COLLEGE OF ENGINEERING
(AUTONOMOUS)

Topic: Unit 5
Course Name: Industrial Automation and Control(20EE11Q3)

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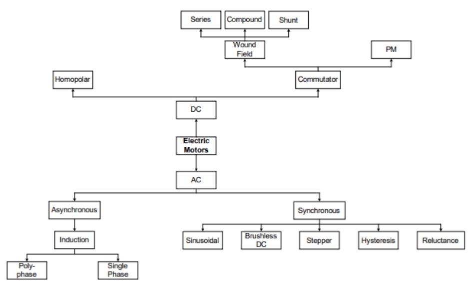
Classification



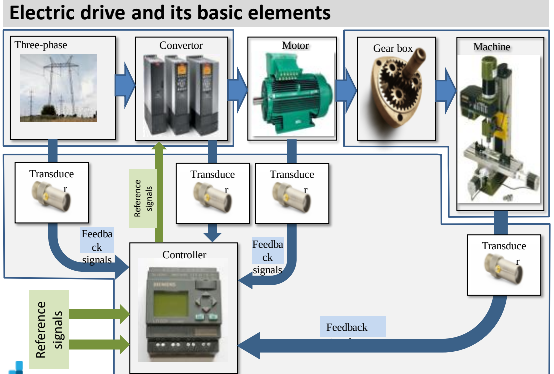
Introduction

- Motion control and drives are very important actuation subsystems for process and discrete manufacturing industries.
- Motion control systems are critical for product quality in discrete manufacturing, while variable speed drives lead to significant energy savings in common industrial loads such as pumps, compressors and fans.

Introduction

- Variable speed drives can be categorized into adjustable speed drives and servo drives.
- In adjustable speed drives the speed set points are changed relatively infrequently, in response to changes in in process operating points.

Electric drive and its basic elements



Types of electric motors

Function: transformation of electric energy into mechanical

dc motor

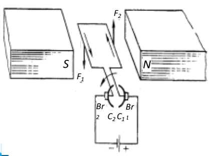
ac motor

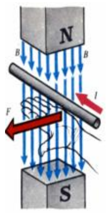
synchronous

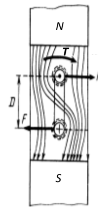
DC motor

Stator

Armature







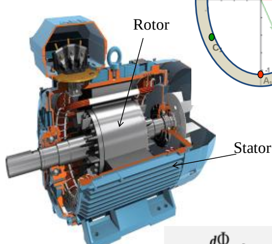
$F = B\cdot I\cdot L$

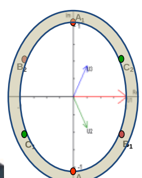
B - induction
I - current
L – length of the conductor

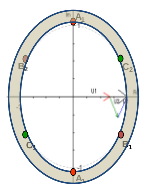
$T = F\cdot D$

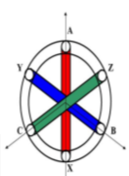
F - force
T - torque
D - diameter

AC motor









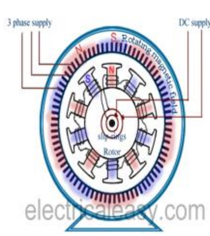
$E = -\frac{d\Phi}{dt} = k\cdot\omega_r\cdot\Phi$

$i_A = I_m \sin(\omega t)$
$i_B = I_m \sin(\omega t - 120^\circ)$
$i_C = I_m \sin(\omega t + 120)$

ynchronous motor

Synchronous motor with permanent

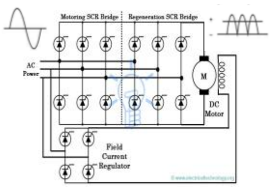
Synchronous motor with exiting winding



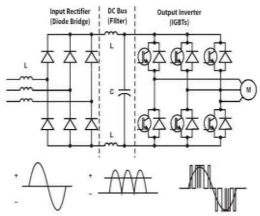
Converters

Function: conversion of electrical energy of one type into electrical energy of another type

