Motion Control System

Xie Bao-chang

Nov. 10, 2010

Definition of Motion Control

- Motion control is a sub-field of automation, in which the position and/or velocity of machines are controlled using some type of device such as a hydraulic pump, linear actuator, or an electric motor, generally a servo (servo-mechanism or -motor). Motion control system sometimes is called a servo system.
- Motion control is an important part of robotics and computer numerical controlled (CNC) machine tools, however it is more complex than in the use of specialized machines, where the kinematics are usually simpler.
- Motion control is widely used in the packaging, printing, textile, semiconductor production, and assembly industries.

Curricular information

- **Curricular code: X**031503
- Scores: 2.0
- Hours: 36
- **Prerequisites:**
  - **Electric Machinery**
  - Electrotechnology
  - Power Electronics
  - Computional Methodologies

Curricular information (contd')

- Motion control system is composed of plant, converter, controller and sensors. The objectives of this course are to design and develop motion control system for specific environment.
- The plant includes any kind of electric **motor**s together with the load. For instance, induction motor, permanent magnet synchronous motor, brushless DC motor, switched reluctance motor, synchronous reluctance motor, and stepping motor.
- The converter or driver converts electric power with conventionally constant voltage and constant frequency into the one with adjustable voltage, and variable frequency in order to control the torque, speed, position of the plant.
- The controller commands the driver by means of digital or analogous signals based on the specific technology.
- The sensors or transducers transform electric currents or non-electric signals into electric voltages fed-back to the controller.
- The curriculum focuses on fundamental theories, functionalities of devices and their algorithms. The fundamental theories refer to principles and control methods of aforementioned motors. The devices are composed of frequently used sensors, power devices, micro-controller and other electric components. The algorithm uses fundamental theory, control strategy and functionality of devices to implement concrete, creative, integrated programming module.

Contents

Modern motion control system

A modern motion control system has five components:

1. Electric Motor
2. Power Converter
   - Rectifiers
   - Choppers
   - Inverters
   - Cycloconverters
   - Matrix Converters
   - Multilevel Converters
3. Controllers – matching the motor and power converter to meet the load requirements
4. Load
5. Sensor or transducer

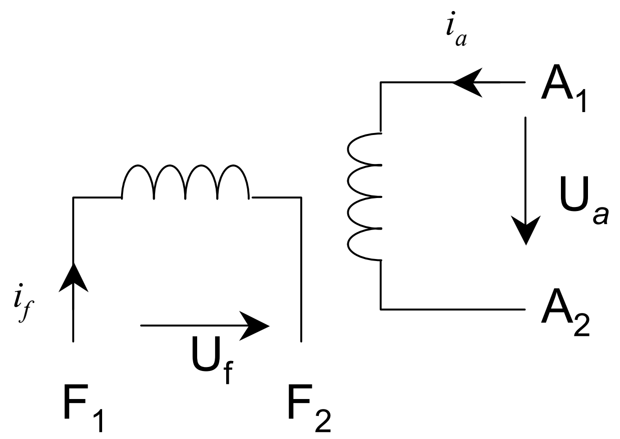
Part I: Electric Motors

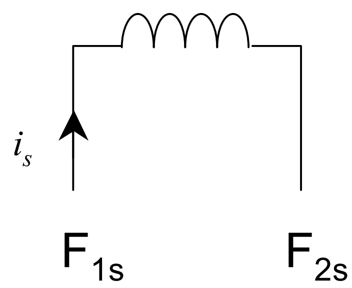
- Which types of electric motors are?
- How to select electric motor?
- What are requirements of electric motor characteristics for servo system?

Types of electric motors presently used for motion control applications

1. DC motors

- Shunt (F_1A_1--F_2A_2)
- Series (F_{1s}--F_{2s}--A_1--A_2)
- Short Compound (F_{1s}--$F_{2s}A_1F_1$--A_2F_2)
- Long Compound (F_1F_{1s}--$F_{2s}A_1$--A_2F_2)
- Separately excited (F_1--$F_{2\,;}\,A_1$--A_2)
- Universal (F_{1s}--F_{2s}--A_1--A_2) using single phase alternating current power source

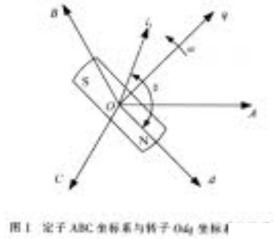


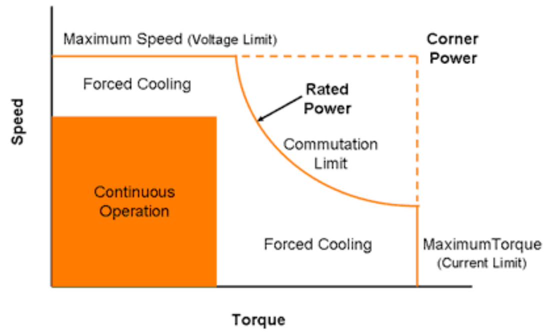


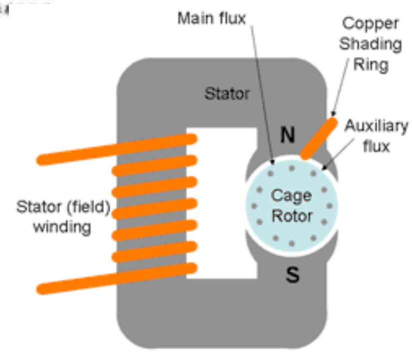
Types of electric motors presently used for motion control applications (contd')

