Introduction

By

Dr. Mohammad Salah

Mechatronics Engineering Department

The Hashemite University

Introduction

- **Motor controller** and **Motor Driver** are both used **interchangeable** for “the thing that makes the motor works”.
- However, the **“driver”** unit is normally the power semiconductors, and the **“controller”** unit is the part that controls the speed/torque and commutation (if applicable) of the motor.
- In other words, the controller controls the motor through the driver unit.
- Sometimes they are separate units, sometimes they are integrated.

Introduction

- The **motor controller’s output** is connected to the **motor driver’s input**.
- The motor current passes through drives and drives include controlling as well. Whereas controllers monitor and control power circuit components.
- For example, the same motor controller can control either a small dc motor or a locomotive traction motor, using the appropriate sized motor drivers.
- As a result, when motor control equipment is selected and installed, many factors must be considered to ensure that the control will function properly for the motor and the machine for which it is selected

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Introduction

- In general, five basic factors influence the selection and installation of a controller.

  1. Electrical Service: DC or AC

  2. Motor: correctly sized for the machine load, appropriate speed and torque, and suitable protection

  3. Operating Characteristics of Controller: protecting, starting, stopping, reversing, jogging or inching, plugging, or operating at several speeds

  4. Environment: providing safety protection for operating personnel and protecting from environmental conditions (water, rain, snow, sleet, dirt or noncombustible dust, or lubricants)

Introduction

5. Electrical Codes and Standards: Motor control equipment is designed to meet the requirements of the National Electrical Code® (NEC®). Also, local code requirements must be considered and met when installing motors and control devices. Standards established by the National Electrical Manufacturers Association (NEMA) assist users in the proper selection of control equipment. NEMA standards provide practical information concerning the construction, testing, performance, and manufacture of motor control devices such as starters, relays, and contactors.

Introduction

- **Factors to be considered when selecting and installing** motor control components for use with particular machines or systems are:

  1. Starting: The motor may be started by connecting it directly across the source of voltage. Slow and gradual starting may be required, not only to protect the machine, but also to ensure that the line current inrush on starting is not too great for the power company's system. Some driven machines may be damaged if they are started with a sudden turning effort.

Introduction

- **Factors to be considered when selecting and installing** motor control components for use with particular machines or systems are:

  2. Stopping: Most controllers allow motors to coast (i.e., move easily without using power) to a standstill. Some impose braking action when the machine must stop quickly. Quick stopping is a vital function of the controller for emergency stops. Controllers assist the stopping action by retarding centrifugal motion of machines and lowering operations of crane hoists.

Introduction

- **Factors to be considered when selecting and installing** motor control components for use with particular machines or systems are:

  3. Reversing: Controllers are required to change the direction of rotation of machines automatically or at the command of an operator at a control station. The reversing action of a controller is a continual process in many industrial applications.

Introduction

- **Factors to be considered when selecting and installing** motor control components for use with particular machines or systems are:

  4. Running: The maintaining of desired operational speeds and characteristics is a prime purpose and function of controllers. They protect motors, operators, machines, and materials while running.

Introduction

- **Factors to be considered when selecting and installing** motor control components for use with particular machines or systems are:

  5. Speed Control: Some controllers can maintain very precise speeds for industrial processes. Other controllers can change the speeds of motors either in steps or gradually through a continuous range of speeds.

Introduction

- **Factors to be considered when selecting and installing** motor control components for use with particular machines or systems are:

  6. Safety of Operator: Many mechanical safeguards (i.e, protections) have been replaced or aided by electrical means of protection. Electrical control pilot devices (i.e, pushbuttons, selector switches, indicator lamps, toggle switches) in controllers provide a direct means of protecting machine operators from unsafe conditions.

Introduction

- **Factors to be considered when selecting and installing** motor control components for use with particular machines or systems are:

  7. Protection from Damage: Part of the operation of an automatic machine is to protect the machine itself and the manufactured or processed materials it handles. For example, a certain machine control function may be the prevention of conveyor pileups. A machine control can reverse, stop, slow, or do whatever is necessary to protect the machine or processed materials.

Introduction

- **Factors to be considered when selecting and installing** motor control components for use with particular machines or systems are:

  8. Maintenance of Starting Requirements: motor starters will provide reliable operation of starting time, voltages, current, and torques for the benefit of the driven machine and the power system. The NEC®, supplemented by local codes, governs the selection of the proper sizes of conductors, starting fuses, circuit breakers, and disconnect switches for specific system requirements.

Introduction

- Required **protective features** for any motor application may include:

  1. Overload protection
  2. Open-field protection in DC motors
  3. Open-phase protection in AC motors
  4. Reversed-phase protection
  5. Overtravel protection
  6. Overspeed protection
  7. Reversed-current protection in DC systems
  8. Mechanical protection (enclosures of switches)
  9. Short-circuit protection

Introduction – Motor Nameplate/Tag

Motor (filled-out) tag

WEIER		
TYPE DVX 160/2MK		
3~	MOT	No.7163
Δ	440V	23 A
13.5KW	51	cos ϕ 0.9
3500 rpm	60 Hz	
Ins. Class F	IP 55	0.08 t

Empty/blank tag

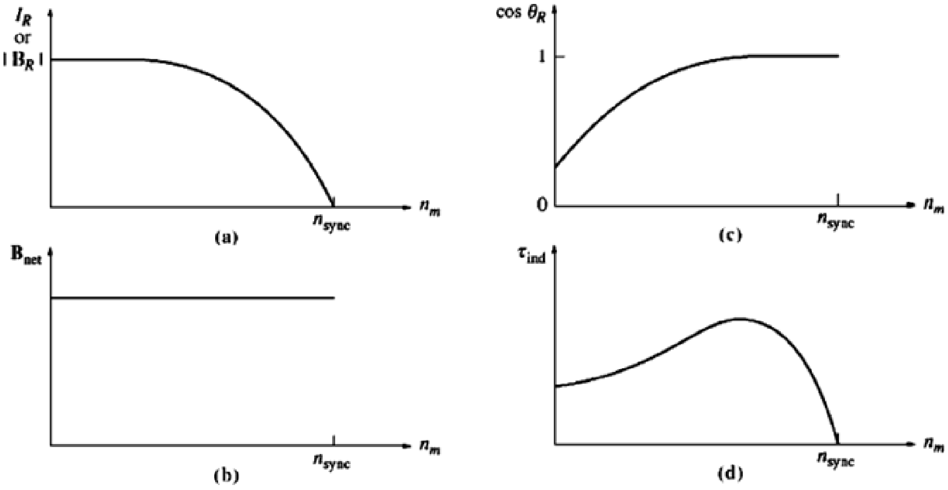
1		
2		
3	4	5
6	7	
9/10	11	
13	14	
15		
17	18	19
20		

Introduction – Motor Nameplate/Tag

Cell	Contents	Example
1	Manufacturing company	Weier
2	Model	Type DVX 160/2MK
3	Operating current type	3~
4	Machine type : generator/motor	Mot
5	Serial number	7163
6	Connection	Δ
7	Operating voltage	440 V
8	Operating current	23 A
9	Machine power (KW)	135 KW
10	Apparent power (KWA)	-
11	Operating type according to German system	S 1
12	Power factor	cos ϕ 0.9
13	Rated speed	3500 rpm
14	Frequency	60 Hz
15	Rotor voltage	-
16	Rotor current	-
17	Insulation level	F
18	Protection level	IPSS
19	Weight (ton)	0.08 t
20	Additional notes	-

Introduction – Motor Nameplate/Tag

Curves that represent the characteristics of induction motors



(a) (c) (b) (d)

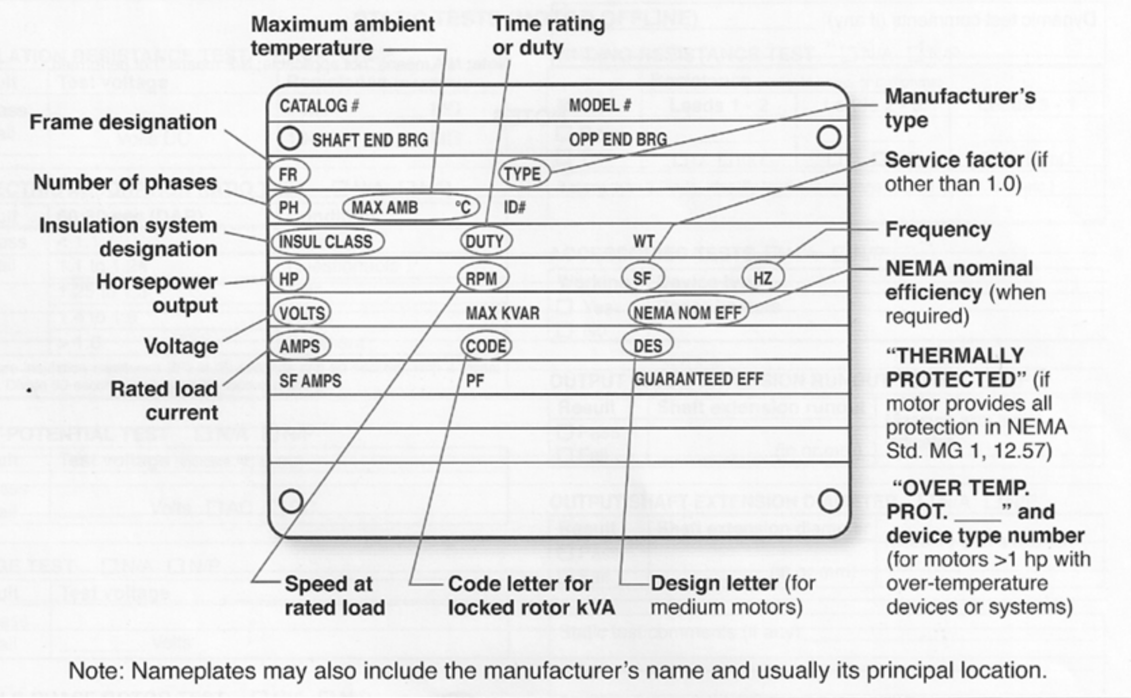
$$\boxed{X_L = 2\pi f\,L}$$

$$\tau_{\text{ind}} = k\mathbf{B}_R \times \mathbf{B}_{\text{net}}$$

$$s = \frac{n_{\text{sync}} - n_m}{n_{\text{sync}}}$$

$$f_r = sf_e$$

Introduction – Motor Nameplate/Tag



Maximum ambient temperature

Time rating or duty

Frame designation

Number of phases

Insulation system designation

Horsepower output

Voltage

Rated load current

Manufacturer's type

Service factor (if other than 1.0)

Frequency

NEMA nominal efficiency (when required)

"THERMALLY PROTECTED" (if motor provides all protection in NEMA Std. MG 1, 12.57)

"OVER TEMP. PROT. ____" and device type number (for motors >1 hp with over-temperature devices or systems)

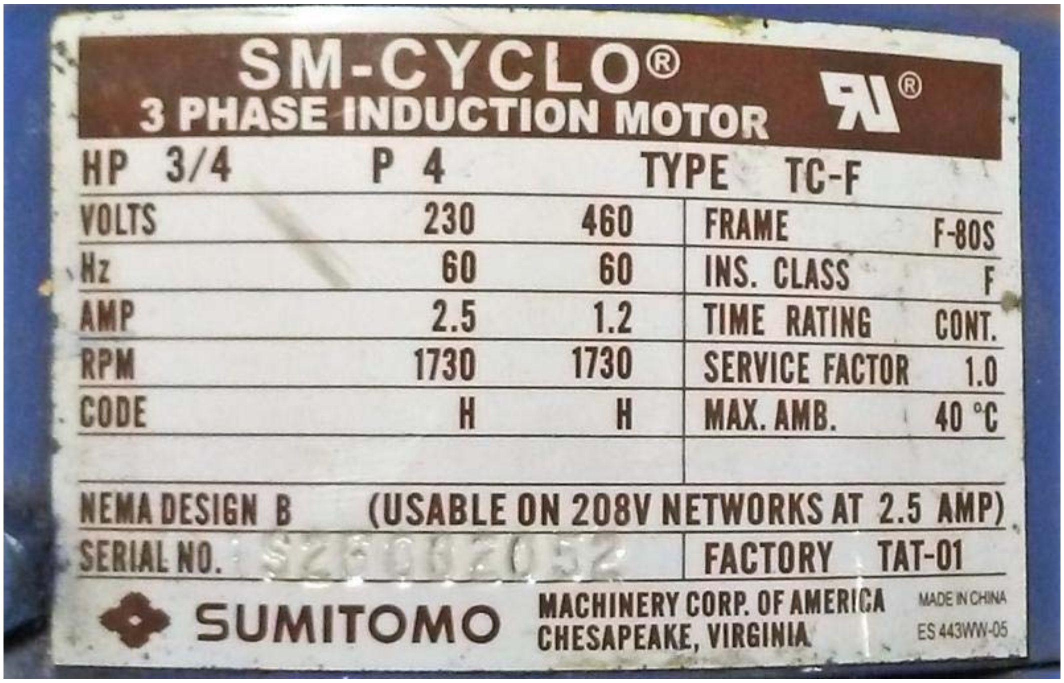
Speed at rated load

Code letter for locked rotor kVA

Design letter (for medium motors)

Note: Nameplates may also include the manufacturer's name and usually its principal location.

Introduction – Motor Nameplate/Tag



SM-CYCLO®

3 PHASE INDUCTION MOTOR

HP 3/4 P 4 TYPE TC-F

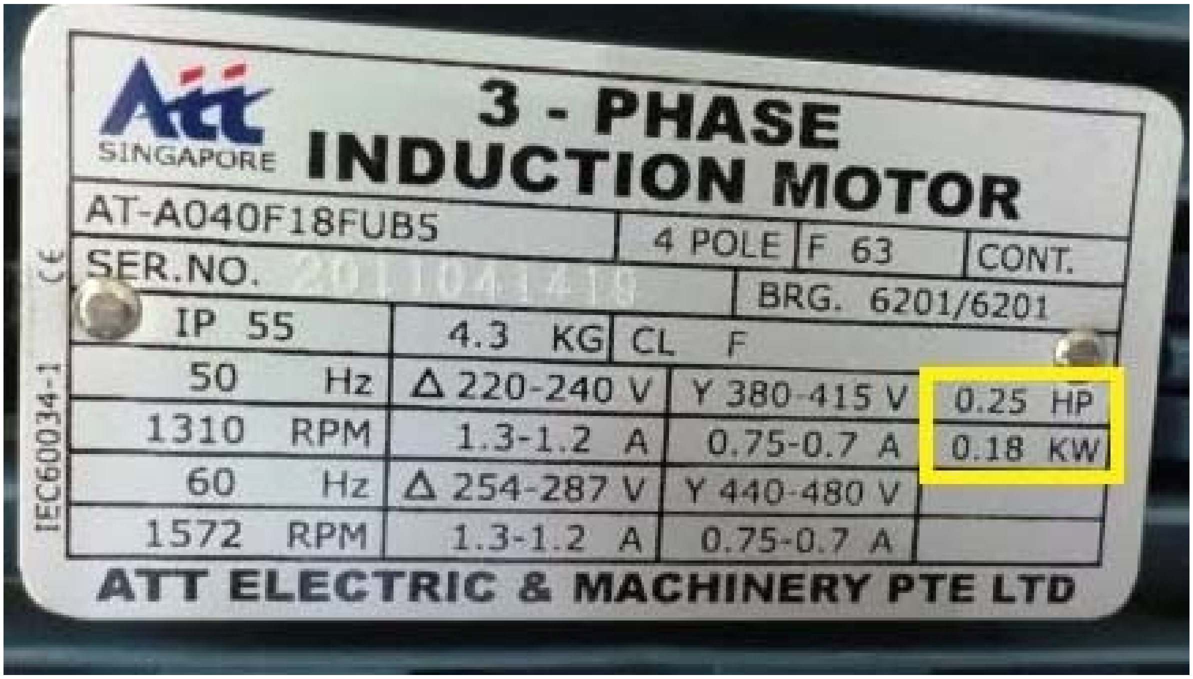
VOLTS	230	460	FRAME	F-80S
Hz	60	60	INS. CLASS	F
AMP	2.5	1.2	TIME RATING	CONT.
RPM	1730	1730	SERVICE FACTOR	1.0
CODE	H	H	MAX. AMB.	40 °C

NEMA DESIGN B (USABLE ON 208V NETWORKS AT 2.5 AMP)

SERIAL NO. [redacted] FACTORY TAT-01

SUMITOMO MACHINERY CORP. OF AMERICA
CHESAPEAKE, VIRGINIA
MADE IN CHINA
ES 443WW-05

Introduction – Motor Nameplate/Tag



Att SINGAPORE

3 - PHASE INDUCTION MOTOR

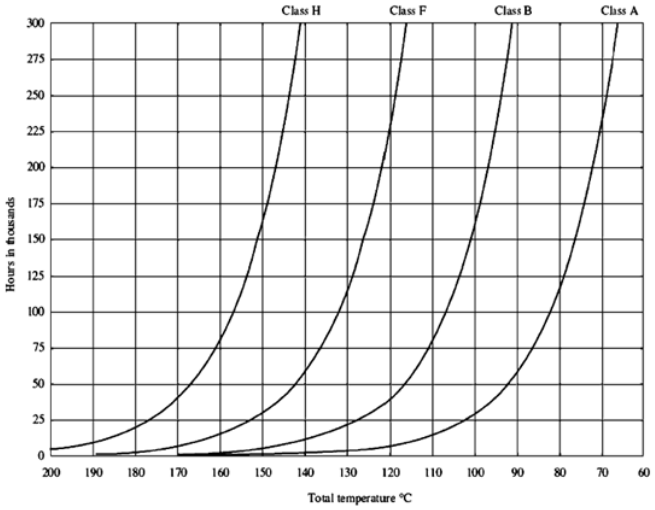
AT-A040F18FUB5	4 POLE	F 63	CONT.
SER.NO. [redacted]		BRG. 6201/6201	
IP 55	4.3 KG	CL F	
50 Hz	Δ 220-240 V	Y 380-415 V	0.25 HP
1310 RPM	1.3-1.2 A	0.75-0.7 A	0.18 KW
60 Hz	Δ 254-287 V	Y 440-480 V	
1572 RPM	1.3-1.2 A	0.75-0.7 A	

IEC60034-1 CE

ATT ELECTRIC & MACHINERY PTE LTD

Introduction – Insulation in Motors

Insulation level	C	H	F	B	E	A	Y
Maximum temperature handled by motor in Celsius (^oC)	>180	180	150	130	120	100	90



Introduction – Symbols

German System		International System	Description
Old	**Modern**		
R, S, T	L1, L2, L3	R, S, T	3 phase
MP	N	MP	Neutral
SL	PE	SL	Earth
U, V, W	U1, V1, W1	U1, V1, W1	Delta/Star connection terminals
X, Y, Z	U2, V2, W2	U2, V2, W2	
U, V, W	M	L.M	Rotor terminals
k	C	C	Capacitors
c.d	KM.KA	KM.K	Main contactors and relays
KT	KT	D	Timers
m	M	M	Motors
G	G	G	Generators

Introduction – Electrical Schematics

- **Electrical schematics** represent the most detailed category of electrical drawings.
- They depict every component in a circuit, and how each component is wired into the circuit.
- A **wiring diagram** is a simple visual representation of the physical connections and physical layout of an electrical system or circuit.
- It shows how the electrical wires are interconnected and can also show where fixtures and components may be connected to the system

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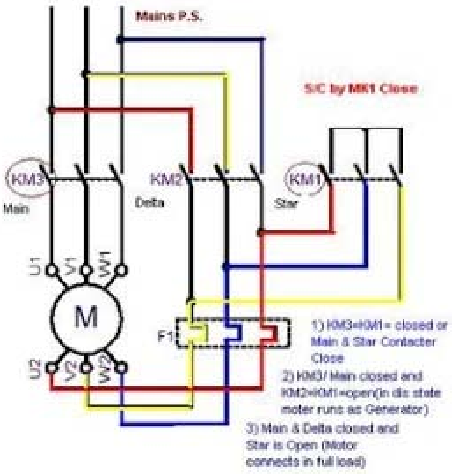
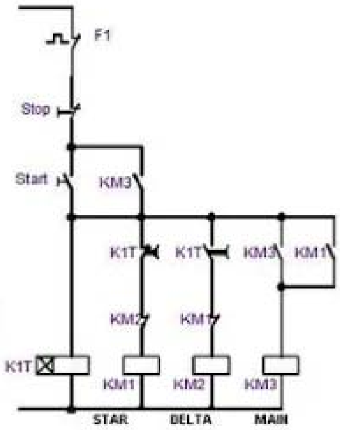
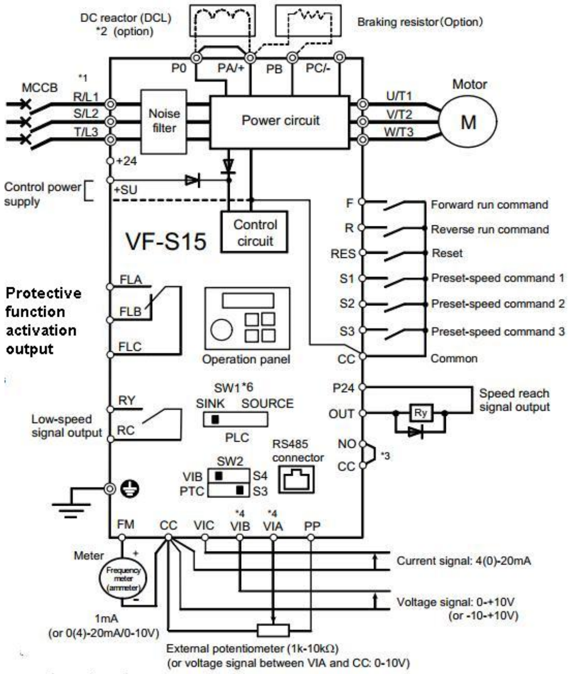
Introduction – Electrical Schematics





Introduction – Electrical Schematics



inverter-plc.com

Either AC reactors or DC reactors (link chokes) serve the same primary purpose, to smooth the current flow to the inverter/converter, and reduce damaging harmonics produced on the power lines. -DC reactors (link chokes) are connected after the input diodes in the power circuit.

