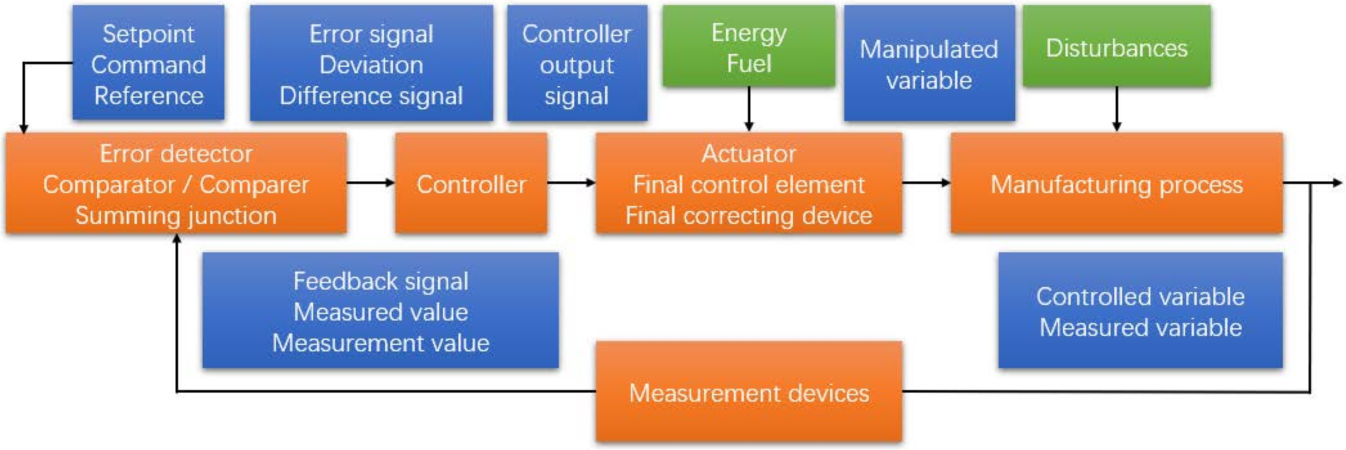
Introduction

2 Motion control devices control the position, speed, acceleration, or deceleration of an object. milliseconds



13 Error sources: The setpoint is changed. A disturbance appears. The load demand varies.

15 A measure of the loop's corrective action is referred to as its dynamic response.

16 Dynamic response delay = response time + time duration + dead time = time lag of instruments + one instrument to the next + controlled variable occurs to the corrective action

17 Feedback control limitations: large magnitude disturbances, long delays in the dynamic response of control loop.

18 Feed-forward control prevents errors from occurring and minimizes them, but cannot handle unmeasurable disturbances without feedback control.

Controller

23 Controller differs in response speed and accuracy

27 On-Off control: oscillate

$$\text{Differential Gap (Deadband)} = \frac{\textit{Differential Gap}}{\textit{Total Control Range}}$$ Hysteresis percentage

28 Lagged effect in process is called process lag time.

$$\text{Gain} = \frac{\textit{Percentage of Output Change}}{\textit{Percentage of Input Change}} \qquad \text{PB} = \frac{\textit{Controlled Varaible \% Change}}{\textit{Final Control Element \% Change}} \times 100 \qquad PB = \frac{1}{Gain} \times 100$$

31 A temperature change of 2 percent of the span causes valve to vary by 4 percent of its span. Gain = 2 PB = 50

34 The difference between setpoint and the measured value is called steady-state error, or offset.

36 Offset depends on three factors: Load or demand. The low gain or wide PB. The setpoint.

37 The integral (reset) mode of control is to eliminate the offset in proportional mode control.

37 PI control is used when load disturbances is frequent, setpoint changes are infrequent and load changes are slow.

44 Derivative (rate of change) control is sometimes referred to as anticipatory or predictive control.

44 The derivative mode is used only when the controlled variable lags behinds a setpoint change.

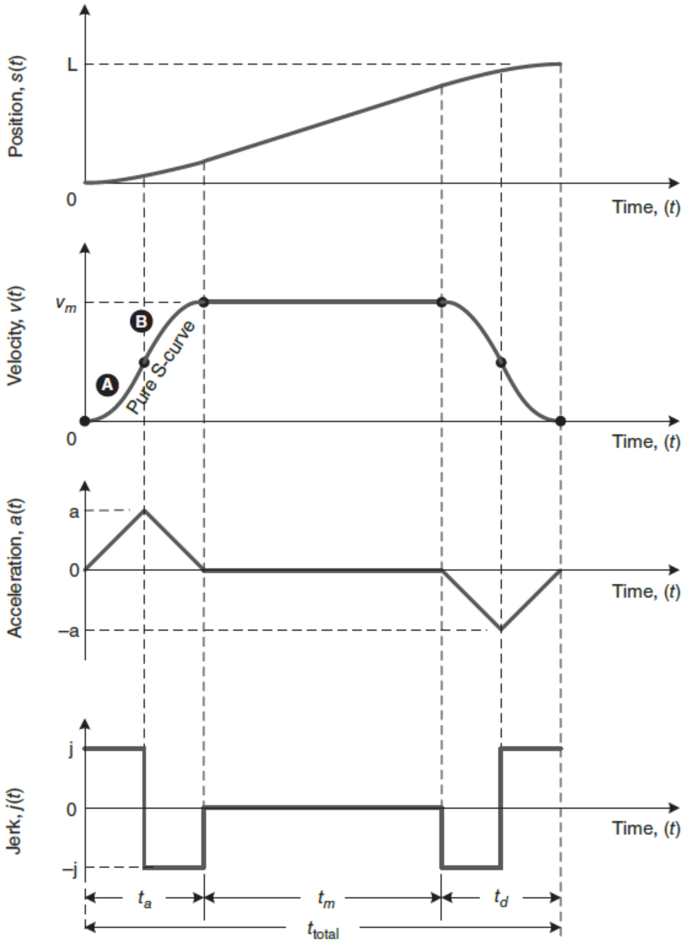
39 The boosting and braking reduce overshoot and dampen oscillations of controlled variable.

50 PWM Average Voltage = Duty Cycle * On-State DC Voltage

Motion Profile

53 The trajectory is also called motion profile, leading to smooth acceleration from “A” to a constant operational speed. After moving at this speed for a while, the axis needs to smoothly decelerate to come to a stop at “B”.

60 Trapezoidal Velocity Profile / 70 S-curve Velocity Profile



$$t_a = \frac{2v_m}{a} \qquad C = \frac{a^2}{2v_m}$$

$$a_A(t) = 2Ct \quad v_A(t) = Ct^2 \quad s_A(t) = \frac{C}{3}t^3$$

$$a_B(t) = 2C(t_a - t)$$

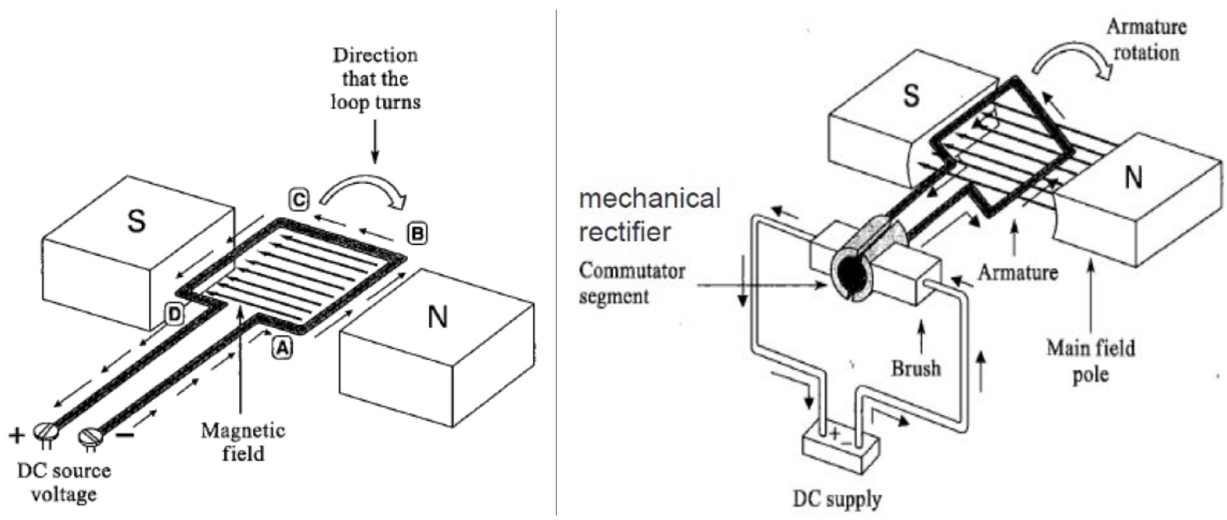
$$v_B(t) = v_m - C(t_a - t)^2$$

$$s_B(t) = v_m t_a - \frac{C}{3}(2t_a - t)^3$$

76 Multi-axis Motion: Move one axis at a time. Start moving all axes at the same time (slew motion). Adjust the motion of the axes so that they all start and finish at the same time (interpolated motion).

DC Motor

81 For motor action, there is a current flow through a conductor and the conducting wire is placed inside the magnetic field formed between two magnetic poles.



85 Neutral plane: perpendicular to the field, no interaction
91 Two-loop armature SOLVED: Cannot start the motor when the armature is in the neutral position. Speed is erratic because its torque is irregular.
92 Connect loops of armature to adjacent commutator segments, dead weight is avoided.

94 CEMF: The physical properties of the armature. The strength of the magnetic field supplied by the field poles. The rotational speed of the armature.

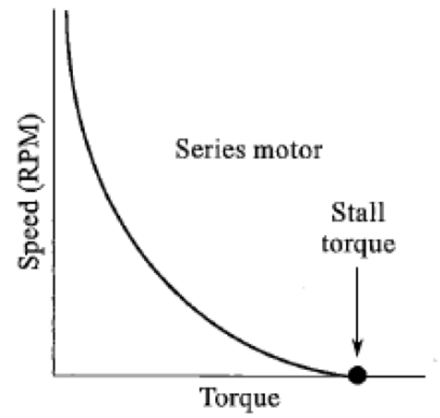
96 The shifting of the neutral plane is known as armature reaction. As more current is applied, the more rapidly the motor runs and the larger the armature reaction becomes.
97 It reduces torque. It makes the motor less efficient. The continuous sparking shortens the life of the brushes and damages the commutator.
98 The effect of armature reaction is corrected with interpoles, sometimes called commutating poles.