2. AC motors

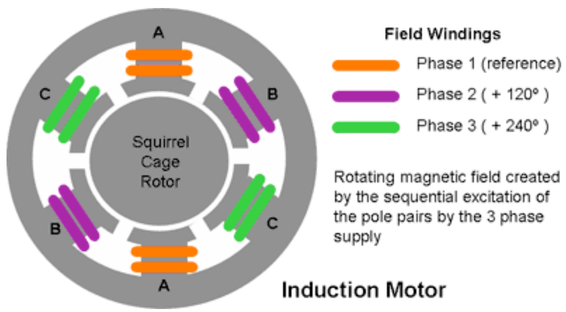
- Induction Machine
  - ✓ Wound rotor
  - ✓ Squirrel cage rotor
  - ✓ Brushless double-fed
- Synchronous Machine
  - ✓ Permanent magnet
  - ✓ Electric excited synchronous
  - ✓ Synchronous Reluctance
  - ✓ Brushless DC motor
  - ✓ Switched reluctance motor
  - ✓ Stepping motor



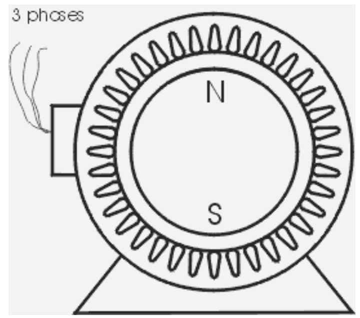




Shaded Pole Induction Motor



Induction Motor



Performances for motor selection

1. Cost
2. Thermal capacity
3. Efficiency
4. Torque-speed profile
5. Acceleration
6. Power density, volume of the motor
7. Ripple, cogging torque
8. Peak torque capability
9. Suitability for hazardous environment
10. Availability of spare parts
11. Cog: Mechanical transmission

- a wheel or bar with a series of projections on its edge that transfers motion by engaging with projections on another wheel or bar.

For examples:

Gear, Toothed wheel

Requirements of electric motors for position servo applications

- The peak torque and thermal capabilities together with ripple and cogging torques are important characteristics for servo application.

- Higher peak torques decrease the acceleration and/or deceleration times.

- Minimum cogging and ripple torques help to attain higher positioning repeatability and higher thermal capability leading to a longer motor life and a higher amount of loading.

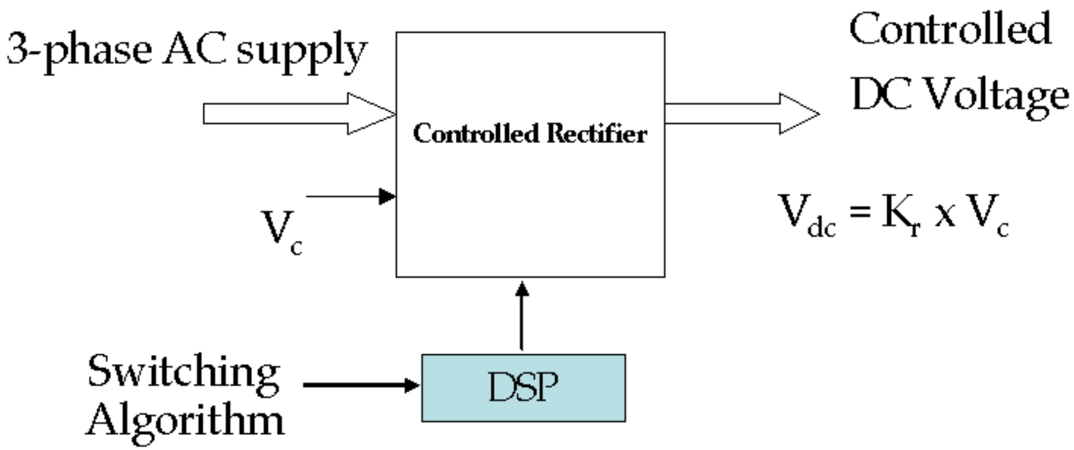
Part II: Power Converters

The power converters driving the motors are:

1. Controlled Rectifiers

Controlled rectifiers are fed from single and three-phase AC main supply.

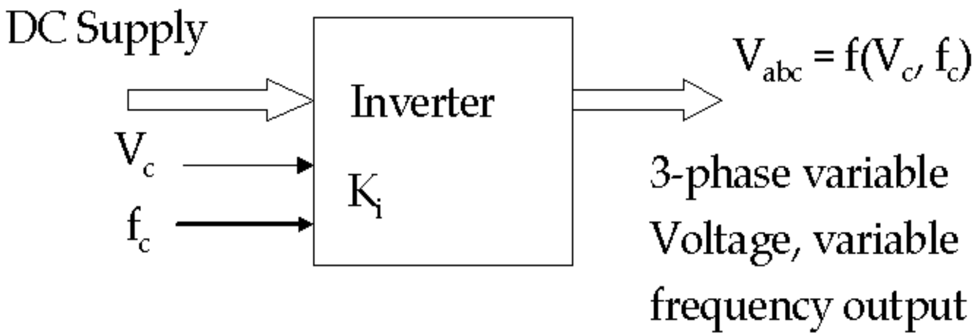
where: V_c is voltage controlled and K_r is gain (proportionality constant)



Power Converters (contd')

2. Inverters

Voltage and current source converters are fed from a DC link. The DC link is generated with either a controlled or uncontrolled rectifier.