Introduction – Control Panels

- A **control panel** is a flat, often vertical, area where control or monitoring instruments are displayed or it is an enclosed unit that is the part of a system that users can access, such as the control panel of a security system (also called control unit).

Introduction – Control Panels

- They are found in factories to monitor and control machines or production lines and in places such as nuclear power plants, ships, aircraft and mainframe computers.
- Older control panels are most often equipped with push buttons and analog instruments, whereas nowadays in many cases touchscreens are used for monitoring and control purposes.

Introduction – Control Panels

- Electrical panel components control every piece of equipment in every industry. It’s difficult to describe all possible combinations because every industry and most companies have defined component preferences.

Introduction – Control Panels

Control panels contain all electrical/electronic devices/components needed to operate the system on site such as:

- Circuit Breakers, Switches, and Push Buttons
- Contactors/Relays
- Solid-State Relays
- Fuses, Overloads, Phase Failure Relays
- Inverters, VFDs, and V3Fs
- PLCs
- Transformers
- DC Power Supplies

Contactors and Relays

By

Dr. Mohammad Salah

Mechatronics Engineering Department

The Hashemite University

Definition

- **Contactors** and **Relays** are **electromagnetic switches** that have electromagnet controlled contacts, actuated by electric signals in one circuit to control current or supply in another circuit.
- **Contactors** sometimes are called **magnetic starters**

Comparison

- Both have a magnet coil (6/12/24/48Vdc or 110/220/380Vac and it depends whether it is within a **relay** or **contactor**).
- **Contactors** have **main contacts** (always normally open - NO) to connect power to the electrical load and **auxiliary contacts** (usually one normally open – NO and one normally closed - NC) for control circuit while **relays** have one type of contacts (NO, NC, or/and changeover type) for power and control circuits.
- Some **contactors** can be fitted externally with auxiliary contacts which can be NO or NC. However these are used to perform additional functions related the control of the contactor.

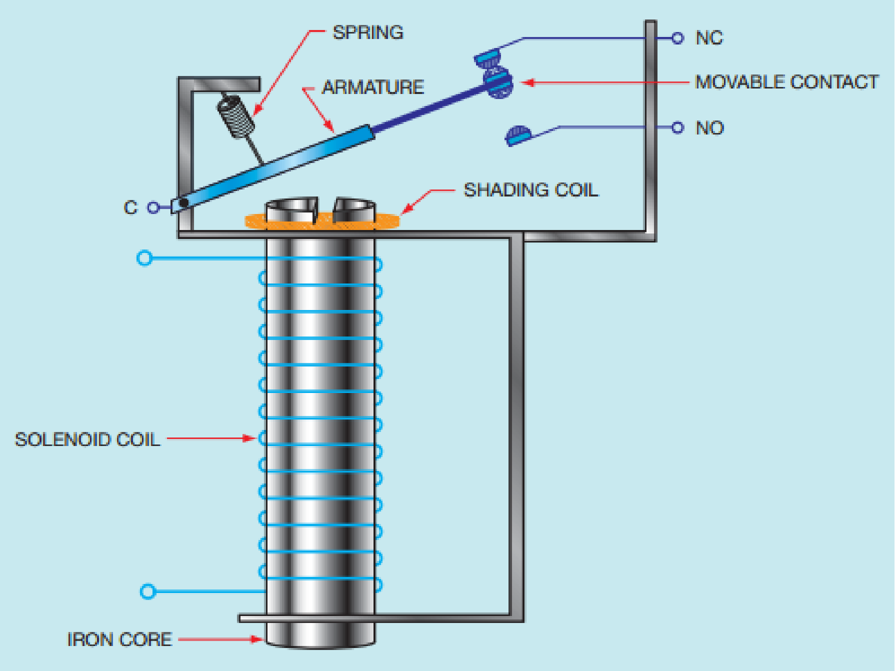
Comparison

- **Relays** are usually used for low voltage applications while **contactors** are used for higher voltage application.

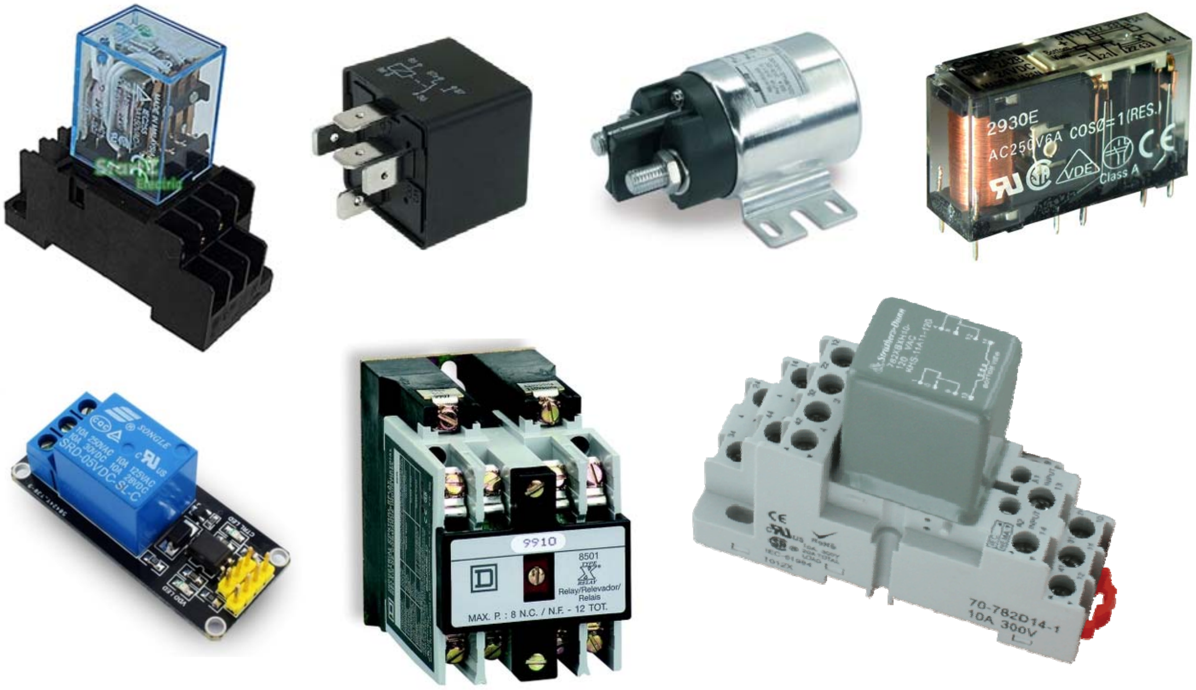
When to Use a Relay	When to Use a Contactor
☐ 10A or less current	☐ 9A or more current
☐ Up to 250VAC	☐ Up to 1000VAC
☐ 1 phase	☐ 1 or 3 phase

- **Contactors** are commonly connected to overloads to that will interrupt the circuit if the current exceeds a set threshold for a selected time period, usually 10-30seconds. This is to protect the equipment downstream of the **contactor** from damage due to current. **Overloads** are much less common on **relays**.

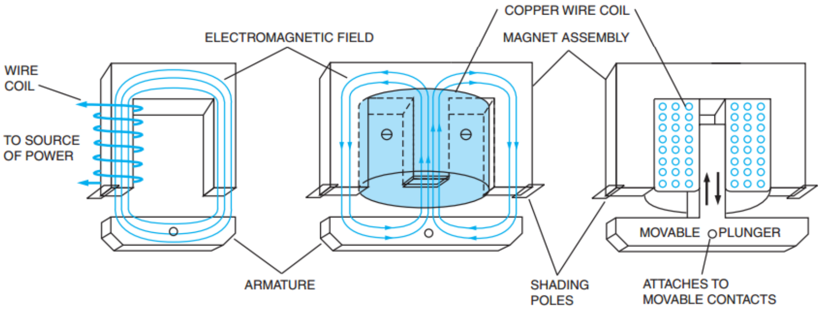
Relay Structure



Relay Appearance



Contactor Structure

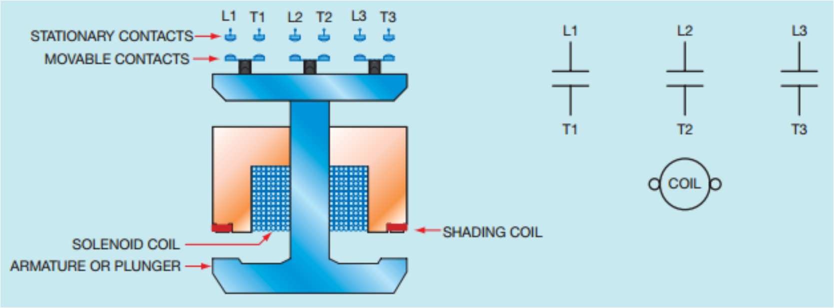


(A) U- OR C-SHAPED MAGNET CORE

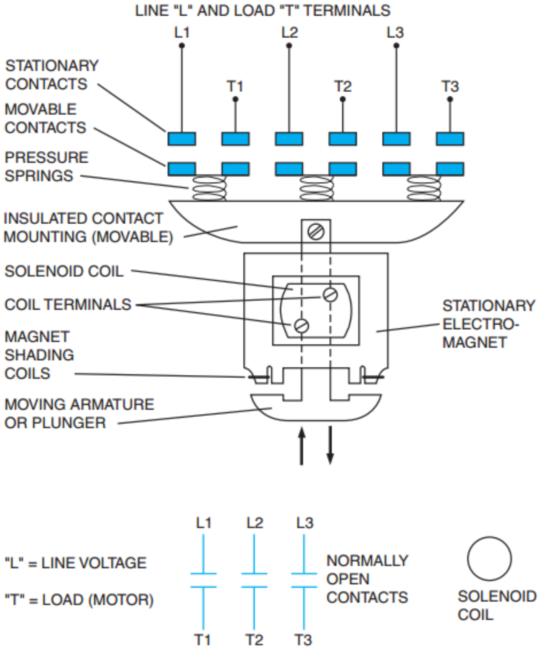
(B) BALANCED MAGNETIC ATTRACTION IS POSSIBLE WITH E-SHAPED IRON CORE

(C) SOLENOID DESIGN IS A VARIATION OF E-SHAPED ELECTROMAGNET

(Source: Delmar/Cengage Learning)



Contactor Structure



(Source: Delmar/Cengage Learning)

Contactor Appearance

Contactor Appearance

Numbering System

- The numbering system of control devices is similar in both German and International systems.
- Numbering the **main contacts** in **contactors**, **overloads**, **circuit breakers** and **fuses**

First contact: (L1 - T1) or (1 - 2)
Second contact: (L2 - T2) or (3 - 4)
Third contact: (L3 - T3) or (5 - 6)

- The **auxiliary contacts** are numbered with two numbers.
- The number on the right side indicates the type, and the one on the left indicates the order in the device

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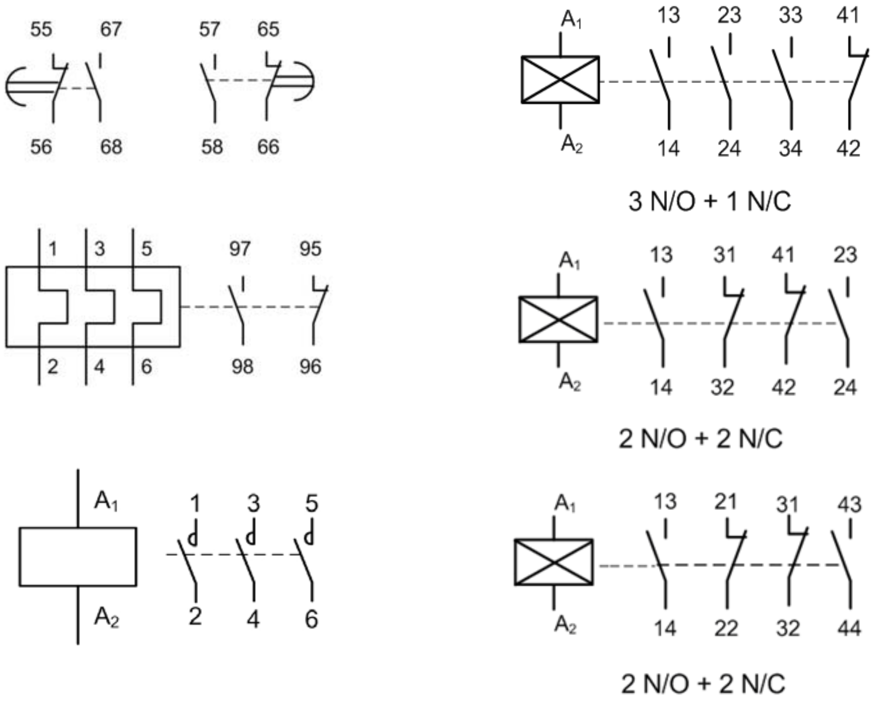
Numbering System

- The number on the right depends on the switch types (normally open or closed) and device types (contactor or timer…etc.).
- For example, the normally open contacts in contactors, push buttons and different switches (pressure switches, level switches, temperature switches, proximity switches…etc.) takes numbers (3-4) and normally closed takes (1-2), while open contacts for timers takes (7-8) and closed takes (5-6).
- The energizing terminals of the electromechanical Control Devices is numbered by (A_1-A_2) for devices with one coil and (A_1-A_2) or (B_1-B_2) for devices with two coils.

Numbering System



Numbering System

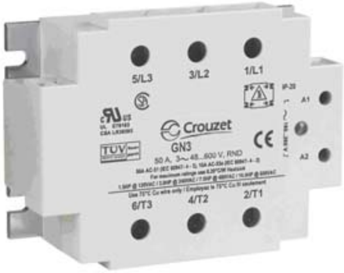
RELAY CONTACT COMMON FORMS

	Form description	Short description	NARM designator	Circuit symbol
Make contact	Form A	NO	SPST-NO	
Break contact	Form B	NC	SPST-NC	
Changeover contact	Form C	CO	SPDT	
Double-make on armature	Form U		SPST-NO DM	
Double-break on armature	Form V		SPST-NC DB	
Double-make contact	Form X		SPST-NO DM	
Double-break contact	Form Y		SPST-NC DB	
Double-break, double-make contact	Form Z		SPDT-NC-NO DB-DM	
Triple-make contact	Form 3			

Solid-State Relays

- **A Solid-State Relay (SSR)** is a semiconductor device that can be used in place of a mechanical relay to switch electricity to a load in many applications.
- **SSRs** are purely electronic, normally composed of a low current control side (equivalent to the coil on an electromechanical relay) and a high-current load side (equivalent to the contact on a conventional relay).
- **SSRs** are typically feature electrical isolation to several thousand volts between the control and load sides.

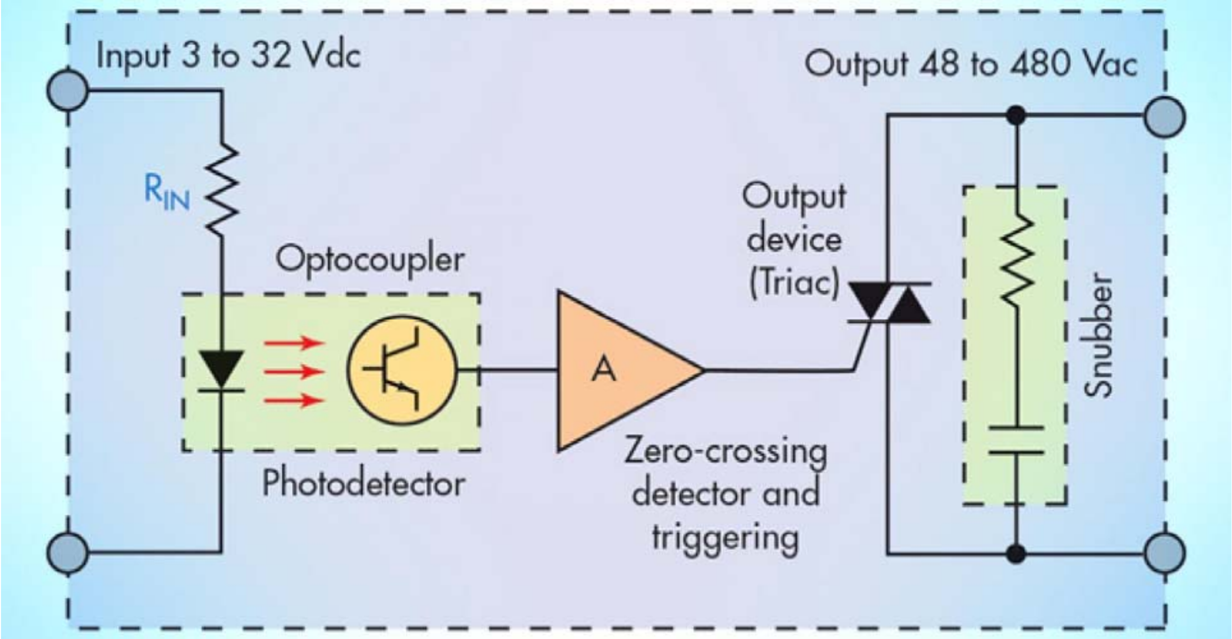
Solid-State Relays



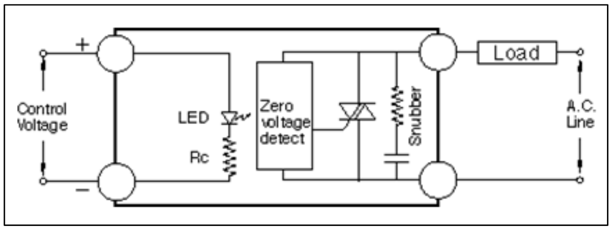
Solid-State Relays

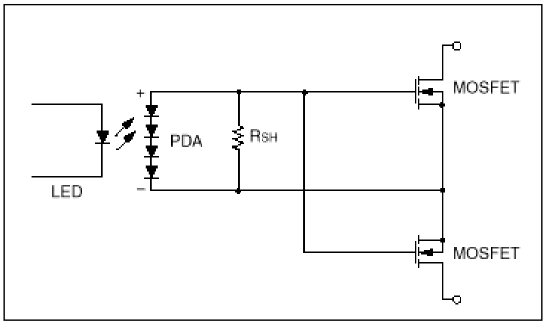
- **SSR** contains one or more LEDs in the input (drive) section. The **SSR** provides optical coupling to a phototransistor or photodiode array, which in turn connects to driver circuitry that provides an interface to the switching device or devices at the output. The switching device is typically a **MOSFET** or **TRIAC**.
- Several **SSRs** that incorporate **TRIACs** provide a built-in series-RC snubber network to protect the **TRIAC** against line voltage surges. A snubber protects the **TRIAC** against small to moderate surges.