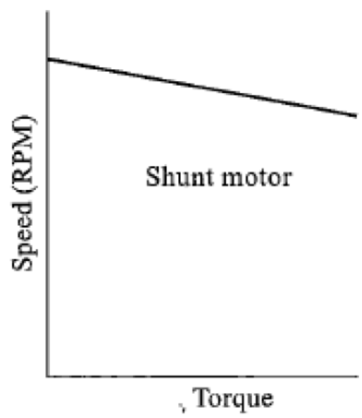
101 Speed Regulation = (No-Load Speed – Full-Load Speed) / Full-Load Speed x 100
Torque: Strength of the main field, armature current, physical construction of the motor.
The torque when driving its rated mechanical load is called the rated load torque.
T = 100 lb X 1.5 ft = 150 lb-ft W = 10 ft X 250 lb = 2500 ft-lb PkW = 11.42 X 0.746 = 8.52 kW
P = 250000 ft lb / 2 min = 125000 ft-lb/min = 125000 / 33000 = 3.79hp
Power-efficiency = power-out / power-in * 100% (copper losses and mechanical losses)

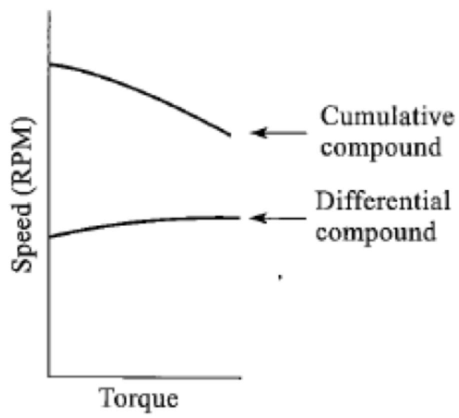
112 All motors: the armature and the field poles. DC motor: armature winding, commutator, brushes, field winding.
114 Shunt Motor
The field winding is connected in parallel with the armature windings.
The shunt field coil has many turns of fine wire and a higher resistance.
Since the coil is connected to the fixed-line voltage terminals, it's a constant-speed motor for self-regulate ability.
The shunt type has the highest starting armature current and the lowest torque.
Control of speed: field flux control, terminal voltage control and armature voltage control (preferred).
Applications: exact control such as numerical control machines.

120 Series Motor
The field coil develops little resistance because it is wound with few turns.
Poor speed-regulation. Largest starting torque. No load: runaway

123 Compound Motor
In practice, it is standard to change the armature connections to change the direction.
In a compound motor, both the shunt and series field coils must be changed.
Applications: freight elevators, stamping presses, rolling mills and metal shears.







AC Motor

Components: armature winding (rotor) and field winding (stator).

150 Factors for rotor's speed:

1. The frequency of the applied voltage
2. The number of stator poles per phase (smooth)
3. The inductance of the stator coils

Synchronous speed N = (f X 60) / P

N = RPM, P = Number of pole pairs (per phase), f = applied frequency

Slip = (Synchronous Speed – Rotor Speed) / Synchronous Speed X 100%

Excessive slip for induction motor: stall, overheat and breakdown.

162 Resistance-Start Induction-Run Motor

The second coil, called the auxiliary or start winding, has a comparatively high resistance and lower inductance.

Since the run winding is more inductive, the current flow through it will appreciably lag the applied voltage.

Start winding is removed by centrifugal switch when motor speeds up.

Advantages: inexpensive, requires very little maintenance, and has constant speed characteristics.

Disadvantages: low starting torque and noise

Applications: easy to start, no require reversing, no need to start and stop frequently. drill presses, oil burners, sump pumps, some washing machines, and a number of other household appliances.

167 Capacitor-Start Induction-Run Motor

The start-winding current leads the applied voltage. Larger starting torque.

In practice, the start winding circuit leads are interchanged to change the direction.

Applications: frequent starting and hard-to-start loads, machine tools requiring single-phase power. pumps, conveyors, and compressors used by refrigeration systems and air conditioners

171 Shaded-Pole Motor

The smaller segment is called the shaded pole and is surrounded by a shading coil.

Advantages: inexpensive, rugged, require very little maintenance, and consume little electricity.

Disadvantages: small and inefficient.

Applications: light load applications requiring little horsepower. clocks, fans, blowers, pumps, toys and other items that are inexpensive to make and operate

177 Universal Motor

high starting torque, high no-load speed but no break apart, poor speed regulation.

Compensating windings is connected in series with the rotor and stator. They correct the neutral plane position. They compensate for undesirable reactive voltages.

Speed determines on change in the applied voltage / load / frequency of the power supply.

To control speed, insert a variable resistor in series with the field coil or tap a field coil at various points.

In practice, the armature connections are interchanged to change the direction.

Malfunctions: worn-out brushes, shorted armature windings

Applications: high power. vacuum cleaners, polishers, hedge trimmers, circular saws, and mixers

182 Three-phase (polyphaser) Motor

Advantages: simpler in construction, more efficient, less likely to become defective, more powerful.

183 Induction motor (squirrel cage)

Applications: good speed regulation. large conveyor systems, large pumps, and machine tools

188 Wound-rotor Motor
Its rotor consists of three coils replacing the conducting bars of the squirrel cage rotor.
Disadvantages: low efficiency, poor speed regulation at low RPMs, increased maintenance, high manufacturing cost
Applications: large load, frequent and smooth starting, stopping and reversing of high-inertia loads and speed control. rock crusher which sudden loads that bog down during the starting period

191 Synchronous Motor
Squirrel cage + pull-in torque from exciter DC power = synchronous rotating
Advantages: durable, dependable, efficient, insensitive to variations, constant speed, powerful.
Disadvantages: low starting torque
Applications: constant speed, no frequently starts and stops. pumps
Functions: Convert AC electrical energy into mechanical power at accurate speeds. Performs power correction.
Under excited: It has lagging power factor like an induction motor.
Normally excited: The current supplied to the motor is at its lowest level.
Over excited. The CEMF causes the stator current to lead the applied voltage.

Servo Motor
196 DC PM motors are smaller and lighter than would field DC motors that produce the same amount of torque. They are often used in applications that require portability and low maintenance requirements.

201 Wound Armature PM Motor
Since permanent magnets are used for pole pieces, the field flux remains constant. There is no EMF induced into the field poles to cause the flux strength to vary. This gives the motor linear speed-torque characteristics similar to a conventional DC shunt motor.
Disadvantages: thermally inefficient, no high torque for long time, brushes wear out soon
Applications: office machines, printers, disk drives, industrial robot (large)

203 Moving Coil PM Motor
The stator field is provided by eight pairs of permanent magnets on each side of disk and parallel to motor shaft.
The speed of the motor is varied by changing the amount of voltage supplied to the armature (PWM)
Advantages: low inertia, long brush life, run smoothly at low speed

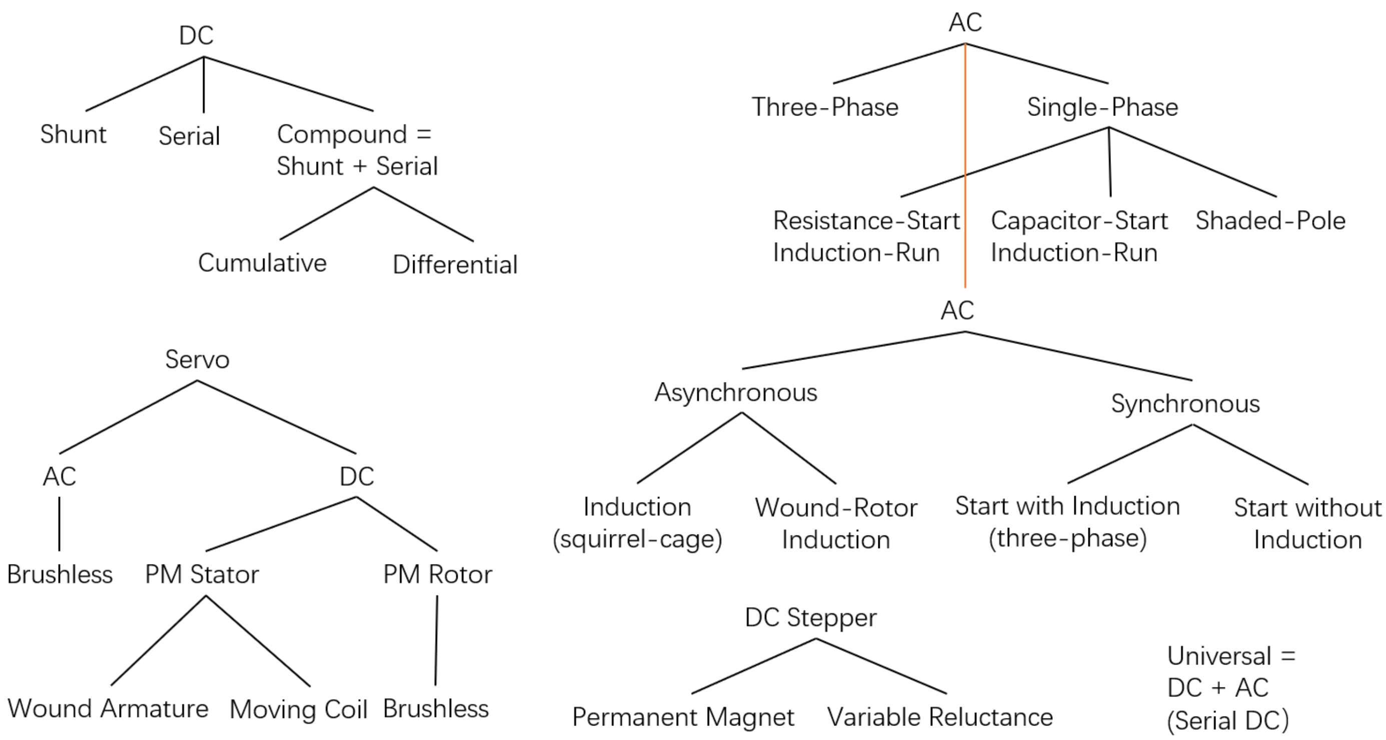
206 Brushless DC motors (three-phase)
The BDCM also contains a converter and a rotor position sensor. The converter is an electronic commutator that changes direct current into pulsating DC voltages, which are applied to the stator windings to create magnetic field. The amount of force required to move the rotor away is called holding torque.
Advantages: maintenance-free, no electrical noise, low inertia, readily dissipated heat
Applications: requires high speed, high peak torque capacity, and quick acceleration or deceleration. screen printing machinery, material handling equipment and grinders

209 Stepper Motor
In a stepper motor, the armature turns through a specific number of degrees and then stops.
It also produces a holding torque at standstill to prevent unwanted motion.
Stepping rate Y is the maximum number of steps the motor can make in a second.
Step angle S is the number of degrees that the motormoves per step.
$N = Y * S / 6$
Disadvantages: jerks in low speed, limited resolution (solved by micro stepping)
Applications: require accurate positioning

210 Permanent Magnet Stepper Motors (PM rotor)
It is constructed of four electromagnets located 90 degrees apart in the stator.
An external transistor is connected to each of the coils.

