DC–AC Converters

Dr. Suneel Kommuri

Email: Suneel.Kommuri@xjtlu.edu.cn

Dept. Electrical & Electronic Engineering

Xi'an Jiaotong-Liverpool University
西交利物浦大學

Outline

- Principle of single phase DC-AC inverters
  - Performance parameters
  - Half bridge voltage source inverter (VSI)
  - Full bridge VSI
- PWM Technique
  - SPWM – Sinusoidal PWM
- Motors
  - DC motor drives
  - AC motor drives (induction motor & synchronous motor)

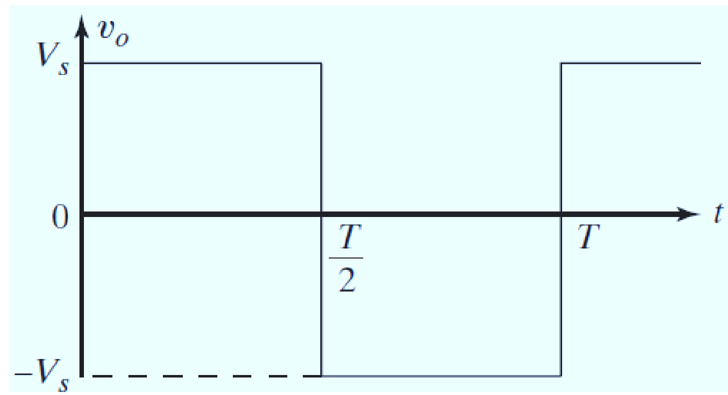
1.0 Introduction

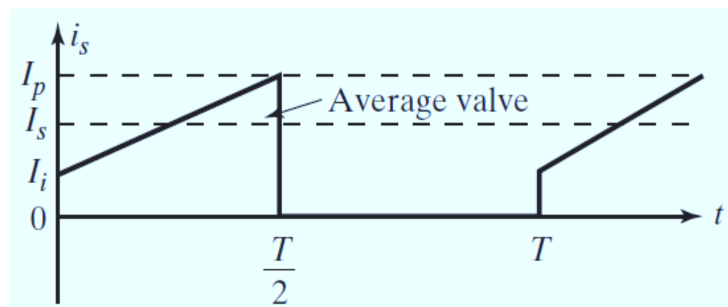
- Changes DC input voltage to a symmetric AC output voltage of desired magnitude and frequency – *Inverter*
- Variable output voltage can be obtained by *varying the input dc voltage* and maintaining the gain of the inverter constant
- If the *DC input voltage is fixed*, the output voltage can be controlled using – *pulse-width-modulation (PWM)*
- The output voltage should be sinusoidal, *however*, practical inverters are non-sinusoidal and contain *certain harmonics*
- Inverters are widely used in industrial applications – inputs may be battery, fuel cell, solar cell, or other dc source
- The inverters use *fully controlled devices* – BJTs, MOSFETs

1.1 Performance Parameters

- The *input voltage* to an inverter *is dc* and the *output voltage (or current) is ac*.
- The *output* should ideally be an *ac of pure sine wave*, but the output voltage of a practical inverter *contains harmonics or ripples*.
- The *inverter draws current from the dc input source* only when the inverter *connects the load* to the supply source & the *input current is not pure dc.*
- Output power, $P_{AC} = I_o{}^2 R$
- Input power, $P_{DC} = V_s I_s$

V_o & I_o are rms load voltage and current
θ is angle of load impedance, R is load resistance
V_s & I_s are average input voltage and current
I_i & I_s → rms & average values of dc supply current





1.1 Performance Parameters

The output of practical inverters contain harmonics & the *quality of an inverter* is normally evaluated in terms of these parameters:

- Harmonic factor of nth harmonic (HF_n): measure of an individual harmonic contribution in the output voltage, is defined as

$$\mathrm{HF}_n = \frac{V_{on}}{V_{o1}} \qquad \text{for } n > 1$$

where V_{o1} & V_{on} → rms values of fundamental & nth harmonic components.

- Total harmonic distortion (THD): measure of closeness in shape between the output voltage waveform and its fundamental component, is defined as

$$\mathrm{THD} = \frac{1}{V_{o1}}\left(\sum_{n=2,3,\ldots}^{\infty} {V_{on}}^2\right)^{1/2} = \frac{\sqrt{{V_o}^2 - {V_{o1}}^2}}{V_{o1}}$$

1.1 Performance Parameters

– Distortion factor (DF): gives total harmonic content, but does not indicate the level of each harmonic component.

$$\mathrm{DF} = \frac{1}{V_{o1}}\left[\sum_{n=2,3,..}^{\infty}\left(\frac{V_{on}}{n^2}\right)^2\right]^{1/2}$$

The DF of an individual (or nth) harmonic component is defined as

$$\mathrm{DF}_n = \frac{V_{on}}{V_{o1}\times n^2} \qquad \text{for } n > 1$$

– Lowest order harmonic (LOH): harmonic component whose frequency is closest to the fundamental one, and its amplitude is greater than or equal to 3% of the fundamental component.

1.2 Single-phase half-bridge VSI

- Inverter consists of *two choppers* – 1) when *only* Q_1 is turned ON for $T_0/2$, the instantaneous voltage across the load is $V_s/2$. 2) If *only* Q_2 is turned ON for $T_0/2$, instantaneous voltage across load is $-V_s/2$.

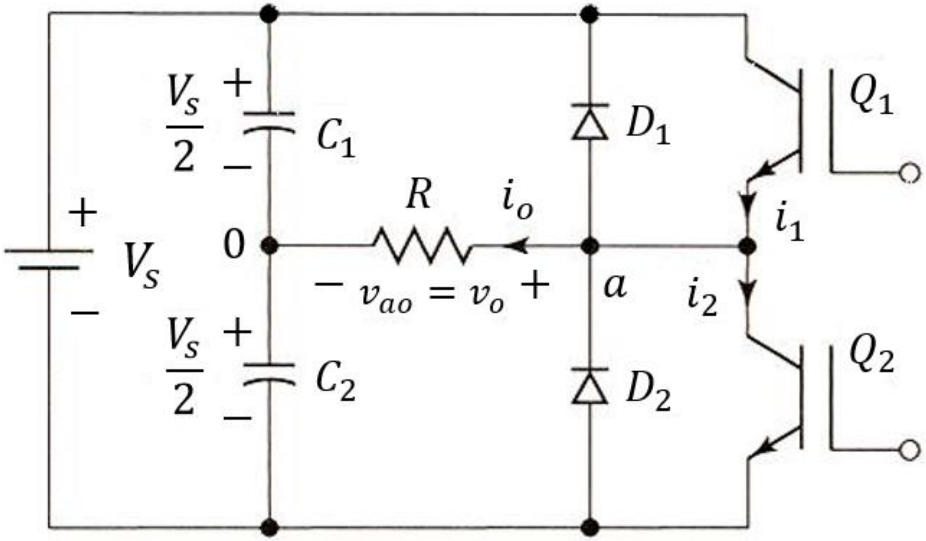
- The logic circuit should be designed such that Q_1 & Q_2 *are not* turned ON at the *same time*.