Solid-State Relays

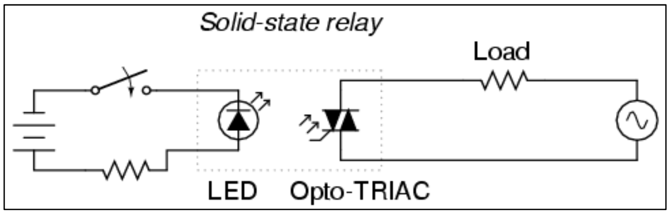


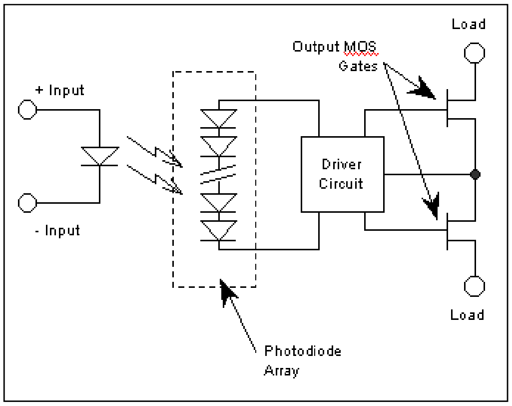
Solid-State Relays





Typical block diagrams of SSR circuits



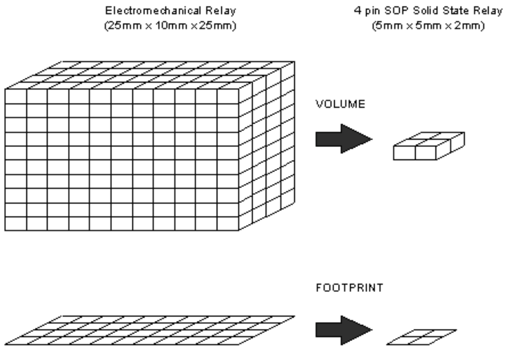


Solid-State Relays - Benefits

- No mechanical moving parts so No contact materials which will wear out in frequent use
- No arching or sparking in contacts
- No inductors on control side
- No contact bounce (spring back)
- High switching speed
- High reliability
- Long operating life
- Resistant to shock and vibration
- Wide input voltage range possible
- Possible to always turn on and off only at zero phase
- High input-output isolation

Solid-State Relays – Bad Sides

- Output gets damaged quite easily by over voltages
- Typical failure mode is output short-circuit
- Output has minimum voltage and current in order to work
- Output has some leakage current on off-state
- More expensive than normal relays
- Low to moderate volumetric efficiency



Solid-State Relays – Bad Sides

- Restricted to single pole, normally open (NO) configurations
- Heats up noticeably when large current passes through it
- More sensitive to voltage transients
- Most types work only on AC current (there are also special DC **SSR** available)
- Electromagnetic relays usually have an edge over SSRs in applications requiring extremely high voltages and currents. **SSRs** can't match the current-carrying capacity and low on-resistance of the biggest electromechanical relays

Solid-State Relays – Questions

What does a zero-crossing turn-on circuit refer to?

- Zero-crossing turn-on and turn-off refer to the point on the AC wave form when the voltage is zero. It is at this point that an AC **SSR** will turn on or off. When the AC circuit voltage is at zero, no current is flowing. This makes it much easier and safer for the semiconductor device in the relay to be turned on or off. It also generates much less electrical EMI/RFI noise.

Solid-State Relays – Questions

Can I use an AC SSR to switch a DC load?

- No. Because of the zero crossing circuit described above, the relay will most likely never turn on, and even if it is on, it will likely not be able to turned off, as DC voltage typically never drops to zero.

Solid-State Relays – Questions

Can I use a DC SSR to switch a AC load?

- No. If the DC semiconductor relay is polarized, it may break down and conduct for the portion of the waveform that is reversed in polarity. There are available also non-polarized semiconductor relays which can be used on DC and AC but those are more expensive.

Solid-State Relays – Questions

Can I hook up SSRs in parallel to achieve a higher current rating?

- No. There is no way to guarantee that two or more relays will turn on simultaneously when operated in parallel. Each relay requires a minimum voltage across the output terminals to function; because of the optical isolation feature, the contact part of the **SSR** is actually powered by the line it switches. One relay turning on before the other will cause the second relay to lose its turn-on voltage, and it won't ever turn on, or at least not until the first relay fails from carrying too much current.

Protection Devices

By

Dr. Mohammad Salah

Mechatronics Engineering Department

The Hashemite University

Introduction

- Motors can be damaged by excessive currents going through their windings.
- **Protection devices** must be added to motor circuits to prevent the machines from burning up.
- **Circuit-breakers** or **fuses** are necessary to avoid high current levels rushing into the motor windings.
- Under such conditions, these protection devices open the circuit immediately.
- Low levels of excessive current may also cause damage to the motor over a certain period of time.

Introduction

- **Overload protection devices** will open the circuit when the current drawn by the motor is relatively high after a time delay.
- When sizing the protection devices, it is important to note that all electric motors suffer from a condition called **inrush current**.
- When starting the motor, there is a brief spike of current that can be several times the steady-state current.
- **Protection devices** must be carefully chosen so that they do not unnecessarily disrupt the system under those normal conditions

Circuit Breakers

- **Circuit breakers** are switches that open the circuit automatically over a predetermined current level.
- **Circuit-breakers** can be reset to resume normal operation.
- When electrical contacts open to interrupt a large current, there is a tendency for an arc to form between the contacts, which would allow the flow of current to continue.
- The maximum short-circuit current that a breaker can interrupt safely is called the **interrupting capacity**

Circuit Breakers

Fuses

- A **fuse** protects the circuit from an overcurrent condition.
- Its metal alloy melts when heated by a prescribed electric current, hence opening the circuit.
- A **fuse** also has a rated interrupting capacity, which is the maximum current the fuse can safely interrupt.
- Compared to **circuit-breakers**, **fuses** have the advantage of being cheaper for similar ratings.
- However, blown **fuses** must be replaced with new devices, which is less convenient than simply resetting a breaker.

Fuses

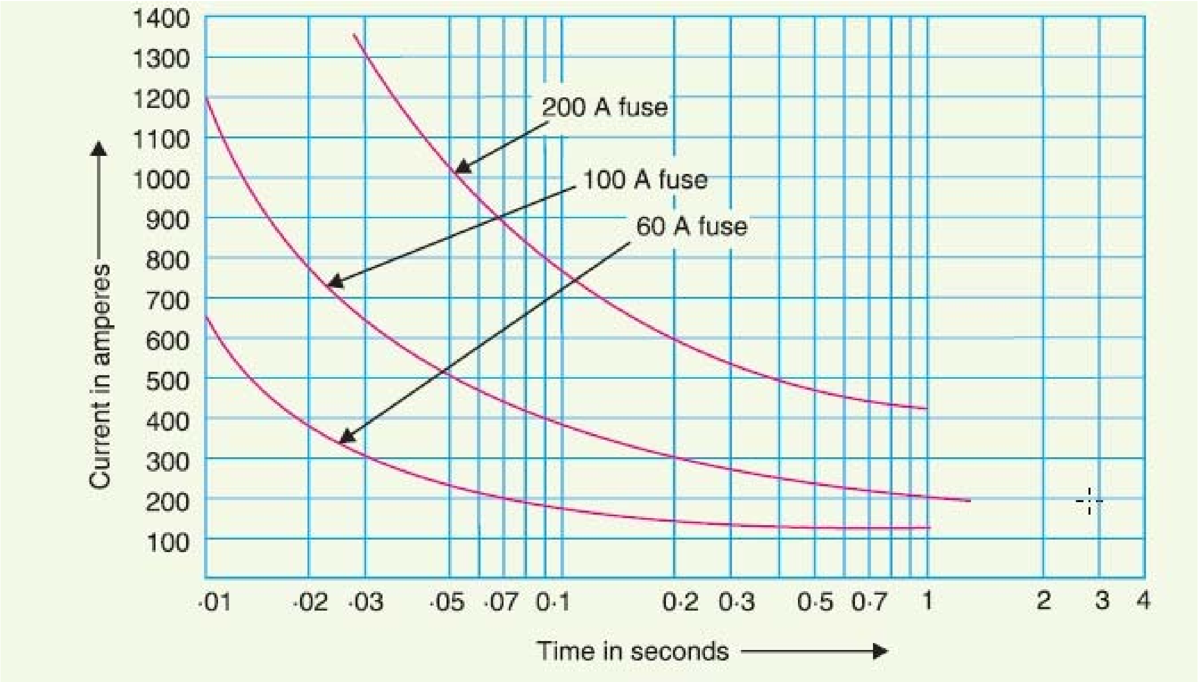
- In addition, when a single **fuse** blows in a three-phase system, the two other phases may still be operational, which is possibly hazardous.
- In comparison, a three-phase circuit-breaker interrupts all phases simultaneously.



Fuses

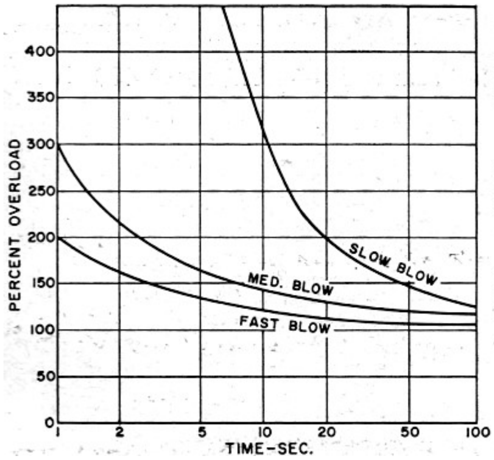
- A **Fuse** operates when its element melts due to heat produced by I^2R_F, where R_F is Fuse resistance.
- This heat produced increases if the current flowing through the Fuse element increases
- A **Fuse** element will melt faster for large fault current while it will take some time for lower value of fault current.
- This time-current relationship of **Fuse** is known as **Characteristics of Fuse** and is very useful for proper selection of **Fuse** for a particular circuit and for coordination purpose.

Fuses

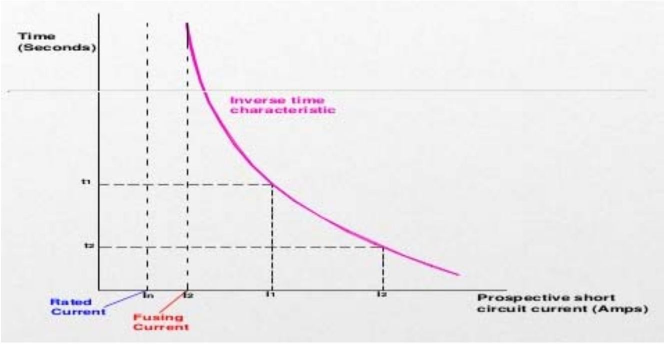


1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
Current in amperes
200 A fuse
100 A fuse
60 A fuse
·01
·02
·03
·05
·07
0·1
0·2
0·3
0·5
0·7
1
2
3
4
Time in seconds

Fuses



400
350
300
250
200
150
100
50
0
PERCENT OVERLOAD
SLOW BLOW
MED. BLOW
FAST BLOW
1
2
5
10
20
50
100
TIME-SEC.



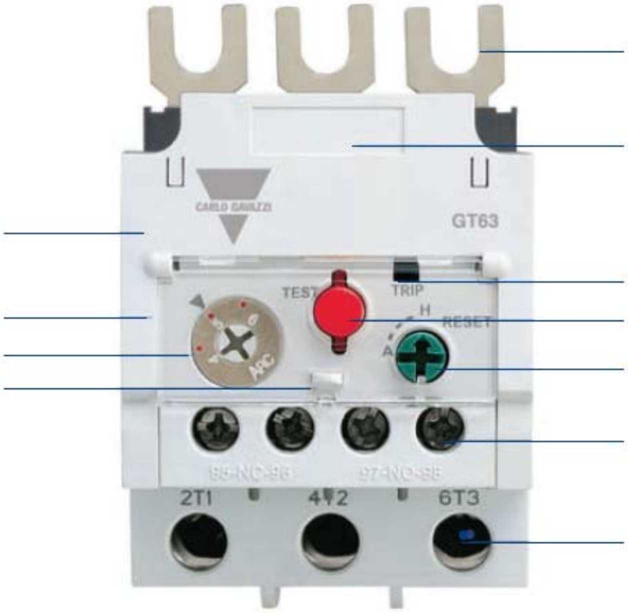
Time
(Seconds)
Inverse time
characteristic
t1
t2
In
I2
I1
I2
Rated
Current
Fusing
Current
Prospective short
circuit current (Amps)

Overload Relays

- An **overload relay** is essentially a sensor that is connected between the power supply and the load and upon the detection of a current overload condition, disconnects the load from the power supply.
- Electric motor **overload protection** is necessary to prevent burnout and ensure maximum operating life of the motor. Motor overloads may be caused by:
  1. An undersized motor
  2. Increased load on the driven machine
  3. Low input voltage
  4. Numerous start/stop cycles
  5. An open phase in a polyphase system

Overload Relays

Overload Relays



Upstream connections

Circuit identification

Relay type

Trip indicator

Protection cover

Stop/Test button

Adjustment dial

Reset button/Selector (manual or automatic reset)

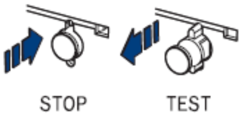
Sealing the protection cover

Auxiliary contacts(1NO+1NC)

Downstream connections

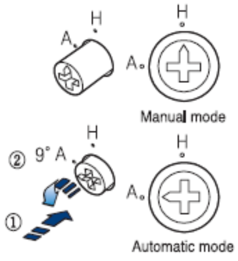
Overload Relays

Stop/Test button



STOP function is executed by pushing the button, which causes the next sequence.
In case of operation test pull this button.

Reset button/Selector



Using a driver the reset mode can be set.
In case of Manual mode(H) push the button to reset the relay.
To change to Automatic mode(A) from Manual mode push the button and rotate as shown in the fig.

Overload Relays

- **Overloads** are mounted directly under the contactor in most circumstances.

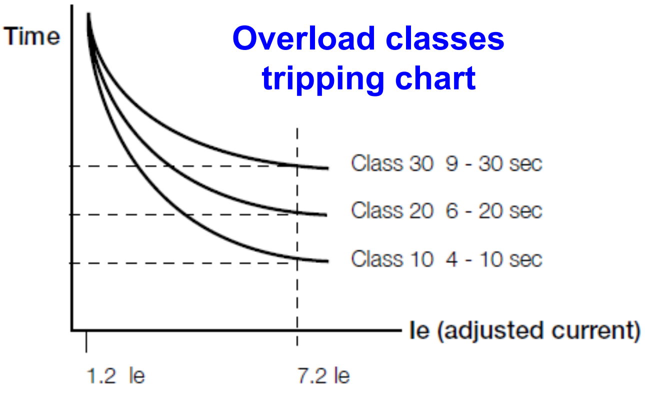
Overload Relays

Overload Relays – Class Number

- The **class number** indicates how long the **overload relay** takes to trip when carrying a current equal to 6 times its current rating (or the value set when the overload is adjustable):
- **Class 10** overload relay will trip in 10 seconds or less at a current equal to 6 times its rating.
- **Class 20** overload relay will trip in 20 seconds or less at a current equal to 6 times its rating.
- **Class 30** overload relay will trip in 30 seconds or less at a current equal to 6 times its rating.

Overload Relays – Class Number

- **Class 10 overload relays** are usually used with motors that heat faster.
- **Class 30 overload relays** are mostly used with motors driving high inertia loads, that take more time to accelerate.



Overload Relays – Types

1. Traditional thermal overloads

A. **Bimetallic thermal overloads** were originally built using bimetallic strips that actually warped when heated to break contact and trip the devices. In other words, this design uses a bimetal strip associated with a current-carrying heater coil. When an overload occurs, the heat causes the bimetal to deflect and actuate a tripping mechanism which opens a set of contacts in the control circuit interrupting power to the coil and opening the power contacts.

Overload Relays – Types

1. Traditional thermal overloads

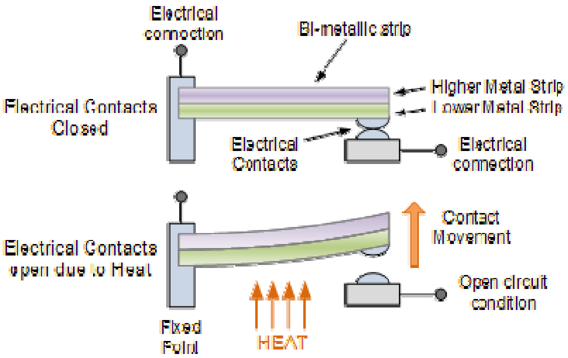
A. **Bimetallic thermal overloads**

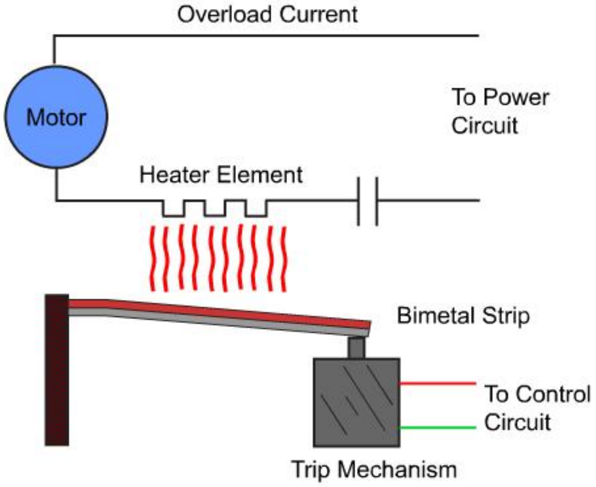
Most bimetallic thermal relays are adjustable over a range from 85% to 115% of their value. In fact, having the overload relays work with thermal effect creates problems when ambient temperatures fluctuated greatly. Thus, some modules are available with ambient compensation. An ambient compensated devices' trip point is not affected by ambient temperature and performs consistently at the same value of current.

Overload Relays – Types

1. Traditional thermal overloads

A. Bimetallic thermal overloads

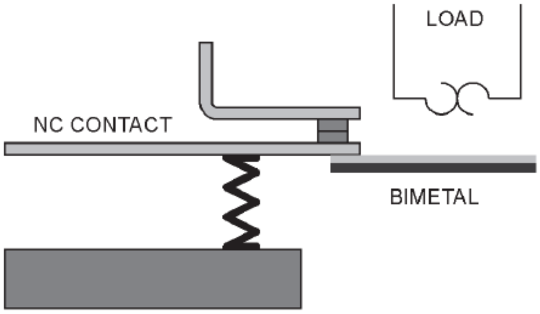




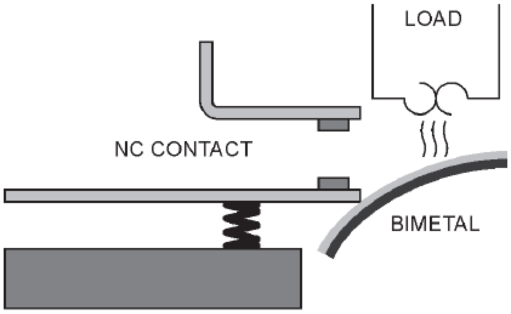
Overload Relays – Types

1. Traditional thermal overloads

A. Bimetallic thermal overloads



NORMAL OPERATION

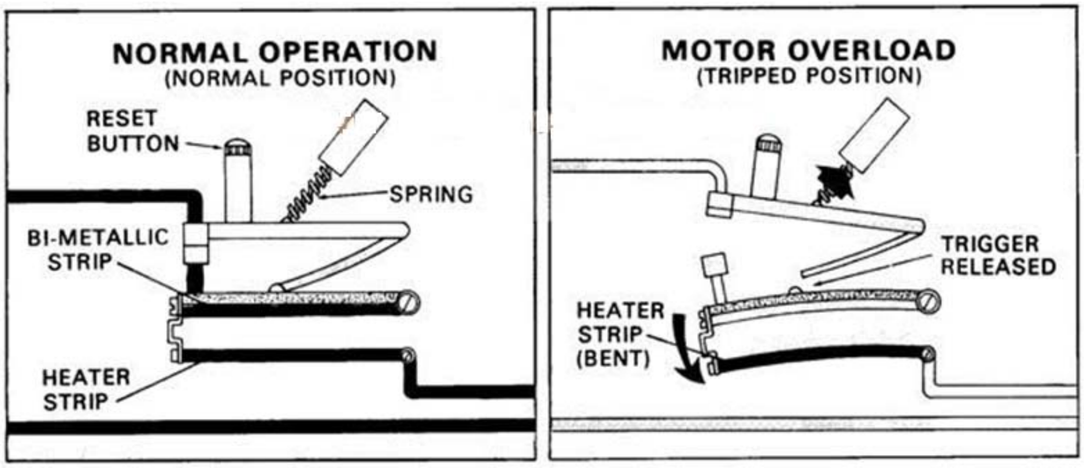


OVERLOAD CONDITION

Overload Relays – Types

1. Traditional thermal overloads

A. Bimetallic thermal overloads



Overload Relays – Types

1. Traditional thermal overloads

B. Melting Alloy thermal overloads were developed to overcome the temperature problem until ambient compensated bimetallic overloads were introduced. These **overload devices** are still slow and inaccurate and do not protect the motor against single phase or unbalance conditions. When the motor current exceeds the rated value, the temperature will rise to a point where the alloy melts.

Overload Relays – Types

1. Traditional thermal overloads

B. Melting Alloy thermal overloads

The ratchet wheel is then free to rotate, and the contact pawl moves upward under spring pressure allowing the control circuit contacts to open. After the heater element cools, the ratchet wheel will again be held stationary and the overload contacts can be reset. Severe fault currents can damage the heater element and they should be replaced after such an occurrence.