Rectifier

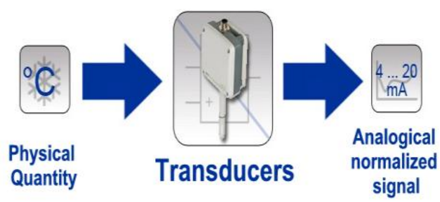


Inverter



Transducers

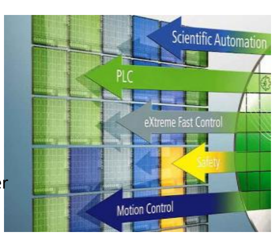
Function: conversion of signals of various nature into standard electrical signals



Controllers

Function: equipping machine-tools with control and automation functions

- industrial PC (IPC),
- programmable logic controller (PLC),
- programmable automation controller (PAC)



Basic concepts and determinations

Classification of electric drives

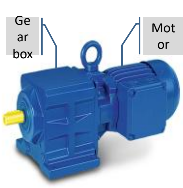
Classification of electric drives

- ❑ <u>By the sort of current of drive engine</u>:
  - ✓ direct current (DC)

  - ✓ alternating current

Classification of electric drives

- ❑ *<u>By the sort of mechanical transmission:</u>*
  - ✓ geared electric drive in which an electric motor is connected with a working machine by means of one of types of transmission devices

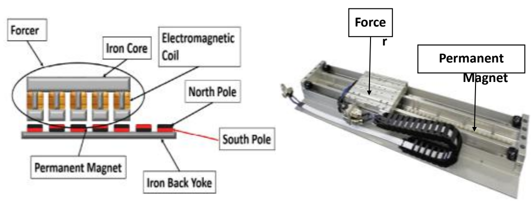


  - ✓ gearless electric drive (direct drive), when an electric motor is connected directly with a machine tool

Classification of electric drives

- ❑ *By the type of motion:*
  - ✓ unidirectional and reversing rotating
  - ✓ unidirectional and reversing linear motion

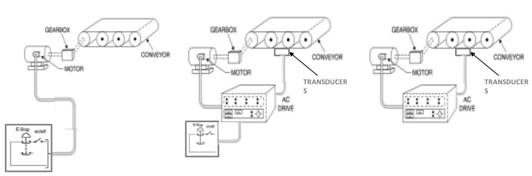
Linear motion



Classification of electric drives

- ❑ *By the level of automation:*
  - a) uncontrolled electric drive
  - b) automated electric drive in which a part of control operations is executed without operator participation;
  - c) automatic electric drive, in which full control operations are executed without operator participation.

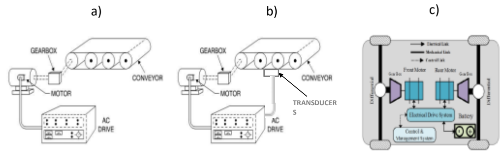
a) b) c)



Classification of electric drives

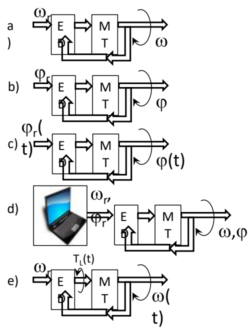
- ❑ *By the type of control system:*
  - a) open-loop control. It is an electric drive control system in which a feed-back of output coordinate absents;
  - b) closed-loop control. It is an electric drive control system in which a feed-back of output coordinate presents;
  - c) electric shaft – it is an interconnected electric drive which provides synchronous motion two or more machine tools, not having a mechanical connection.

a) b) c)



Classification of electric drives

- *By principles of output coordinates control:*
  - a) controllable electric drive which provides a guided change of machine tool motion coordinates in accordance with requirements of a technological process;
  - b) positional electric drive which provides a machine tool transferring to a set position;
  - c) follow-up electric drive which provides a machine tool moving in accordance with an arbitrarily changing reference signal;
  - d) software programmable electric drive which provides a machine tool moving in accordance with a set program;



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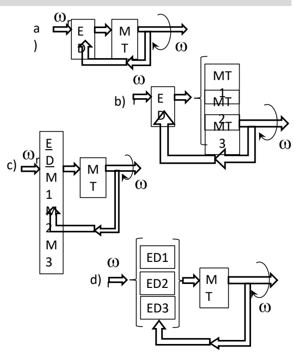
Classification of electric drives