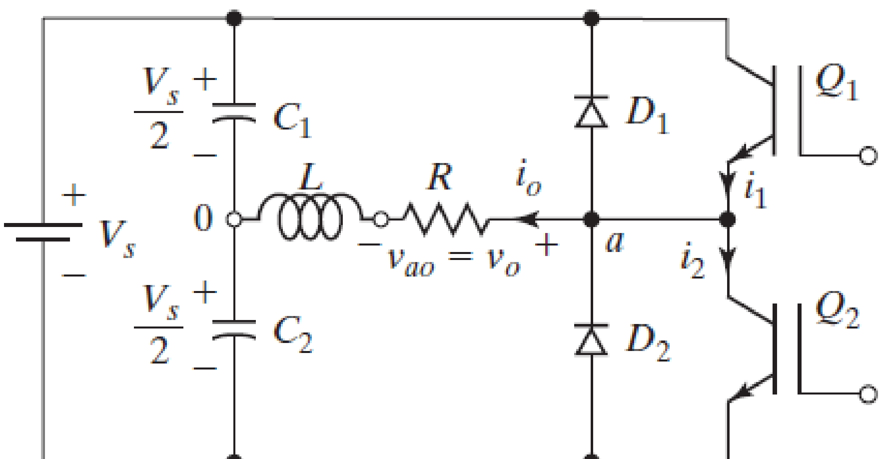
- DC side is constant voltage, low impedance.

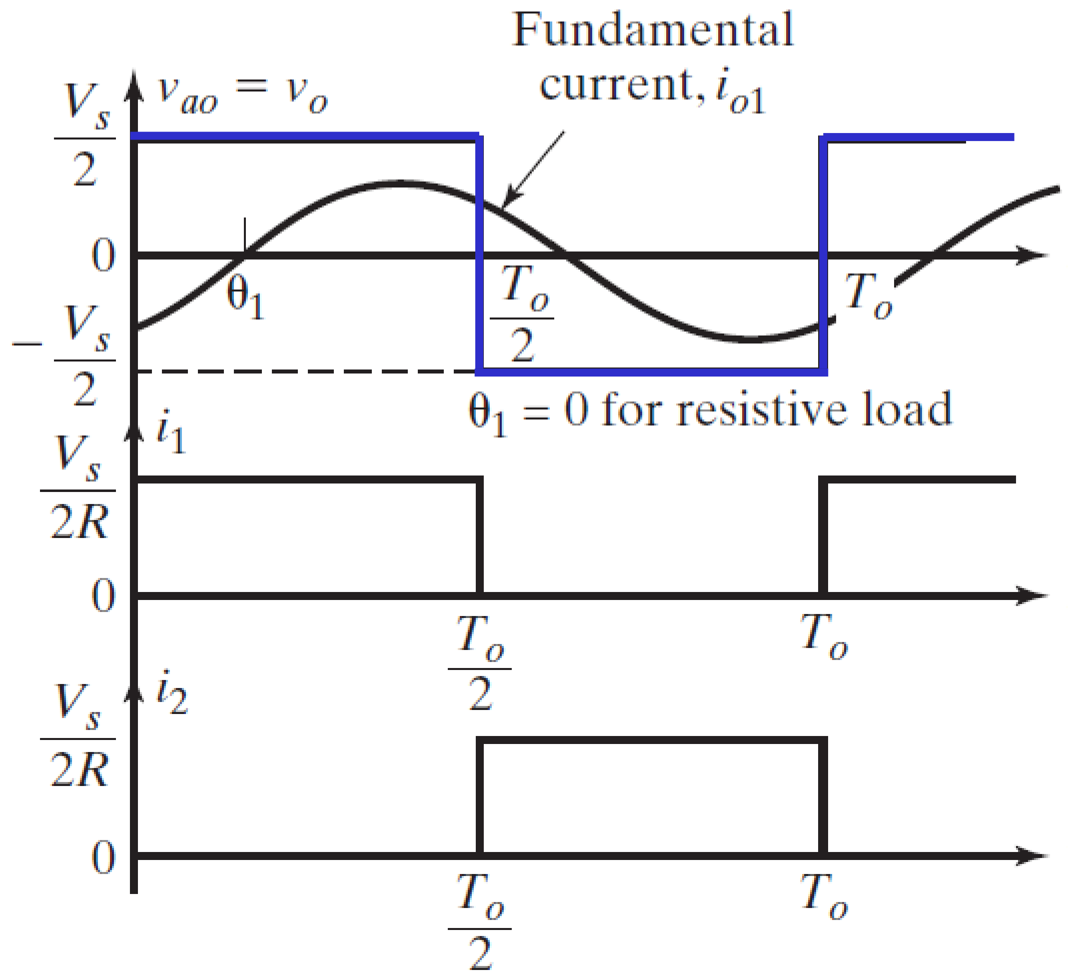
- The magnitude of output square-wave voltage is $V_s/2$.

- Note that the phase shift is $\theta_1 = 0$ for a resistive load.

1.2 Single-phase half-bridge VSI







Waveforms of output voltage & transistor currents with resistive load

Quantitative analysis 1

- The rms output voltage, $V_o = \left(\frac{1}{T_o/2}\int_0^{T_o/2}\frac{{V_s}^2}{4}dt\right)^{1/2} = \frac{V_s}{2}$ $\Longrightarrow$ Why?

- Instantaneous output voltage can be expressed in Fourier series,

$$v_o = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t) = \sum_{n=1,3,5,..}^{\infty}\frac{2V_s}{n\pi}\sin n\omega t = 0 \text{ for } n = 2,4,..$$

  – Due to the symmetry, all a_n (including a_0) are 0 and b_n are calculated as

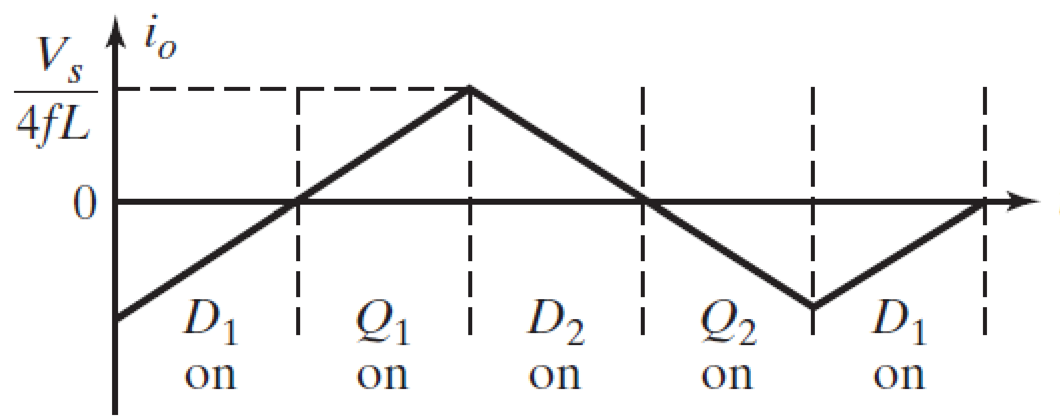
$$b_n = \frac{1}{\pi}\left[\int_{-\pi/2}^{0} -\frac{V_s}{2}\sin n\omega t \, d\omega t + \int_0^{\pi/2}\frac{V_s}{2}\sin n\omega t \, d\omega t\right] = \frac{2V_s}{n\pi}$$

where $\omega = 2\pi f_0$ is the frequency of output voltage in rad/sec

- The rms value of fundamental component of output is, $V_{o1} = \frac{2V_s}{\sqrt{2}\pi} = 0.45V_s$

1.2.1 Inductive load

- For an inductive load, the *load current cannot* change immediately with the output voltage.
- If Q_1 is turned *OFF* at $t = T_0/2$, the load current would continue to flow through D_2*, load, and the lower half* of the dc source until current fall to zero.
- Similarly, when Q_2 is turned OFF at $t = T_0$, load current flows through D_1*, load, and the upper half* of the dc source.
- If diodes D_1 or D_2 conducts, energy is fed back to the dc source – *feedback diodes*
- For a purely inductive load, transistor conducts for $T_0/4$.



Load current with highly inductive load

Quantitative analysis 2

- For an RL load, the instantaneous load current i_o can be found by dividing the instantaneous output voltage by the load impedance $Z = R + jn\omega L$, therefore

$$i_o = \sum_{n=1,3,5..}^{\infty} \frac{2V_s}{n\pi\sqrt{R^2 + (n\omega L)^2}} \sin(n\omega t - \theta_n)$$

where $\theta_n = \tan^{-1}(n\omega L/R)$ is the phase of load impedance.

