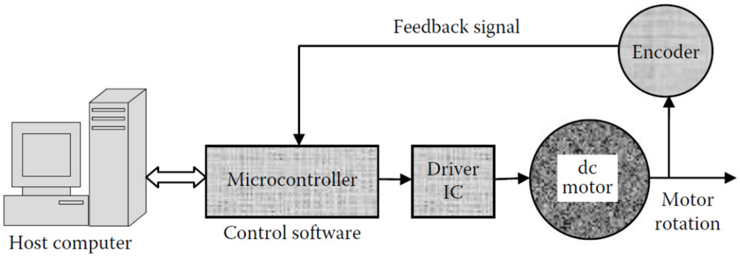
Motor Driver and Feedback Control:

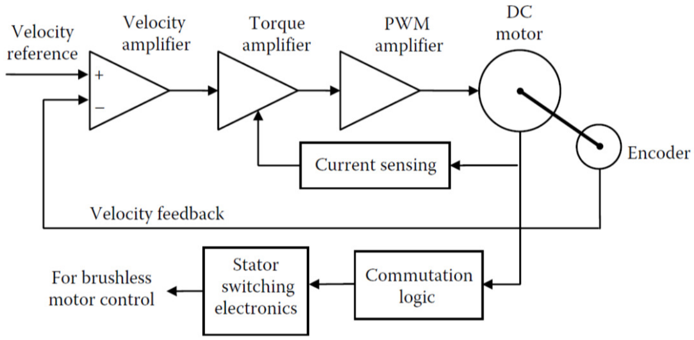


- The feedback control system of a dc motor typically consists of a microcontroller, *which provides drive commands (rotation and direction) to the driver*.
- The driver is a hardware unit, typically an IC package, which generates the necessary current to energize the windings of the motor. The *motor torque can be controlled by controlling the current generated by the driver*.
- By *receiving feedback from a motion sensor (encoder, tachometer, etc.)*, the *microcontroller can control the angular position and the speed of the motor*.

Driver Hardware:

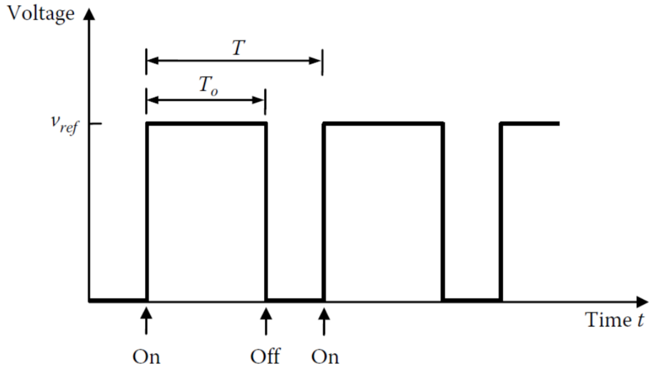
- Main hardware component of the motor drive system is the driver IC package.
- In traditional motion control applications, there are amplifiers called *drive amplifiers or servo amplifiers*, *which are included in the drive hardware*.
- The name servo amplifier is used specifically when feedback signals are received by it for proper servoing (*following a motion trajectory*).
- Two basic types of drive amplifiers are commercially available:
  1. *Linear amplifier*
  2. *PWM amplifier*

- A linear amplifier generates a voltage output:
  - Which is proportional to the input provided to it.
  - Since the output voltage is proportioned by dissipative means (using resistor circuitry), *this is a wasteful and inefficient approach.*
  - Fans and heat sinks have to be provided to remove the generated heat, particularly in continuous, long-term operation.
- **Example:**
  - To understand the inefficiency associated with a linear amplifier, suppose that the operating output range of the amplifier is 0–20 V, and that the amplifier is powered by a 20 V power supply. Under a particular operating condition, suppose that the motor is applied 10 V and draws a current of 4 A. The power used by the motor then is 10 × 4 W = 40 W.
  - Still, the power supply provides 20 V at 5 A, thereby consuming 100 W. This means, 60 W of power is dissipated, and the efficiency is only 40%. *The efficiency can be made close to 100% using modern PWM amplifiers*, which *are non-dissipative devices*, and *depend on high-speed switching at constant voltage to control the power supplied to the motor*.