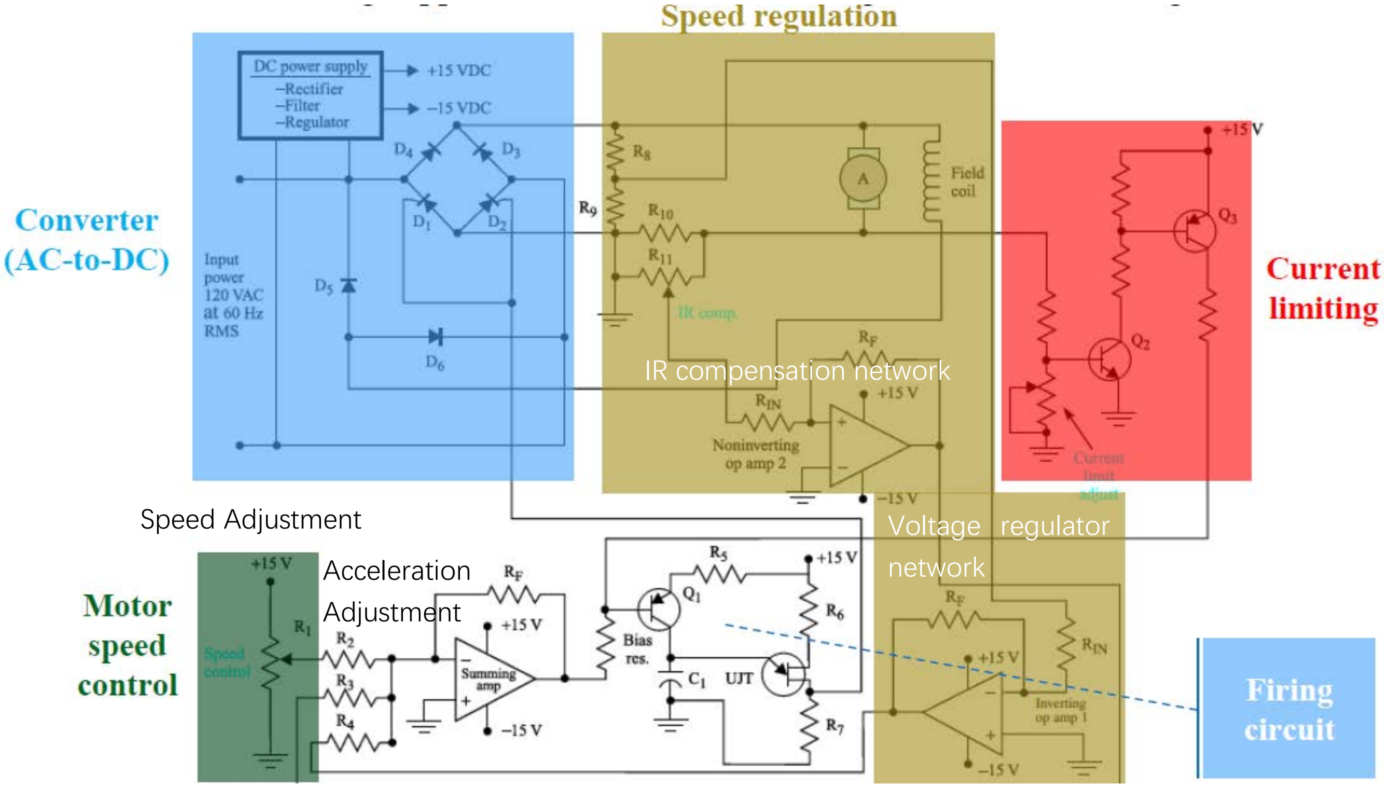
212 Variable Reluctance Stepper Motors (PM rotor)
Advantages: small and light
Applications: variable-speed fans, blowers, and hazardous

218 AC Brushless Servo Motors
AC servo motors are controlled by AC command signals that are applied to coils, which become electromagnets.
It operates on the same principle as the single-phase induction motor. Auxiliary phase by AC servo drive amplifier.
To prevent turning in desired position caused by unchanged main field voltage (no auxiliary field), the rotor has high-resistance conducting bars.



Variable-Voltage DC Drive

12 Variable-voltage drive regulates voltage applied to the armature winding, shunt field winding, or both.



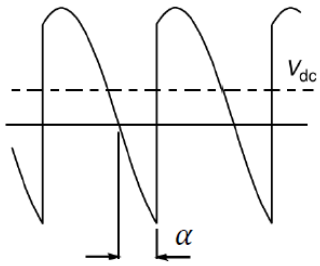
13 Converter / Rectifier

The half-wave rectifier

The full-wave bridge rectifier

The three-phase half-wave rectifier

The three-phase full-wave rectifier



$$V_{DC} = \frac{2\sqrt{2}}{\pi} V_{RMS} \cos(\alpha)$$

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T v_i^2 dt} = \frac{V_M}{\sqrt{2}}$$

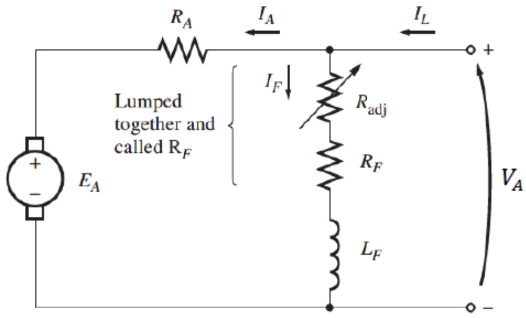
16 Speed Regulation

$$N = \frac{E_A}{K\emptyset} = \frac{V_A - I_A R_A}{K\emptyset} \qquad \tau = K\emptyset I_A \qquad P = \tau N$$

Factors: applied voltage, physical load

Voltage regulator: keep V_A constant

IR compensation: keep I_A constant



Equivalent circuit of a shunt DC motor

Speed Control of Shunt DC Motors – example in Variable-voltage DC drive → Speed Regulation

23 Field resistance control

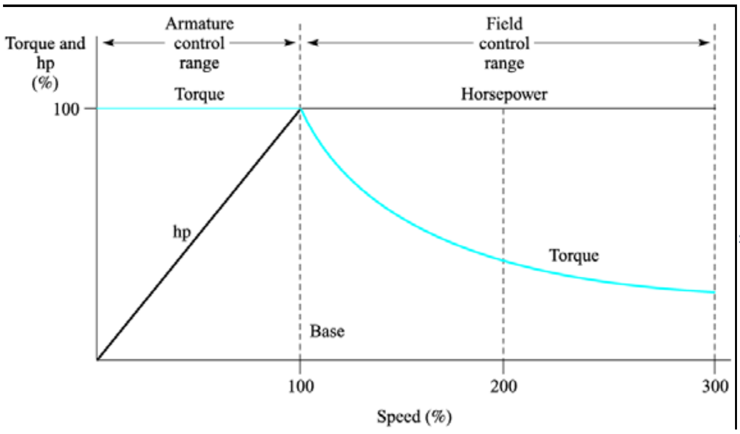
An increase in field current causes a decrease in speed, there is a minimum achievable speed.

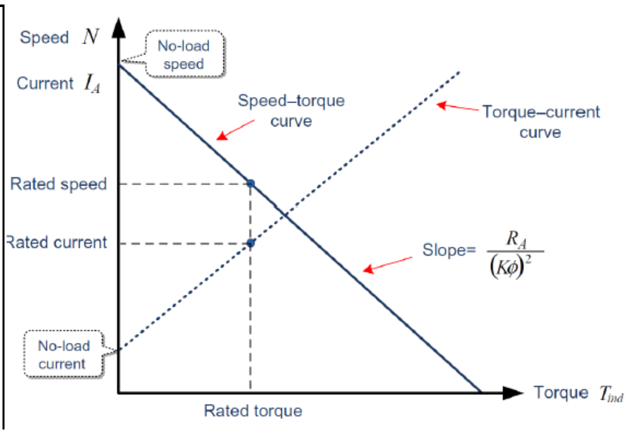
25 Armature voltage control

An increase in armature voltage causes an increase in speed, there is a maximum achievable speed.

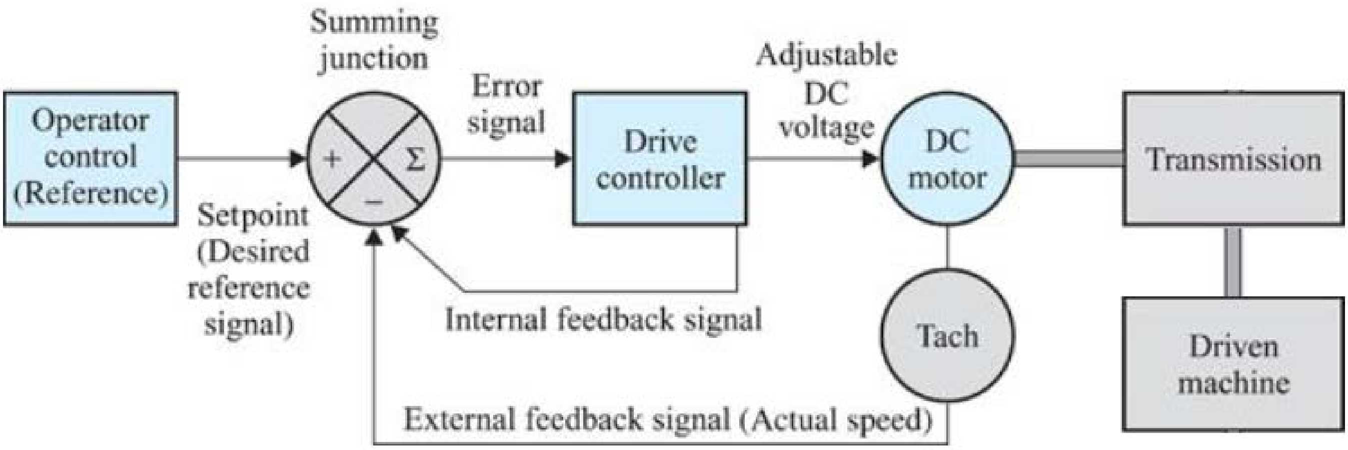
1. Increasing R_F causes I_F to decrease.
2. Decreasing I_F decreases ϕ.
3. Decreasing ϕ lowers E_A.
4. Decreasing E_A increases I_A
5. Increasing I_A increases τ_{ind}, with the change in I_A dominant over the change in flux ϕ.
6. Increasing τ_{ind} makes $\tau_{ind} > \tau_{load}$, and the speed N increases.
7. Increasing N increases E_A again.
8. Increasing E_A decreases I_A.
9. Decreasing I_A decreases τ_{ind} until $\tau_{ind} = \tau_{load}$ a higher speed N.

1. An increase in V_A increases I_A [$= (V_A\uparrow - E_A)/R_A$].
2. Increasing I_A increases τ_{ind} [$= K\phi I_A \uparrow$].
3. Increasing τ_{ind} makes $\tau_{ind} > \tau_{load}$ increasing N.
4. Increasing N increases E_A [$= K\phi N \uparrow$].
5. Increasing E_A decreases I_A [$= (V_A - E_A\uparrow)/R_A$].
6. Decreasing I_A decreases τ_{ind} until $\tau_{ind} = \tau_{load}$ at a higher N.