- *By a method of passing to mechanical energy:*
  - a) individual electric drive – only one machine tool is operated by one engine;
  - b) group electric drive – a few machine tools are operated by one engine;
  - c) multimotor electric drive – one machine tool is operated by a few electric motors;
  - d) interconnected electric drive – an electric drive contains two or a few electric or mechanically connected electric drives, during working



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Basic concepts and determinations

Basic directions of electric drive development

Basic directions of electric drive development

- Expansion of automated drives, mainly frequency controlled drives of alternating current with a usage of the fully controlled semiconductor devices
- Increase of requirements to accuracy indexes of dynamic and static modes of operations
- Expansion and complication of electric drives functions
- Expansion of functional possibilities of an electric drive in different production operations and technological processes by application of the numerical control systems and microprocessor devices
- Standardization of an element base and creation of a complete electric drive for requirements satisfying of a wide class of production mechanisms
- Expansion of power ratings to ten of thousands of kilowatts and considerable variety of their design
- Creation of powerful gearless drives of ball and autogenous mills, mine winder, basic mechanisms of excavators and other mechanisms
- Increase efficiency and power factor of all electric drive types
- Usage of grouped electric drive systems with a common supply for flexible control of electric power streams, energy storage, reactive power compensation etc.

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AC DRIVES

AC motor Drives are used in many industrial and domestic application, such as in conveyer, lift, mixer, escalator etc.

The AC motor have a number of advantages :

- Lightweight (20% to 40% lighter than equivalent DC motor)
- Inexpensive
- Low maintenance

The Disadvantages AC motor :
*** The power control relatively complex and more expensive**

There are two type of AC motor Drives :
1. Induction Motor Drives
2. Synchronous Motor Drives

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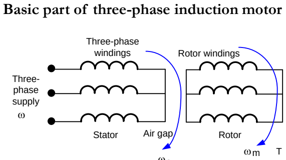
INDUCTION MOTOR DRIVES

Three-phase induction motor are commonly used in adjustable-speed drives (ASD).

Basic part of three-phase induction motor :



- Stator
- Rotor
- Air gap

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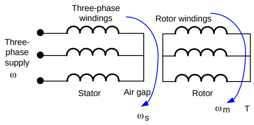

The stator winding are supplied with balanced three-phase AC voltage, which produce induced voltage in the rotor windings. It is possible to arrange the distribution of stator winding so that there is an effect of multiple poles, producing several cycle of magnetomotive force (mmf) or field around the air gap.

The speed of rotation of field is called the **synchronous speed** ω_s , which is defined by :

$$\omega_s = \frac{2\omega}{p} \quad \text{or}$$

$$N_s = \frac{120\ f}{p}$$

ω_s is syncronous speed [rad/sec]
N_s is syncronous speed [rpm]
p is numbers of poles
ω is the supply frequency [rad/sec]
f is the supply frequency [Hz]
N_m is motor speed

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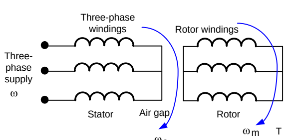
The motor speed

The rotor speed or motor speed is : $\omega_m = \omega_s\,(1 - S)$

Where S is slip, as defined as : $S = \frac{\omega_S - \omega_m}{\omega_S}$ Or $S = \frac{N_S - N_m}{N_S}$



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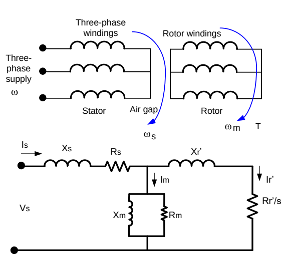
Equivalent Circuit Of Induction Motor



Where :

Rs is resistance per-phase of stator winding

Rr is resistance per-phase of rotor winding

Xs is leakage reactance per-phase of the winding stator

Xs is leakage reactance per-phase of the winding rotor

X_m is magnetizing reactance

$R_{m\ is}$ Core losses as a reactance

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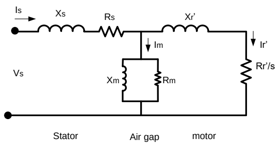
Performance Characteristic of Induction Motor