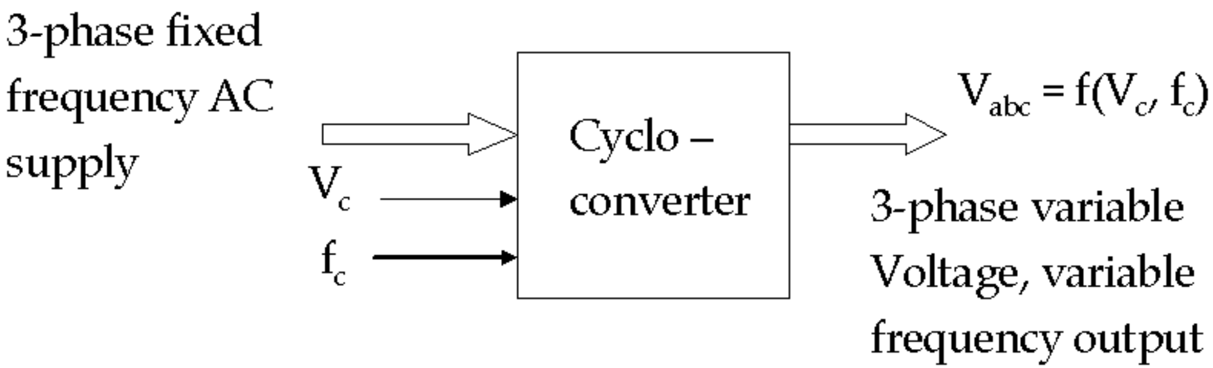


where V_c is controlled magnitude command and f_c is frequency command.

3. Cycloconverters

4. Matrix converters

5. Multilevel conver

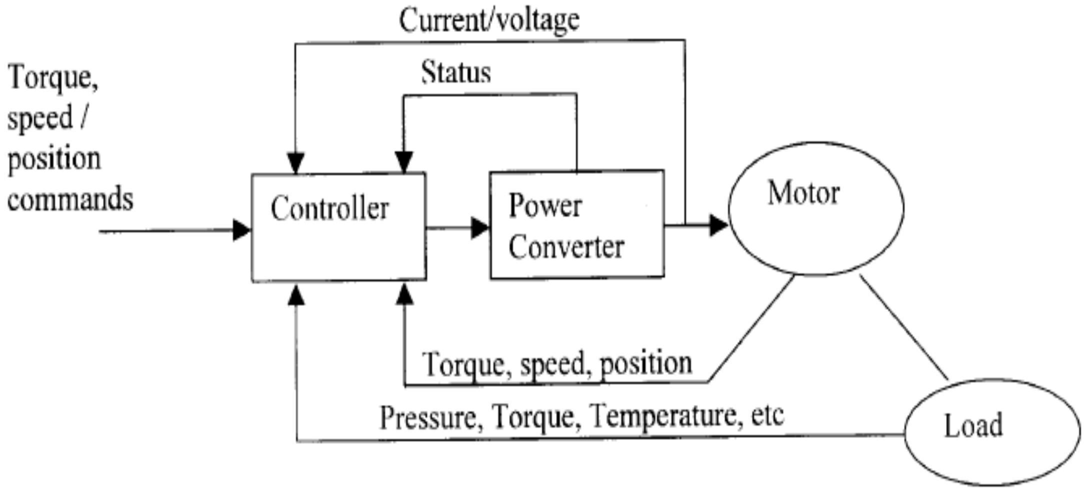


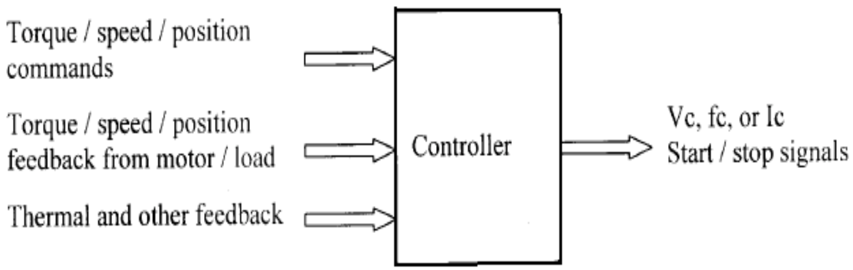
Part III: Controllers

- The controllers implement the control strategy governing the load and motor characteristics

- To match the load and motor, the input to the power converter is controlled (manipulated) by the controller

Motor Drive Schematic





Vc: controlled voltage
fc: controlled frequency
Ic: controlled current

Controllers (contd')

1. The inputs to the controller consists of Torque, flux, speed, and/or position commands
2. Their rate of variations to facilitate soft start, to preserve the mechanical integrity of the load
3. The actual values of torque, flux, speed, and/or position for feedback control.
4. Limiting values of currents, torque, acceleration, etc.
5. Temperature feedback, instantaneous currents and/or voltages in the motor and/or converter.

The motor drives a load which has a certain characteristics torque-speed requirement.

In general, where, k may be an integer of a fraction.