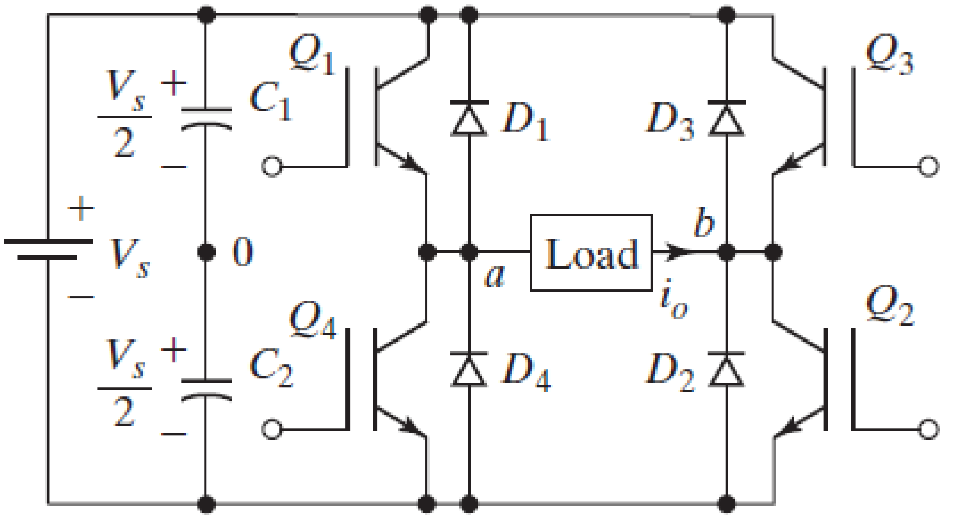
- The rms fundamental load current ($n = 1$) is:

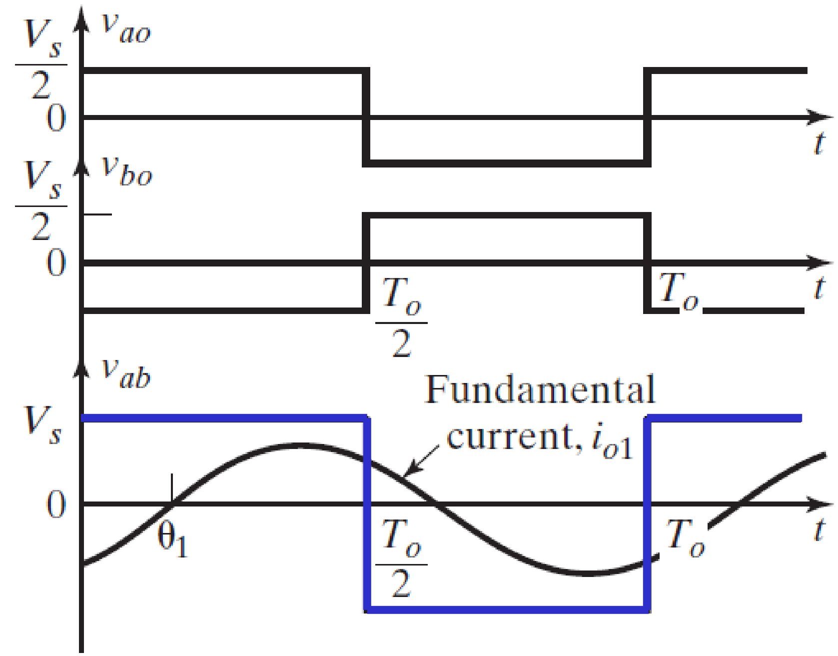
$$I_{o1} = \frac{2V_s}{\sqrt{2}\pi\sqrt{R^2 + (n\omega L)^2}}$$

- The fundamental output power ($n = 1$) is, $P_{o1} = {I_{o1}}^2 R$

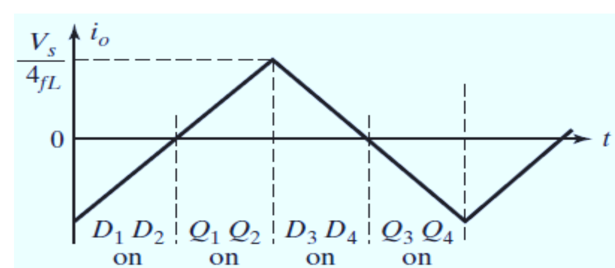
- Power due to 1) fundamental current is the useful power, 2) harmonic currents is dissipated as heat and increases the load temperature.

1.3 Single-phase full(H)-bridge VSI



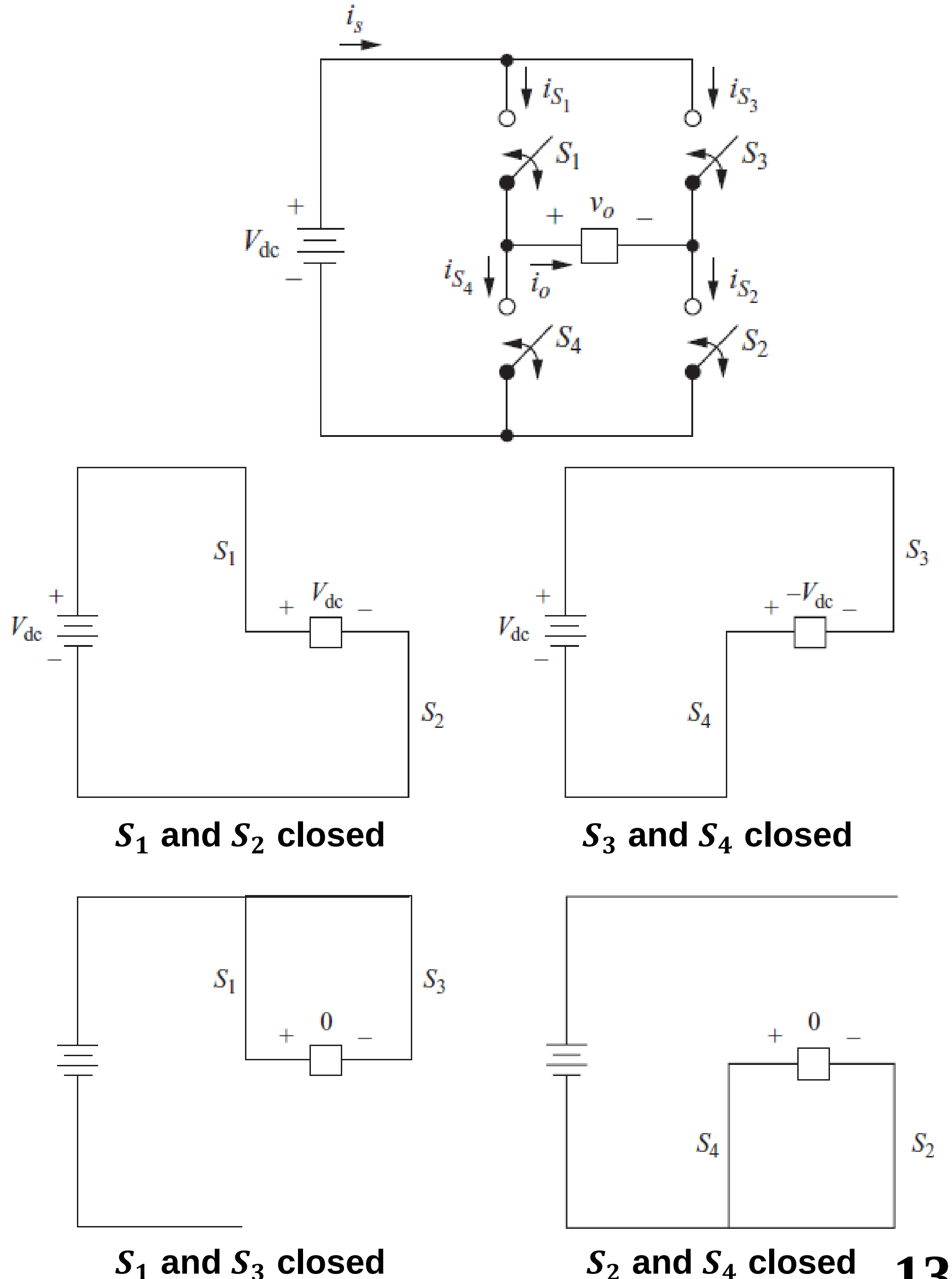


- Consists of 4 choppers – 1) When Q_1 & Q_2 are turned ON simultaneously, V_s appears across the load, 2) If Q_3 & Q_4 are turned ON simultaneously, $-V_s$ appears across the load.
- When the load is highly inductive, the current waveform is triangular.
- The RMS output voltage is,