Stator copper loss : $P_{scu} = 3 I_s^{\,2} R_s$

Rotor copper loss : $P_{rcu} = 3 (I_r^{'})^2 R_r^{'}$

Core losses : $P_c = 3\frac{V_m^{\,2}}{R_m} \approx 3\frac{V_s^{\,2}}{R_m}$

Performance Characteristic of Induction Motor

- **Power developed on air gap (Power fropm stator to rotor through air gap) :**

$$P_g = 3(I_r^{'})^2 \frac{R_r^{'}}{S}$$

- **Power developed by motor :** $P_d = P_g - P_{rcu} = 3(I_r^{'})^2 \frac{R_r^{'}}{S}(1-S)$

or $P_d = P_g\,(1-S)$

- **Torque of motor :** $T_d = \frac{P_d}{\omega_m}$ **or** $T_d = \frac{P_d\,60}{2\pi\,N_m}$

or $= \frac{P_g(1-S)}{\omega_S(1-S)} = \frac{P_g}{\omega_s}$

Performance Characteristic of Induction Motor

Input power of motor : $P_i = 3V_s\,I_s\cos\phi_m$

$$= P_c + P_{scu} + P_g$$

Output power of motor : $P_o = P_d - P_{no\,load}$

Efficiency : $\eta = \frac{P_o}{P_i} = \frac{P_d - P_{no\,load}}{P_c + P_{scu} + P_g}$

Performance Characteristic of Induction Motor

If $P_g >> (P_c + P_{scu})$

and $P_d >> P_{noload}$

so, the efficiency can calculated as :

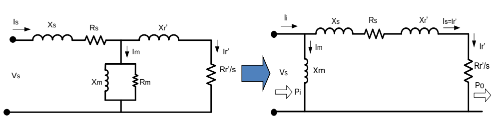
$$\eta \approx \frac{P_d}{P_g} = \frac{P_g(1-S)}{P_g} = 1-S$$

Performance Characteristic of Induction Motor

Generally, value of reactance magnetization X_m >> value Rm (core losses) and also $X_m{}^2 >> (R_s{}^2 + X_s{}^2)$

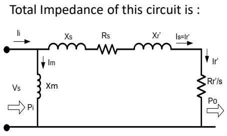
So, the magnetizing voltage same with the input voltage : $V_m \approx V_s$

Therefore, the equivalent circuit is ;



Performance Characteristic of Induction Motor

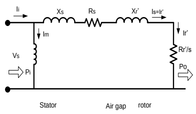
Total Impedance of this circuit is :



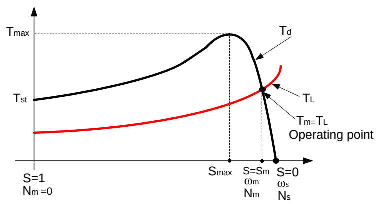
$$Z_i = \frac{-X_m(X_s + X_r') + jX_m\left(R_s + \frac{R_r'}{S}\right)}{R_s + \frac{R_r'}{S} + j(X_m + X_s + X_r')}$$

The rotor current is :

$$I_r' = \frac{V_s}{\left[\left(R_s + \frac{R_r'}{S}\right)^2 + \left(X_s + X_r'\right)^2\right]^{\frac{1}{2}}}$$



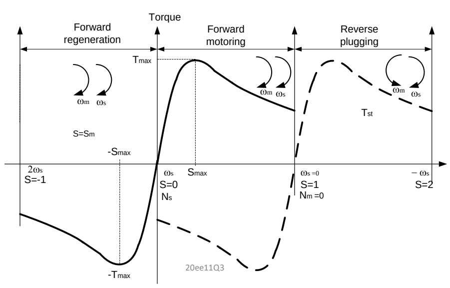
$$T_d = \frac{3 R_r' V_s^2}{S\,\omega_s \left[\left(R_s + \frac{R_r'}{S} \right)^2 + \left(X_s + X_r' \right)^2 \right]}$$



Torque – speed Characteristic

Three region operation :

1. **Motoring :** $0 \le S \le 1$
2. **Regenerating :** $S < 0$
3. **Plugging :** $1 \le S \le 2$