- In a feed drive,
- In fans and pumps,
- The motor can be connected to the load through a set of gears
- The gears have teeth ratio and can be treated as torque transformers

$$T_L \propto \omega_m^k \qquad k=1,2$$

Part IV: Load

- The gears are used to amplify the torque on load side at lower speed compared to the motor speed
- The motors are designed to run at high speeds because it has been found that the higher the speed, the lower is the volume and size of the motor

The following laws govern the gear system operation:

- The power handled by the gear is the same on both sides
- Speed on each side is inversely proportional to its tooth number,

$$T_1\omega_1 = T_2\omega_2$$

or,

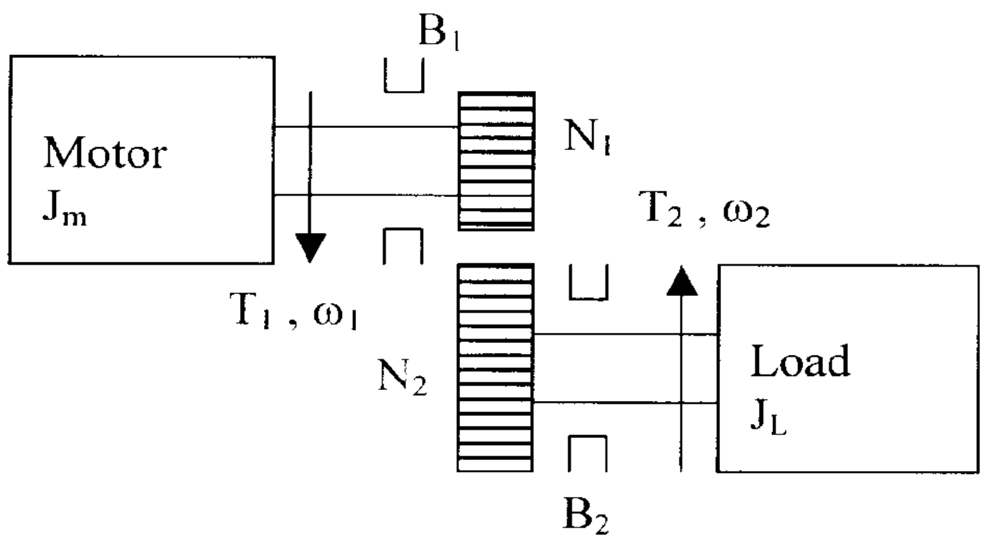
$$T_2 = T_1 \frac{\omega_1}{\omega_2}$$

and,

$$\frac{\omega_1}{\omega_2} = \frac{N_2}{N_1}$$

N_1 and N_2 are number of tooth.

Motor-load connection through a gear



N_1, N_2--Teeth number in the gear
B_1, B_2--Bearings and their friction coefficients
J_m, J_L--Moment of inertia of the motor and load
the resultant mechanical constants are

$$J = J_{eff\_motor} = J_m + (N_1/N_2)^2 J_L$$

J: moment of inertia of gear system and load

$$B = B_{eff\_motor} = B_1 + (N_1/N_2)^2 B_2$$

B:friction due to gear system and load

The torque equation of the motor-load combination is

$$J\frac{d\omega}{dt} + B\omega = T_1 - (N_1/N_2)^2 T_2$$

Part V: Sensor or transducer

- Sensors are based on electric, magnetic, optical, thermal, chemical, sonic and mechanical principles to detect signals in application system.

1. Sensing Current
   - Shunt resistor
   - Current transformer
   - Hall effect LEM
2. Sensing voltage
   - Divider resistor
   - Voltage transformer
   - Hall effect LEM
3. Tachometer
4. Angle transducer
   - ✓ Incremental encoder
   - ✓ Absolute encoder
   - ✓ Rotatory transformer
   - ✓ capacitance
   - ✓ Hall effect component
5. Proximity sensor
   - ✓ Ultrasonic proximity sensor

Control of Electric Machines

Servo controllers offer extremely fast response and precise control of acceleration/ deceleration, speed and torque.

Servo control systems can accelerate from standstill to 100 RPM in several milliseconds.

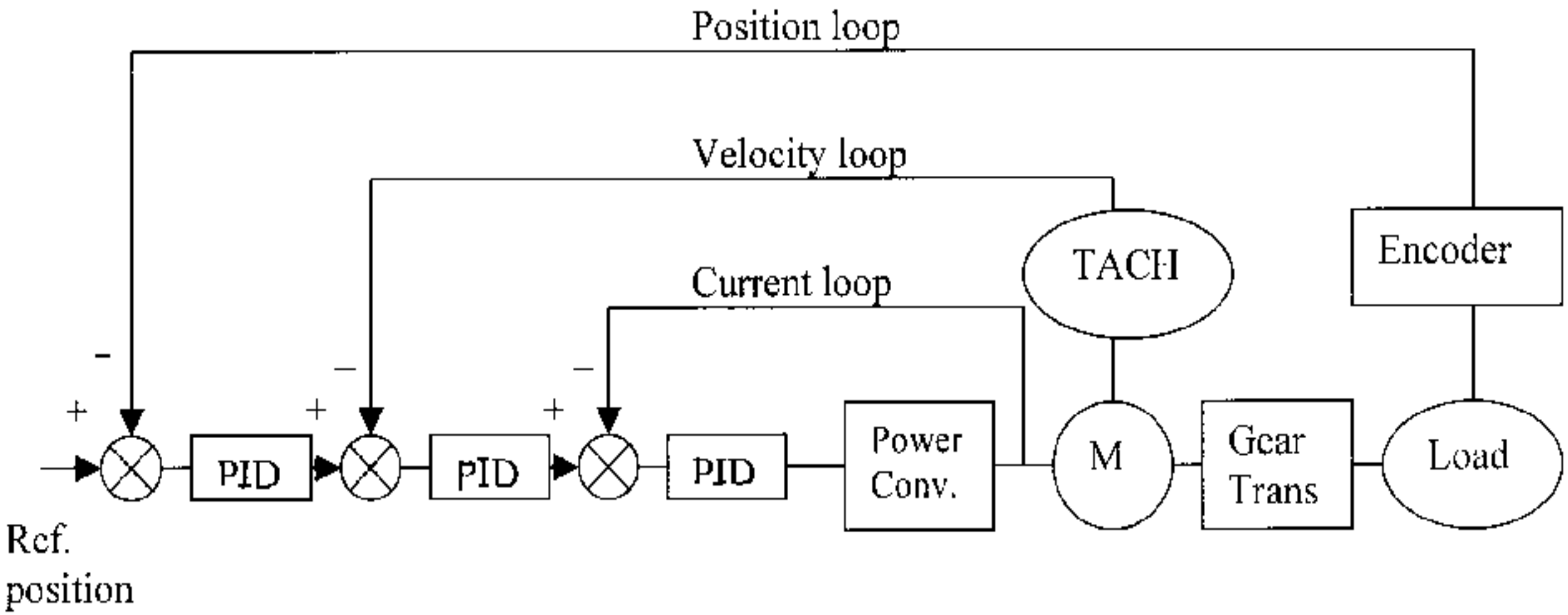
Servo control systems are designed with three feedback loops:

1) Position loop
2) Velocity loop
3) Current loop

Elements of servo control system are:

- Motor
- Power Converter
- Load and Transmission Systems
- Encoder (position transducer)
- Tachometer (speed transducer)
- Current and Voltage Sensors
- Potentiometers

Control of Electric Machines (contd')



Load Characteristics

- The process of selecting an adjustable AC or DC drive is one where load is primary consideration.
- When considering load characteristics, the following should be evaluated:
  - ✓ What type of load is associated with the application ?
  - ✓ What is the size of the load?
  - ✓ Does the load involve heavy inertia ?
  - ✓ What are the motor considerations ?
  - ✓ Over what speed range are heavy loads encountered ?

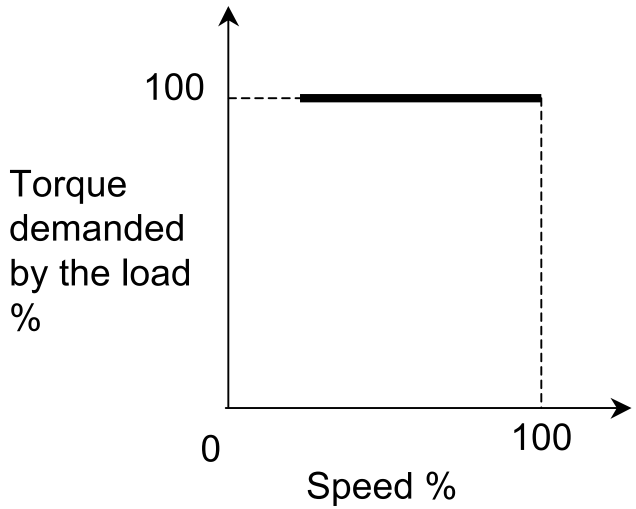
Motor Load Types

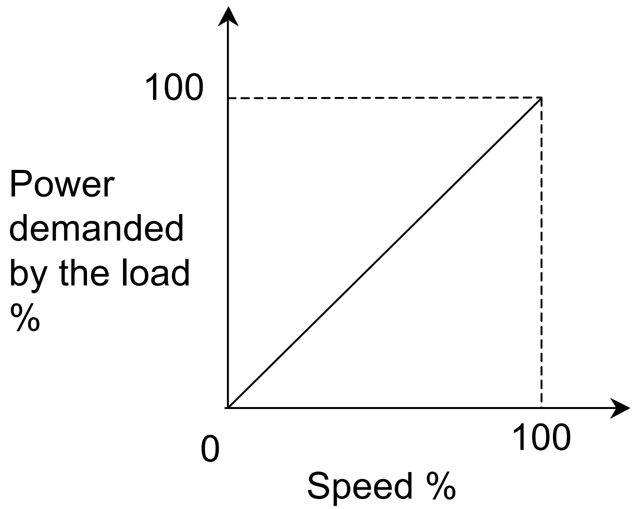
1.Constant Torque Load

The torque demanded by the load is constant throughout the speed change.

The load requires the same amount of torque at low speeds as at high speeds. Loads of this type are essentially friction loads.

Examples: Conveyors, Extruders, and Surface Winders.