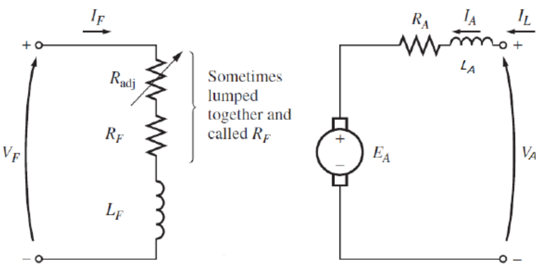


Shunt Motor System Model

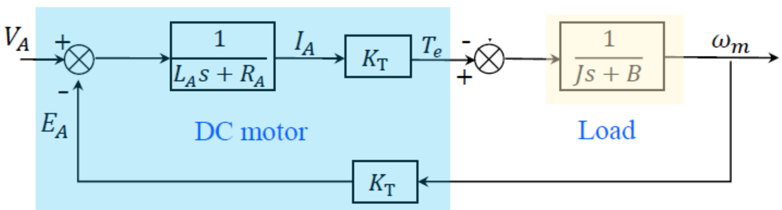


where T_e (τ_{ind}) is the induced torque, T_L is the load torque, $T_b = B\omega_m$ is the viscous friction load, J is the rotor inertia, ω_m is the motor speed.

$$K_T = K\phi$$



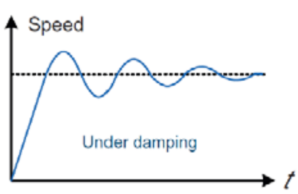
A shunt (or separately excited) DC motor



Block diagram for a DC motor

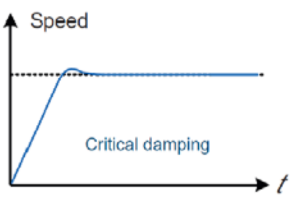
34 Assuming $B = 0$, let

$$\boxed{K_m = \frac{JR_A}{K_T^2}, \quad K_A = \frac{L_A}{R_A}}$$



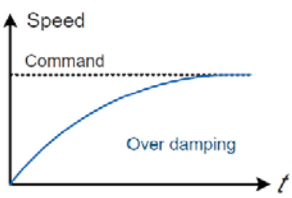
$K_m < 4K_A$

- ✓ The characteristic equation has two complex roots.
- ✓ Reaches equilibrium but has an oscillatory response.



$K_m = 4K_A$

- ✓ The characteristic equation has two equal real roots.
- ✓ Reaches equilibrium rapidly without oscillating
- ✓ The most desirable!



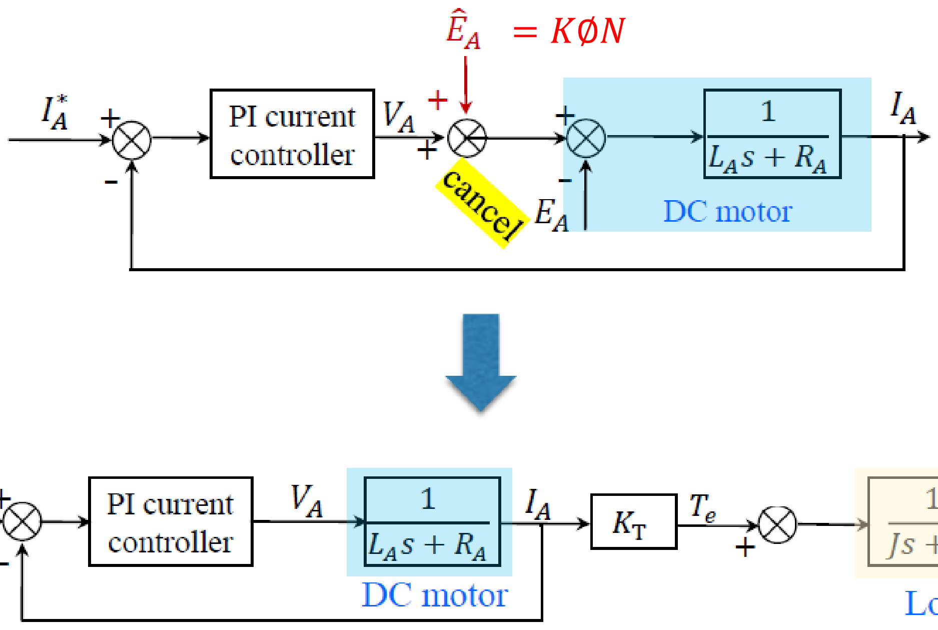
$K_m > 4K_A$

- ✓ The characteristic equation has two different real roots.
- ✓ Not oscillate, but has a very slow response.

- Normally, small motors have $K_m > 4K_A$, while servo motors or high power motors have $K_m < 4K_A$, resulting in oscillatory response.

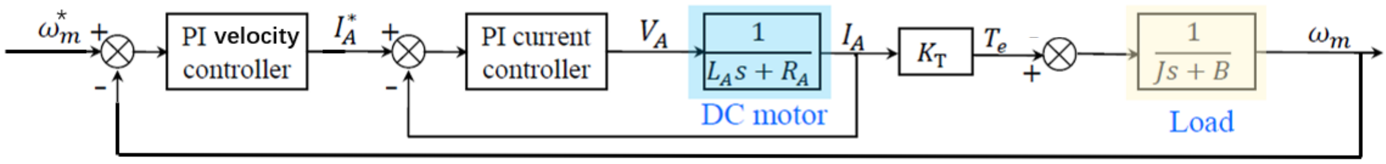
39 Current control

of E_A by adding the CEMF compensation $\hat{E}_A$.

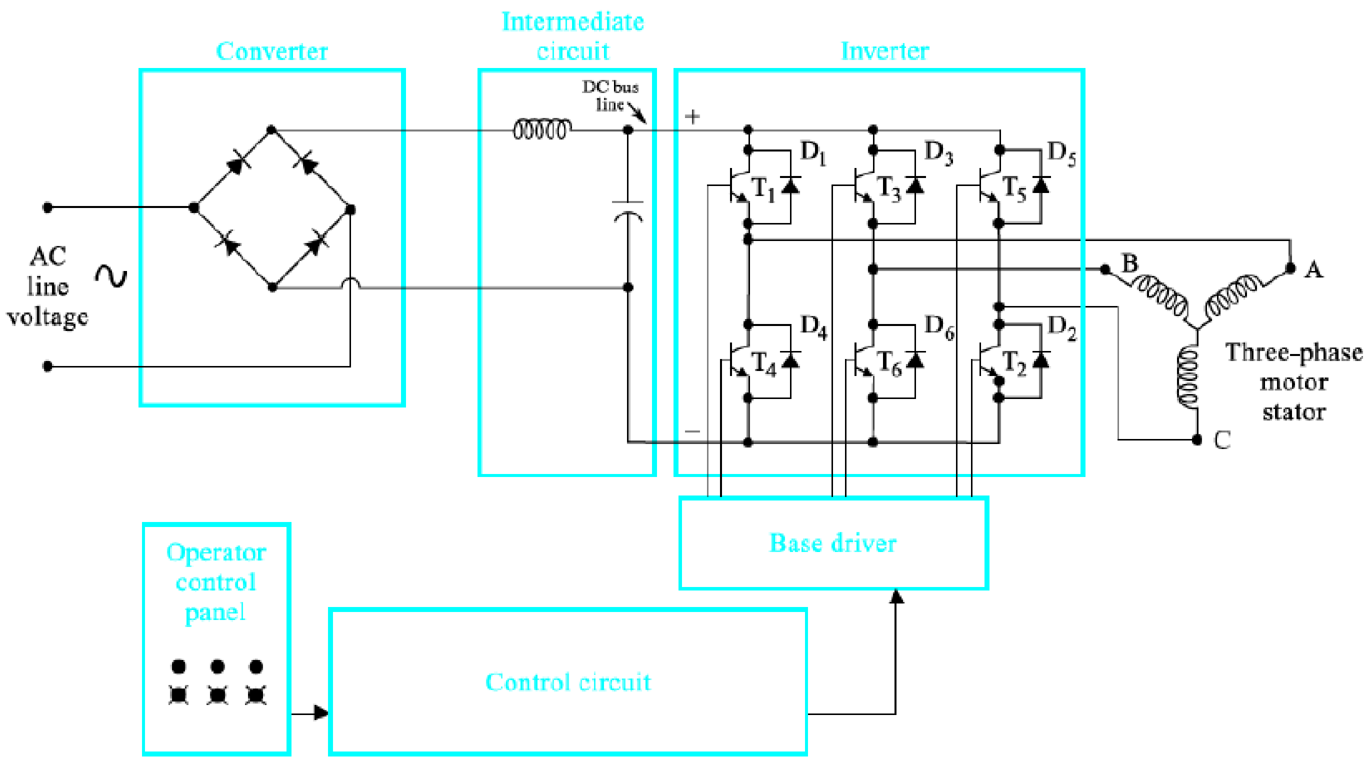


Current control system

40 Velocity control



AC Drive



50 A converter is a rectifier that convers AC line voltage to a pulsating DC voltage.

Three-phase full-wave rectifier converts the incoming three-phase AC line power into a DC voltage with ripple.

54 The intermediate circuit transforms the pulsating DC signal to a smooth DC wave called the DC bus line.

55 There are two typical circuit configurations: inductive (L) filter and LC filter.

The function of the inverter is to “invert” the DC bus line back to simulated AC power at the desired frequency.

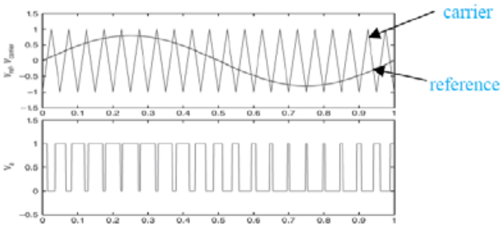
59 The inverter is controlled by PWM: AC ref / carrier → PWM. PWM + DC from converter → AC

By changing the frequency and amplitude of the reference signal, we can control the frequency and amplitude of the line voltages applied to the motor. The regenerative AC wave has the same f as the reference voltage and its maximum amplitude is $\frac{V_{ref\ max}}{V_{carrier\ max}}$

A **reference signal**, V_{ref}, and a **triangular carrier signal**, V_{carrier}, are used as control signals to generate a PWM signal.

- The voltage and frequency of the carrier signal are fixed;
- The reference signal have adjustable voltage and frequency;
- At any given time, the magnitudes of the signals are compared to each other.

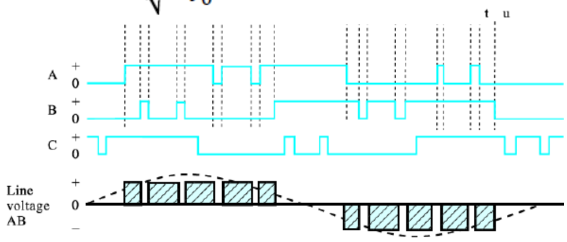
$$\Delta v = V_{\mathrm{ref}} - V_{\mathrm{carrier}} \begin{cases} > 0, \text{PWM signal is set to 1} \\ < 0, \text{PWM signal is set to 0} \end{cases}$$



$$D = \frac{t_{on}}{T} \times 100\%$$

$$V_{\mathrm{ave}} = \frac{1}{T}\int_0^T \mathrm{PWM}\, dt = D \times V_H$$

$$V_{\mathrm{RMS}} = \sqrt{\frac{1}{T}\int_0^T \mathrm{PWM}^2\, dt} = \sqrt{D} \times V_H$$



PWM Control Methods

66 Volts/Hertz: The simplest control process. No feedback device that monitors the load.

$$\tau = K\emptyset I_A \quad I = \frac{V}{X_L} = \frac{V}{2\pi f L}$$

In order to keep current under control, we must lower V to the motor as f is reduced. “volts per hertz”.

At a slow RPM, some volts/hertz drives can supply the extra current by called torque boost (auto boost).

69 AC closed-loop vector: Use both inner and outer loops.

The model will use a lookup table to see what the motor should do at the given frequency, current and voltage.

70 Sensorless vector: Use only inner loop to measure the current from motor for monitoring speed and torque.

This inner loop feedback signal is used for calculations in the same way as the AC closed-loop drive.