Performance Characteristic of Induction Motor

Starting speed of motor is $\omega_m = 0$ or $S = 1$,

Starting torque of motor is : $$T_{st} = \frac{3 R_r' V_s^2}{\omega_s \left[\left(R_s + \frac{R_r'}{S} \right)^2 + \left(X_s + X_r' \right)^2 \right]}$$

Slip for the maximum torque S_{max} can be found by setting : $$\frac{d\,T_d}{dS} = 0$$

So, the slip on maximum torque is : $$S_{max} = \pm \frac{R_r'}{\left[(R_s)^2 + \left(X_s + X_r' \right)^2 \right]^{\frac{1}{2}}}$$

Performance Characteristic of Induction Motor

Torque maximum is : $$T_{\max} = \frac{3\,V_s^2}{2\omega_s\left[R_s + \sqrt{R_s^2 + \left(X_s + X_r^{'}\right)^2}\right]}$$

And the maximum regenerative torque can be found as :

$$T_{\max} = \frac{3\,V_s^2}{2\omega_s\left[-R_s + \sqrt{R_s^2 + \left(X_s + X_r^{'}\right)^2}\right]}$$

Where the slip of motor s = - S_m

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Speed-Torque Characteristic : $$T_d = \frac{3R_r^{'}V_s^2}{S\,\omega_s\left[\left(R_s + \frac{R_r^{'}}{S}\right)^2 + \left(X_s + X_r^{'}\right)^2\right]}$$

For the high Slip S. (starting) $$\left(X_s + X_r^{'}\right)^2 >> \left(R_s + \frac{R_r^{'}}{S}\right)^2$$

So, the torque of motor is : $$T_d = \frac{3R_r^{'}V_s^2}{S\,\omega_s\left(X_s + X_r^{'}\right)^2}$$

And starting torque (slip S=1) is : $$\boxed{T_{st} = \frac{3R_r^{'}V_s^2}{\omega_s\left(X_s + X_r^{'}\right)^2}}$$

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For low slip S region, the motor speed near unity or synchronous speed, in this region the impedance motor is : $$\left(X_s + X_r^{'}\right)^2 << \frac{R'_r}{S} >> R_s$$

So, the motor torque is : $$\boxed{T_d = \frac{3V_s^2\,S}{\omega_s\;R'_r}}$$

And the slip at maximum torque is : $$S_{\max} = \pm\frac{R_r^{'}}{\left[\left(R_s\right)^2 + \left(X_s + X_r^{'}\right)^2\right]^{\frac{1}{2}}}$$

The maximum motor torque is : $$\boxed{T_d = \frac{3R_r^{'}V_s^2}{S\,\omega_s\left[\left(R_s + \frac{R_r^{'}}{S}\right)^2 + \left(X_s + X_r^{'}\right)^2\right]}}$$

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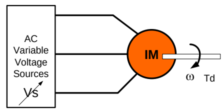
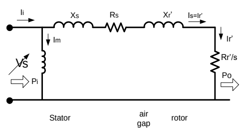
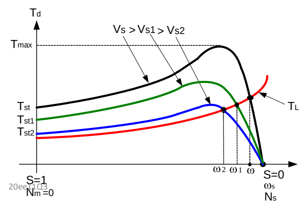
Stator Voltage Control

Controlling Induction Motor Speed by Adjusting The Stator Voltage



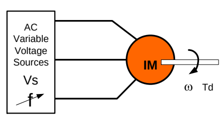
$$T_d = \frac{3R_r^{'}V_s^2}{S\,\omega_s\left[\left(R_s+\frac{R_r^{'}}{S}\right)^2+\left(X_s+X_r^{'}\right)^2\right]}$$



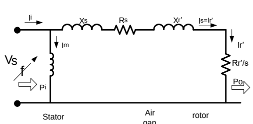


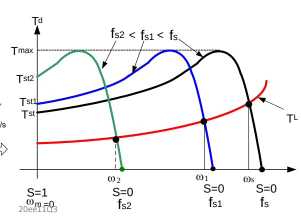
Frequency Voltage Control

Controlling Induction Motor Speed by Adjusting The Frequency Stator Voltage



$$T_d = \frac{3R_r^{'}V_s^2}{S\,\omega_s\left[\left(R_s+\frac{R_r^{'}}{S}\right)^2+\left(X_s+X_r^{'}\right)^2\right]}$$





