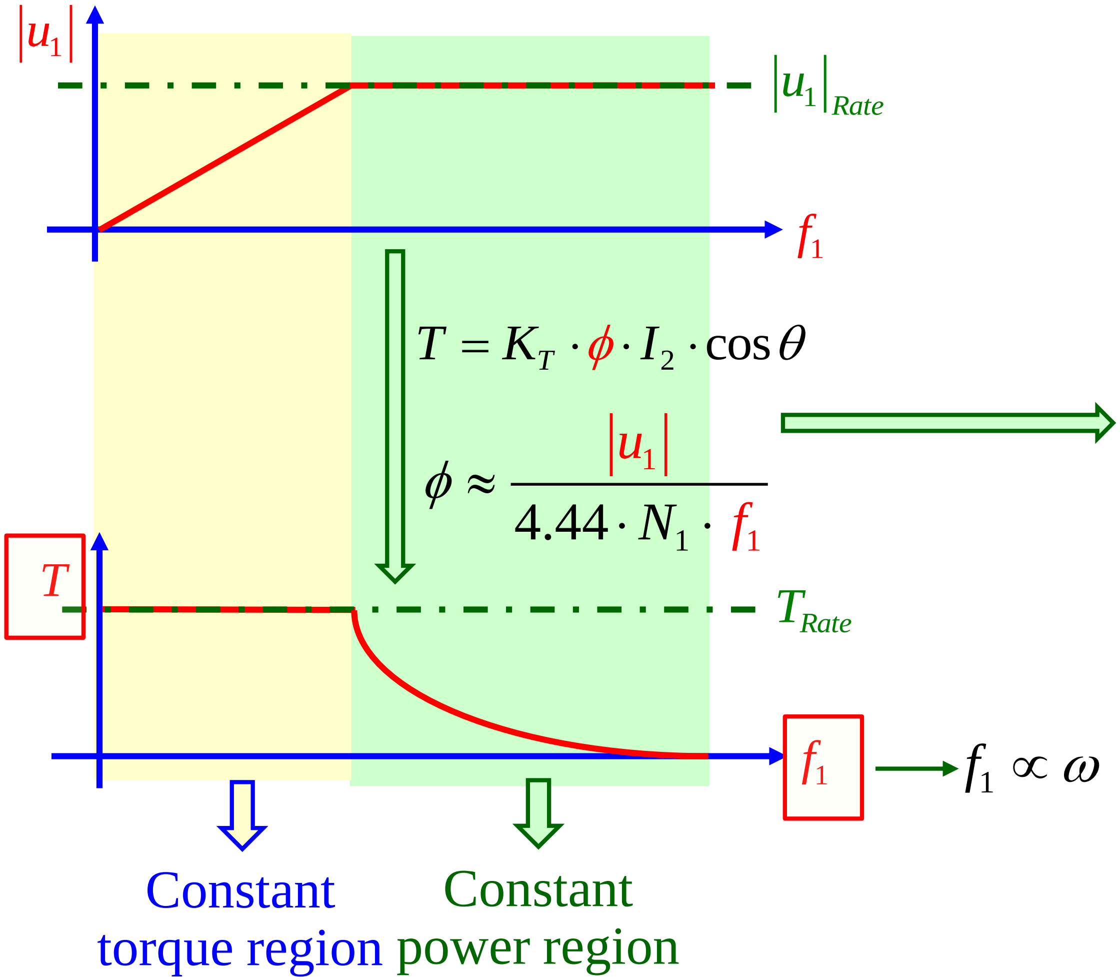
Practical issues of the FOC

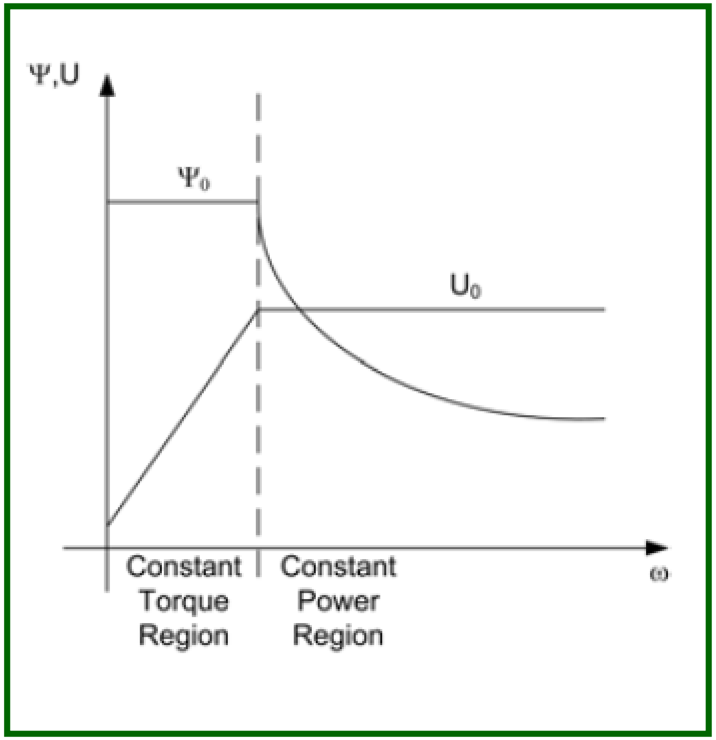
In practice, they have relationship



Recall: the relationship between the motor speed and flux

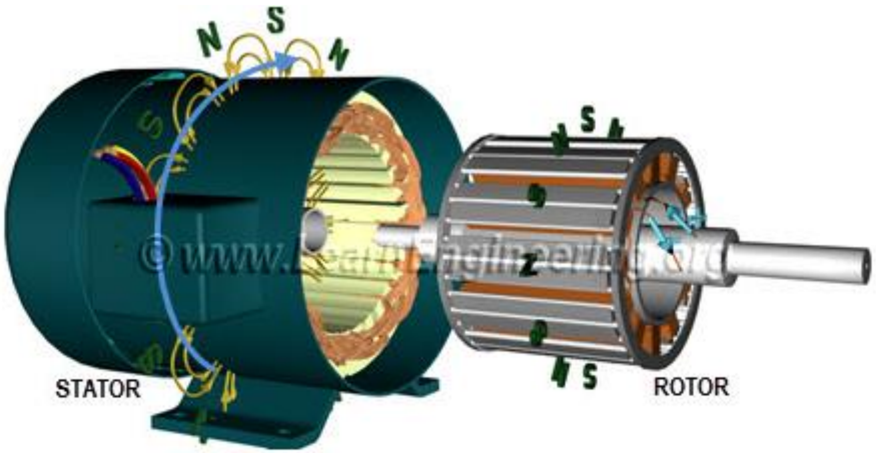
- The motor cannot exceed its rated voltage

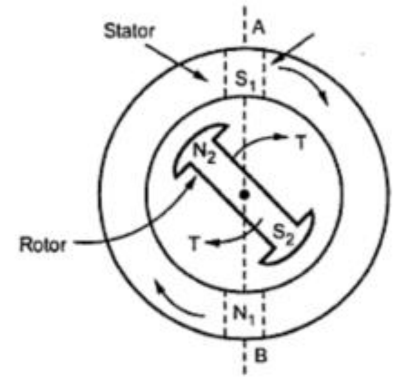




- Why we need to learn synchronous motor?