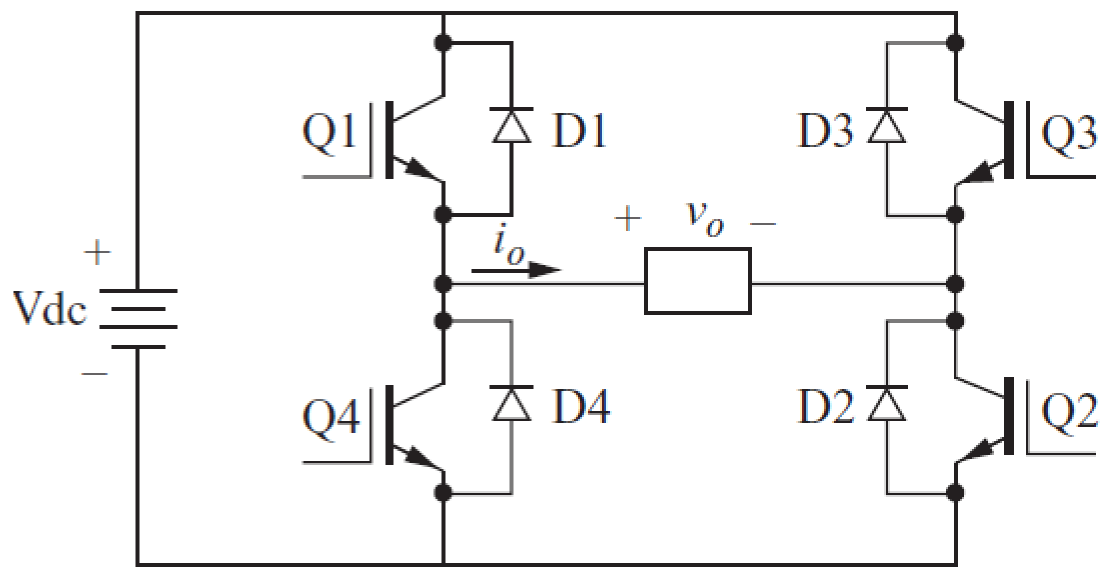
- $$V_o = \left(\frac{2}{T_0}\int_0^{T_0/2} {V_s}^2 dt\right)^{1/2} = V_s$$

- There are four states available in the H-bridge, as shown at right.
- The voltages that can be applied to the load are $+V_{dc}, -V_{dc}$, and 0.
- Notice that switches 1 and 4 should never be turned "on" simultaneously, and the same for switches 2 and 3 – *a short circuit would exist across the dc source*.
- Such a condition would be called a ***shoot-through*** fault.
  - To prevent shoot-through, a very short time interval called *the blanking time* must be inserted between the turning "off" of switch 1 and the turning "on" of switch 4.



Why use diodes?

- They appear in case the load is not purely resistive. If it's inductive, which it usually is, then when switch 1 (for example) turns off, the inductive load current can commutate over to the diode D_4 until it goes to zero and reverses direction. Then switch Q_4 can pick it up.



Quantitative analysis 3

- The instantaneous output voltage in Fourier series form

$$v_o = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_s}{n\pi} \sin n\omega t$$

- The rms value of fundamental component of output ($n = 1$) is

$$V_{o1} = \frac{4V_s}{\sqrt{2}\pi} = 0.9V_s$$

- The instantaneous load current i_o for an RL load becomes

$$i_o = \sum_{n=1,3,5..}^{\infty} \frac{4V_s}{n\pi\sqrt{R^2 + (n\omega L)^2}} \sin(n\omega t - \theta_n)$$

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2.0 PWM Inverters

- Usually, the output voltage of an inverter is a *square wave*. Drawbacks are:

  1) output voltage is constant & equal to supply voltage (cannot be controlled)

  2) output voltage consists of 3rd harmonic & other harmonics

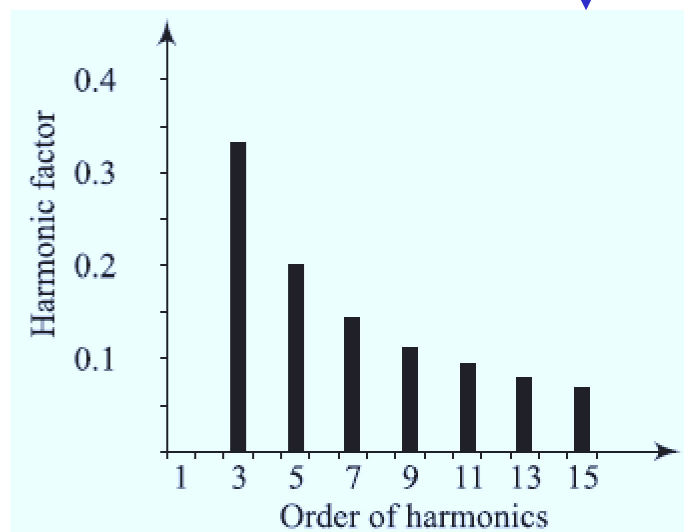
- Pulse width modulation (PWM) should be used in the inverter to avoid above drawbacks – the *output pulse duration is modulated or varied* to control the output voltage. Most commonly used PWM techniques are:

  1) Single-pulse width modulation (SPWM)

  2) Multi-pulse width modulation (MPWM)

  3) Sinusoidal pulse width modulation

  4) Modified sinusoidal pulse width modulation

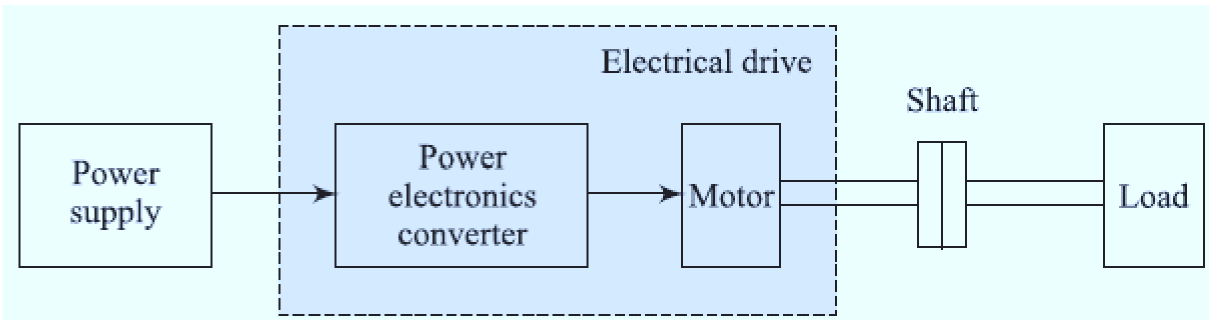


2.1 Other PWM Techniques

- Optimised PWM
  - PWM waveform are constructed based on certain performance criteria, e.g. THD.
- Harmonic elimination/minimisation PWM
  - PWM waveforms are constructed to eliminate some undesirable harmonics from the output waveform spectra.
  - Highly mathematical in nature
- Space-vector PWM
  - Using vectors to approximate a circle
  - Easy to generate and very commonly used