If the frequency is increased above its rated value, the flux and torque would decrease. If the synchronous speed corresponding to the rated frequency is call the base speed ω_b, the synchronous speed at any other frequency becomes:

$$\omega_s = \beta\,\omega_b$$

And : $S = \dfrac{\beta\omega_b - \omega_m}{\beta\omega_b} = 1 - \dfrac{\omega_m}{\beta\omega_b}$

The motor torque : $\boxed{T_d = \dfrac{3R_r^{'}V_s^2}{S\,\omega_s\left[\left(R_s+\frac{R_r^{'}}{S}\right)^2+\left(X_s+X_r^{'}\right)^2\right]}}$

$$\boxed{T_d = \frac{3R_r^{'}V_s^2}{S\,\beta\omega_b\left[\left(R_s+\frac{R_r^{'}}{S}\right)^2+\left(\beta X_s+\beta X_r^{'}\right)^2\right]}}$$

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If R_s is negligible, the maximum torque at the base speed as :

$$T_{mb} = \frac{3\,V_s^2}{2S\,\omega_b\left(X_s + X_r^{'}\right)}$$

And the maximum torque at any other frequency is :

$$T_m = \frac{3}{2S\,\omega_b\left(X_s + X_r^{'}\right)}\frac{V_s^2}{\beta^2}$$

At this maximum torque, slip S is : $S_m = \frac{R_r'}{\beta\left(X_s + X_r^{'}\right)}$

Normalizing : $$\frac{T_m = \frac{3}{2S\,\omega_b\left(X_s + X_r^{'}\right)}\frac{V_s^2}{\beta^2}}{T_{mb} = \frac{3\,V_s^2}{2S\,\omega_b\left(X_s + X_r^{'}\right)}} \Rightarrow \boxed{\frac{T_m}{T_{mb}} = \frac{1}{\beta^2}}$$

And $T_m\,\beta^2 = T_{mb}$

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❑Requirement of speed control

- Speed control means change the drive speed as desired by the process to maintain different process parameter at different load.
- Energy saving.
- Speed control is different concept from speed regulation where there is a natural change in speed due to change on load on the shaft.
- Speed control either done is manually by the operation or by the means of some automatic control device.
- Low speed starting requirement.

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❑ Method of speed control of induction motor

- **Stator voltage control**
- **Stator frequency control**
- **Stator current control**
- **V/F control**
- **Static rotor resistance control**

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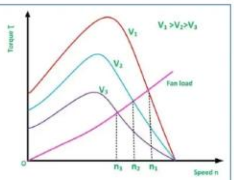
❑Stator voltage control

- ➢ **Synchronous speed**

$$N_s = \frac{120f}{p}$$

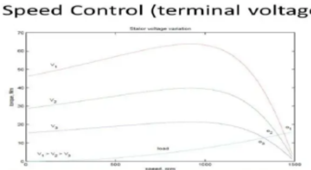
- ➢ **Toque equation**

$$T \propto w^2$$



❑Variable terminal voltage control

Induction Motor
- Speed Control (terminal voltage) -



❑Frequency control method

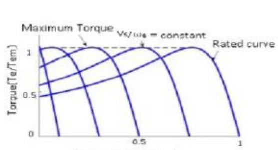
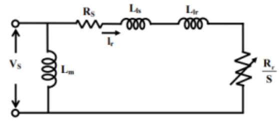


Figure2. Torque-speed characteristics of the induction motor

Approximate per phase equivalent circuit



$$I_r = \frac{V_m}{\left(\frac{R_r}{S}\right) + j\omega_e L_{lr}}$$

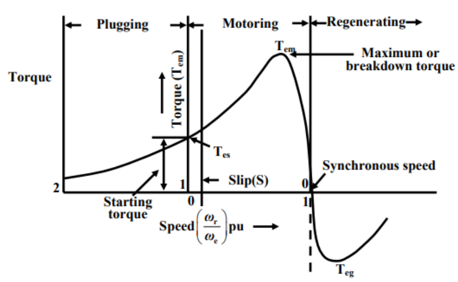
and parameters R_r and L_{lr} stand for the resistance and inductance parameters referred to to the stator.