Overload Relays – Types

1. Traditional thermal overloads

B. Melting Alloy thermal overloads

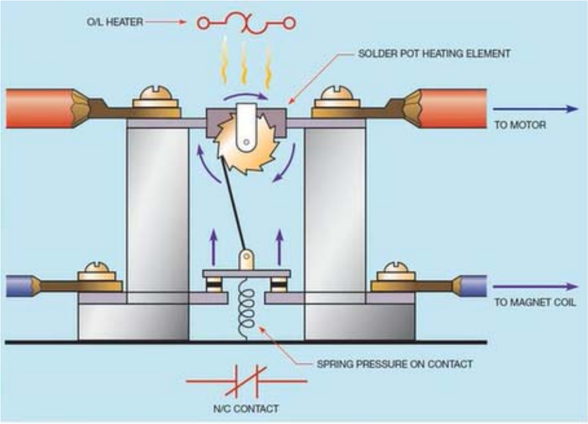
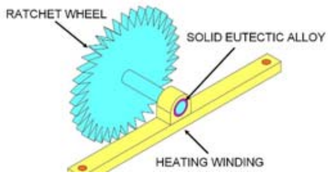
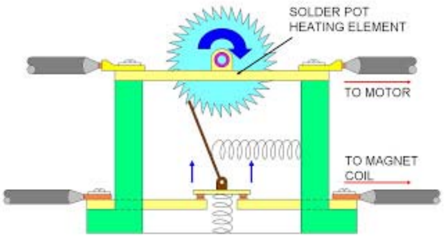


FIGURE 4-4
Melting alloy thermal overload relay. A spring pushes the contacts open if heat melts the solder and permits the serrated wheel to turn freely. Note the electrical symbols for the normally closed overload contact and the heater element.





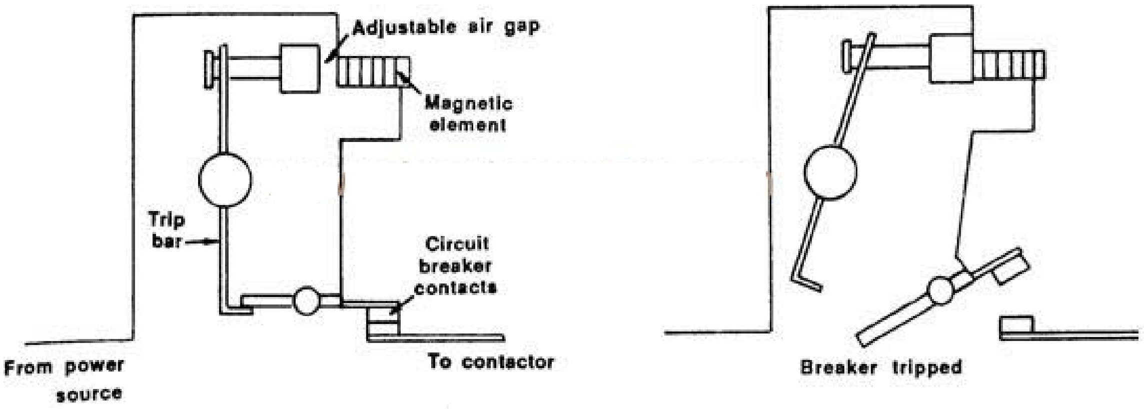
Overload Relays – Types

2. Magnetic overloads

They are an electro-mechanical relays operated by the current flow in a circuit. When the level of current in the circuit reaches a preset value, the increased magnetic field opens a set of contacts. **Electromagnetic overload relays** operate on the magnetic action of the load current flowing through a coil. When the load current becomes too high, a plunger is pulled up into the coil interrupting the circuit. The tripping current is adjusted by altering the initial position of the plunger with respect to the coil.

Overload Relays – Types

2. Magnetic overloads



Overload Relays – Types

3. Electronic (solid-state) overloads

They are the newest form of overloads. They replace thermal-based protection with electrical measurements. Electronic overloads can be simple and inexpensive or quite sophisticated, premium priced devices. Some are programmable, have a digital readout, and allow the user to accurately set trip levels, trip classes, and time delays, voltage protection, ground fault protection, and communication interface. They utilize embedded current transformers to detect and measure actual current.

Overload Relays – Types

3. Electronic (solid-state) overloads

Phase Failure Relays

- Under phase loss conditions motors, pumps, blowers, and other equipment draw excessive current on the remaining two phases which quickly overheats the motor windings.
- Power output is greatly reduced and starting is not possible in this condition.
- This can potentially leave the equipment in a 'locked rotor' state which will overheat and damage the equipment even more rapidly.

Phase Failure Relays

- Quickly troubleshooting a phase loss and determining the root cause is often difficult.
- Voltages and currents in a three-phase system do not typically just drop to zero when a phase is lost.
- Often measurements yield confusing values that require a great deal of complex analysis to correctly interpret.
- Meanwhile, damage and downtime of the equipment continues to rise.

Phase Failure Relays

- **A three-phase monitor relay**, also called a **phase failure relay**, protects against damage caused by phase loss as well as other three-phase fault conditions (such as wrong sequence).
- These relays notify of fault conditions and provide control contacts to turn off motors or other equipment before damage occurs.
- Further, the relay provides clear indication of the fault present allowing for rapid troubleshooting and reduced downtime.

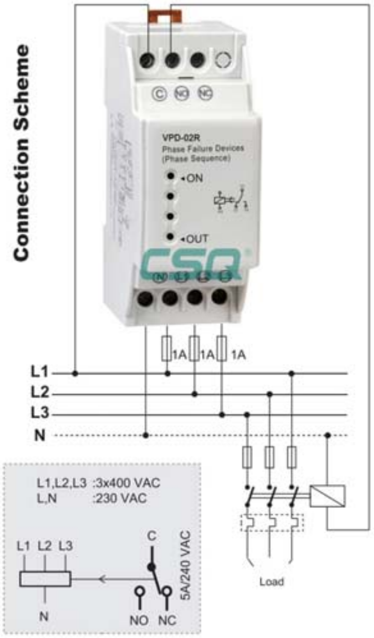
Phase Failure Relays – Causes

- Loss of one of the phases from the supply.
- One of the cables that supply the motor is damaged.
- Broken connection terminals due to vibrations or aging.
- Connection terminals that are not properly tightened.
- One of the fuses of the three-phase circuit opens.
- The starter contactor is damaged/rusty and leaves an open phase.
- Damaged relay contacts.
- Protections poorly configured.

Phase Failure Relays – Effects

- The engine operates at a reduced speed.
- Considerable loss of the relative power of the motor.
- Because only 2 phases are providing the power, the insulation in the motor windings is not able to withstand the increase in current and heat. When the insulation is damaged, a short circuit is created in the winding that causes the motor to burn.
- It can cause generator overload.
- If the motor is off when the failure occurs, it may not start when its operation is required and if it does, it will burn.

Phase Failure Relays



3-Phase Induction Motor Starting Methods

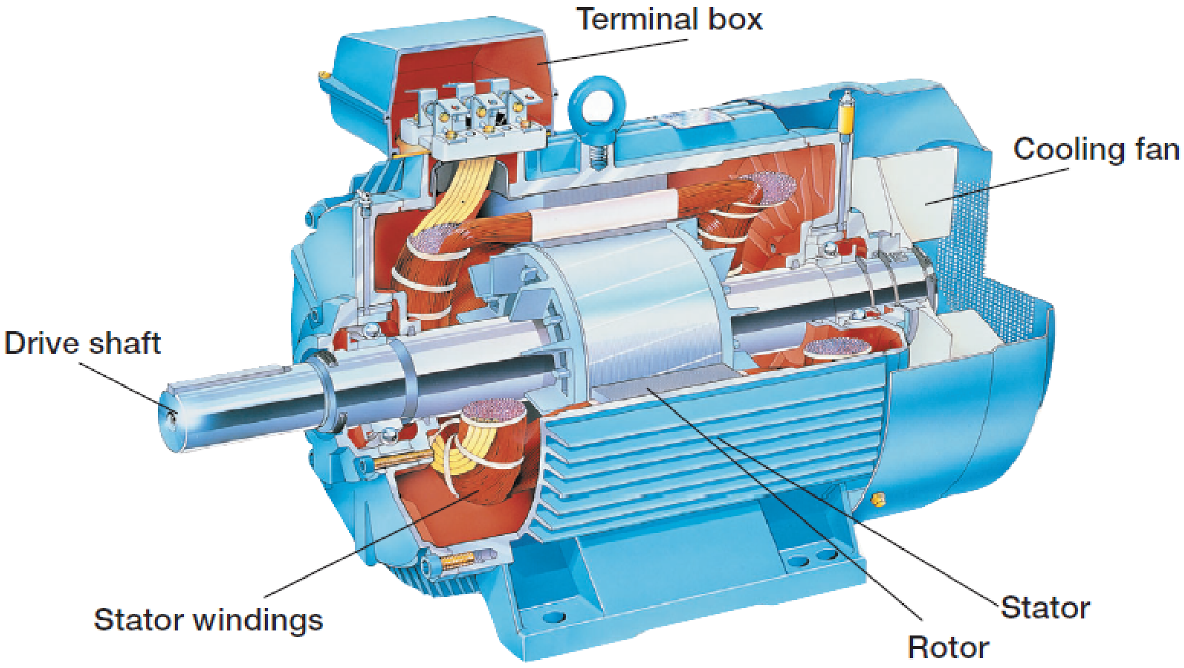
By

Dr. Mohammad Salah

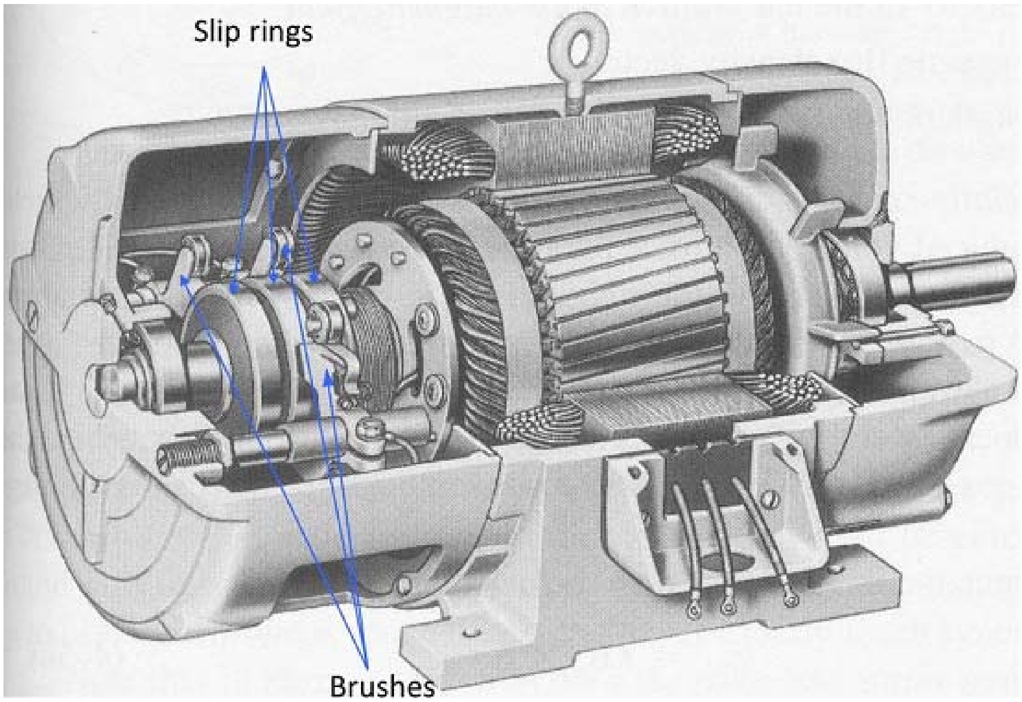
Mechatronics Engineering Department

The Hashemite University

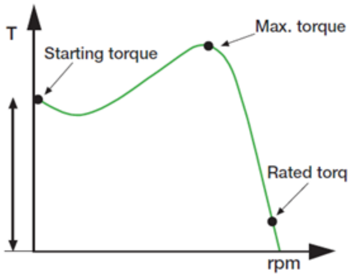
Introduction



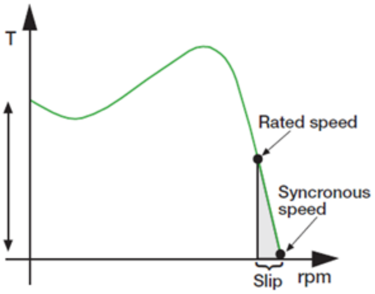
Introduction

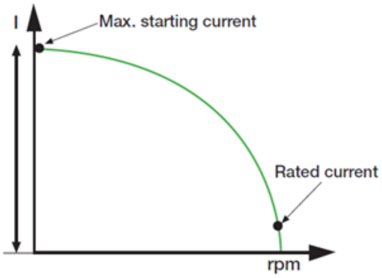


Introduction

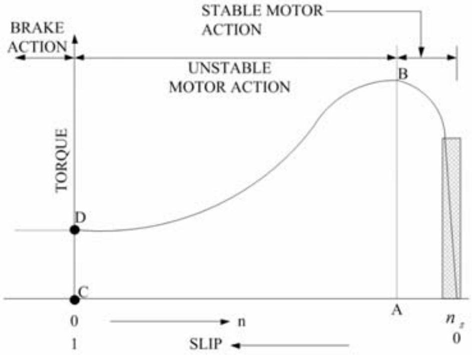


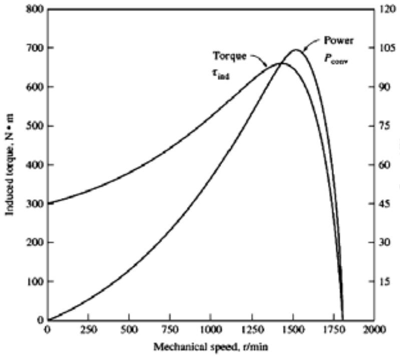
Torque diagram for a typical squirrel cage motor

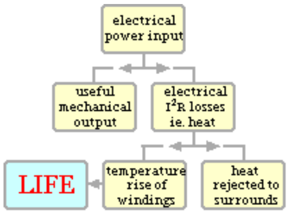




Current diagram for typical sqirrel cage motor







electrical power input

useful mechanical output

electrical I^2R losses ie. heat

LIFE

temperature rise of windings

heat rejected to surrounds

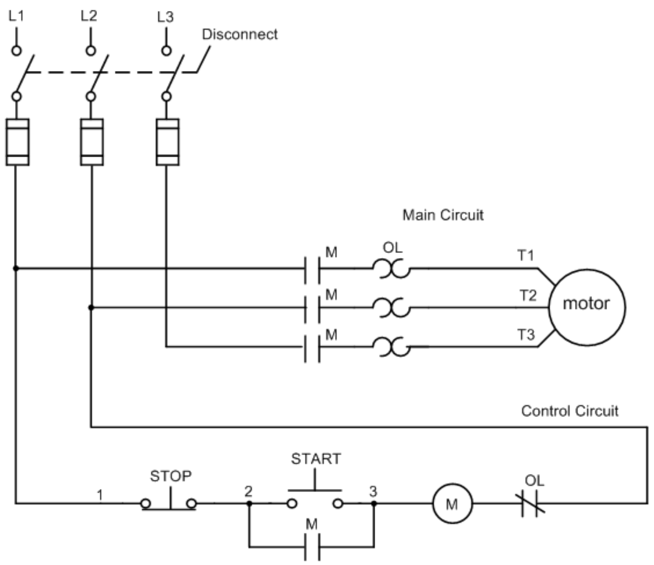
Introduction

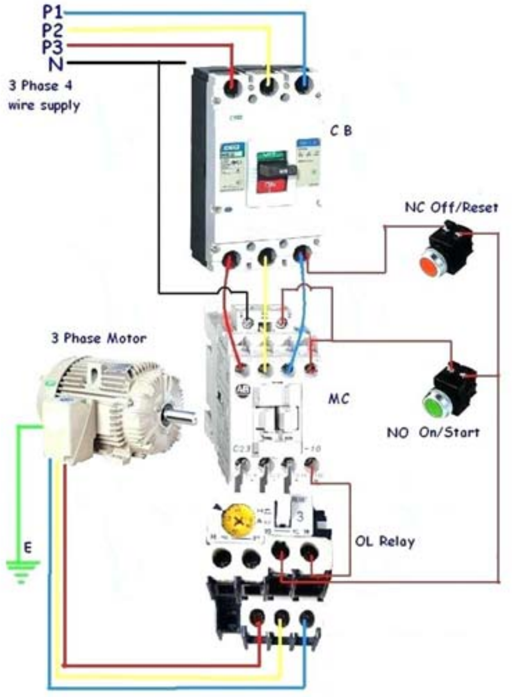
- Motor starting methods are primarily used to reduce voltage or current at the starting, thereby protecting the machine from heavy currents and over voltages.
- Starting methods are not a one-size-fits-all technology. Take in all aspects of a system before selecting a starting method.
- During direction-on-line (DOL) starting and stopping, low- and medium-voltage motors experience starting currents of up to eight times the nominal current and high acceleration rate or torque. These characteristics cause voltage dips in the network as well as mechanical wear and in some cases destruction of equipment, such as gearing, couplings, shafts, belts, or fragile parts or products.

Introduction

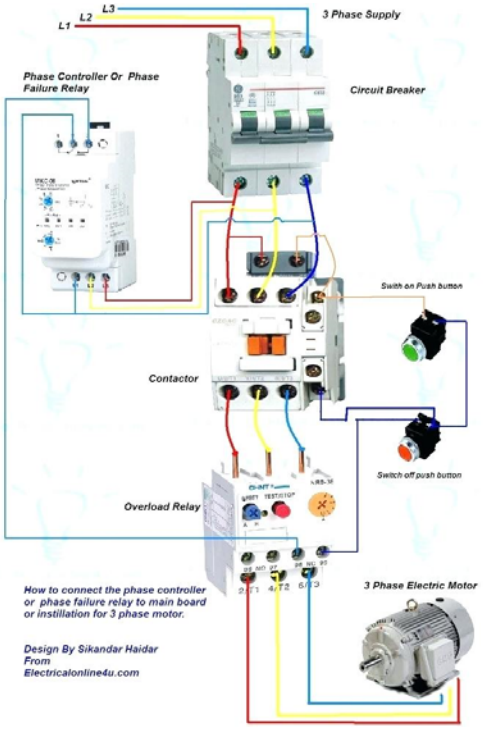
- In general, starting methods for induction motors include:
  1. Direct-on-line (across-the-line)
  2. Using an autotransformer
  3. Using starting resistors
  4. Star-delta connection
  5. Using inverter
  6. Using soft / electronic starters

Direct-On-Line (Across the Line)

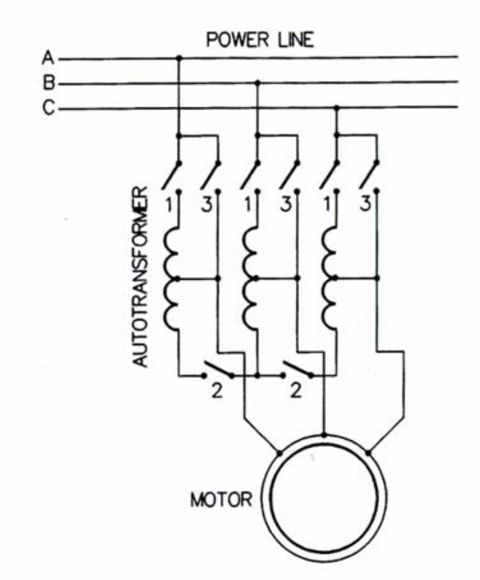




Direct-On-Line (Across the Line)



Using an Autotransformer



- Controlled using time relays Stator voltages and currents reduced by autotransformer turns ratio (a)
- $T \propto (V_T) \rightarrow T$ reduced by a^2
- At starting, contacts 1 and 2 are closed
- After preset time (full speed reached), contact 2 opens and contact 3 closes, then contact 1 closes