3.0 Electric Drives

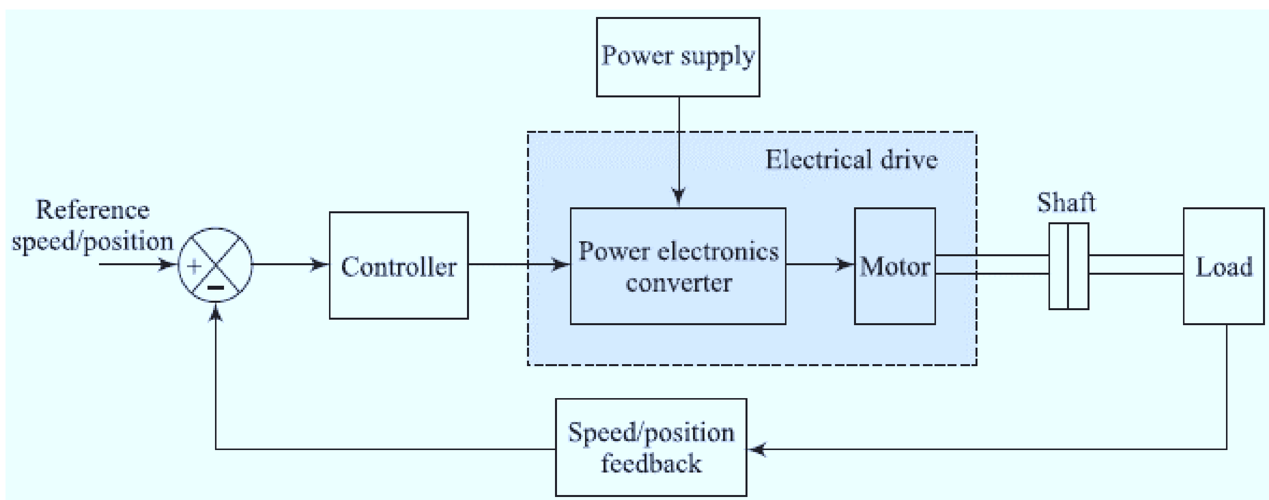
- Electric drives are commonly used in many industrial applications
  - centrifugal pumps, robotics, elevators, conveyer belts etc.



Open-loop electric drive

- Power electronics converter used for interfacing between input power supply and electric motor.

Closed-loop electric drive



3.0 Electric Drives

- The *output of a power electronics converter* may be a variable dc or a variable ac with variable voltage and frequency.
- The *feedback signals* are the measured parameters of the load, i.e., speed and position.
- The *control circuit* is the heart of power electronics converter – generates triggering pulses to control thyristors of power converters.
  – low power circuit built using analog circuits, microprocessors, etc
- Electric drives are usually of mainly two types:
  – DC motor drives
  – AC motor drives ⟹ 1) Induction motor drives
    2) Synchronous motor drives

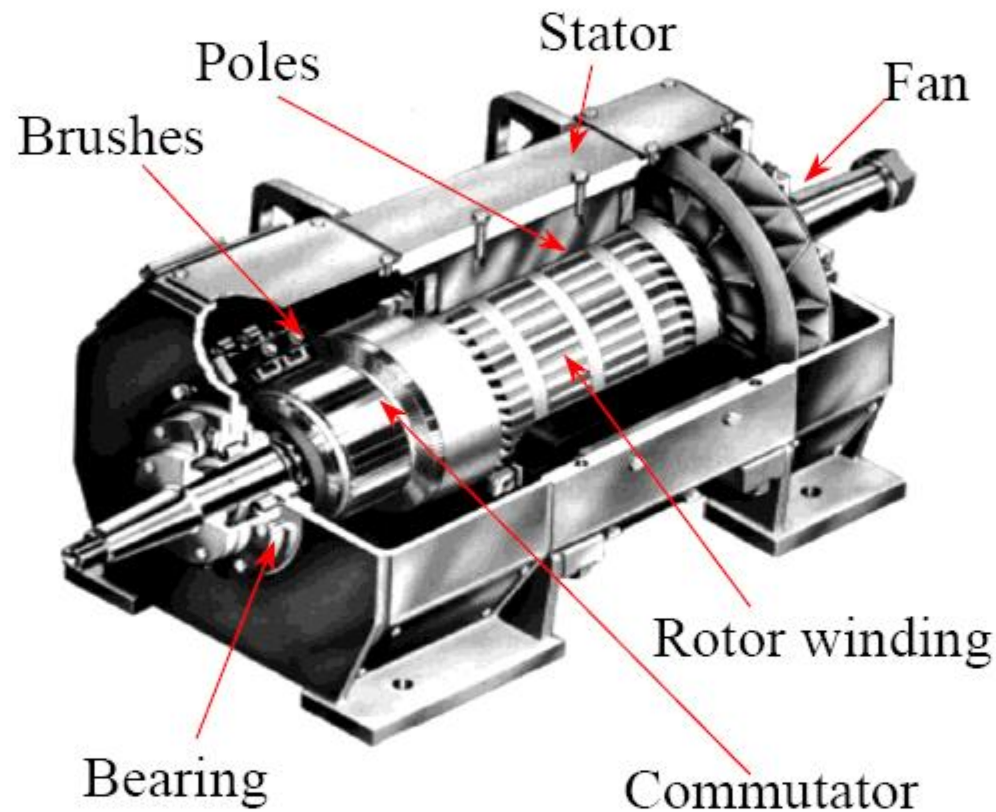
3.1 DC Motor Drives

Three parts:

Rotor (Armature) –The rotating centre portion.

Stator–The static (stationary) windings around the rotor. In many small motors, the stator can be replaced with permanent magnets.

Commutator–The brush connection to the winding on the rotor.



3.1 Types of DC Motors

- Two types depending on type of field winding connections:

  – **Shunt:** field excitation is independent of armature circuit

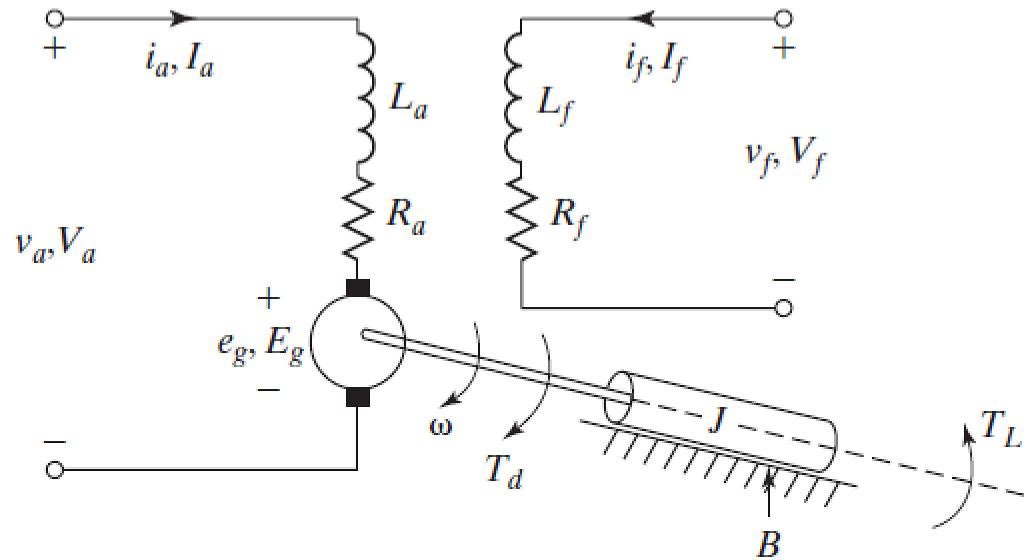
    – controlled independently (*separately excited motor*)

    – armature and field currents are different

  – **Series:** the field excitation is in series with the armature

    – armature and field currents are same

3.1.1 Separately Excited DC Motor



Equivalent circuit

- When *excited* by a field current (i_f) and an armature current of i_a flows in the circuit, the *motor develops* a back *EMF* & a *torque* to balance the load torque at particular speed of motor.