- Structure and operation of the synchronous motor
- How to start the synchronous motor? What is the challenge?
- Understand the FOC control of the synchronous motor.

Rotor speed of the synchronous motors





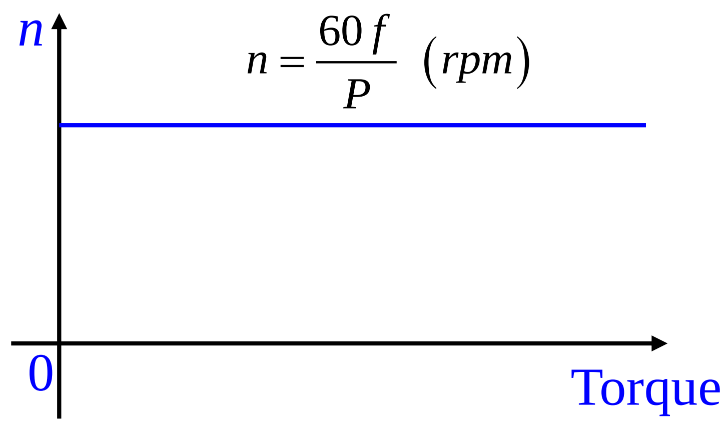
$n = n_o$

Synchronous motor

$$n_o = \frac{60\,f}{P}\ (rpm)$$

$$n = \frac{60\,f}{P}\ (rpm)$$

- f: Rotated frequency of the magnetic field
- P: Pole-pairs
- m (in rpm): Minutes