Pros and Cons

Advantages

- Simple, “look-up table” control of voltage and frequency
- Good speed regulation (1%–3%)
- No motor speed feedback needed
- Multi-motor capability

Limitations

- Low dynamic performance on sudden load changes
- Limited starting torque
- Lacks torque reference capability
- Overload limited to 150%

Best for General Purpose and Variable Torque

- Centrifugal pumps and fans
- Conveyors
- Mixers and agitators
- Other light-duty nondynamic loads

Pros and Cons

Advantages

- Ultra-high torque and speed loop performance and response
- Excellent speed regulation to .01%
- Full torque to zero speed
- Extra-wide speed range control

Limitations

- Requires encoder feedback
- Single motor operation only
- May require premium vector motor for full performance benefits
- 4-quadrant (regenerative) operation requires additional hardware

Best for High-Performance Applications

- Converting applications
- Spindles and lathes
- Extruders
- Other historically DC applications

Pros and Cons

Advantages

- High starting torque capability (150% at 1 Hz)
- Improved speed regulation (<1%)
- No motor speed feedback needed
- Self-tuning to motor
- Separate speed and torque reference inputs

Limitations

- Speed regulation may fall short in certain high-performance applications
- Lacks zero-speed holding capability
- Multi-motor usage defaults to V/Hz operation
- Torque control in excess of 2 × base speed may be difficult

Suitable for all general-purpose, variable-torque, and moderate- to high-performance applications

- Extruders
- Winders and unwind stands
- Process lines

Inverter Self-Protection Function

To protect itself, the drive (inverter) will stop running and allow motor to coast to a stop, called fault trip function.

72 Overcurrent protection

Inertia of the load is excessively large.

A short circuit develops in the output leads or motor windings.

A component inside the inverter section has short circuited.

72 Overload protection

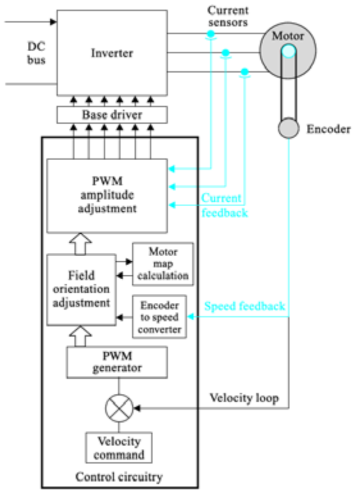
Slower than overcurrent

73 Overvoltage protection

Monitor DC bus-line

73 Undervoltage protection

73 Overheating protection



$$f_{slip} = sf_s = \frac{P}{60}(N_s - N_m)$$

Speed Control of Induction Motors

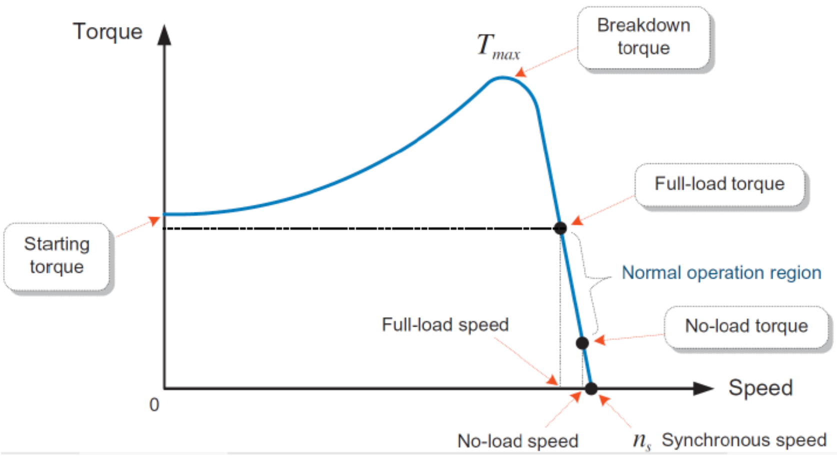
Slip frequency: All normal motor speeds fall somewhere between s = 0 (synchronous) and s = 1 (stationary)

- In the low-slip region: the normal operating range of an induction motor

$$\tau_{ind} \approx \frac{3}{\omega_s}\frac{V_s^2}{R_r'}s \Rightarrow \tau_{ind} \propto s$$

- In the low-speed range with larger values of the slip:

$$\tau_{ind} = \frac{3}{\omega_s}\frac{V_s^2}{(X_{ls} + X_{lr}')^2}\frac{R_r'}{s} \Rightarrow \tau_{ind} \propto \frac{1}{s}$$



- The starting torque is slightly larger than its full-load torque, so the motor will start carrying any load that it can supply at full power.
- There is a maximum possible torque that cannot be exceeded (letting $d\tau_{ind}/ds = 0$).
- The normal operating range is confined to less than 5% slip, and the speed variation over that range is more or less directly proportional to the load on the shaft of the motor.

80 Slip control: inefficient, restricted speed control range

vary the stator voltage

change the rotor resistance (wound-rotor type motors)

$$N_m = (1 - s)N_s$$

82 Synchronous speed control: efficient wide speed control range

× change the number of poles

change the stator frequency: keep volts per hertz a constant to maintain torque

$$N_s = \frac{60 f_s}{P}$$

83 Closed-loop speed control under constant V/f control: more accurate

Vector Control of AC Motors

d-axis: The d-axis is normally chosen as the direction of the magnetic flux in the AC motor. In the vector control, the d-axis is regarded as the reference axis, and the flux-producing component of motor current is aligned along it.

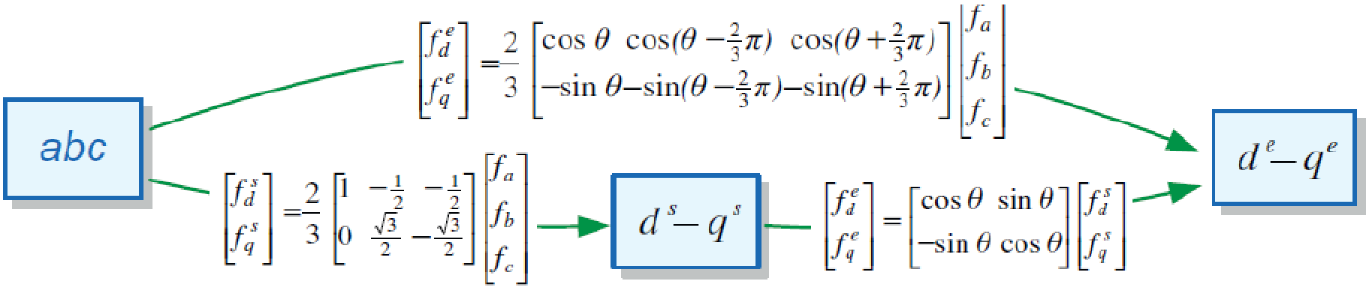
q-axis: The q-axis is defined as the direction 90° ahead of the d-axis. In the vector control, the torque-producing component of motor current or the CEMF is aligned along the q-axis.

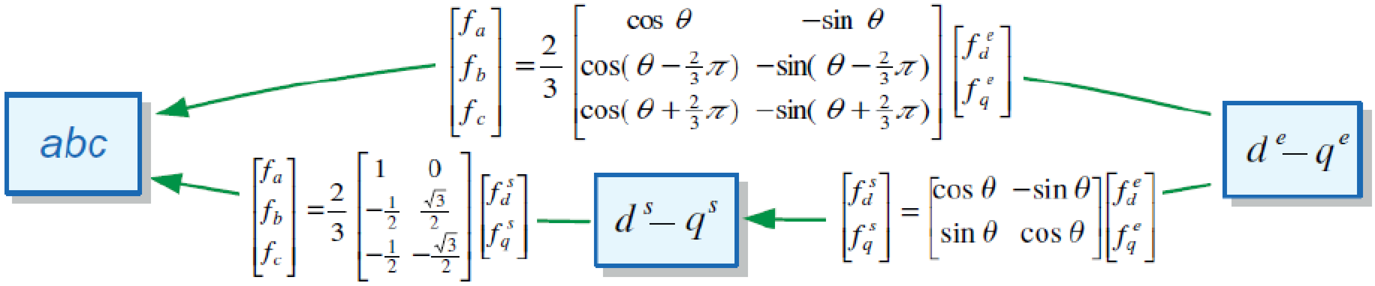
89 Stationary reference frame $d^s - q^s$

Rotating reference frame $d^w - q^w$

Synchronous $d^e - q^e$

Rotor $d^r - q^r$





$$T_e = \frac{3}{2}\frac{P}{2}L_m\left(I_{qs}^e I_{dr}^e - I_{ds}^e I_{qr}^e\right) = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\lambda_{dr}^e I_{qs}^e - \lambda_{qr}^e I_{ds}^e\right)$$

94 First, the three-phase stator currents are separated into d and q-axis stator currents by using the synchronous reference frame transformation in which the d-axis is assigned to the position of the flux vector.

Then, the flux can be controlled by the d-axis stator current I_{ds}^e while the instantaneous torque can be controlled by the q-axis stator current I_{qs}^e independently.

93 Induction motor

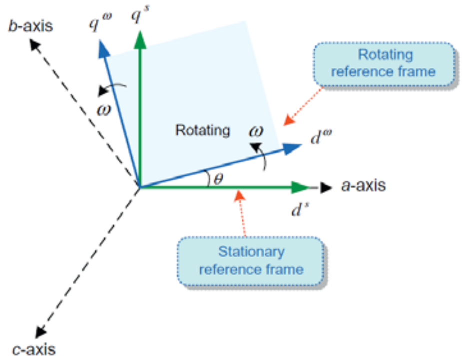
$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\lambda_{dr}^e I_{qs}^e - \lambda_{qr}^e I_{ds}^e\right) = K|\lambda|I_{qs}^e$$

$$\lambda_{dr}^e = |\lambda|, K = \frac{3P}{4}\frac{L_m}{L_r}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left[\phi_f I_{qs}^r + (L_{ds} - L_{qs}) I_{ds}^r I_{qs}^r\right]$$

98 Synchronous motor

$$T_e = \frac{P}{2}\frac{3}{2}\phi_f I_{qs}^r$$



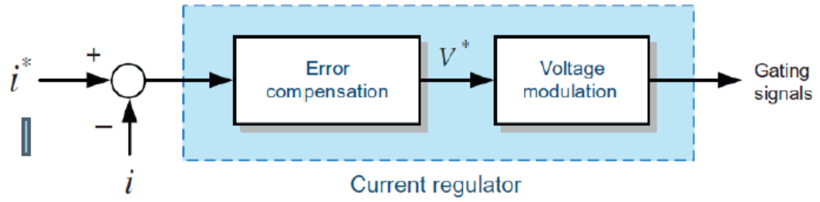
95 The performance of torque control depends on the accuracy of the rotor flux angle θe. To find the rotor flux angle, the d-q axes rotor flux linkages in the stationary reference frame are required as we can see $\theta_e = \tan^{-1}\left(\frac{\lambda_{qr}^s}{\lambda_{dr}^s}\right)$ or measure the flux linkages or the physical quantity proportional to the flux linkages.