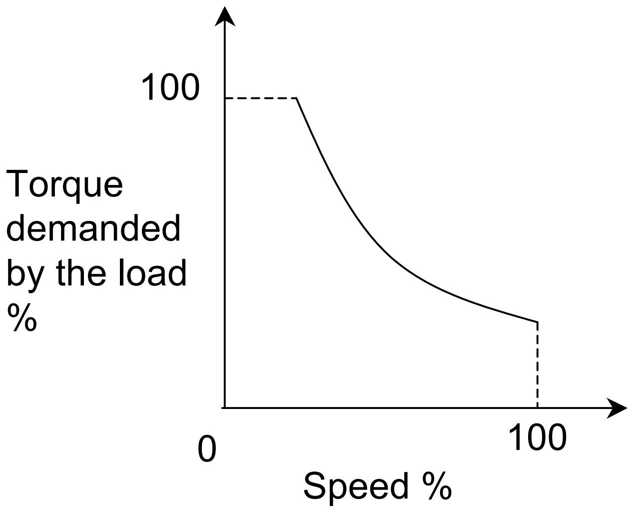


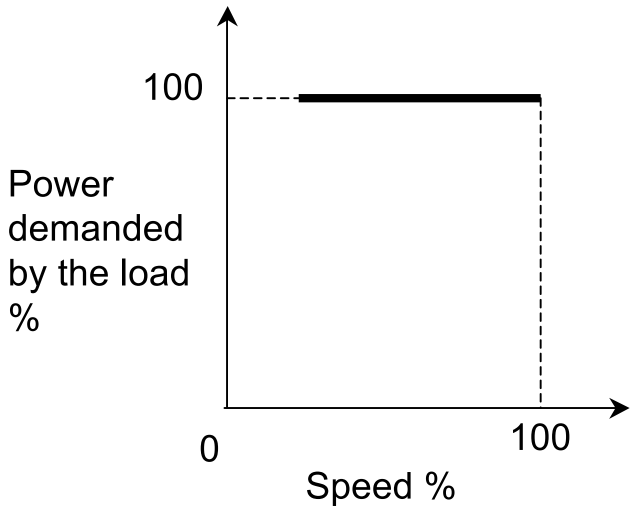
Motor Load Types (contd')

2. Constant power Load

The power demanded by the load is constant within the speed range. The load requires high torque at low speeds.

Examples: Center-driven winders and Machine tool, spindles.

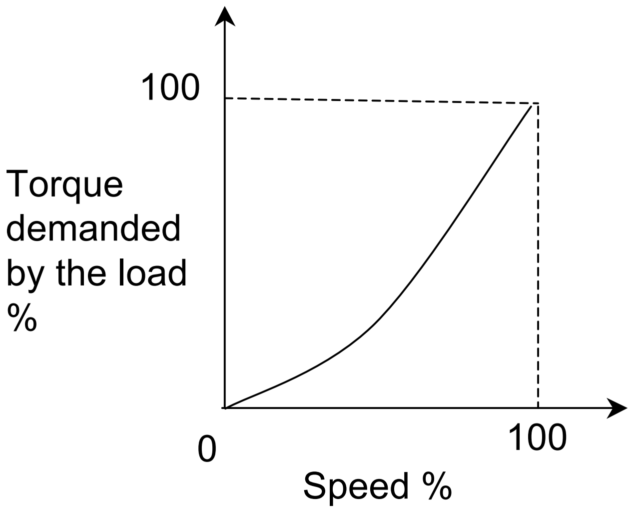


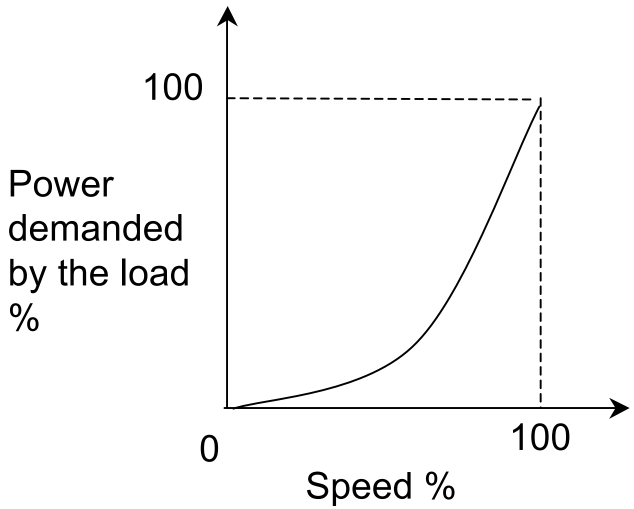


Motor Load Types (contd')

3. Variable torque load

Example: Torque is proportional to square of speed.
Thus, the power is proportional to cubic speed.