- The i_f is *independent* of i_a and any change in one of them would not affect other current. Normally, $i_f \ll i_a$.

- Instantaneous field current i_f is described as

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

- Instantaneous armature current can be found from, $v_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$

- The motor back emf (or *speed voltage*) is, $e_g = K_v \omega i_f$

3.1.1 Separately Excited DC Motor

- The torque developed by the motor, $T_d = K_t i_f i_a$
- The developed torque must be equal to $T_d = J\frac{d\omega}{dt} + B\omega + T_L$
- Under steady-state conditions, the time derivatives in the above equations are zero. Therefore, the speed of a separately excited motor can be found as

$$\omega = \frac{V_a - R_a i_a}{K_v i_f}$$

where, B = viscous friction constant, N.m/rad/s; K_v = voltage constant, V/A-rad/s

K_t = torque constant, same as voltage constant, K_v.

L_a = armature circuit inductance, H; R_a = armature circuit resistance, **Ω**.

L_f = field circuit inductance, H; R_f = field circuit resistance, **Ω**.

T_L = load torque, N.m.

3.1.2 Series Excited DC Motor

- The field circuit is designed to carry the armature current. The steady-state quantities:
- The motor back emf is, $E_g = K_v \omega I_a$
- Instantaneous armature current can be found:

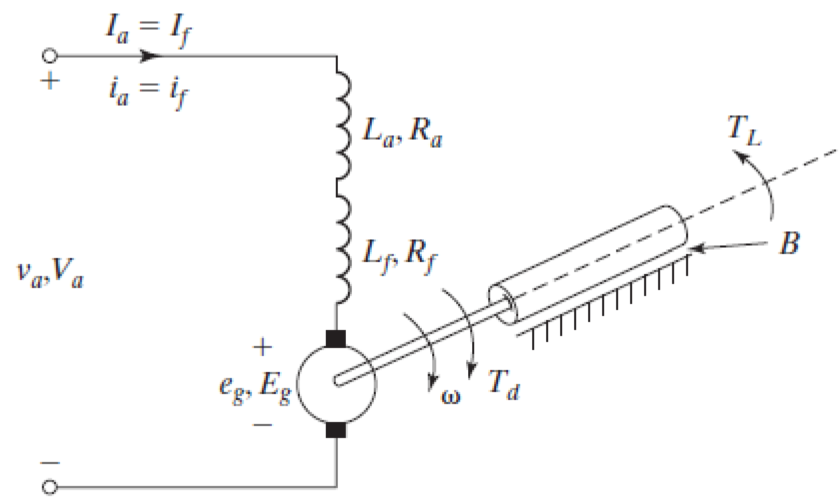
$$V_a = (R_a + R_f) I_a + E_g = (R_a + R_f) I_a + K_v \omega I_f$$

- The torque developed by the motor,

$$T_d = K_t I_f I_a = B\omega + T_L$$

- The speed of a series motor can be found as

$$\omega = \frac{V_a - (R_a + R_f) I_a}{K_v I_f}$$



Equivalent circuit

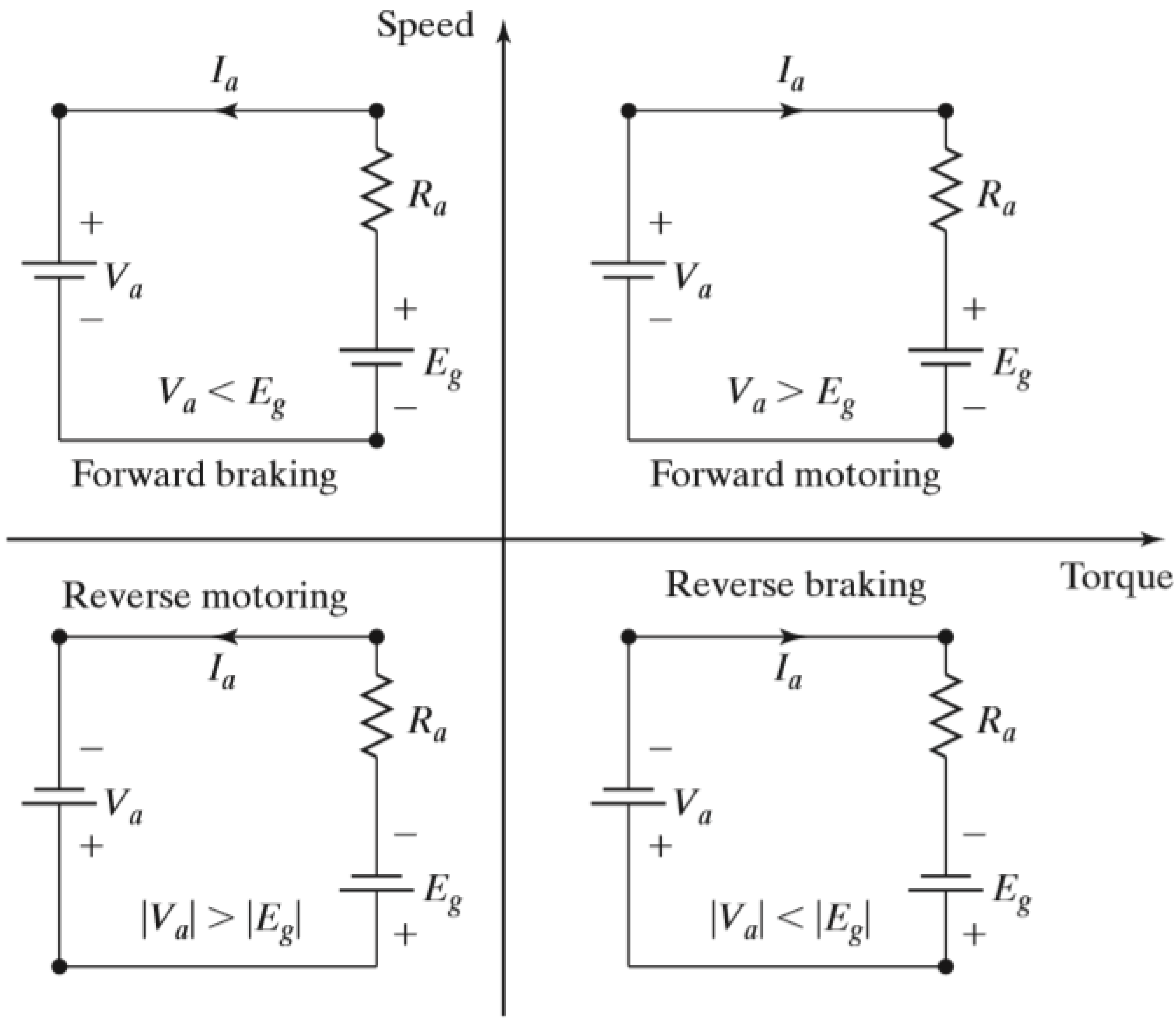
- The speed can be varied by controlling the 1) armature voltage; or 2) armature current, which is a measure of the torque demand.
- Series motor can provide a high torque, especially at starting – commonly used in traction applications.