100 Current controllers (regulators) of AC motors (next page)

Synchronous reference frame d-q current regulator (PI)

Cross-coupled components: feedforward control (also called the decoupling control)

- The main function of the current regulator is to transform the current error into gating signals for the switching devices of a PWM inverter in the time domain, which can produce the output voltage to make the required current flow into the motor.



- The error compensation part produces a command voltage to reduce the error between the actual and command currents
- The voltage modulation part generates gating signals for switching devices to accurately produce the command voltage.

Drive-Train Design

110 The motor and transmission combination is often called drive-train.

Design: Given the desired load motion, find the motor (motor sizing) and transmission

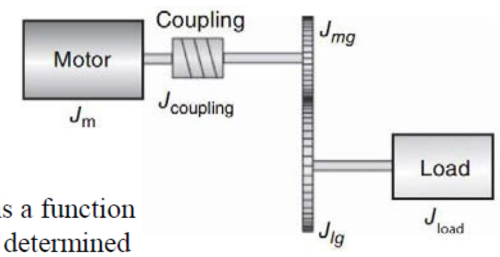
Ensure that torque available from motor (at maximum load speed) is greater than torque required by the application by a safety margin

Ensure that proper inertia relationship between the motor and the load is met.

Meet any additional criteria (cost, precision, stiffness, cycle time, etc.)

$$J_{\text{total}} = \underbrace{J_m}_{\text{motor inertia}} + \underbrace{J_{on}}_{\text{external inertia on the motor shaft}} + \underbrace{J_{ref}}_{\text{inertial reflected to the motor shaft}}$$

$$J_R = \frac{J_{on} + J_{ref}}{J_m}$$



$$J_{\text{total}} = J_m + J_{\text{coupling}} + J_{mg} + f(J_{lg} + J_{\text{load}})$$

$f(\cdot)$ is a function to be determined

117 Gearbox **rotation → rotation**

$$N_{GB} = \frac{\omega_m}{\omega_l} = \frac{r_l}{r_m} = \frac{n_l}{n_m} = \frac{T_l}{\eta T_m} \qquad J_{ref} = \frac{J_l}{\eta {N_{GB}}^2} \qquad T_{load\to m} = \frac{T_l}{\eta N_{GB}}$$

121 Belt-and-pulley **rotation → rotation**

$$N_{BP} = \frac{\omega_{ipulley}}{\omega_{lpulley}} = \frac{r_{lpulley}}{r_{ipulley}} \qquad J_{ref} = J_{ipulley} + \left(\frac{W_{belt}}{g}\right) r_{ipulley}^2 + \frac{1}{\eta {N_{BP}}^2}(J_{lpulley} + J_l + J_{coupler2}) \qquad T_{load\to m} = \frac{T_{ext}}{\eta N_{BP}}$$

124 Leadscrew **rotation → translation**

p = pitch (rev/m): Number of screw revolutions required for the nut to travel 1m

l = lead (m/rev): Distance along the screw's axis that is covered by one complete rotation of the screw

$$\omega_m = 2\pi l \qquad N_S = 2\pi p \qquad J_{ref} = J_{screw} + \frac{1}{\eta {N_S}^2}\left(\frac{W_l + W_{table}}{g}\right) \qquad T_{load\to m} = \frac{F_{ext}}{\eta N_S}$$

128 Rack-and-pinion **rotation → translation**

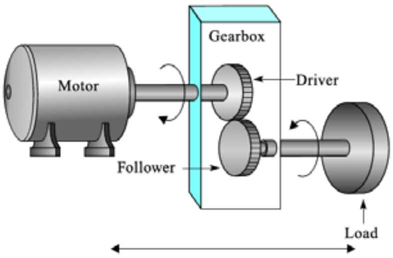
$$N_{RP} = \frac{1}{r_{pinion}} \qquad J_{ref} = J_{pinion} + \frac{1}{\eta {N_{RP}}^2}\left(\frac{W_l + W_{table}}{g}\right) \qquad T_{load\to m} = \frac{F_{ext}}{\eta N_{RP}}$$

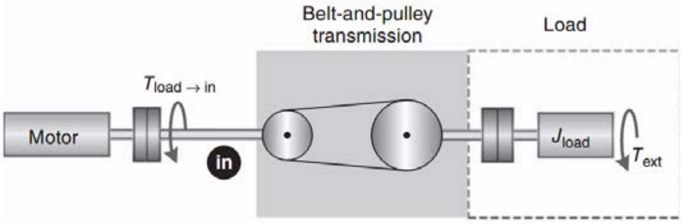
130 Belt drive for linear motion rotation → translation

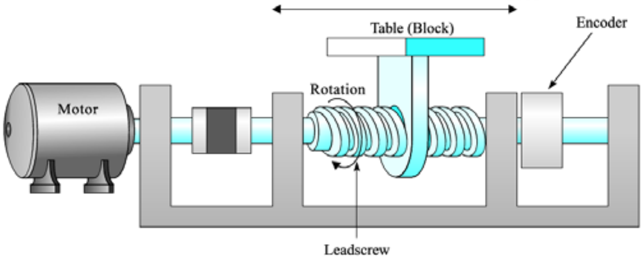
$N_{BD} = \frac{1}{r_{ip}}$ $\quad J_{ref} = 2J_{pulley} + \frac{1}{\eta {N_{BD}}^2}(\frac{W_l + W_{table} + W_{belt}}{g})$ $\quad T_{load\to m} = \frac{F_{ext}}{\eta N_{BD}}$

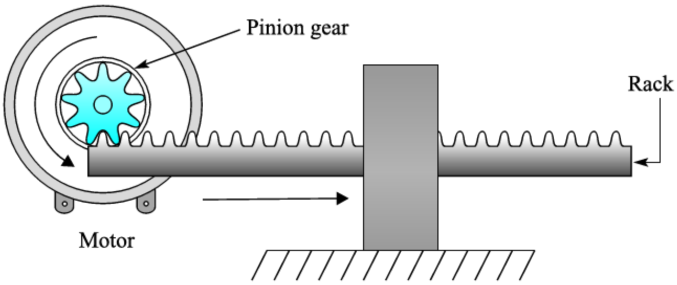
$T_{ext} = T_{friction} + T_{gravity} + T_{process}$

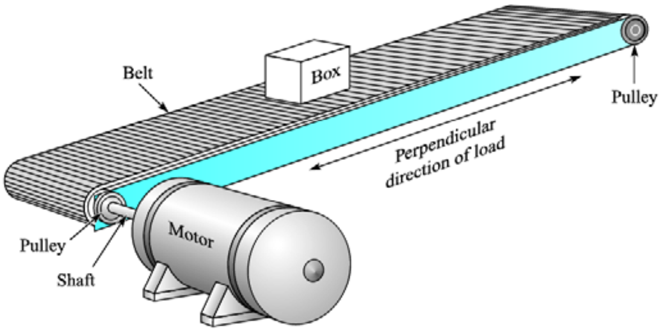
$F_{ext} = F_{friction} + F_{gravity} + F_{process}$











$$T_m - T_{\text{load}\to m} = J_{\text{total}}\ddot{\theta}_m \qquad T_{\text{RMS}} = \sqrt{\frac{T_{\text{acc}}^2 \cdot t_a + T_{\text{run}}^2 \cdot t_m + T_{\text{dec}}^2 \cdot t_d}{t_a + t_m + t_d}}$$

- Acceleration (Peak) Torque

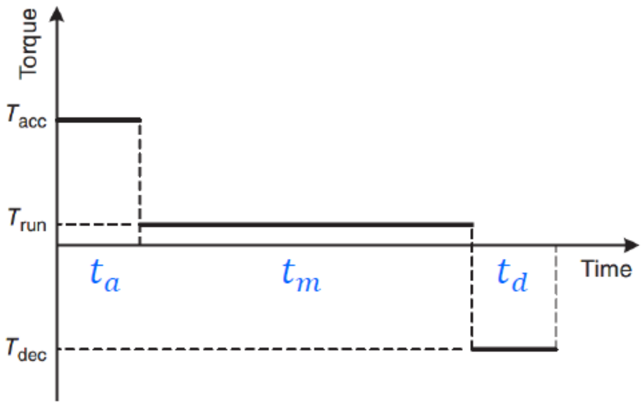
$$T_{\text{acc}} = J_{\text{total}}\ddot{\theta}_m + T_{\text{load}\to m}$$

- Running Torque

$$T_{\text{run}} = T_{\text{load}\to m}$$

- Deceleration Torque

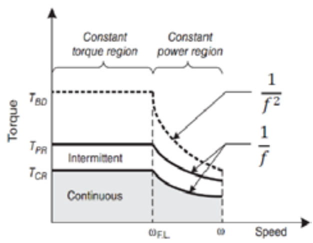
$$T_{\text{dec}} = -J_{\text{total}}\ddot{\theta}_m + T_{\text{load}\to \text{m}}$$



140 Motor Torque-Speed Curves

- Constant torque region: An induction motor with vector control drive can produce constant torque at any speed from zero up to the *base speed*. The drive achieves this by adjusting the input voltage and frequency so that V/f remains constant.
- Constant power region: The region beyond the base frequency f_b is called constant power region.

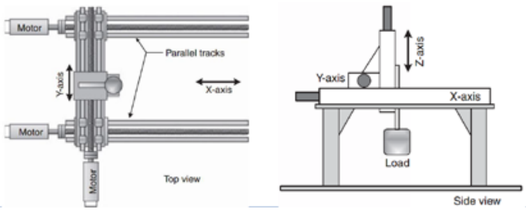
- The continuous rated torque T_{CR} can be taken as the lesser of the full-load torque of the motor or the continuous torque generated by the drive and motor combination due to the continuous current limit of the drive.
- Similarly, the peak rated torque T_{PR} can be taken as the lesser of the breakdown torque of the motor or the peak torque generated by the drive and motor combination due to the peak current limit of the drive.



Torque-speed curves for a generic motor

- The breakdown torque T_{BD} creates an absolute maximum limit a motor can deliver for short periods of time without overheating. Beyond the base frequency, the breakdown torque T_{BD} falls proportional to $1/f^2$.

- **Example:** The gantry machine carries a 20 kg load and 0.495 kg carriage.The X-axis of the machine uses two linear tracks in parallel. The X- and Y-axis tracks have 10 mm screw leads and 3.58 kg mass. The Z-axis has 5 mm screw lead and 1.81 kg mass. Each axis is equipped with a 0.67 kg mass, inertia 5.2×10^{-6} kg-m² motor which is connected to its axis using a cylindrical coupler with inertia 6.92×10^{-6} kg-m². What are the acceleration and continuous torque required to move each linear track of the X-axis at 31.25 rev/s speed for 1 s? Acceleration time is $t_a = 50$ ms. The screw inertial is 1.17×10^{-5} kg-m². And the screw has efficiency 90%.