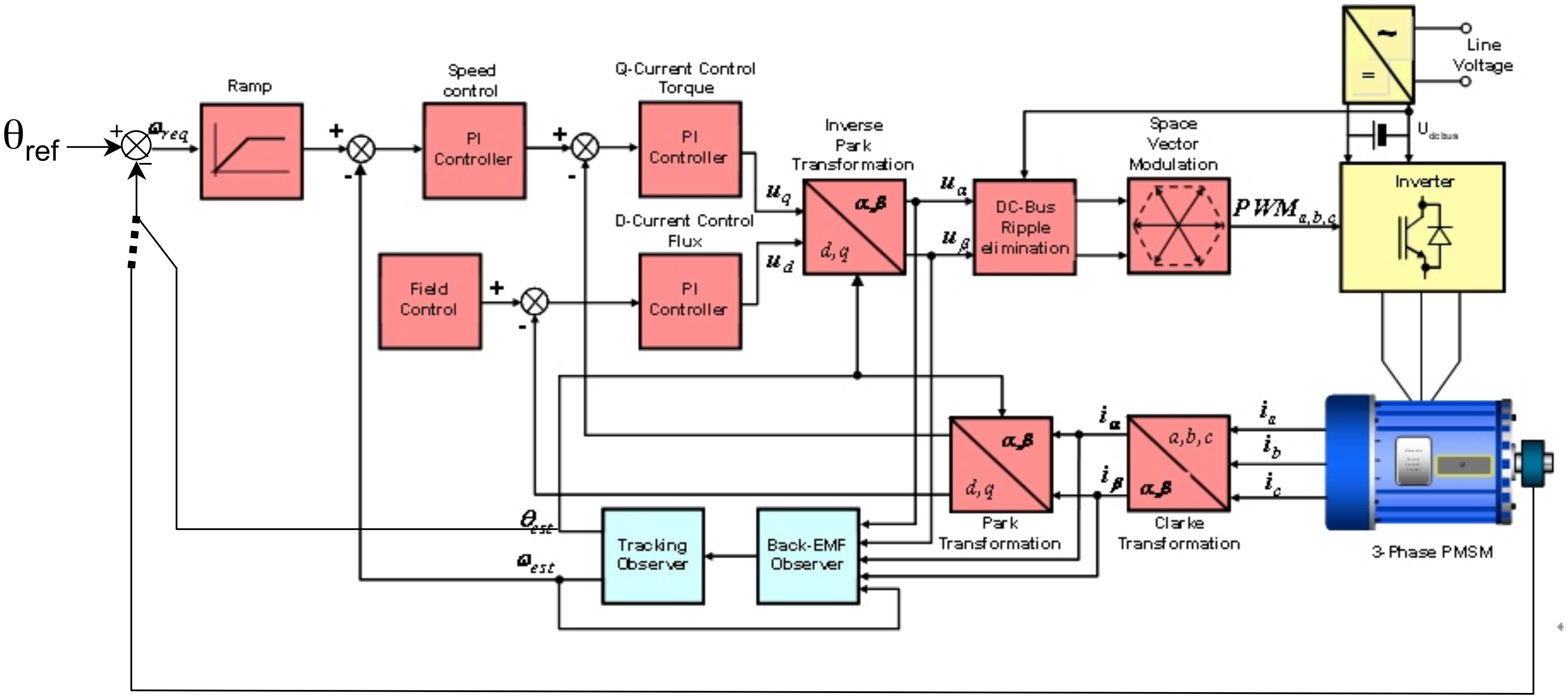


Load power and torque characteristics

1. Constant power, torque varies inversely with speed
   - Applications: Metal cutting tools operating over wide speed range, mixer, extruder and special machines where operation at low speed may be continuous
2. Constant torque, power varies as the speed
   - Applications: General machinery hoists, conveyors, printing press
3. Power varies as square of the speed, torque varies with speed
   - Applications: Positive displacement pumps, some mixers, some extruders
4. Power varies as cube of the speed, torque varies as square of speed
   - Applications: All centrifugal pumps and some fans (Note that fan power may vary as the power of speed)
5. High inertial loads
   - Applications: Are typically associated with machines using flywheel to supply most of the operating energy, punch press
6. Shock loads
   - Applications: Drives of crushers, separators, grinders, conveyors, and vehicular systems

➢ Power converters and motors can be damaged if they are not protected from the overload conditions

Typical MCS of three-phase PMSM



Dynamics of Motion Control System

- Control Methods
  - Conventional Joint PID Control
    - Widely used in industry
  - Advanced Control Approaches
    - Computed torque approach
    - Nonlinear feedback
      - H-inf robust control
    - Adaptive control
      - Model reference adaptive control
      - Internal model control
    - Variable structure control
      - Sliding mode control
    - Fuzzy logic control
    - Neural network control

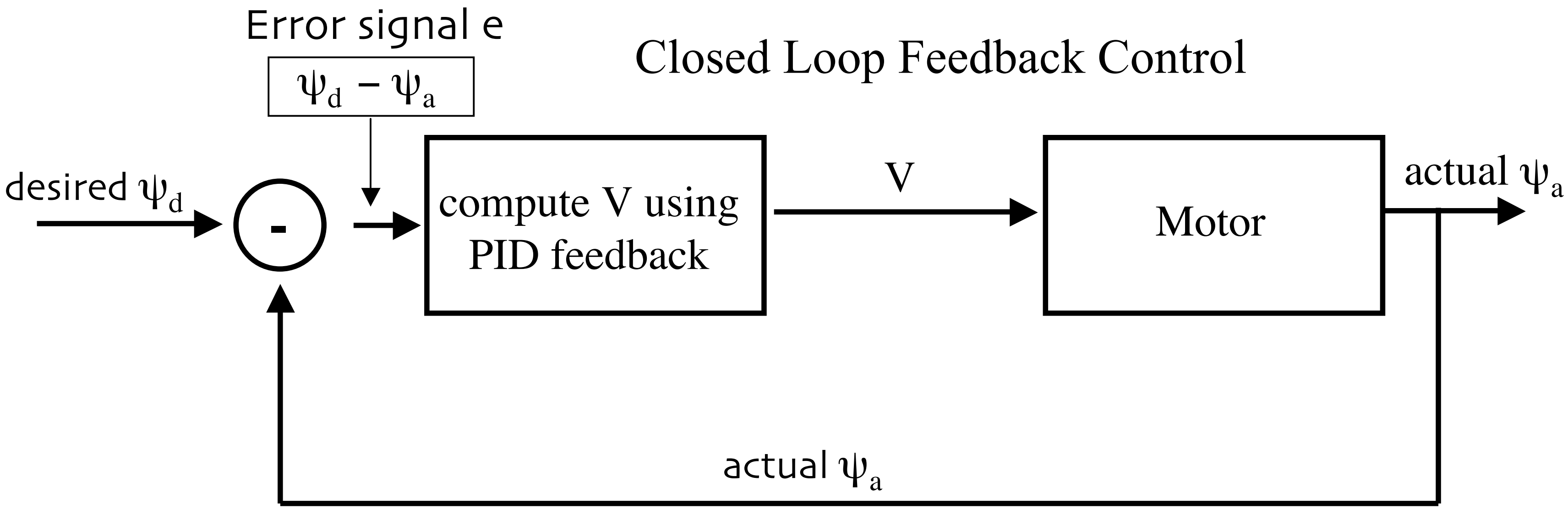
Control Theory Review (PID control)