- *Integrated microelectronic design makes them compact accurate, and inexpensive*. The components of a typical PWM-drive system are shown in the diagram.
- Other signal-conditioning hardware (e.g., filters) and auxiliary components such as isolation hardware, safety devices including tripping hardware, and cooling fan are not shown in the figure, but note the following components, connected in series:
  1. *A velocity amplifier (a differential amplifier)*
  2. *A torque amplifier*
  3. *A PWM amplifier*

- The *reference velocity signal* and *the feedback signal (from an encoder or a tachometer)* are used by the velocity amplifier.
- The *resulting difference (error signal) is conditioned and amplified by the torque amplifier to generate a current corresponding to the required torque* (corresponding to the driving speed).
- The *motor current is sensed and fed back to this amplifier, to improve the torque performance of the motor*.
- The *output from the torque amplifier is used as the modulating signal to the PWM amplifier*.
- The *PWM is accomplished by varying the duty cycle of the generated pulse signal, through switching control*.
- Chopper circuits that use discrete thyristor elements (a solid-state switch that is also known as *silicon-controlled rectifier or SCR)* were commonly used to generate PWM signals to control dc motors.
- Since a *chopper circuit takes dc power and switches it to different levels at some frequency, it is like converting dc to ac*. Hence, it called an inverter circuit.



Looking @ Diagram Duty Cycle $= \frac{T_o}{T} * 100\%$; T_o = ON Period

T = Pulse Period

Keeping V_{ref} and Pulse frequency '$\frac{1}{T}$' FIXED ; VARY T_o

∴ PWM achieved by chopping V_{ref} over part of switching period.

Meaning Average voltage is varied → Proportional to T_o.

$$\text{Duty cycle} = \frac{\text{Average Output}}{\text{Peak output}} * 100\%$$

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Practise 9.1 → 9.11 chapter 9. 9.2, 9.3, 9.5, 9.8, 9.11

Motor Selection Criteria

- Mechanical data:
  - Rated torque
  - Mechanical time constant
  - No load speed/ Full load speed
  - Maximum acceleration at peak torque
  - Rated output power
  - Frictional torques
  - Damping
  - Moment of inertia
  - Dimensions
- Electrical data:
  - Electrical time constant
  - Input power
  - Armature resistance and inductance
  - Field Resistance and inductance
  - Compatible drive circuit data (V, I, etc.)
- General Data
  - Brush life
  - Motor life
  - Efficiency (input/output power)
  - Operating temperature, humidity, etc
  - Mounting configuration

Induction Motors

- Because of the rapid improvement, ac motors have managed to replace dc motors in many industrial applications until the revival of the dc motor, particularly as a servomotor in control system applications.
- AC motors are generally more attractive than conventional dc motors, in view of their robustness, lower cost, simplicity of construction, and easier maintenance, especially in heavy duty (high-power) applications (e.g., rolling mills, presses, vehicle drives, elevators, cranes, material handlers, and operations in paper, metal, petrochemical, cement, and other industrial plants).