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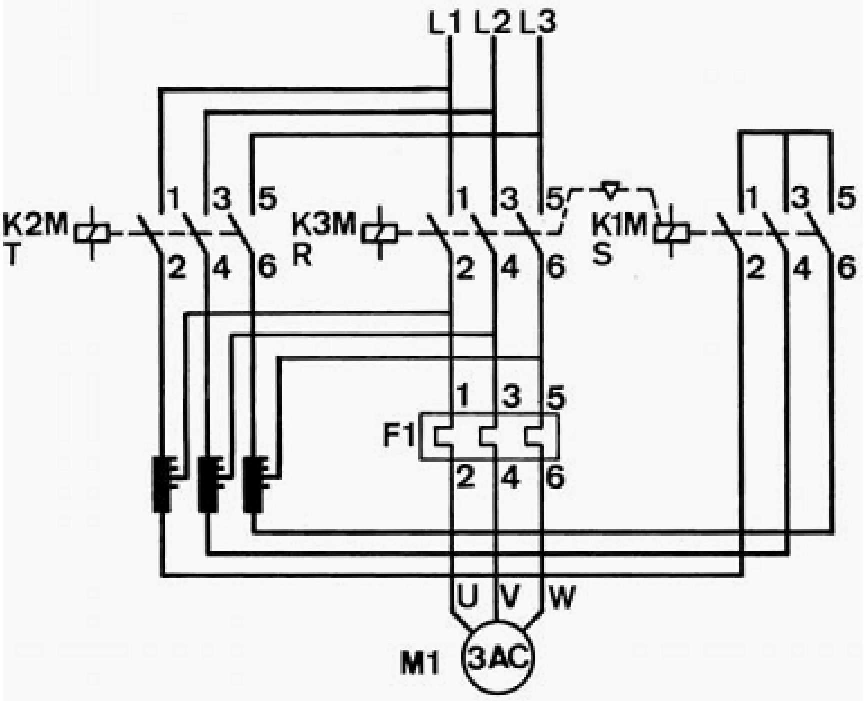
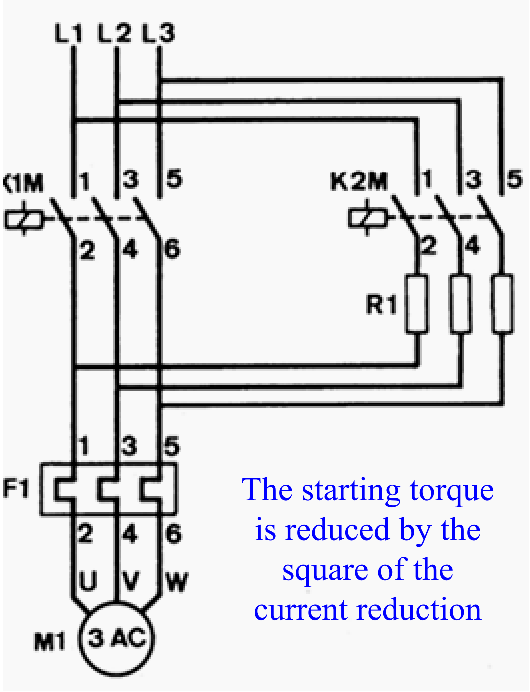
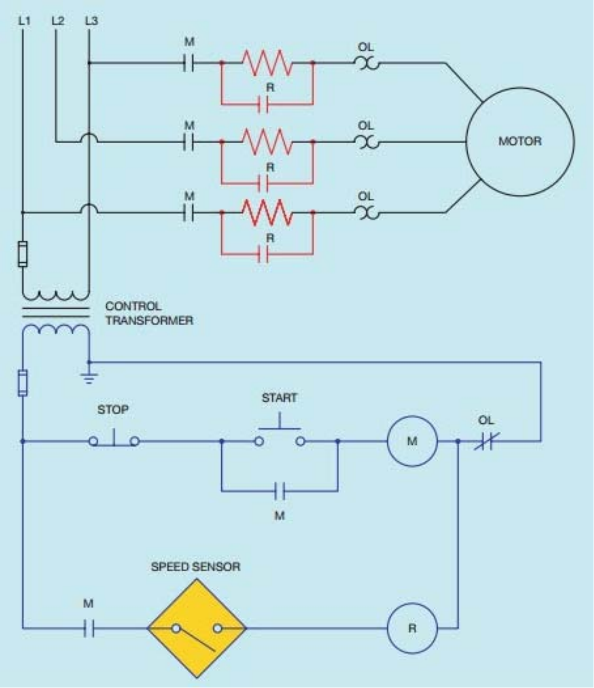
Using an Autotransformer



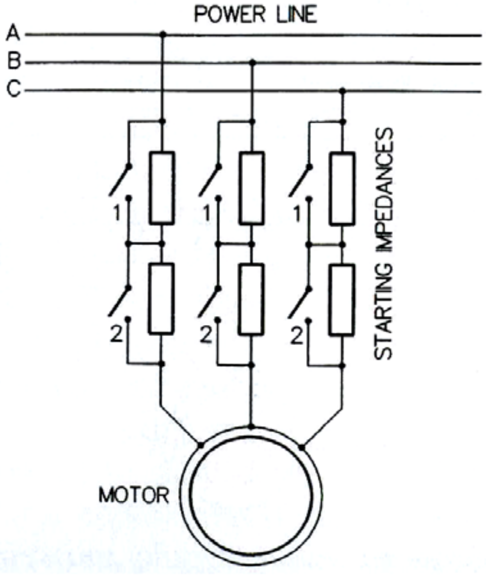
Using Starting Resistors

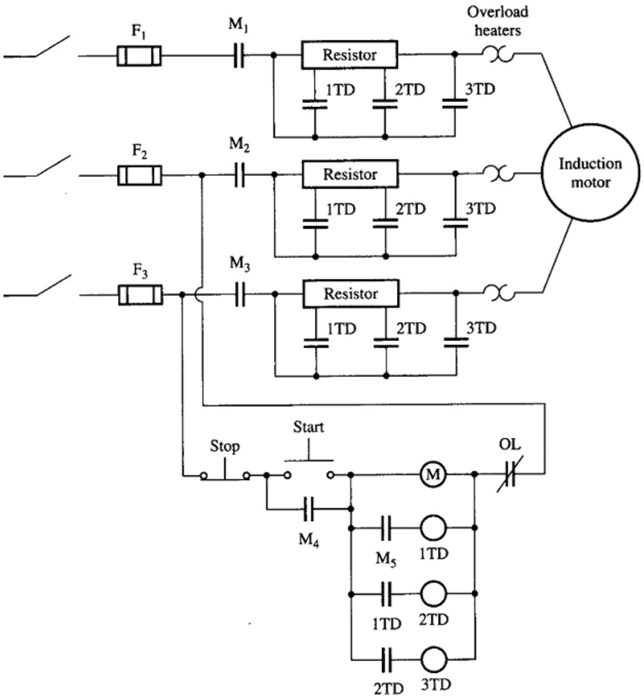


The starting torque is reduced by the square of the current reduction

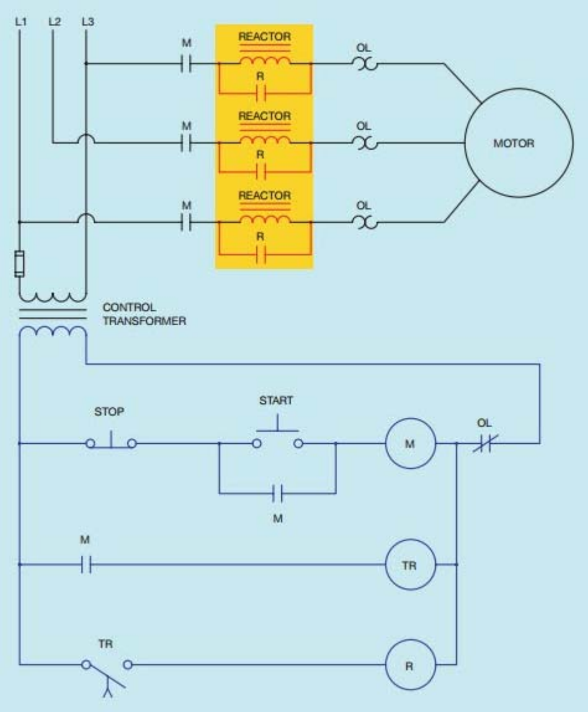


Using Starting Resistors





Using Starting Resistors



- A large percentage of the mains voltage is reduced at the chokes.
- Therefore, the motor’s starting torque is considerably reduced.
- As the torque increases, the voltage applied to the motor increases due to a reduction in current consumption
- This leads to an increased motor torque.
- After a successful run-up, the chokes are short-circuited.

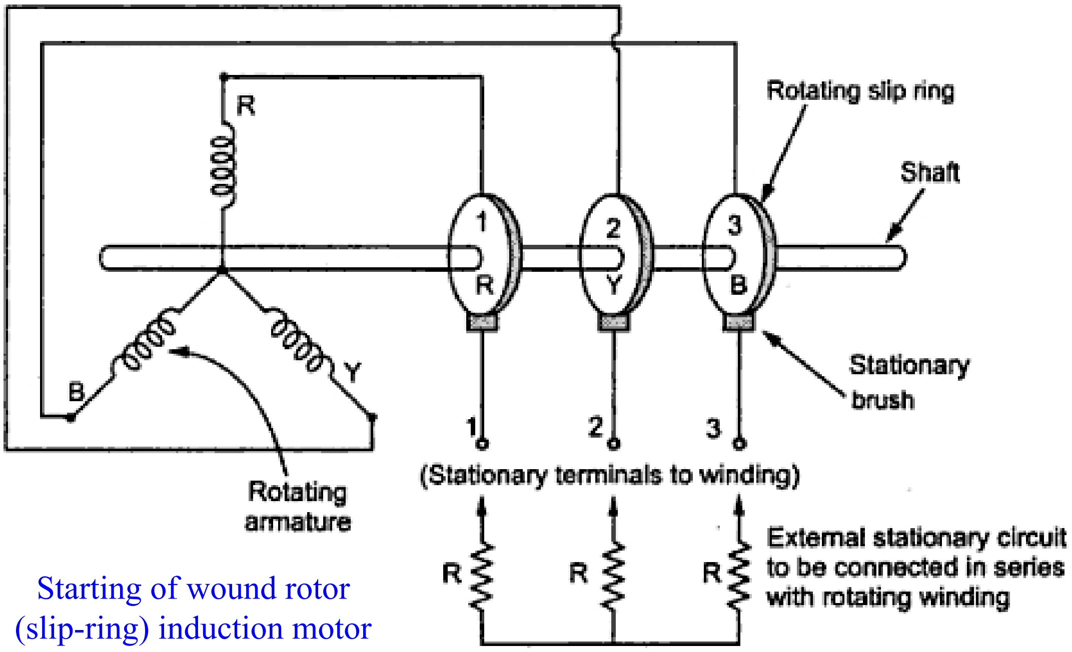
Using Starting Resistors

- As a replacement for the chocks, lower-cost resistors are used.
- This method is less helpful in reducing the starting current for the same torque requirement, because the motor torque reduces as a value of the **square of the voltage** and the voltage applied to the motor increases only due to the motor’s reduced current consumption during increasing speed.
- **It is better to reduce the resistor step by step during start**. But this requires considerably more switch gear.

Using Starting Resistors

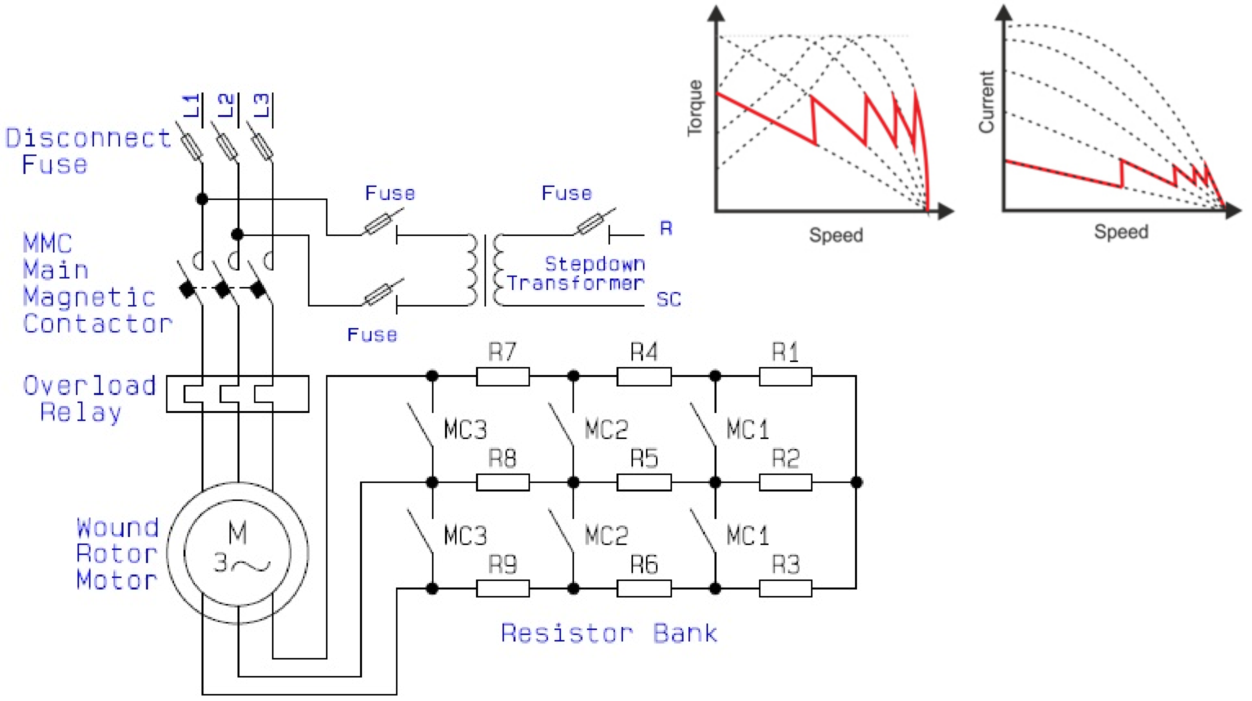
- Another possibility is the use of encapsulated wet (electrolytic) resistors.
- For these resistors, the ohmic resistance reduces in line with the temperature increase caused by the starting current's heating capability.

Using Starting Resistors

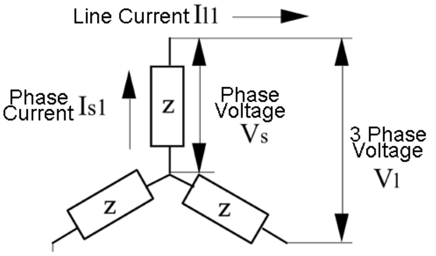


Starting of wound rotor (slip-ring) induction motor

Using Starting Resistors



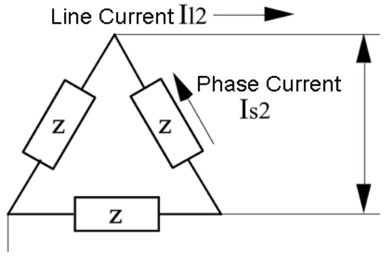
Star-Delta Connection



$$\text{Phase Voltage } V_s = \text{3 Phase Voltage } V_l \times \frac{1}{\sqrt{3}}$$

$$\text{Phase Current } I_{s1} = \frac{\text{Phase Voltage } V_s}{Z} = \frac{\sqrt{3} \times V_l}{3Z}$$

$$\text{Line Current } I_{l1} = \text{Phase Current } I_{s1} = \frac{\sqrt{3} \times V_l}{3Z}$$



$$\text{Phase Voltage } V_s = \text{3 Phase Voltage } V_l$$

$$\text{3 Phase Voltage } V_l = \text{Phase Voltage } V_s$$

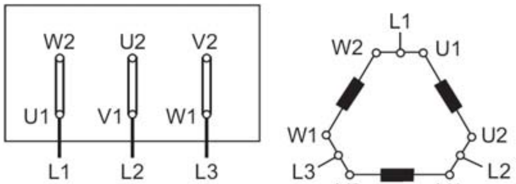
$$\text{Phase Current } I_{s2} = \frac{\text{Phase Voltage } V_s}{Z} = \frac{V_l}{Z}$$

$$\text{Line Current } I_{l2} = \sqrt{3} \times \text{Phase Current } I_{s2} = \frac{\sqrt{3} \times V_l}{Z}$$

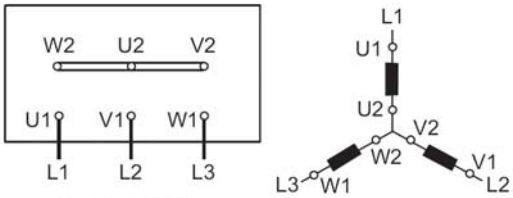
The comparison result of the line currents between the star and delta connections is shown here.

$$\frac{\text{Line Current } I_{l1}}{\text{Line Current } I_{l2}} = \frac{\sqrt{3} \times V_l}{3Z} \times \frac{Z}{\sqrt{3} \times V_l} = \frac{1}{3}$$

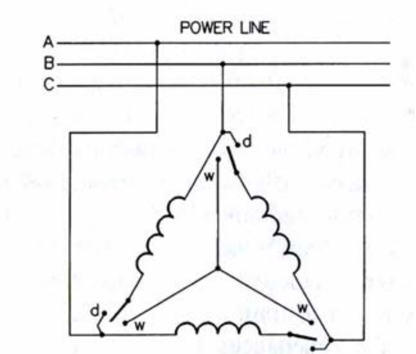
Star-Delta Connection



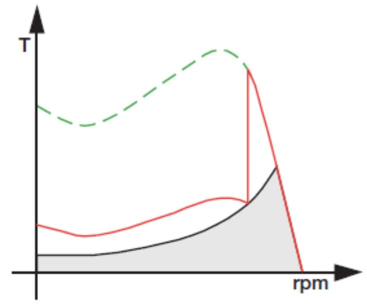
Δ – Connection
230 V
(400 V)



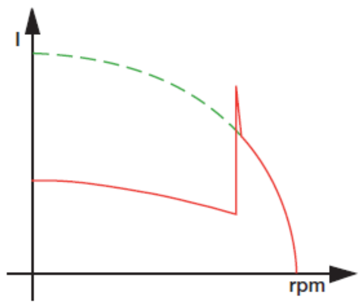
Y – Connection
400 V
(690 V)



STATOR PHASE WINDINGS
AND WYE–DELTA SWITCH



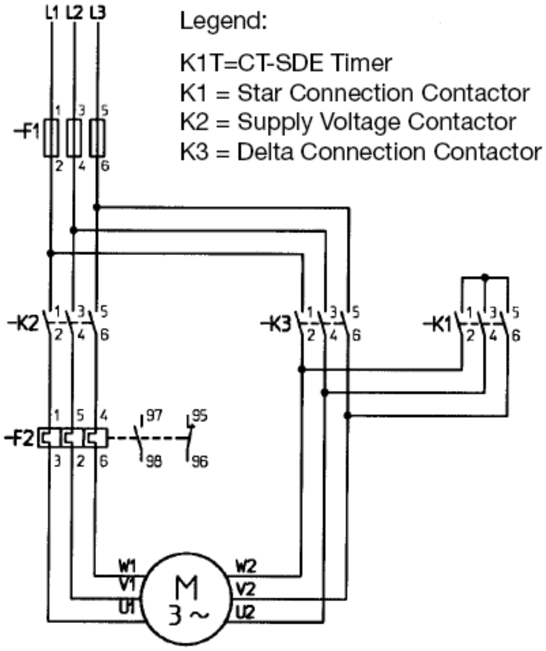
Torque/speed curve at Star-Delta start



Current curve at Star-Delta start

Star-Delta Connection

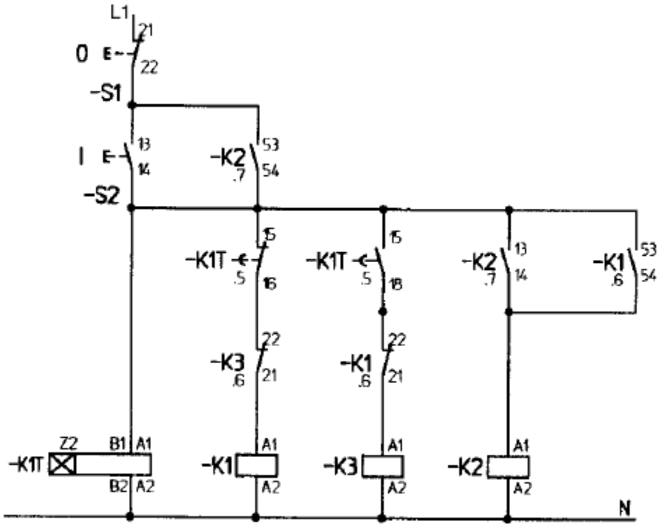
Power Circuit Diagram



Legend:

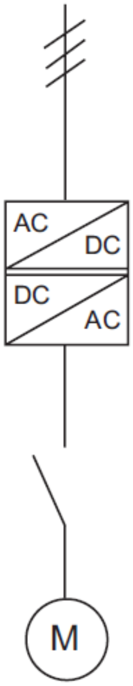
K1T=CT-SDE Timer
K1 = Star Connection Contactor
K2 = Supply Voltage Contactor
K3 = Delta Connection Contactor

Control Circuit Diagram



Inverters

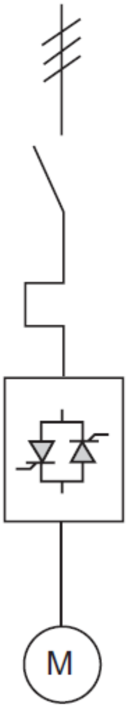
- The inverter sometimes called Variable Speed Drive (VSD), Variable Frequency Drive (VFD), or Variable Voltage Variable Frequency (VVVF)/(V3F)
- In many applications a drive is still only used for starting/stopping the motor, despite the fact that there is no need for speed regulation during a normal run.
- Of course this will create a need for much more expensive starting equipment than necessary.
- If speed control is not required, and it is only desirable to have a soft starting performance in aim of minimizing electric network disturbance as well as mechanical wear, the **soft starter** is the obvious choice.



Inverters

Soft Starters

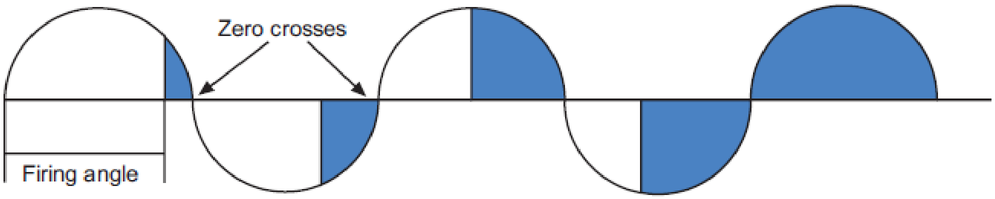
- **A soft starter** has different characteristics to the other starting methods. It has thyristors in the main circuit, and the motor voltage is regulated with a printed circuit board.
- The **soft starter** makes use of the fact that when the motor voltage is low during start, the starting current and starting torque is also low.
- During the first part of the start the voltage to the motor is so low that it is only able to adjust the play between the gear wheels or stretching driving belts or chains etc. In other words, eliminating unnecessary jerks during the start.