PID controller: Proportional / Integral / Derivative control

$e = \psi_d - \psi_a$

$V = K_p \bullet e + K_i \int e\, dt + K_d\, de/dt$ $\qquad V(s) = (K_p + K_i s + K_d / s) E(s)$

Closed Loop Feedback Control



Control Theory Review (Linear Control System)

State space equation of a system

$$\dot{x} = Ax + Bu \qquad \text{(Equ. 1)}$$

Example:

A two-order system:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = u \end{cases} \Rightarrow \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u$$

Eigenvalues of A are the roots of characteristic equation

$$|\lambda I - A| = 0 \Leftrightarrow$$

$$|\lambda I - A| = \begin{vmatrix} \lambda & -1 \\ 0 & \lambda \end{vmatrix} = \lambda^2 = 0$$

Asymptotically stable refers to all eigenvalues of A have negative real part.

Control Theory Review (feedback control)

- Find a state feedback control such that the closed loop system is asymptotically stable
- Closed loop system becomes
- Choose K, such that all eigen-values of A'=(A-BK) have negative real parts

$$\dot{x} = Ax + Bu$$

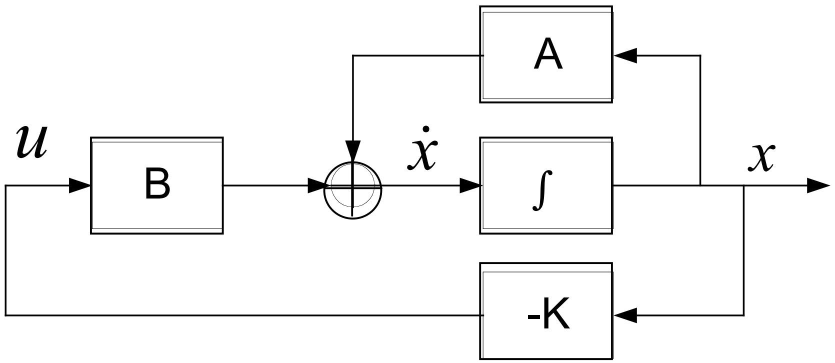
$$u = -K \cdot x \qquad \text{(Equ. 2)}$$

$$u = \begin{bmatrix} k_1 & k_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\dot{x} = (A - BK)x$$

$$|\lambda I - A'| = \begin{vmatrix} \lambda & -1 \\ k_1 & \lambda + k_2 \end{vmatrix}$$

$$= \lambda^2 + k_2 \lambda + k_1 = 0$$



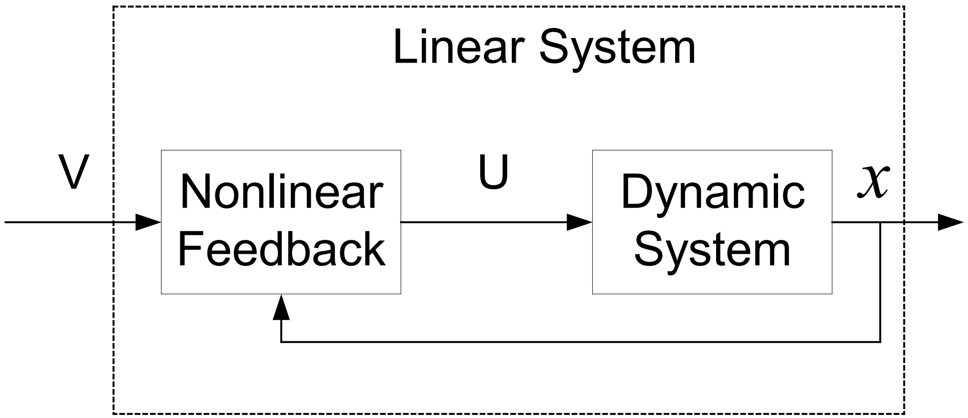
Control Theory Review (Nonlinear Control)

- Feedback linearization
  - Nonlinear system

$$\dot{X} = f(x) + G(x)U$$

$$U = [-G^{-1}(x)f(x) + G^{-1}(x)V]$$

$$\dot{X} = V$$



Original system:

$$\ddot{x} + \cos x = U$$

Nonlinear feedback:

$$U = \cos x + V$$

Linear system:

$$\ddot{x} = V$$

Thank you

for attention!

Glossary

- Kinematics: the branch of mechanics concerned with the motion of objects without reference to the forces that cause the motion.
- Actuator: operating mechanism.
- Motor:a machine, especially one powered by electricity, that supplies motive power for a vehicle or for some other device with moving parts.
- Reluctance: the property of a magnetic circuit of opposing the passage of magnetic flux lines, equal to the ratio of the magneto-motive force to the magnetic flux.
- Robotics: the branch of technology that deals with the design, construction, operation, and application of robots.
- Induction:the production of an electric or magnetic state by the proximity (without contact) of an electrified or magnetized body; the production of an electric current in a conductor by varying the magnetic field applied to the conductor.
- Synchronous: moving in the same speed.
- Cogging torque: a torque caused by cog effect.
- Proximity:nearness in space, time, or relationship.