3.1.3 Operation Modes of a DC Motor

In variable-speed applications, dc motor may be operating in one or more modes:

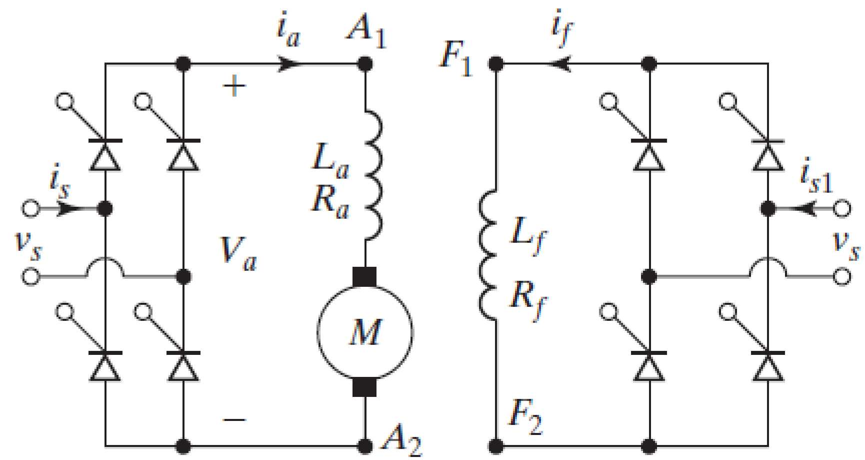
- **Motoring:** $E_g < V_a$ and the motor drives the mechanical load.
- **Generating:** the motor is driven by a rotating machine.
- **Braking** (short-period operation):
  - Dynamic braking: re-connecting the motor as a generator by temporarily replacing the supply with a braking resistance R, and dissipating the generated power into a resistive load.
  - Regenerating braking: an extension of dynamic braking. The kinetic energy of the motor is converted into electricity and returned to the supply, which means E_g is greater than V_a.
  - Plugging: another type of braking by temporarily reversing the armature terminals to forcefully stop it.

Four-quadrant operation (conditions)



3.1.4 Single-phase Full-converter Drives

- The armature voltage is varied by a single-phase full-wave converter.



- The average armature voltage, with a single-phase full-wave converter in the armature, as

$$V_a = \frac{2V_m}{\pi}\cos\alpha_a \quad \text{for } 0 \le \alpha_a \le \pi$$

- Similarly, the field voltage is,

$$V_f = \frac{2V_m}{\pi}\cos\alpha_f \quad \text{for } 0 \le \alpha_f \le \pi$$

- For three-phase full-wave converter,
  - the average armature voltage, $V_a = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha_a \quad \text{for } 0 \le \alpha_a \le \pi$
  - the average field voltage, $V_f = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha_f \quad \text{for } 0 \le \alpha_f \le \pi$

Example

A 15-hp, 220 V, 2000 rpm separately excited dc motor controls a load requiring a torque of $T_L = 45\ N.m$ at a speed of 1200 rpm. The field circuit resistance is $R_f = 147\Omega$, the armature circuit resistance is $R_a = 0.25\Omega$, and the voltage constant of the motor is $K_v = 0.7032$. The field voltage is $V_f = 220\ V$. The viscous friction and no-load losses are negligible. The armature current may be assumed continuous and ripple free. Determine a) the back emf E_g, b) the required armature voltage V_a, and c) rated armature current.

<u>Solution</u>

$R_f = 147\ \Omega$, $R_a = 0.25\ \Omega$, $K_v = K_t = 0.7032$ V/A rad/s, $V_f = 220$ V, $T_d = T_L = 45$ N · m, $\omega = 1200\ \pi/30 = 125.66$ rad/s, and $I_f = 220/147 = 1.497$ A.

Example

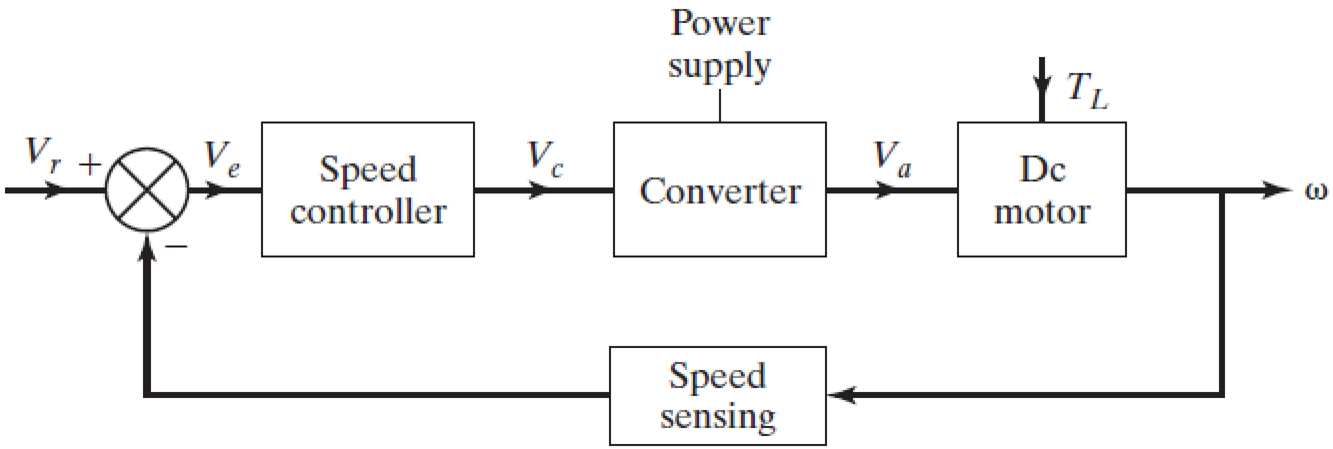
Solution

a) $\mathrm{T}_d = K_t i_f i_a \Rightarrow i_a = 42.75\,A,\ E_g = K_v \omega I_f = 132.28\,V$

b) $V_a = R_a i_a + L_a \frac{di_a}{dt} + E_g \cong R_a i_a + E_g = 0.25 \times 42.75 + 132.28 = 142.97V$