Soft Starters

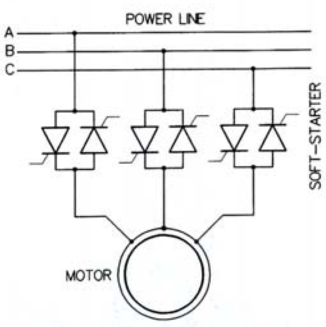
- Gradually, the voltage and the torque increase so that the machinery starts to accelerate.
- One of the benefits with this starting method is the possibility to adjust the torque to the exact need, whether the application is loaded or not.
- Another feature of the **soft starter** is the **soft stop** function, which is very useful when stopping pumps where the problem is water hammering in the pipe system at direct stop as for star-delta starter and direct-on-line starter.
- The **soft stop** function can also be used when stopping conveyor belts to prevent material from damage when the belts stop too quickly.

Soft Starters



Start: The thyristors let part of the voltage through at the beginning and then increase it, according to the set ramp time for the start.

Stop: The thyristors are fully conducting and when soft stopping, they decrease the voltage according to the set ramp time for stop.



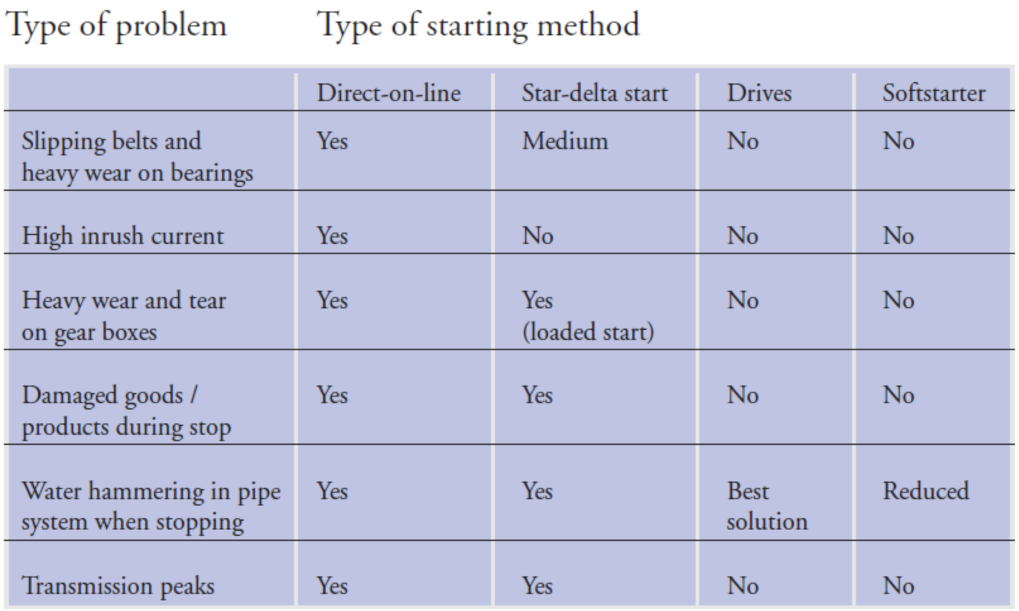
☐ Off : Thyristor is non-conducting

🟦 On : Thyristor is conducting

Soft Starters

Soft Starters

Common problems when starting and stopping motors with different starting methods



Type of problem Type of starting method

	Direct-on-line	Star-delta start	Drives	Softstarter
Slipping belts and heavy wear on bearings	Yes	Medium	No	No
High inrush current	Yes	No	No	No
Heavy wear and tear on gear boxes	Yes	Yes (loaded start)	No	No
Damaged goods / products during stop	Yes	Yes	No	No
Water hammering in pipe system when stopping	Yes	Yes	Best solution	Reduced
Transmission peaks	Yes	Yes	No	No

Soft Starters – Common Settings

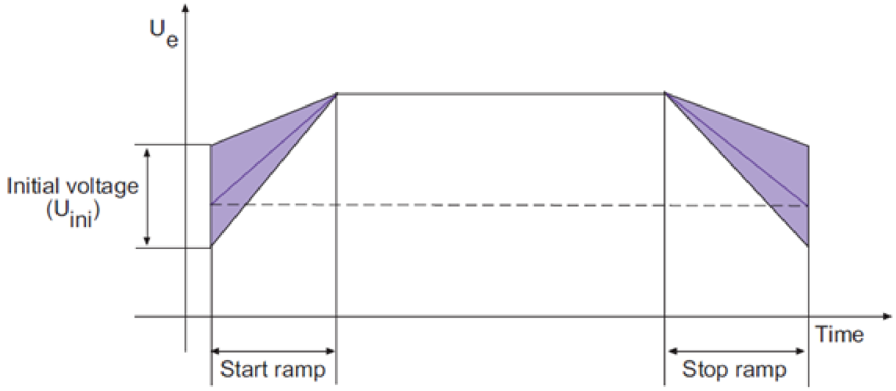
- The most common setting parameters available on most of the **soft starters** are:
  1. Start ramp
  2. Stop ramp
  3. Initial voltage
  4. Current limit
  5. Step down voltage
  6. Adjustable rated motor current
- The setting can be done either by adjusting potentiometers, changing dip switches, using a key pad, a computer or similar.

Soft Starters – Common Settings

- **Start Ramp** is the time from were the **soft starter** start its ramp (initial voltage) until full voltage is reached.
- The ramp time should not be too long, as this will only result in unnecessary heating of the motor and a risk of the overload relay to trip.
- If the motor is unloaded the start time for the motor will probably become shorter than the set ramp time, and if the motor is heavily loaded, the start time will probably become longer.

Soft Starters – Common Settings

- **Stop Ramp** is used when a soft stopping of the motor is required, for example a pump or a conveyor belt. The stop ramp is the time from full voltage until stop voltage (initial voltage) is reached. If the ramp time is set to zero the stop will be like a direct stop.



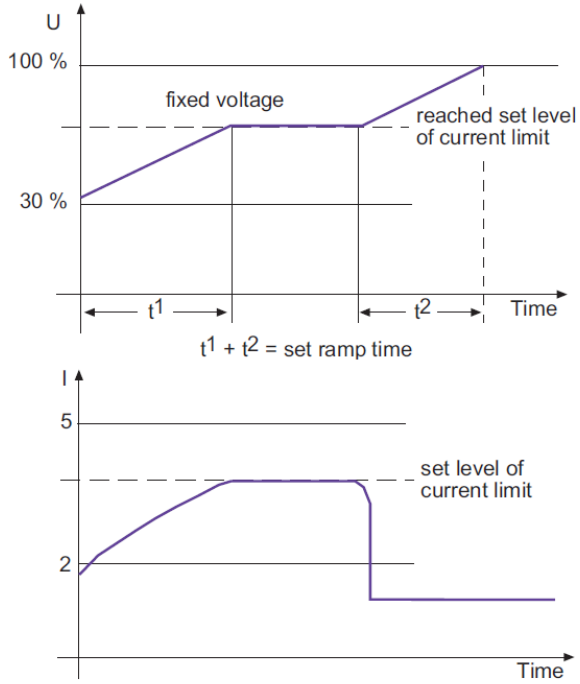
Soft Starters – Common Settings

- **Initial Voltage** is sometimes named pedestrian voltage or torque, this is the point from where the **soft starter** starts or stops its ramps.
- The torque of the motor will drop with the square of the voltage (V^2) and if the voltage is set too low, for example 20%, the starting torque will become $0.2^2 = 0.04 = 4\%$ only, and the motor will not start from the very beginning.
- Therefore it is very important to find a level that is just high enough to make the motor take off directly to avoid unnecessary heating.

Soft Starters – Common Settings

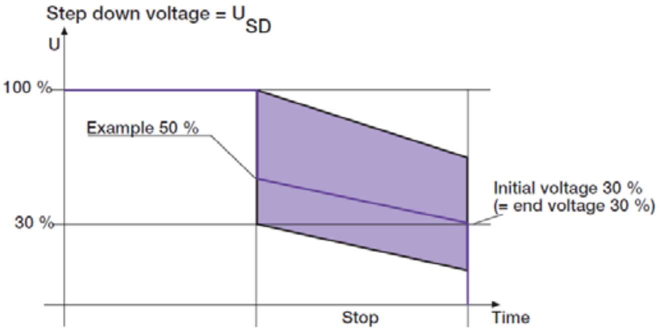
- **Current Limit** can be used in applications where a limited starting current is required, or at a heavy-duty start when it is difficult to achieve a perfect start with the setting of the initial voltage and the start ramp only.
- When the current limit is reached, the **soft starter** will temporarily stop increasing the voltage until the current drops below the set limit, and then continues ramping up to full voltage.
- Note that this feature is not available on all **soft starters**.

Soft Starters – Common Settings



Soft Starters – Common Settings

- **Step Down Voltage** gives a special type of stop ramp.
- It is possible to adjust the voltage to drop to a level where the speed of the motor starts to reduce immediately at the stop command.
- For low loaded motors the speed will not reduce until a very low voltage is reached, but using the step down voltage function can eliminate this phenomenon and is especially useful for stopping pumps.



Soft Starters – Common Settings

- **Adjustable Rated Motor Current** makes it possible to set the motor rated current on the **soft starter** for the used motor.
- This setting may affect other values as well, such as the trip level of the electronic overload relay, the level of the current limit function and so on.

Soft Starters – Indicators

- The indications on a **soft starter** differ very much from one type to another and also between manufacturers. Some of the most common indications are:

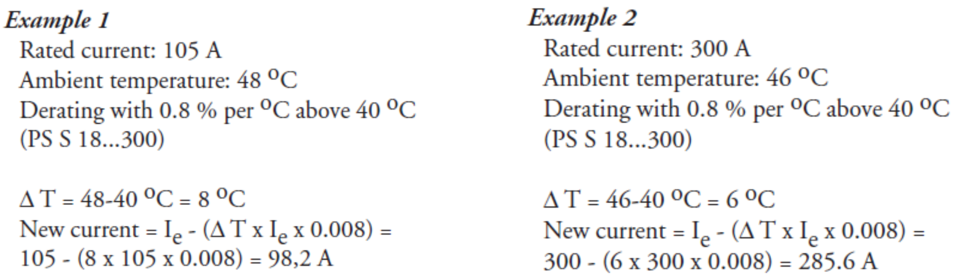
1. **On** indicator (power supply is connected and the **soft starter** is ready to start the motor).
2. **Top of Ramp** indicator (start ramp is completed and full voltage is reached).
3. **Fault** indicator (many reasons)
4. **Overload** indicator (overload protection has tripped due to many reasons)
5. **Overtemperature** indicator (**soft starter** is over-heated due to many reasons)

Soft Starters – Current Derating

Surrounding Temperature

- For most types of **soft starters**, derating the operational current should be done if the surrounding temperature exceeds 40°C.
- For ABB **soft starters** the following formula can be used

$$I_{derated} = I_{rated} - \left(\Delta T \times I \times DF \right) \qquad \text{DF} \triangleq \text{Derating Factor}$$



Example 1
Rated current: 105 A
Ambient temperature: 48 ^{O}C
Derating with 0.8 % per ^{O}C above 40 ^{O}C
(PS S 18...300)

ΔT = 48-40 ^{O}C = 8 ^{O}C
New current = I_e - (ΔT x I_e x 0.008) =
105 - (8 x 105 x 0.008) = 98,2 A

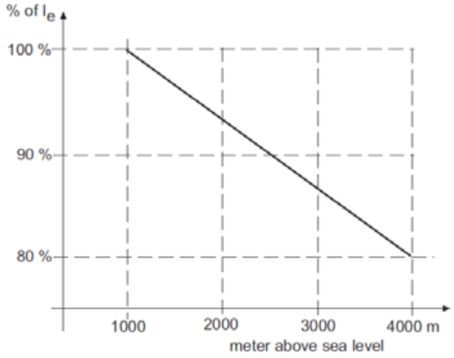
Example 2
Rated current: 300 A
Ambient temperature: 46 ^{O}C
Derating with 0.8 % per ^{O}C above 40 ^{O}C
(PS S 18...300)

ΔT = 46-40 ^{O}C = 6 ^{O}C
New current = I_e - (ΔT x I_e x 0.008) =
300 - (6 x 300 x 0.008) = 285.6 A

Soft Starters – Current Derating

High Altitude

- When a **soft starter** is used at high altitudes, the rated current for the unit has to be derated, due to less cooling.
- For most manufacturers the catalogue values are valid up to 1000m above sea level before derating is necessary.

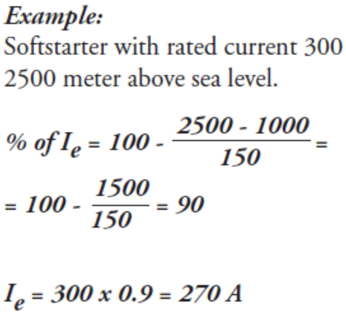


Soft Starters – Current Derating

High Altitude

- For ABB **soft starters** the following formula can be used

$$\boxed{\begin{aligned} \%I_{derated} &= 100 - \frac{\text{Actual Altitude} - 1000}{150} \\ \Rightarrow \quad I_{derated} &= \%I_{derated} \times I_{rated} \end{aligned}}$$



Example:

Softstarter with rated current 300 A used at 2500 meter above sea level.

$$\% \text{ of } I_e = 100 - \frac{2500 - 1000}{150} =$$

$$= 100 - \frac{1500}{150} = 90$$

$$I_e = 300 \times 0.9 = 270 \text{ A}$$

Operation of Single Phase Motors

By

Dr. Mohammad Salah

Mechatronics Engineering Department

The Hashemite University

Introduction

- **Single-phase motors** are less used in the industry when compared to three-phase motors due to many reasons:

  1. At the same power, three-phase motor has smaller size.

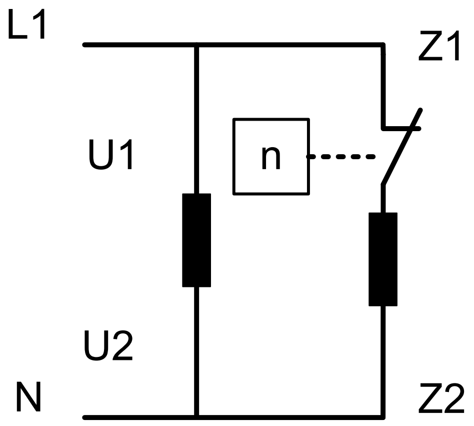
  2. Better power factor and efficiency in the three-phase motor.

- Because single phase motors have one phase, a rotating magnetic field cannot be generated. Hence, motor does not run by itself as three-phase motors.

- Thus, certain configuration is performed inside single phase motors to generate such rotating magnetic field.

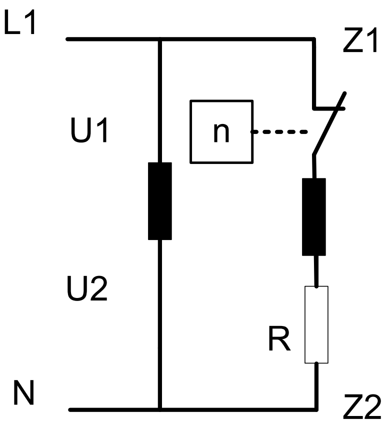
Introduction

- **Configuration 1:** Connecting a starting (auxiliary) coil in parallel with the operating (main) coil of the motor that is disconnected automatically, using a centrifugal switch, when the speed reaches 80% of the rated speed.



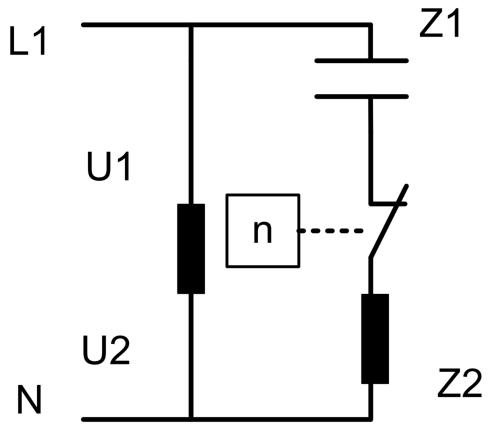
Introduction

- **Configuration 2:** Connecting a starting (auxiliary) coil and starting resistor in parallel with the operating (main) coil of the motor which are disconnected automatically, using a centrifugal switch, when the speed reaches 80% of the rated speed



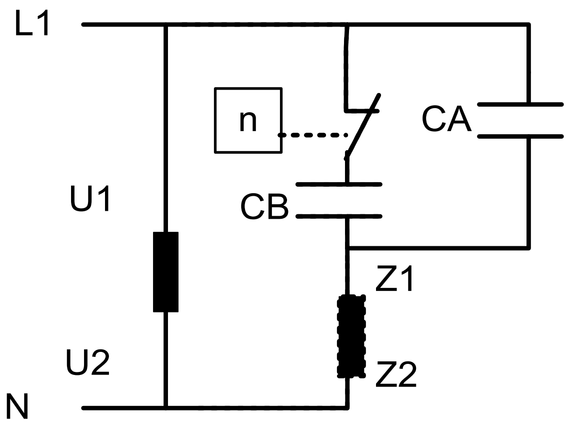
Introduction

- **Configuration 3:** Connecting a starting (auxiliary) coil and starting capacitor in parallel with the operating (main) coil of the motor which are disconnected automatically, using a centrifugal switch, when the speed reaches 80% of the rated speed.



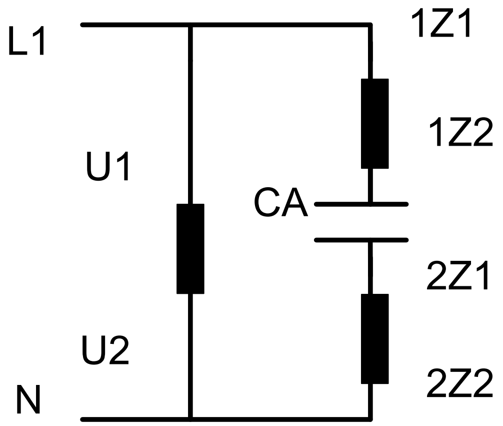
Introduction

- **Configuration 4:** Connecting a starting (auxiliary) coil with starting capacitor and operating capacitor in parallel with the operating (main) coil of the motor which are disconnected automatically, using a centrifugal switch, when the speed reaches 80% of the rated speed.

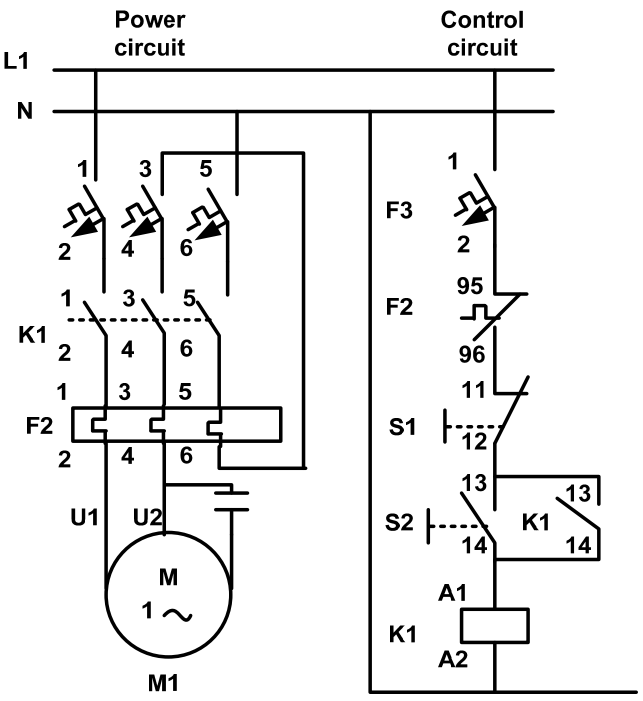


Introduction

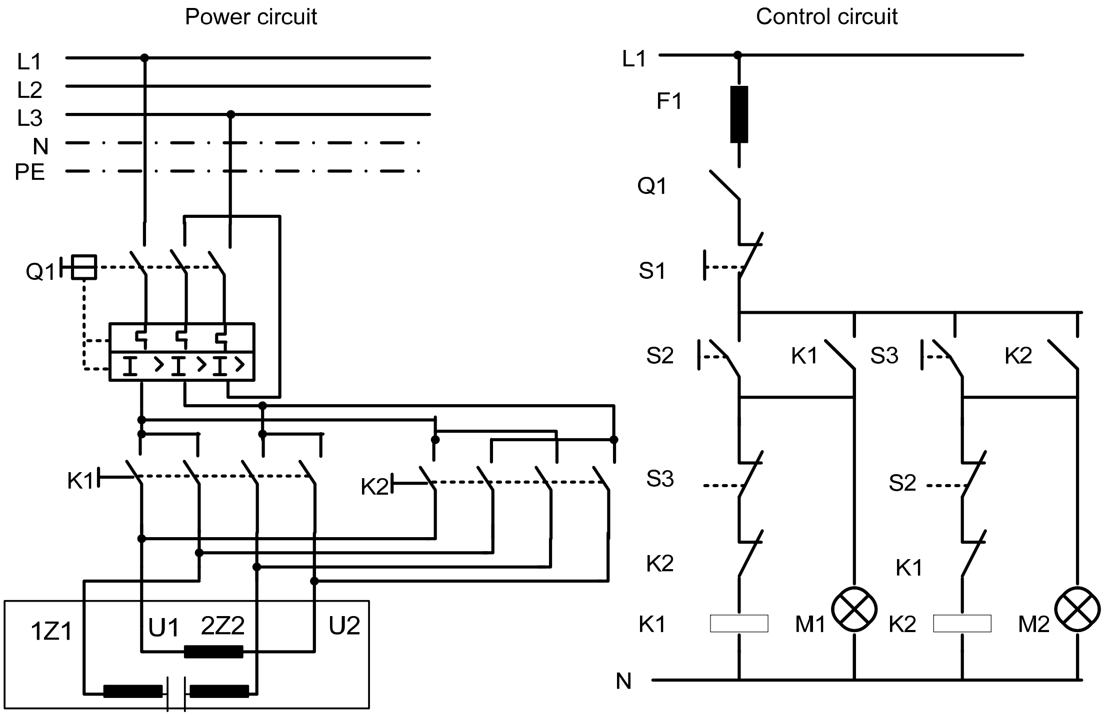
- **Configuration 5:** Connecting two starting (auxiliary) coils which are connected together with a capacitor and connect them in parallel with the operating (main) coil of the motor. This method is used when bidirectional rotation in the motor is needed.