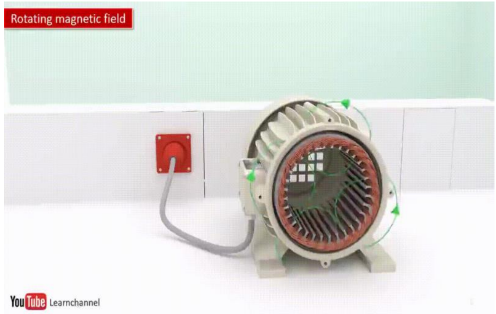


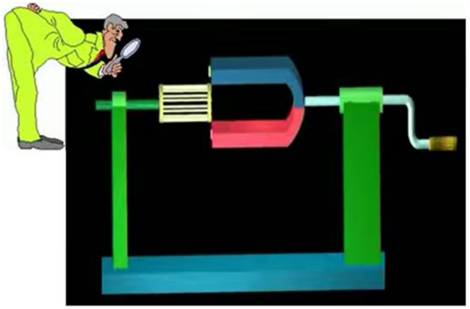
Constant and only determined by f ---(Advantages)

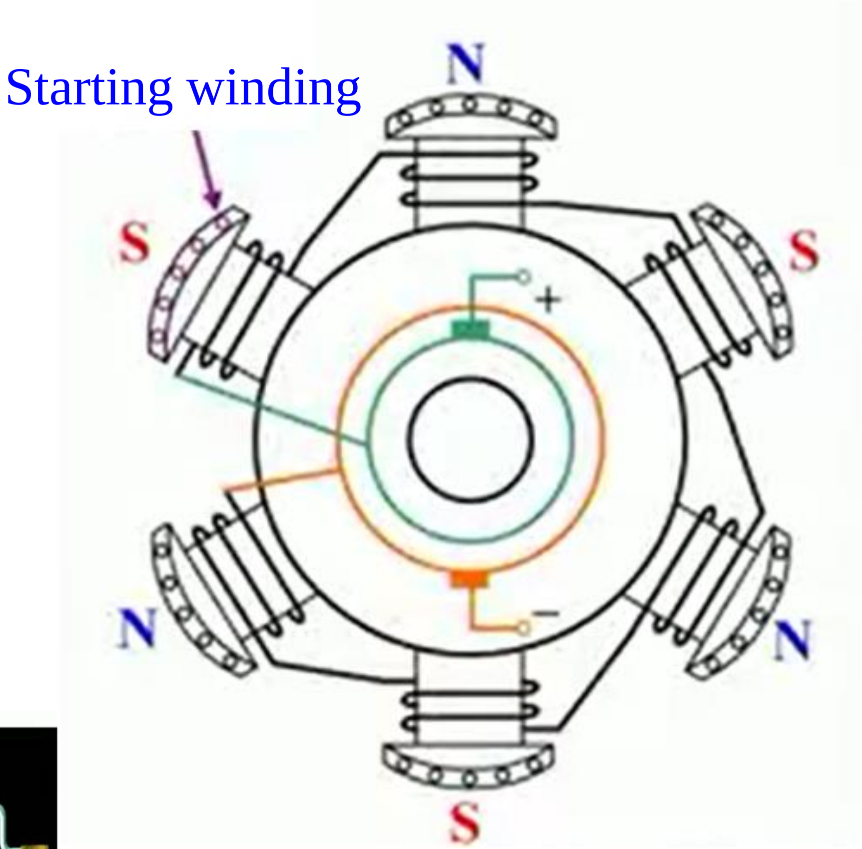
How to start the synchronous motor with external excitation winding?