- **Solution:**
- 1. Find the maximum angular acceleration of the motor

$$\omega_m = 31.25\left(\frac{\text{rev}}{\text{s}}\right)\left(\frac{2\pi\ \text{rad}}{1\ \text{rev}}\right) = 196.35\ rad/s \Longrightarrow \ddot{\theta}_m = \frac{\omega_m}{t_a} = \frac{196.35}{0.05} = 3927\ rad/s^2$$

- 2. The total inertia seen by the motor is $J_{\text{total}} = J_{\text{motor}} + J_{\text{coupling}} + J_{\text{ref}}$
- To compute the total inertial, we need first to compute the inertia reflected by the ball-screw

$$\begin{aligned} J_{\text{ref}} &= J_{\text{screw}} + J_{\text{load}\to m} \\ &= J_{\text{screw}} + \left(\frac{1}{\eta N_S^2}\right)\frac{W_l + W_c}{g} \\ &= 1.17 \times 10^{-15} + \left(\frac{1}{0.9 \cdot (2\pi \cdot 100)^2}\right)\frac{261.93 + 4.856}{9.81} \\ &= 8.824 \times 10^{-5}\text{kg} - \text{m}^2 \end{aligned}$$

Considering the worst case, and taking the total weight as the load carried by each track of the X-axis

where $W_l = W_{Y-\text{axis}} + W_{Z-\text{axis}} + W_{\text{load}} = (3.55 + 1.81 + 2 \cdot 0.67 + 20) \cdot 9.81 = 261.93$ N

- Thus

$$\begin{aligned} J_{\text{total}} &= J_{\text{motor}} + J_{\text{coupling}} + J_{\text{ref}} \\ &= 5.2 \times 10^{-6} + 6.92 \times 10^{-6} + 8.824 \times 10^{-5} = 1.004 \times 10^{-4}\text{kg} - \text{m}^2 \end{aligned}$$

- 3. Load torque reflected by the ball-screw to the motor consists of friction force, gravitational loading, and process forces.

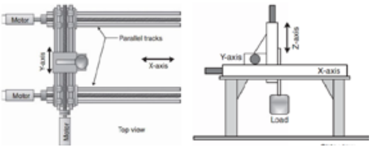
$$F_f = \mu \cdot (W_l + W_c) = 0.01 \cdot (261.93 + 4.856) = 2.67\ \text{N}$$

- Clearly, the gravitational loading that the track has to work against is 0. And $F_p = 0$ since the system is not pushing against any external forces.
- Thus, the total external force is

$$F_{\text{ext}} = F_f + F_g + F_p = 2.67\ \text{N}$$

- The load torque reflected to the motor by the ball screw is given by

$$\begin{aligned} T_{\text{load}\to\text{in}} &= \frac{F_{\text{ext}}}{\eta N_S} \\ &= \frac{2.67}{0.9 \cdot 2\pi \cdot 100} = 0.0047\ \text{Nm} \end{aligned}$$



- 4. The acceleration (peak) torque can be found from

$$\begin{aligned} T_{\text{acc}} &= J_{\text{total}} \cdot \ddot{\theta}_{\text{m}} + T_{\text{load}\to\text{in}} \\ &= 1.004 \times 10^{-4} \cdot 3927 + 0.0047 = 0.3988\ \text{Nm} \end{aligned}$$

- The running torque is simply equal to the load torque reflected to the motor

$$T_{\text{run}} = T_{\text{load}\to\text{in}} = 0.0047\ \text{Nm}$$

- Deceleration torque is

$$\begin{aligned} T_{\text{dec}} &= T_{\text{load}\to\text{in}} - J_{\text{total}} \cdot \ddot{\theta}_{\text{m}} \\ &= 0.0047 - 1.004 \times 10^{-4} \cdot 3927 = -0.3894\ \text{Nm} \end{aligned}$$

- The continuous torque (RMS) is calculated as

$$T_{\text{RMS}} = 0.119\ \text{Nm}$$

where $t_a = t_d = 0.05$ s, $t_m = 1$ s.

Motion Control Elements

151 Operator Interface

153 Controller

  Dedicated controller: designed to perform a specific task

  Indexer: open-loop system

  General-purpose controllers: coordinating several control operations simultaneously, high-speed calculations

154 Amplifier (drive)

155 Actuator

  Brush-Type DC Motors: proven performance, availability at a variety of specification ranges, and favorable cost.

  Brushless DC Motors: low inertia, high torque, wide variable-speed range desirable in positioning operations.

  AC Servo Motors: Have linear torque-speed, which are desirable in some applications for positioning and velocity.

  Induction Motors: Usually limited to high velocities and high-speed positioning applications.

  Stepper Motors: Used in open-loop systems; Maximum RPM is 2000, limitations in velocity-control applications.

156 Transmission

  Gearbox

  Belt-and-pulley

  Leadscrew

  Rack-and-pinion

  Belt drive for linear motion

158 Feedback

  Presence Indicators

  Position Transducers

    Rotary transducers: Optical encoder, Resolver

    Linear displacement transducers: can also be made by rotary detectors using actuator transmission

Servomechanisms

Definition: Systems where the feedback or error signal help control mechanical position, speed or other parameters.

163 Bang-Bang Position Servo

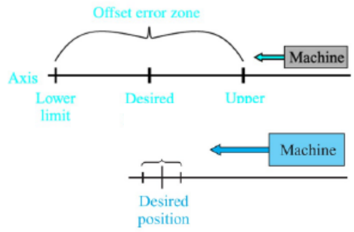
inexpensive, easy to implement

it is necessary to lighten the load, √ reduce the gain of motor amplifier, or widen the offset error zone.

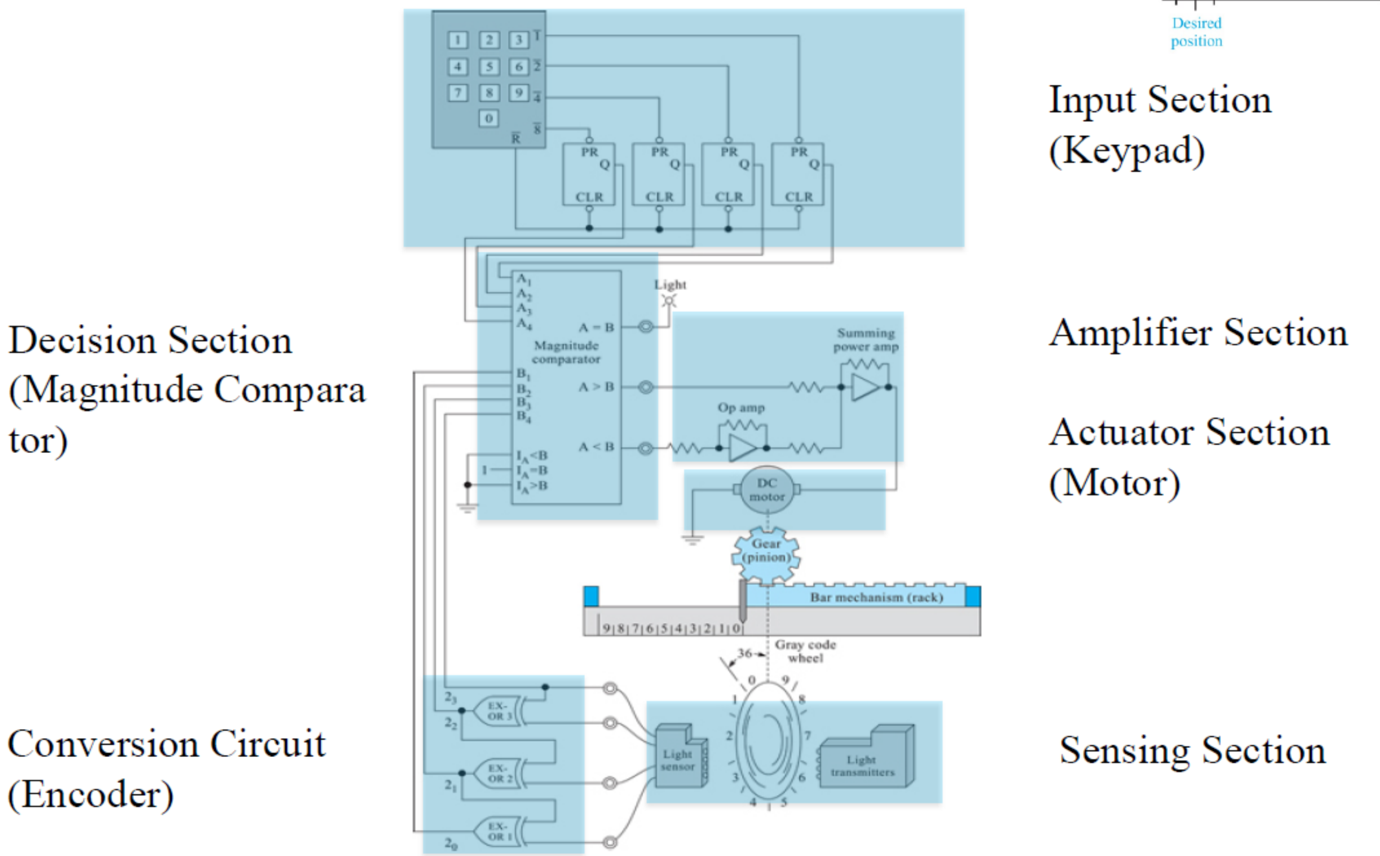
165 Proportional Position Servo

the offset error zone can be made much narrower

an automated insertion machine, a robotic arm, a numerical-control machine tool



168 Digital Position Control



173 Characteristics

The static characteristics relate to the steady-state behavior of the servo system. This condition exists when the load is stationary, such as when it is in the home position or has reached the end point.

Accuracy -- the ability to tell the truth

Repeatability -- the ability to tell the same story each time

Resolution -- how detailed your story is

Stiffness/Robustness -- the reluctance of an actuator to deviate from the desired position

The dynamic characteristics relate to the behavior of the system when a dramatic change in the input signal is applied. This condition exists when the load is moving.

Stability -- the maximum amount of allowable overshoot past the desired position.

Transient response -- the response time required to go from 10% to 90% of the final value.

Bandwidth -- the wider the bandwidth, the faster the response time.

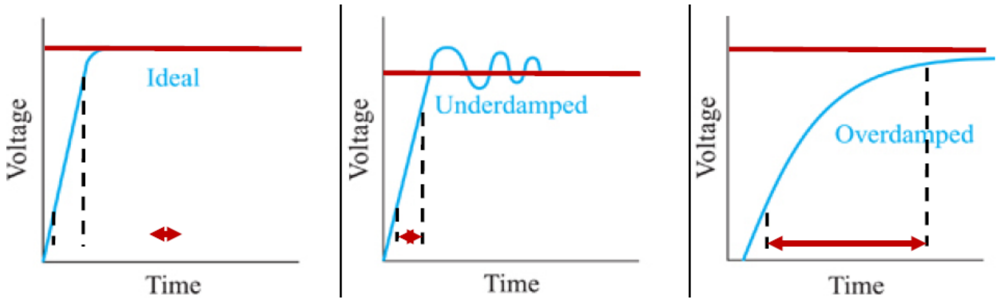
180 Design a Position Servo

Point-to-Point

move the load from one point to another

Dynamic characteristics is important. A transient step response test is performed.

If inertia, or friction on the load are changed in a critically damped system, amplifier gain adjustments alone might not be sufficient to overcome these conditions. Add a velocity loop to solve this problem.



Contouring

It requires continuous path control instead of end positioning from point to point. command signal is a series of smaller steps rather than the step signal. It requires that the actual position precisely tracks the command position steps with a minimal error signal throughout the movement.