Since the output power is the product of developed electrical torque T_e and speed ω_m, T_e can be expressed as

$$I_r = \frac{V_s}{\sqrt{(R_s + R_r/S)^2 + \omega_e^2 (L_{ls} + L_{lr})^2}}$$

This yields that,

$$T_e = 3\left(\frac{P}{2}\right)\frac{R_r}{S\omega_e} \cdot \frac{V_s^2}{(R_s + R_r/S)^2 + \omega_e^2 (L_{ls} + L_{lr})^2}$$



For adjustible speed applications, the induction machine, particularly the cage rotor type, is most commonly used in industry. These machines are very cheap and rugged, and are available from fractional horsepower to multi-megawatt capacity, both in single-phase and poly-phase versions. In this lesson, the basic fundamentals of construction, operation and speed control for induction motors are presented.

In cage rotor type induction motors the rotor has a squirrel cage-like structure with shorted end rings. The stator has a three-phase winding, and embedded in slots distributed sinusoidally. It can be shown that a sinusoidal three-phase balanced set of ac voltages applied to the three-phase stator windings creates a magnetic field rotating at angular speed $\omega_s = 4\pi f_s /P$ where f_s is the supply frequency in Hz and P is the number of stator poles.

If the rotor is rotating at an angular speed ω_r, i.e. at an angular speed $(\omega_s - \omega_r)$ with respect to the rotating stator mmf, its conductors will be subjected to a sweeping magnetic field, inducing voltages and current and mmf in the short-circuited rotor bars at a frequency $(\omega_s - \omega_r)P/4\pi$, known as the slip speed. The interaction of air gap flux and rotor mmf produces torque. The per unit slip ω is defined as

$$S = \frac{\omega_s - \omega_r}{\omega_s}$$

Speed Control

From the torque speed characteristics in Fig. 34.2, it can be seen that at any rotor speed the magnitude and/or frequency of the supply voltage can be controlled for obtaining a desired torque. The three possible modes of speed control are discussed below.

Variable-Voltage, Constant-Frequency Operation

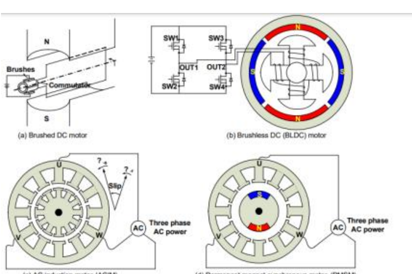
A simple method of controlling speed in a cage-type induction motor is by varying the stator voltage at constant supply frequency. Stator voltage control is also used for "soft start" to limit the stator current during periods of low rotor speeds.
Figure 34.3 shows the torque-speed curves with variable stator voltage. Often, low-power motor drives use this type of speed control due to the simplicity of the drive circuit.

Variable-Frequency Operation

Figure 34.4 shows the torque-speed curve, if the stator supply frequency is increased with constant supply voltage, where ω_b is the base angular speed. Note, however, that beyond the rated frequency ω_b, there is fall in maximum torque developed, while the speed rises.

BLDC Motors

- A BLDC motor accomplishes commutation electronically using rotor position feedback to determine when to switch the current. The structure is shown in Figure.
- Feedback usually entails an attached Hall sensor or a rotary encoder.
- The stator windings work in conjunction with permanent magnets on the rotor to generate a nearly uniform flux density in the air gap.
- This permits the stator coils to be driven by a constant DC voltage (hence the name brushless DC), which simply switches from one stator coil to the next to generate an AC voltage waveform with a trapezoidal shape.