Advantages: Some advantages of ac motors are as follows:

- Cost-effectiveness
- Convenient power source (standard power grid providing single-phase and three-phase ac supplies)
- No commutator and brush mechanisms needed in many types of ac motors
- Low power dissipation, low rotor inertia, and lightweight in some designs
- Virtually no electric spark generation or arcing (less hazardous in chemical environments)
- Capability of accurate constant-speed operation without needing servo control (with synchronous ac motors)
- No drift problems in ac amplifiers in drive circuits (unlike linear dc amplifiers)
- High reliability, robustness, easy maintenance, and long life

Disadvantages: The primary disadvantages of ac motors include the following:

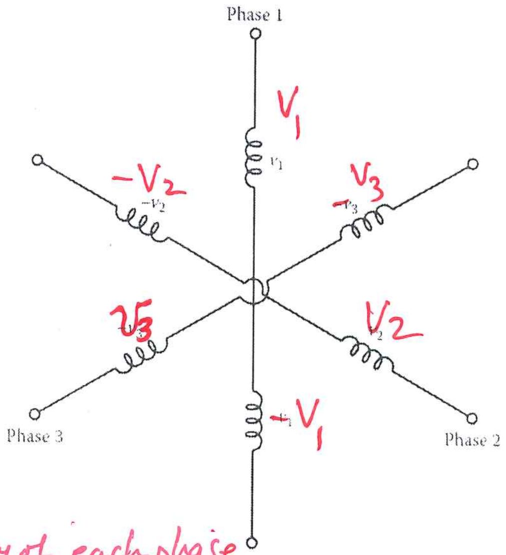
- Low starting torque (synchronous motors have zero starting torque)
- *Need of auxiliary starting devices for ac motors with zero starting torque*
- *Difficulty of variable-speed control or servo control (this problem hardly exists now in view of modern solid-state and variable-frequency drives with devices having field feedback compensation)*
- Instability in low speed operation

We discuss two basic types of ac motors:

1. Induction motors (asynchronous motors)
2. Synchronous motors

Rotating Magnetic Field:

- The operation of an ac motor can be explained using the concept of a rotating magnetic field.
- A rotating field is generated by a set of windings uniformly distributed around a circular stator and excited by ac signals with uniform phase differences.
- To illustrate this, consider a standard three-phase supply. The voltage in each phase is 120° out of phase with the voltage in the next phase. The phase voltages can be represented by



$$\left.\begin{aligned} V_1 &= a\cos\omega_p t \\ V_2 &= a\cos\left(\omega_p t - \frac{2\pi}{3}\right) \\ V_3 &= a\cos\left(\omega_p t - \frac{4\pi}{3}\right) \end{aligned}\right\}$$

ω_p = frequency of each phase of AC Signal

V_1 leads V_2 by $2\pi/3$

V_1 leads V_3 by $4\pi/3$

3ϕ - 2 windings/phase

phase difference between 2 adjacent windings is $\frac{\pi}{3}$

→ Consider $\Delta t = \frac{\pi}{3\omega_p}$ interval

- status of $-V_3$ @ end of time interval Δt is identical to status of V_1 in the beginning of time Interval
- Similarly status of V_2 after Δt become that of V_3 beginning

* Voltage STATUS of one segment becomes identical to adjacent segment in Δt.

* $$\omega_f = \frac{\omega_p}{n}$$

ω_f ← Angular Speed of Rotating Magnetic field.

ω_p ← frequency of AC signal.

n ← # of pairs of Windings used per phase.

$n=1 \Rightarrow$ 2 coils/phase, $n=2 \Rightarrow$ 4 pairs/phase

$\therefore n \Rightarrow$ # of pole pairs per phase in stator.

Example 9.10

Another way to interpret the concept of a rotating magnetic field is to consider the resultant field due to the individual magnetic fields in the stator windings. Consider a single set of three-phase windings arranged geometrically as in Figure 9.32. Suppose that the magnetic field due to phase 1 is denoted by $a \sin \omega_p t$. Show that the resultant magnetic field has an amplitude of $3a/2$ and that the field rotates at speed ω_p.