c) Because 1 hp is equal to 746 W, $I_{rated} = 15 \times 746/220 = 50.87\,A$

3.1.5 Closed-loop Control of DC Drives

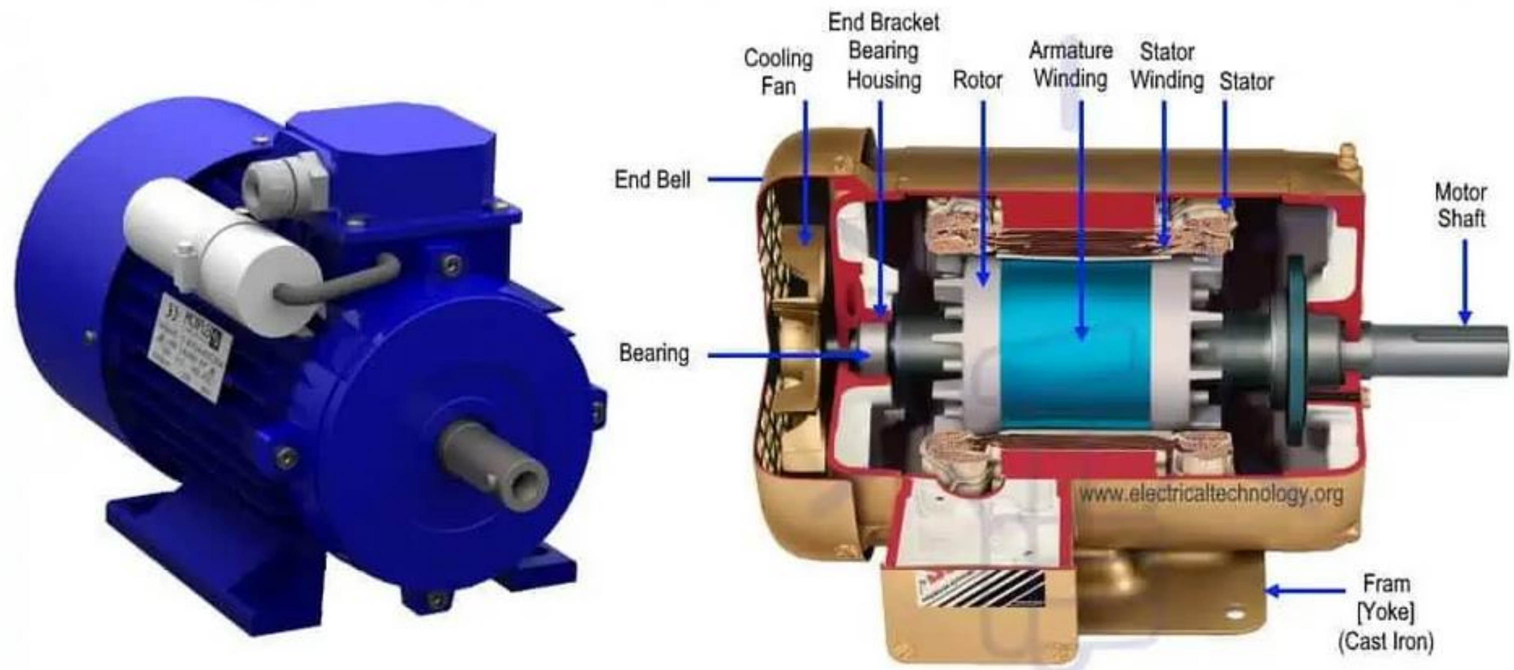


- The speed of dc motors changes with the load torque – to maintain a constant speed in practical drive systems; operate as *closed-loop feedback systems*.
- Advantages of improved accuracy, fast dynamic response, reduced effects of load disturbances and system nonlinearities.
- If the *speed of the motor decreases* due to the application of additional load torque, *the speed error V_ϵ increases*.
- The *speed controller* response with an increased control signal to restore the motor speed to the original value.

3.2 AC Motors

- AC motors exhibit highly coupled, nonlinear, and multivariable structures as opposed to simple decoupled DC motors.
- Control of AC drives generally requires *complex control algorithms* that can be performed by microprocessors or microcomputers.
- AC drives are lightweight, inexpensive, low maintenance.
- Require *advanced feedback controller* such as adaptive control, sliding mode control, and field oriented control.
- **Types:** Induction motors, synchronous motors, stepper motors
- AC drives are replacing DC drives and are used in many industrial and domestic applications.

3.2.1 Induction Motor Drives

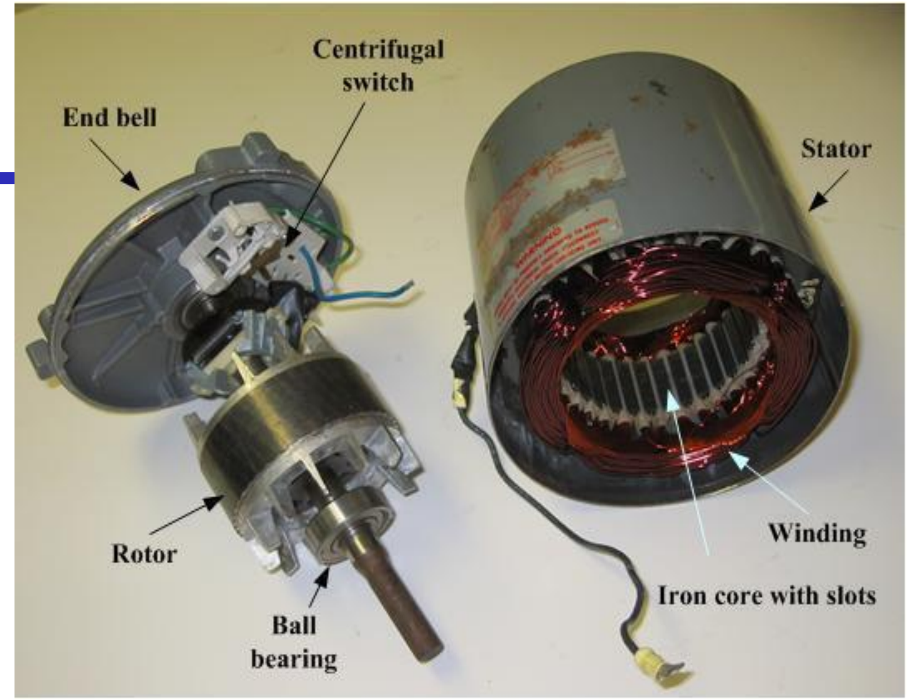


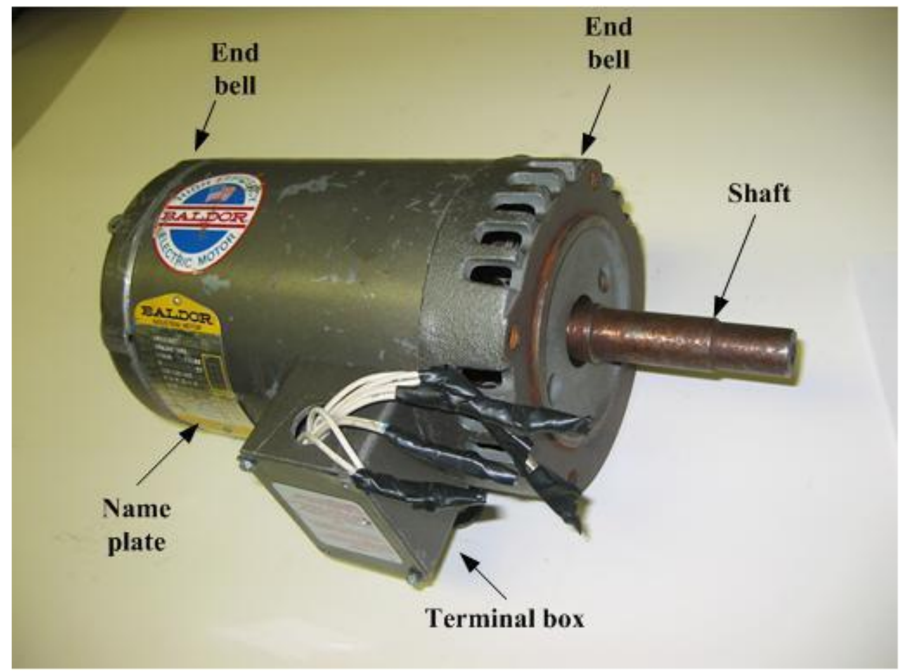
- The single-phase induction motor is the most frequently used motor in the world.
- Highly reliable and economical.
- For industrial applications, three-phase induction motors are used.

Construction

- An induction motor consists of
  – Stator
  – Rotor
  – Housing

- The motor housing consists of
  – **Shaft:** the cylindrical middle piece that holds the stator iron core;
  – **End bell:** the two bell-shaped end covers holding the ball bearings.





3.2.2 Synchronous Motor Drives

- Synchronous motors have two windings: 3-phase armature winding on the stator and a field winding on the rotor.
- Always operates at synchronous speed (constant speed).
- The power factor can be controlled by varying its field current.
  - Cylindrical rotor synchronous motors
  - Salient pole synchronous motors
  - Reluctance synchronous motors
  - *Permanent magnet synchronous motors*

Summary

- DC-AC converters are known as *inverters.*
- *Feedback diodes* are required to transfer the energy stored in the load inductance back to the DC source.
- The most efficient method of controlling the gain is to incorporate *PWM control* in inverters.
- Electrical motors: DC and AC motor drives.
- DC drives: Shunt: field excitation is *independent* of armature circuit
  Series: field excitation is *in series* with armature circuit
- AC Motor drives: Induction motor drives, Synchronous motor drives

See you in the next class (May 05th)

The End