(a) Brushed DC motor (b) Brushless DC (BLDC) motor

(c) AC induction motor (ACIM) (d) Permanent magnet synchronous motor (PMSM)

Feature	BLDC motor	AC induction motor	Actual Advantage
Speed/Torque Characteristics	Flat	Nonlinear — lower torque at lower speeds	Permanent magnet design with rotor position feedback gives BLDC higher starting and low-speed torque
Output Power/ Frame Size (Ratio)	High	Moderate	Both stator and rotor have windings for induction motor
Dynamic Response	Fast	Low	Lower rotor inertia because of permanent magnet
Slip Between Stator And Rotor Frequency	No	Yes; rotor runs at a lower frequency than stator by slip frequency and slip increases with load on the motor	BLDC is a synchronous motor, induction motor is an asynchronous motor

BLDC motors

- Some BLDC motors incorporate Hall sensors to detect the rotor position. These sensors provide feedback to the electronic controller, enabling precise commutation timing and improved motor performance.
- BLDC motors are widely used in industrial automation systems, such as robotics, CNC machines, and conveyor systems. Their high torque density, precise control, and low maintenance make them ideal for such applications.

Speed Control of BLDC Motors

- Speed control of BLDC (Brushless DC) motors can be achieved using various control methods, including sensor or sensorless control, square-wave control, PWM (Pulse Width Modulation) control, and more advanced control strategies such as PI (Proportional-Integral) and PID (Proportional-Integral-Derivative) controllers.

  In sensor-based control, the motor uses feedback from sensors such as hall-effect sensors, which detect the rotor position and provide an electrical signal to the motor controller, allowing it to control the speed and direction of the motor.

  Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

Speed Control of BLDC motors

In sensorless control, rotor position information can be obtained using other measurable parameters such as back electromotive force or stator current, without the need for additional sensors.

Square-wave control is a simple control method that involves switching the voltage applied to the motor on and off in a square wave pattern. This method is inexpensive and can provide high motor speeds.

PWM control involves adjusting the power delivered to the motor by varying the duty cycle of a high-frequency pulse train. This method provides accurate speed control and can be used with sensor or sensorless systems.

In more advanced control strategies such as PI and PID control, the motor controller adjusts the power delivered to the motor based on feedback from sensors or other sources, incorporating proportional, integral, and derivative terms to provide precise control of motor speed.

Applications

- Automotive: BLDC motors are employed in electric vehicles (EVs) for propulsion, power steering, braking systems, and HVAC systems. They offer higher efficiency, reduced noise, and improved reliability compared to traditional brushed motors.
- Appliances: BLDC motors are found in household appliances like refrigerators, washing machines, and air conditioners. They provide energy-efficient operation, quieter performance, and longer lifespan compared to conventional motors.
- Aerospace and Drones: BLDC motors are used in aerospace applications, including actuators, flight control systems, and auxiliary power units (APUs). They are also integral components of drones, where their compact size and high power density are advantageous.
- Medical Equipment: BLDC motors are employed in medical devices such as surgical tools, infusion pumps, and laboratory equipment. Their precise control, compact size, and low electromagnetic interference make them suitable for medical applications.
- Consumer Electronics: BLDC motors are utilized in various consumer electronics, including computer cooling fans, hard disk drives, and printers. They offer efficient and reliable performance in compact form factors.

Advatages	Brushless DC motor	Brushed DC motor	Induction motor
Mechanical Structure	Field Winding on stator and permanent magnets on rotor.	Field Winding on the rotor and stator are made of permanent magnets or electromagnet	Both the rotor and stator have windings but the AC lines are connected to the stator
Maintenance	No maintenance	Periodic maintenance because of brushes	Low maintenance
Speed-Torque characteristic	Flat – operation at all speeds with rated load	Moderate – Loss in torque at higher speeds because of losses in brushes	Non-linear
Efficiency	High	Moderate	High efficiency
Commutatio n method	Using solid state switches	Mechanical contacts between brushes and commutator	Special starting circuit is required

Speed Range	High - no losses in brushes	Moderate – losses in brushes	Low determined by the AC line frequency; increases in load further reduces speed
Detecting method of rotors position	Hall sensors, optical encoders, etc.	Automatically detected by brushes and commutator	NA
Direction reversal	Reversing the switching sequence	Reversing the terminal voltage	By changing the two phases of the motor input
Electrical noise	Low	High – as brushes used	Low
System cost	High-because Of external Controller requirement	Low	Low

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Thank you

- Queries?

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