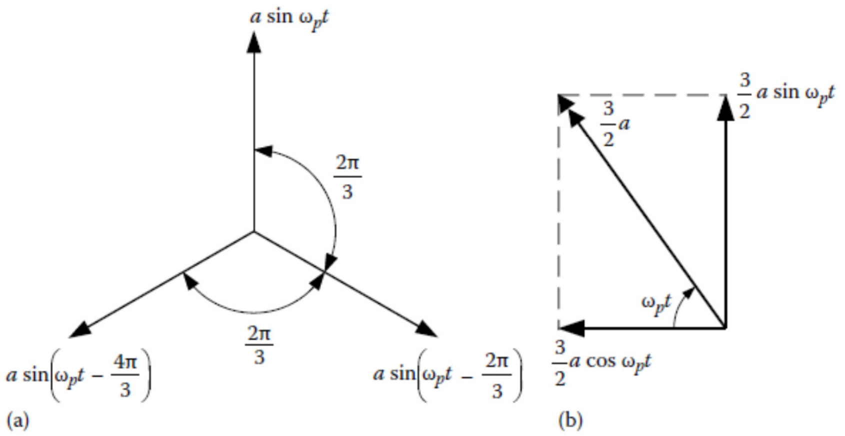
Solution

The magnetic field vectors in the three sets of windings are shown in Figure 9.33a. These can be resolved into two orthogonal components, as shown in Figure 9.33b. The component in the vertical direction (upward) is

$$a\sin\omega_p t - a\sin\left(\omega_p t - \frac{2\pi}{3}\right)\cos\frac{\pi}{3} - a\sin\left(\omega_p t - \frac{4\pi}{3}\right)\cos\frac{\pi}{3}$$

$$= a\sin\omega_p t - \frac{a}{2}\left[\sin\left(\omega_p t - \frac{2\pi}{3}\right) + \sin\left(\omega_p t - \frac{4\pi}{3}\right)\right] = a\sin\omega_p t - a\sin(\omega_p t - \pi)\cos\frac{\pi}{3}$$

$$= a\sin\omega_p t + \frac{a}{2}[\sin\omega_p t] = \frac{3a}{2}\sin\omega_p t$$



Note: In deriving this result, we have used the following trigonometric identities:

$$\sin A + \sin B = 2\sin\left(\frac{A+B}{2}\right)\cos\left(\frac{A-B}{2}\right) \text{ and } \sin(A-\pi) = -\sin A$$

The horizontal component of the magnetic fields, which is directed to the left, is

$$a\sin\left(\omega_p t - \frac{4\pi}{3}\right)\sin\frac{\pi}{3} - a\sin\left(\omega_p t - \frac{2\pi}{3}\right)\sin\frac{\pi}{3} = \frac{\sqrt{3}}{2}a\left[\sin\left(\omega_p t - \frac{4\pi}{\mathbf{3}}\right) - \sin\left(\omega_p t - \frac{2\pi}{3}\right)\right]$$

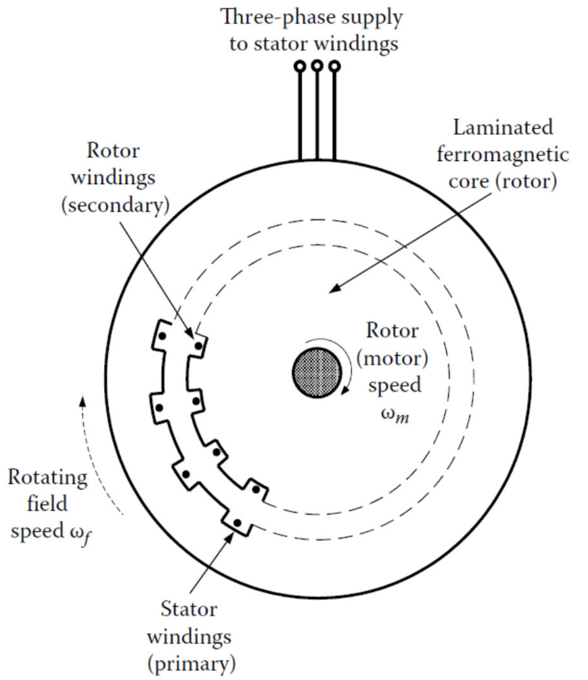
$$= \sqrt{3}a\cos(\omega_p t - \pi)\sin\left(-\frac{\pi}{3}\right) = \frac{3\mathbf{a}}{2}\cos\omega_p t$$