Operation Circuits



Reversing the Direction



Motor Braking Methods

By

Dr. Mohammad Salah

Mechatronics Engineering Department

The Hashemite University

Introduction

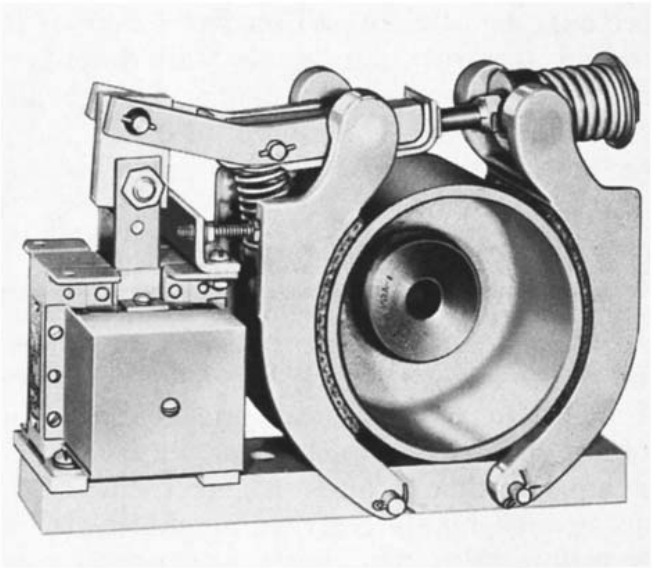
- Motor braking is used to stop the electric motor or to hold the motor shaft at a certain position regardless of the applied load torque.
- Motor braking methods can be classified as

1. Electro-mechanical Braking
2. Electro-magnetic Braking
3. Electrical Braking
   - Plugging Braking
   - Dynamic Braking
   - Regenerative Braking

Electro-mechanical Braking

- Since the early 1900s, **electro-mechanical brakes** have been in use.
- These are also known as **mechanical** or **friction brakes**.
- An **electro-mechanical brake** consists of two friction surfaces, or shoes, which can be made to bear on a wheel on the motor shaft.
- Spring tension holds the shoes on the wheel.
- Braking is achieved because of the friction between the shoes and the wheel.
- A solenoid mechanism is used to release the shoes

Electro-mechanical Braking

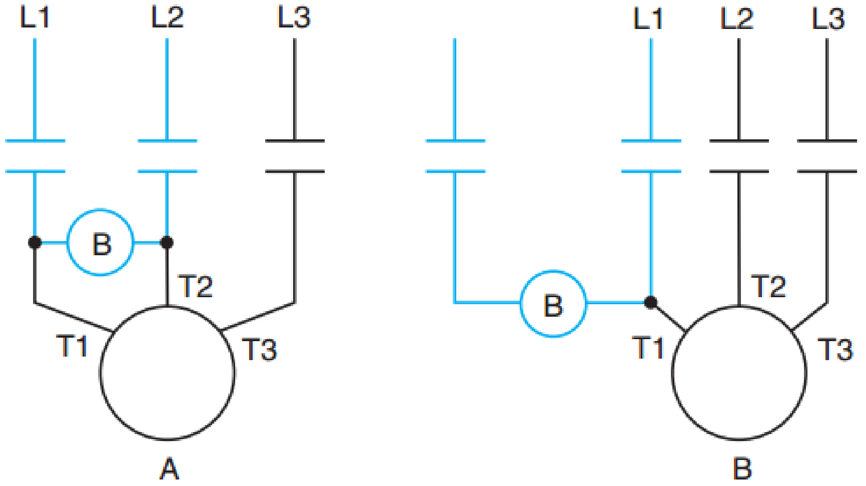


Solenoid brake used on machine tools, conveyors, small hoists, and similar devices. *(Courtesy of Eaton Corporation)*

Electro-mechanical Braking

- In an electromechanically operated brake, the shoes are held in a released position by a magnet as long as the magnet coil is energized.
- However, if a pilot device interrupts the power, or there is a power failure, then the brake shoes are applied instantly to provide a fast, positive stop.
- The coil leads of an AC magnetic brake are normally connected directly to the motor terminals.
- If a reduced-voltage starting method is used, the brake coil should be connected to receive full voltage.

Electro-mechanical Braking



(Source: Delmar/Cengage Learning)

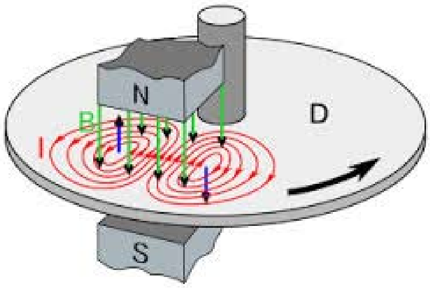
AC brake coil connections for across-the-line starting. Control relays and contactors also are used to control magnetic brakes.

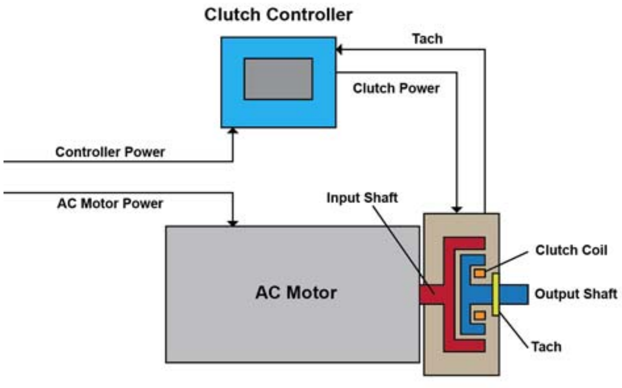
Electro-magnetic Braking

- **Electro-magnetic** or **magnetic brakes** provide a smooth braking action.
- This feature makes them suitable for high-inertia loads.
- Because these brakes apply and remove the braking pressure smoothly in either direction, they are often used on cranes, hoists, elevators, and other machinery where it is desirable to limit the shock of braking.
- **Disc brakes** can also be installed where appearance and available space prohibit the use of **shoe brakes**.
- **Magnetic disc brakes** are used on machine tools, cranes, hoists, conveyors, printing presses, saw mills, overhead doors, and other installations.

Electro-magnetic Braking

- The control adjustments of the torque and wear of **disc brakes** are similar to those for **shoe brakes**.
- **A disc brake** is a self-enclosed unit that is bolted directly to the end bell of the motor.





Eddy Current Clutch

Electrical Braking – Plugging Brk.

- **Plugging** or **counter current braking** is defined by NEMA as a system of braking, in which the motor connections are reversed so that the motor develops a counter torque, which acts as a retarding force.
- **Plugging braking** is used for the rapid stop and quick reversal of motor rotation.
- **Plugging braking** can be performed either manually or with electromagnetic controls.
- **Plugging** is more often used with three-phase squirrel cage motors.

Electrical Braking – Plugging Brk.

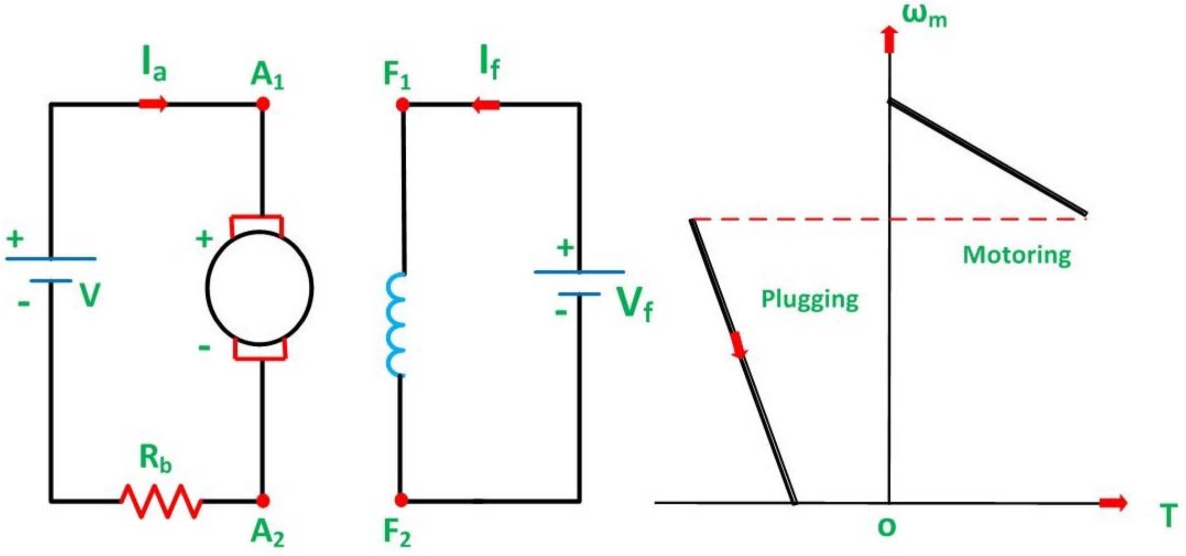
- Before the **plugging** operation is attempted, however, several factors must be considered including:

  1. The need to determine if methods of limiting the maximum permissible currents are necessary, especially with repeated operations and DC motors.

  2. The need to examine the driven machine to ensure that repeated plugging will not cause damage to the machine.

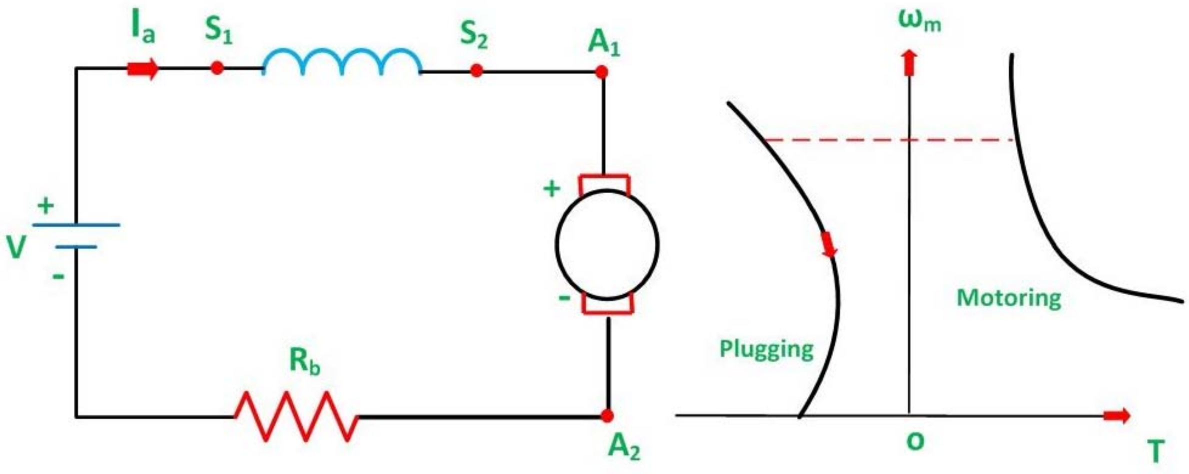
Electrical Braking – Plugging Brk.

Separately Excited DC Motor



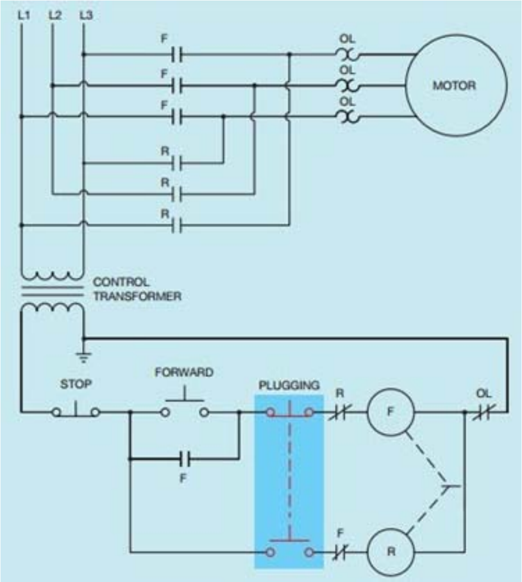
Electrical Braking – Plugging Brk.

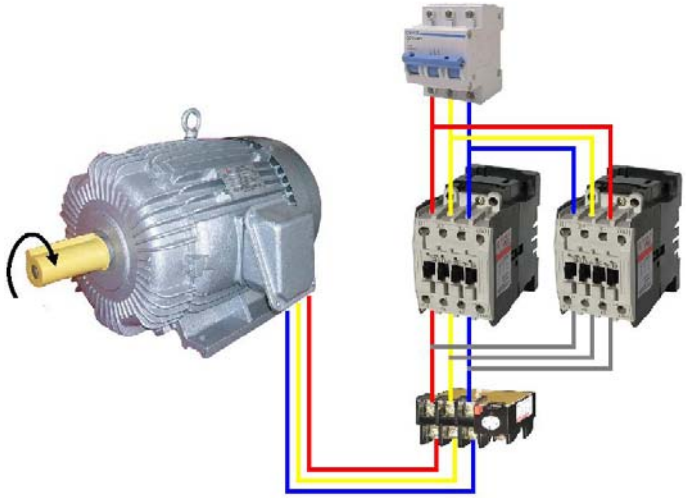
Series DC Motor



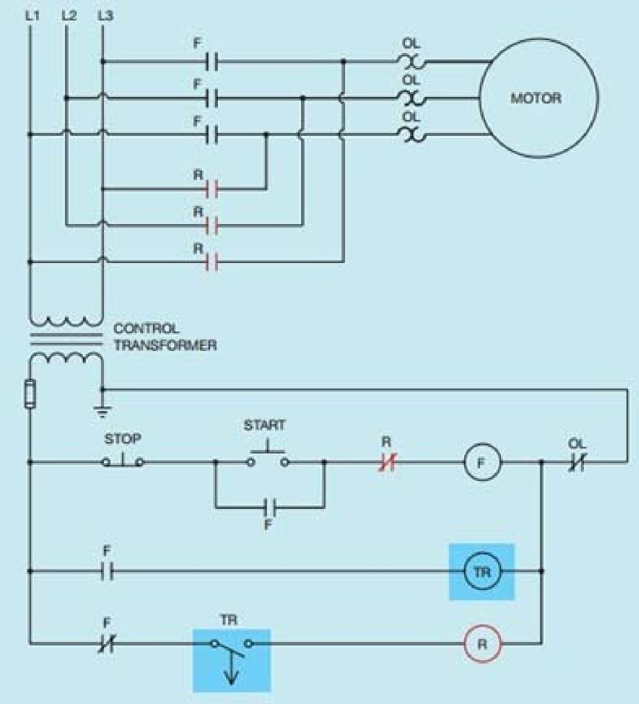
Electrical Braking – Plugging Brk.

Manual Plugging



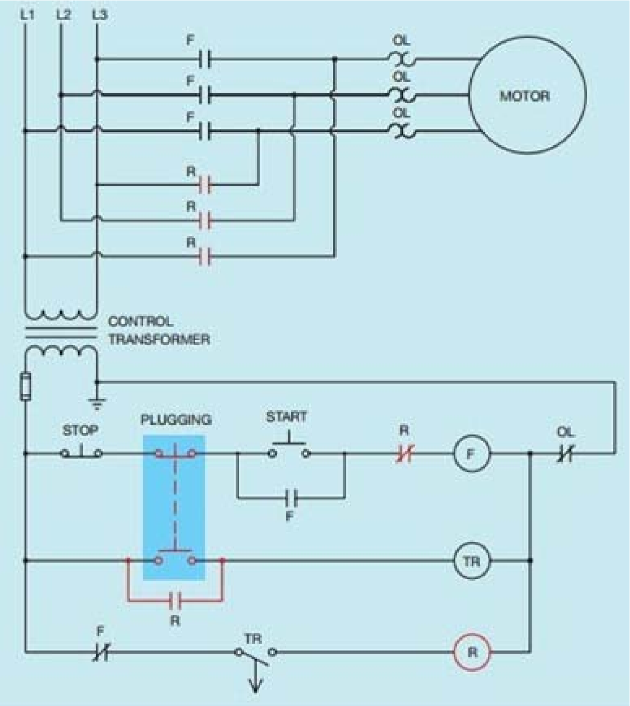


Electrical Braking – Plugging Brk.



Plugging with time-delay off relay

Electrical Braking – Plugging Brk.



Plugging with time-delay off relay controlled by the operator

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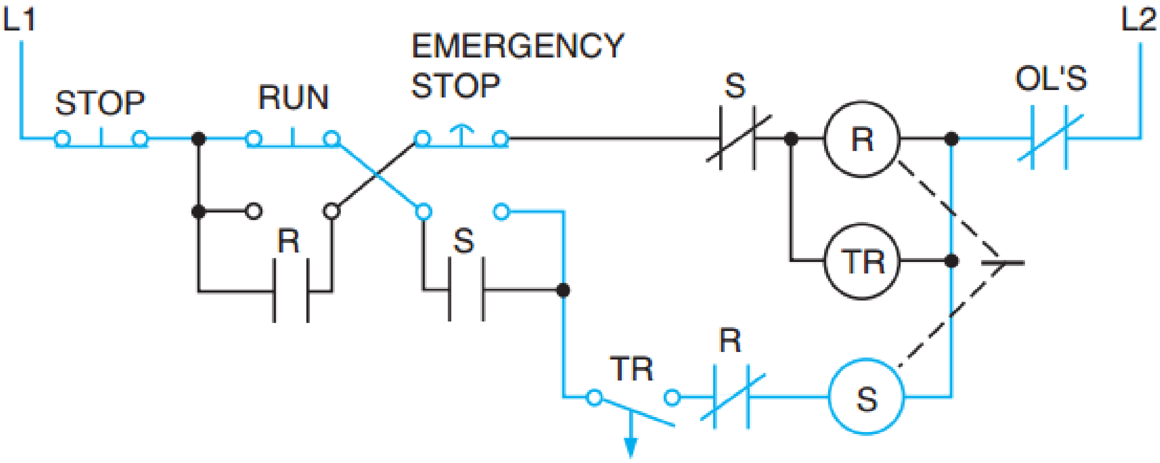
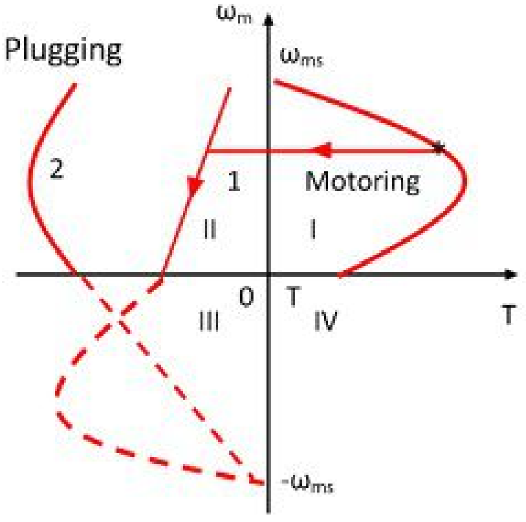
Electrical Braking – Plugging Brk.