186 Basic Control Structures

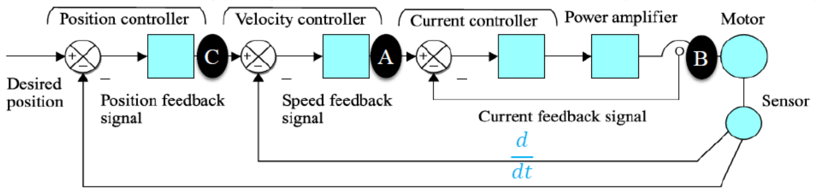
An innermost current loop (armature, fastest, highest bandwidth) that provides torque to the motor

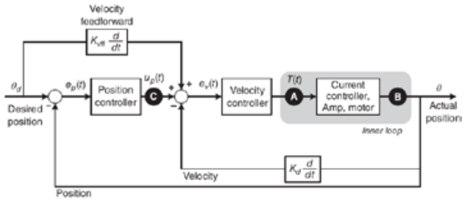
A velocity loop (load, fast, high bandwidth) around the current loop to control speed

A position loop (load, slow, low bandwidth) around the velocity loop that monitors the location of the load

When tuning the system, it is necessary to start with the innermost loop and work outward.

A P or PI controller Typically, a PI controller Two PI controllers (Park transformation)





An important characteristic of a motion control system is that it contains double integrators (position loop).

Cascaded loops with feedforward (velocity) control

without having to wait for an error to occur first

eliminate the following error, but if the feedforward gain is too high, it will cause overshoot

Tuning

Time domain: step response

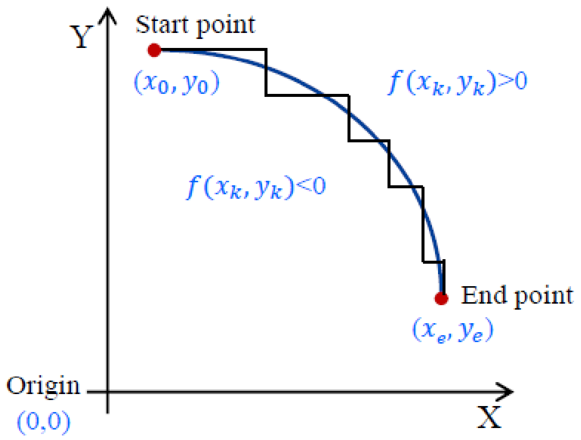
Frequency domain: Bode plots

210 Computer Numerical Control

Math expression of the curve: $D = f(x, y) =? x^2 + y^2 - R^2$

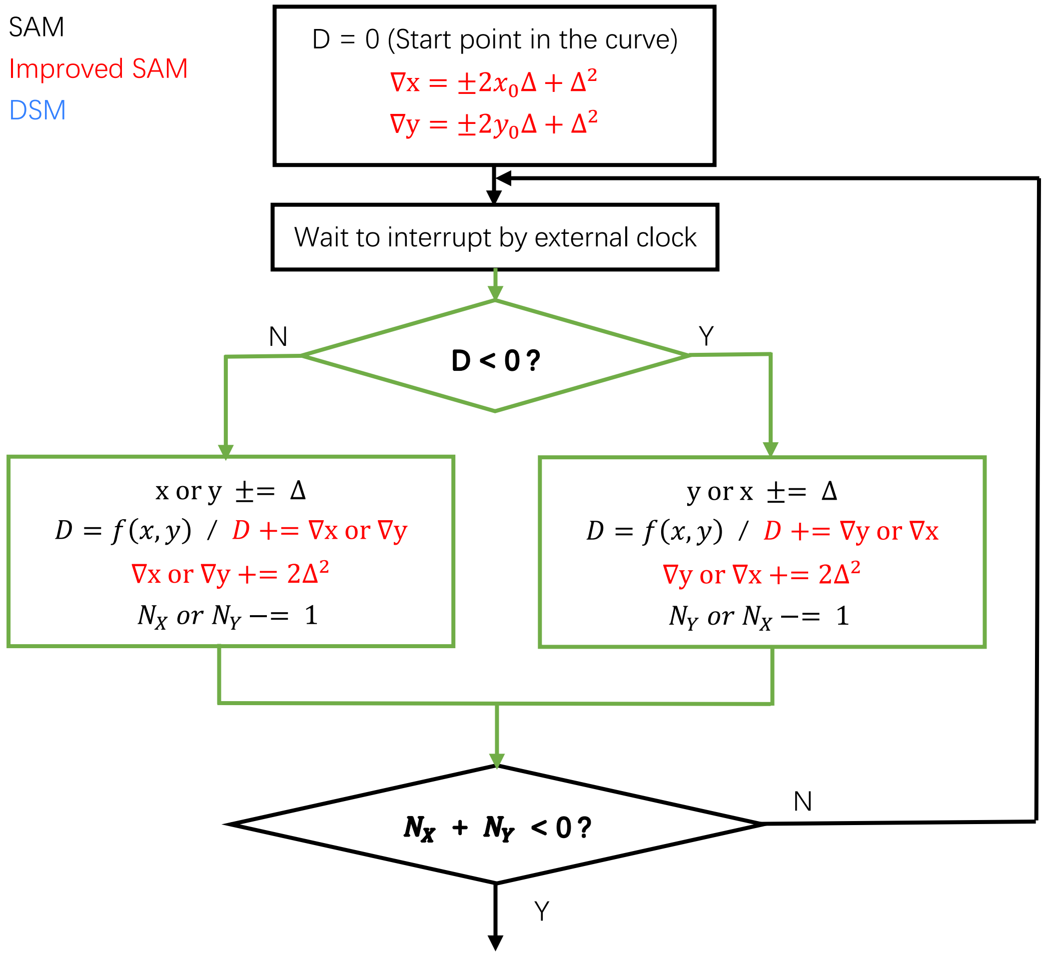
Stepping policy: based on CW or CCW and quadrant

Iterative update: SAM, Improved SAM, DSM

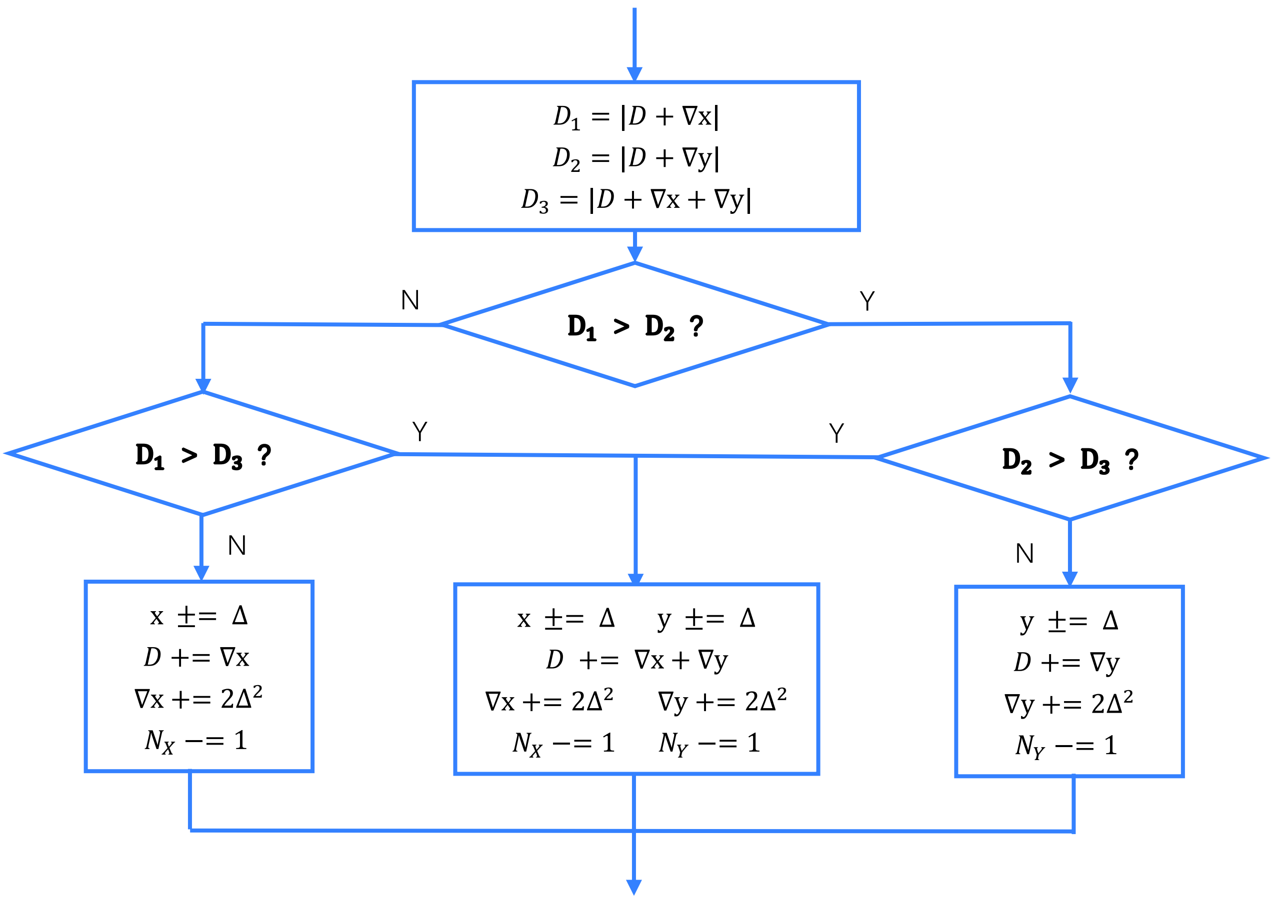


CW for curve in the first quadrant $(\frac{dy}{dx} < 0 \ \frac{d^2y}{dx^2} < 0)$

$$f(x_k, y_k) = x_k^2 + y_k^2 - R^2 = \begin{cases} < 0 & \text{one step } \triangle \text{ along } +X \text{ axis} \\ > 0 & \text{one step } \triangle \text{ along } -Y \text{ axis} \\ = 0 & \text{any of the above cases} \end{cases}$$



SAM
Improved SAM
DSM
D = 0 (Start point in the curve)
$\nabla x = \pm 2x_0\Delta + \Delta^2$
$\nabla y = \pm 2y_0\Delta + \Delta^2$
Wait to interrupt by external clock
D < 0 ?
N
Y
x or y $\pm= \Delta$
$D = f(x,y)$ / D += ∇x or ∇y
∇x or ∇y += $2\Delta^2$
N_X or N_Y −= 1
y or x $\pm= \Delta$
$D = f(x,y)$ / D += ∇y or ∇x
∇y or ∇x += $2\Delta^2$
N_Y or N_X −= 1
$N_X + N_Y < 0$?
N
Y



$D_1 = |D + \nabla x|$
$D_2 = |D + \nabla y|$
$D_3 = |D + \nabla x + \nabla y|$
$D_1 > D_2$?
N
Y
$D_1 > D_3$?
Y
N
$D_2 > D_3$?
Y
N
x $\pm= \Delta$
D += ∇x
∇x += $2\Delta^2$
N_X −= 1
x $\pm= \Delta$ y $\pm= \Delta$
D += $\nabla x + \nabla y$
∇x += $2\Delta^2$ ∇y += $2\Delta^2$
N_X −= 1 N_Y −= 1
y $\pm= \Delta$
D += ∇y
∇y += $2\Delta^2$
N_Y −= 1