Here, we have used the following trigonometric identities:

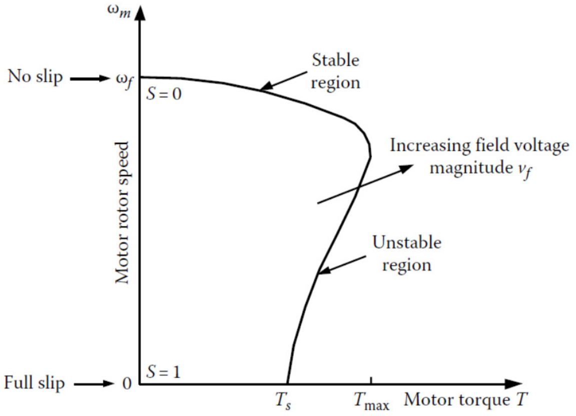
$$\sin A - \sin B = 2\cos\frac{A+B}{2}\sin\frac{A-B}{2}, \quad \cos(A-\pi) = -\cos A, \ \sin(-A) = -\sin A$$

The resultant of the two orthogonal components is a vector of magnitude $3a/2$, making an angle $\omega_p t$ with the horizontal component, as shown in Figure 9.33b. It follows that the resultant magnetic field has a magnitude of $3a/2$ and rotates in the clockwise direction at speed ω_p rad/s.

Induction Motor Characteristics:



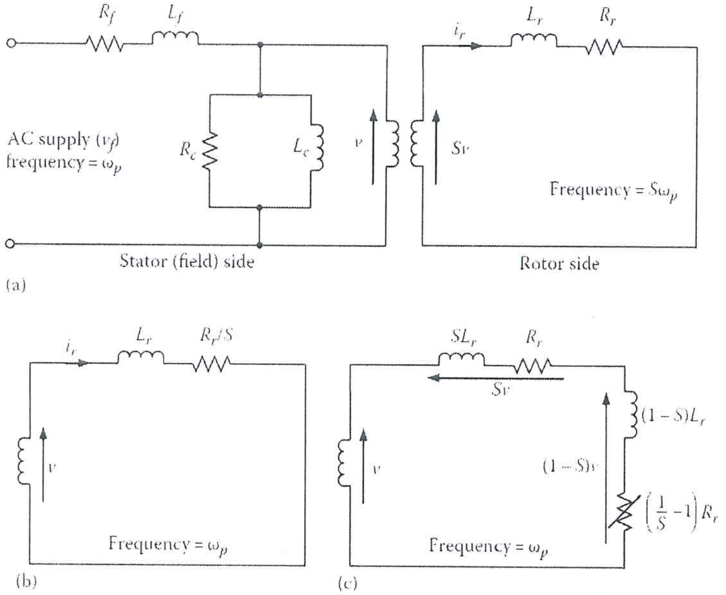
- The *stator windings of an induction motor generate a rotating magnetic field.*
- The *rotor windings are purely secondary windings*, which are not energized by an external voltage and are *used for inducing a magnetic field.*
- For this reason, *no commutator-brush devices are needed in induction motors*.
- The core of the rotor is made of ferromagnetic laminations in order to concentrate the magnetic flux and to minimize dissipation (primarily due to eddy currents).
- As *the rotor speed increases, initially the motor torque also increases* (rather moderately) because of secondary interactions between the stator circuit and the rotor circuit.
- This *increase in torque happens even though the relative speed of the rotating field with respect to the rotor decreases, which reduces the rate of change of flux linkage and hence the direct transformer action*. (*Note: the relative speed is termed the slip rate.*) In this manner, at some speed the maximum torque will be reached.
- Further increase in rotor speed (i.e., a decrease in slip rate) sharply decreases the motor torque, until at *synchronous speed (i.e., zero slip rate) the motor torque becomes zero*.