Step1: do not give the power to the excitation winding

Starting winding has the same function with the rotor winding of the asynchronous motor, which generated induced magnetic field and follow the rotated stator magnetic field



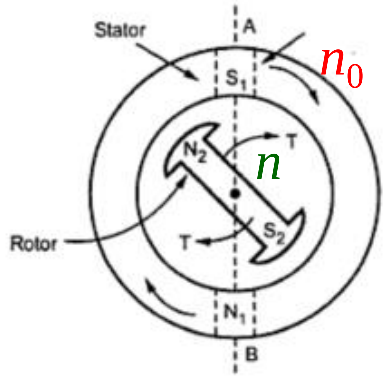


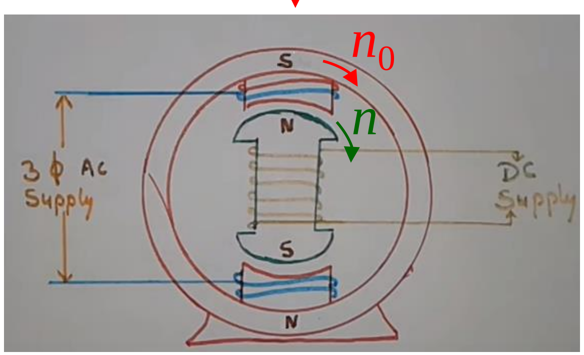


The synchronous motor start like an asynchronous motor!

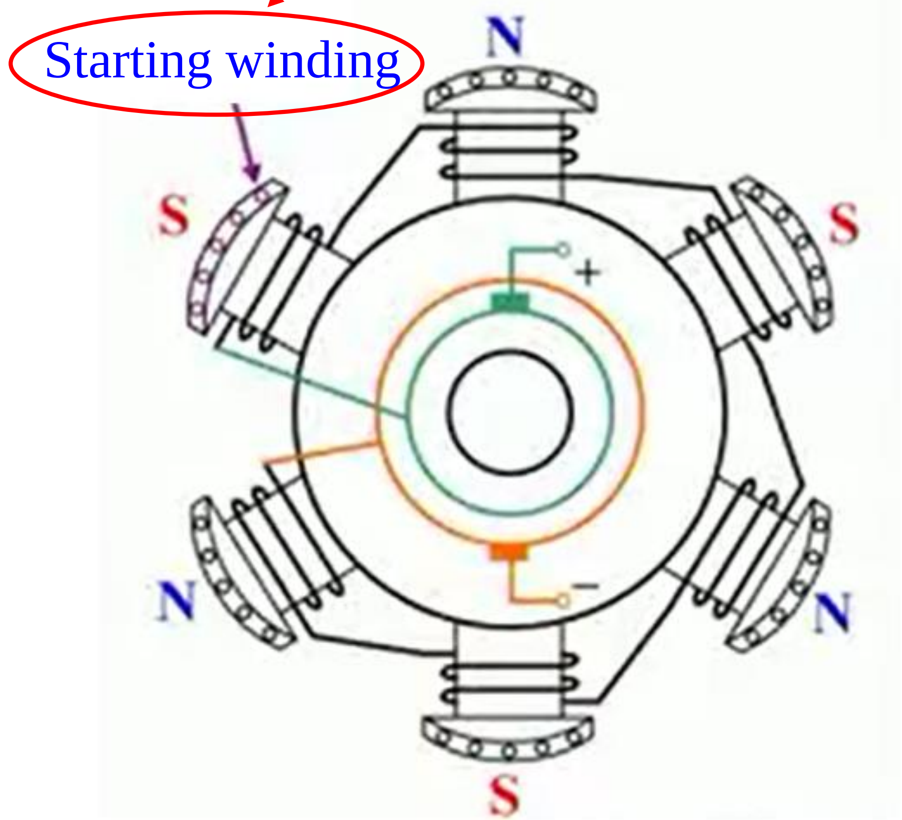
How to start the synchronous motor with external excitation winding?