- This behavior of an induction motor is illustrated by the typical characteristic curve given.
- From the starting torque T_s to the maximum torque (which is known as the breakdown torque) T_{Max}, the motor behavior is unstable.
- *The portion of the curve from T_{Max} to the zero torque (or, no-load or synchronous condition) represents the region of stable operation*.
- *Under normal operating conditions, an induction motor should operate in this region*.
- The fractional slip S for an induction motor is given by: $S = \frac{\omega_f - \omega_m}{\omega_f}$
- If the *rotor speed is increased beyond the synchronous speed* (i.e., S < 0), *the motor becomes a generator*. Note: *When the stator windings are symmetrically distributed around the rotor, as in the foregoing analysis, the motor is called a symmetrical machine (e.g., a symmetrical induction motor)*.

Torque–Speed Relationship:

- It is instructive to determine the torque–speed relationship for an induction motor.
- This relationship provides insight into possible control methods for induction motors.
- The equivalent circuits of the stator and the rotor for one phase of an induction motor are shown.



→ L_f = Stator leakage Inductance

→ R_C = stator Core iron Loss resistance ; L_r = Rotor Leakage Inductance.

→ L_C = stator core (Magnetizing) Inductance; R_r = Rotor Coil Resistance

→ AC Voltage Supply V_f, ω_p = Line frequency; i_r : rotor Current gen. back emf

→ Induced Voltage (on Secondary Rotor Windings) Changes with Slip "S" which is proportional to $(\omega_f - \omega_m)$

→ ∴ Induced voltage in Rotor Windings is Sv

→ At standstill $(S=1)$; frequency of induced voltage is ω_p

→ At Synchronous speed $(S=0)$; frequency = 0 ∴ field is fixed and Const rel. to rotor.

using frequency domain representation.

Rotor Current $i_r = \dfrac{Sv}{R_r + jS\omega_p L_r} = \dfrac{V}{\frac{R_r}{S} + j\omega_p L_r}$

Motor Torque gen. in Rotor

Rotor Speed of Motor

Rotor Current Magn.

Available Mechanical power: $T_m \omega_m = P i_r^2 \left(\frac{1}{S} - 1\right) R_r$

# of phases

i_r Can be obtained as: $\dfrac{V}{\sqrt{R_r^2/S^2 + \omega_p^2 L_r^2}}$; By Substitution we get Mechanical Value $T_m = P v^2 \dfrac{S(1-S)}{\omega_m} \cdot \dfrac{R}{R_r^2 + S^2 \omega_p^2 L_r^2}$

# of Pole-pairs: $n = \dfrac{\omega_p}{\omega_m}(1-S)$

which gives $T_m = \dfrac{P n v^2 S R_r}{\omega_p (R_r^2 + S^2 \omega_p^2 L_r^2)}$.

If the resistance and the leakage inductance in the stator are neglected, v is approximately equal to the stator excitation voltage v_f. This gives the torque–slip relationship:

Motor Torque $\propto$ Square of Supply Voltage

$$T_m = \frac{P n V_f^2 S R_r}{\omega_p(R_r^2 + S^2 \omega_p^2 L_r^2)} = \frac{P V_f^2 S R_r}{\omega_f(R_r^2 + S^2 n^2 \omega_f^2 L_r^2)}$$

Using the fact that $n = \frac{\omega_p}{\omega_m}(1-S)$, we can write the above equation in terms of ω_m (Rotor Speed).

ω_m: Motor Speed is related to slip as:

$$S = \frac{\omega_f - \omega_m}{\omega_f} = \frac{\omega_p - n\,\omega_m \leftarrow \text{Motor Speed}}{\omega_p \leftarrow \text{frequency of Exciting Voltage}}$$