Step2: If the rotor speed is near the speed of the stator rotated magnetic field, give the power to the excitation winding to make the rotor become a magnetic core





No impact after starting the synchronous motor



$n=n_o$

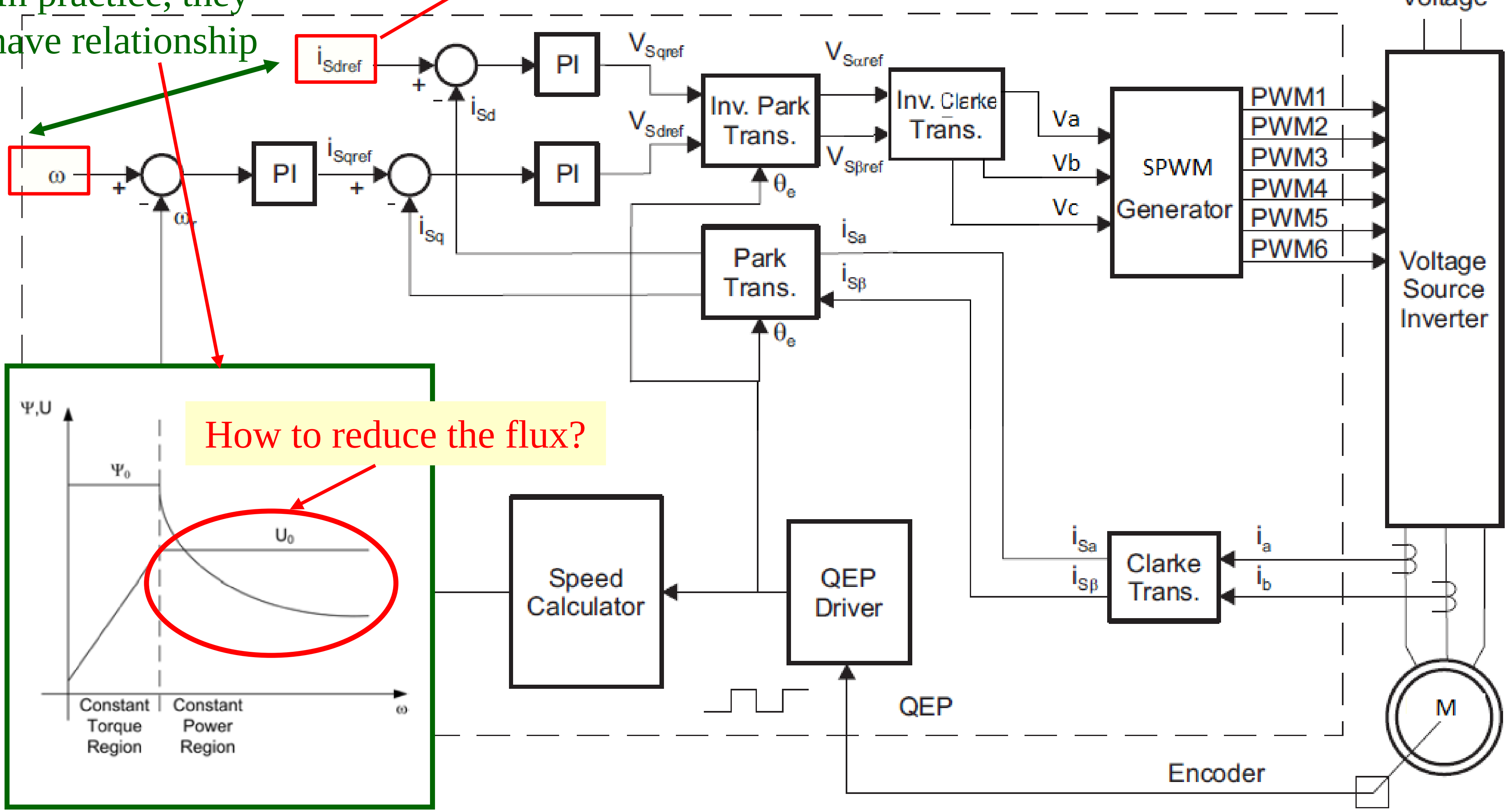
There is no current in the starting winding due to $n=n_0$

Flux-weakening control of the synchronous motor

Let i_{sdref}<0, it means negative flux, which has the flux-weakening function

In practice, they have relationship

How to reduce the flux?



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Thank you!

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