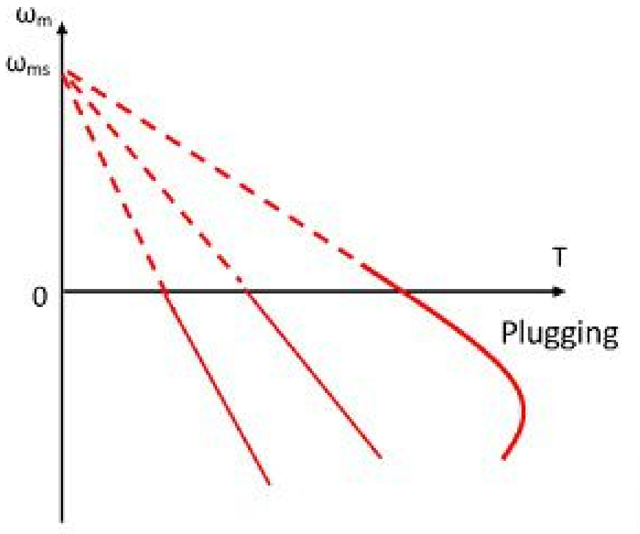


Plugging with time-delay off relay

Electrical Braking – Plugging Brk.



1 : Natural Characteristic
2 : With External Resistance in rotor



Plugging in fourth quadrant with extra large external resistance in rotor

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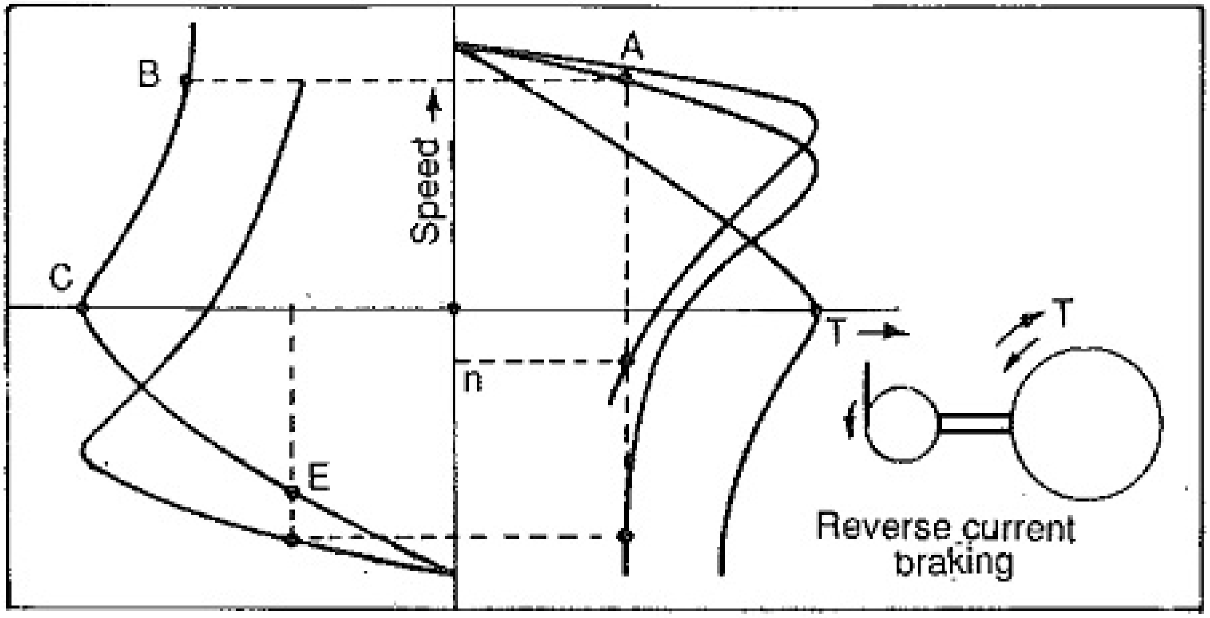
Electrical Braking – Plugging Brk.



Electrical Braking – Dynamic Brk.

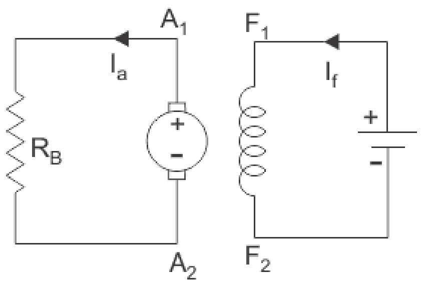
- **Dynamic braking** is called also **rheostatic braking**.
- **Dynamic breaking** is to slow down the machine by converting kinetic energy to heat energy by switching the circuit from line/supply to a breaking circuit that causes motor to behave as a generator with a connected load.
- **For DC motor**, dynamic braking is done by disconnecting the motor which is at a running condition from the source and connected across a resistance.
- When a DC motor is reconnected so that the field is excited and there is a low-resistance path across the armature, the generator action converts some of the mechanical energy of rotation to electrical energy (as heat in discharge resistors).

Electrical Braking – Dynamic Brk.

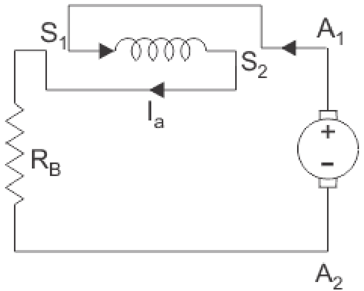
- The result is that the motor slows down sooner.
- However, as the motor slows down, the generator action decreases, the current decreases, and the braking lessens.
- This means that a motor cannot be stopped by dynamic braking alone.
- In this moment, a mechanical brake has to be applied to fully stop the motor.
- **For AC motors**, two methods are used:

  1. DC injection
  2. Self-excited braking using capacitors
  3. AC dynamic braking

Electrical Braking – Dynamic Brk.

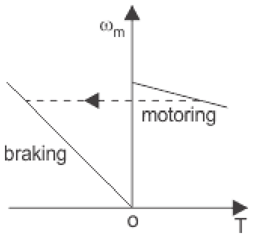


Separately excited motor

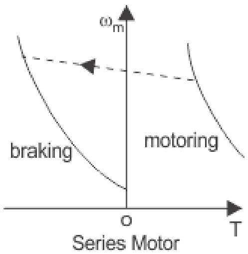


Series Motor

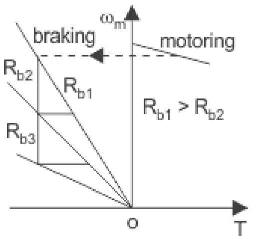
DC motors



Separately excited motor



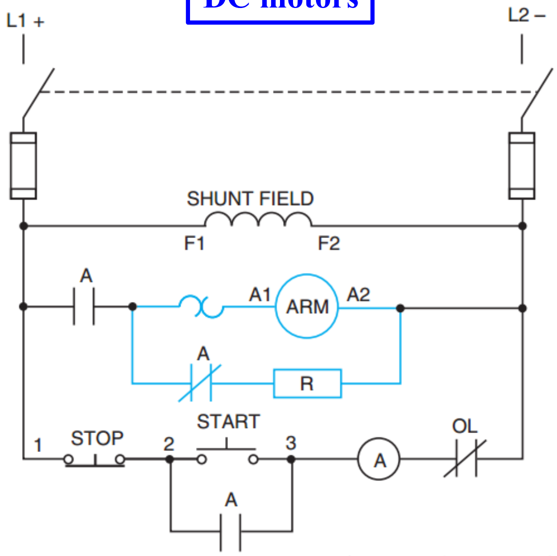
Series Motor



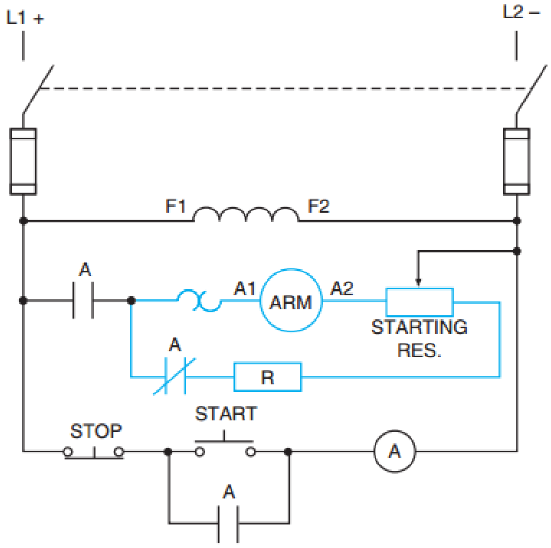
Separately excited motor with variable armature resistance

Electrical Braking – Dynamic Brk.

DC motors

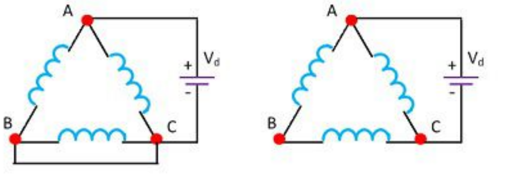


(Source: Delmar/Cengage Learning)

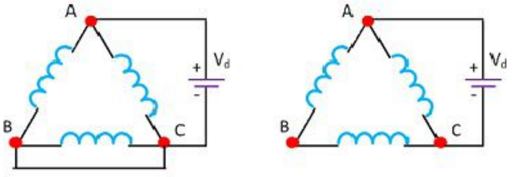


Dynamic braking connections on a motor starter.

Electrical Braking – Dynamic Brk.

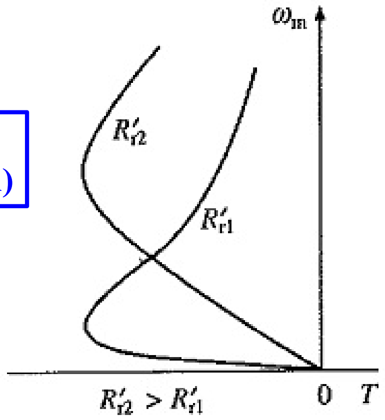


Three Lead Connection of DC Dynamic Braking



Three Lead Connection of DC Dynamic Braking

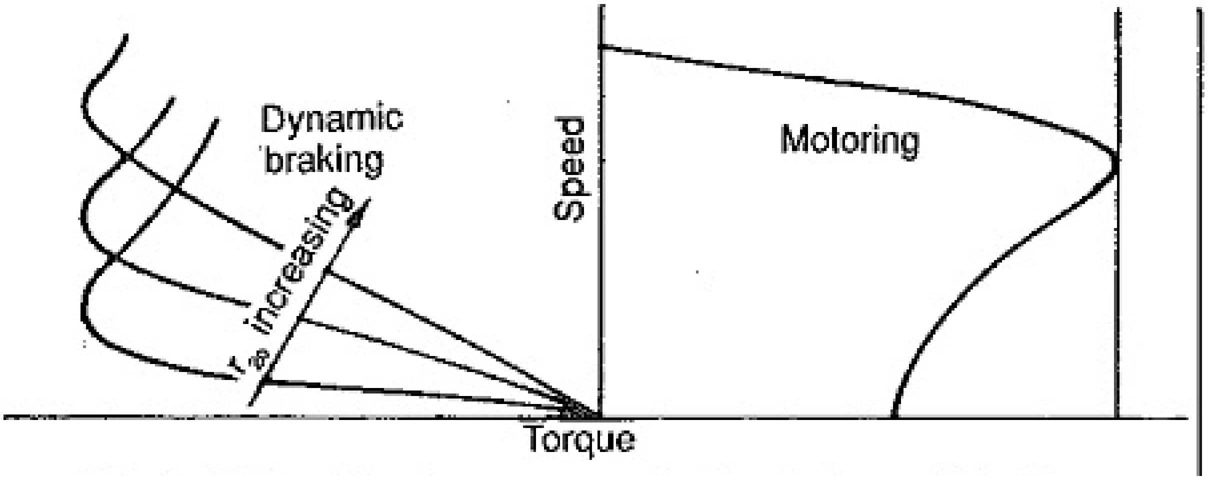
AC motors (DC Injection)



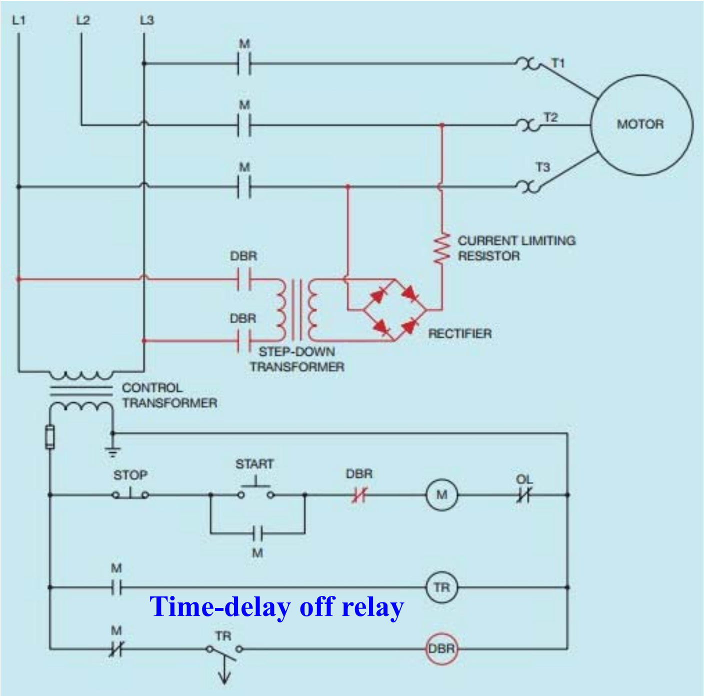
DC current flowing through the stator produces a stationary magnetic field. Motion of rotor in this field induces voltage in the rotor winding. Machine, therefore, works as a generator. Generated energy is dissipated in the rotor circuit resistance, thus giving Dynamic Braking of Induction Motor.

Electrical Braking – Dynamic Brk.

AC motors (DC Injection)

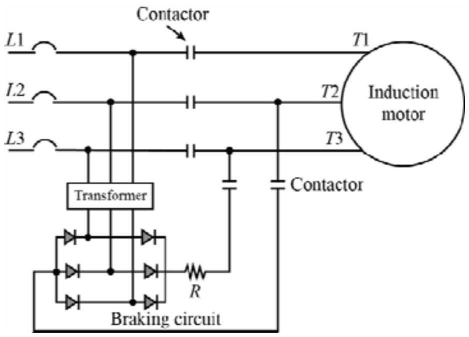


Electrical Braking – Dynamic Brk.

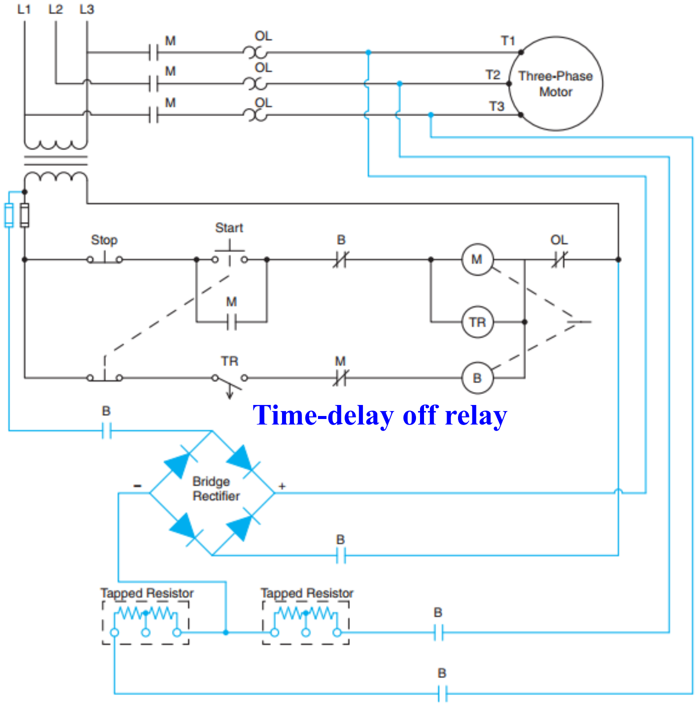


Time-delay off relay

AC motors (DC Injection)



Electrical Braking – Dynamic Brk.



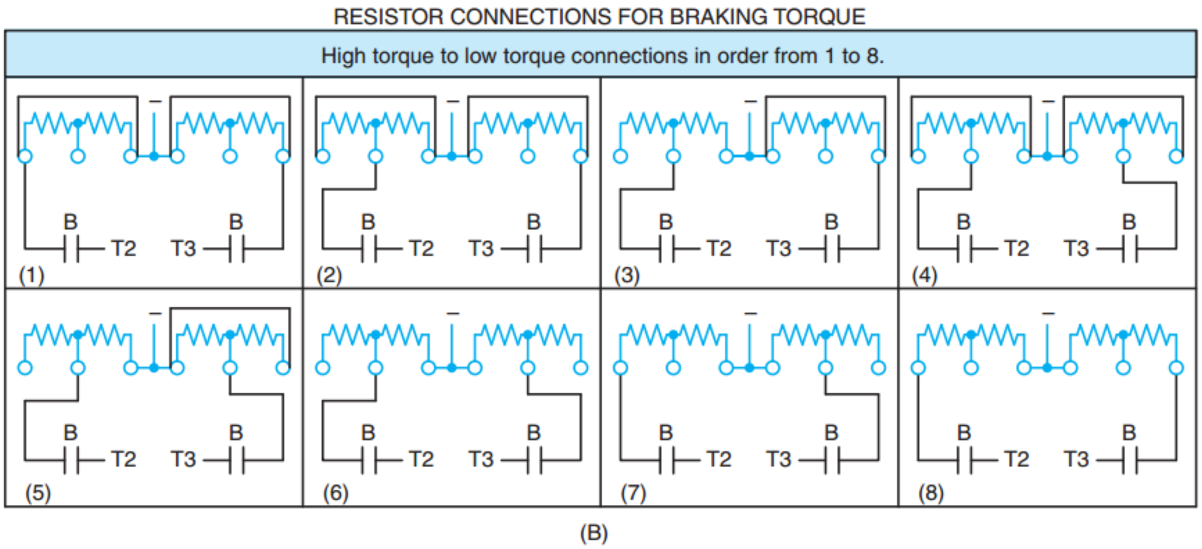
Time-delay off relay

AC motors (DC Injection)

Electrical Braking – Dynamic Brk.

- Braking contactor B connects all three motor leads to a source of direct current through the rectifier and transformer.
- Direct current applied to an induction motor polarizes it to a stationary magnetic field and causes it to brake to a stop.
- Less current is required for the same braking torque on all three phases as compared with applying direct current to one phase.
- More ampere turns are gained with the additional windings, conserving energy, and reducing motor heating.
- The braking torque and the speed of braking can be varied by reconnecting the tapped resistors.

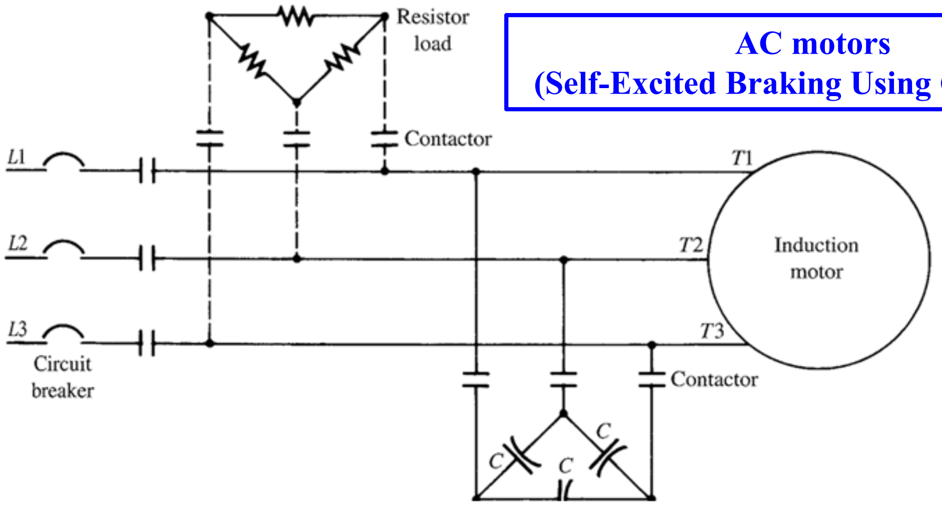
Electrical Braking – Dynamic Brk.



(Source: Delmar/Cengage Learning)

Typical line diagram and resistor connections for an electric braking circuit.

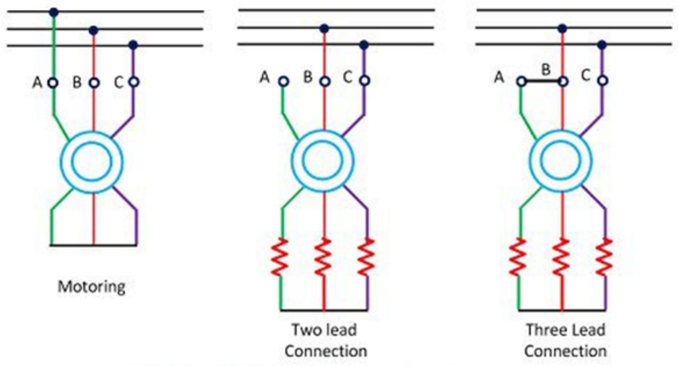
Electrical Braking – Dynamic Brk.



AC motors
(Self-Excited Braking Using Capacitors)

Cutoff the supply, connect a capacitor bank as shown in the figure, the motor will act as a self excited induction generator and rotational energy is dissipated as copper loss or I2R loss in the rotor and stator winding. effect can be enhanced by adding a resistive load. This method is uneconomical, due to the cost of the capacitors

Electrical Braking – Dynamic Brk.



AC dynamic Braking of a Wound Rotor Motor

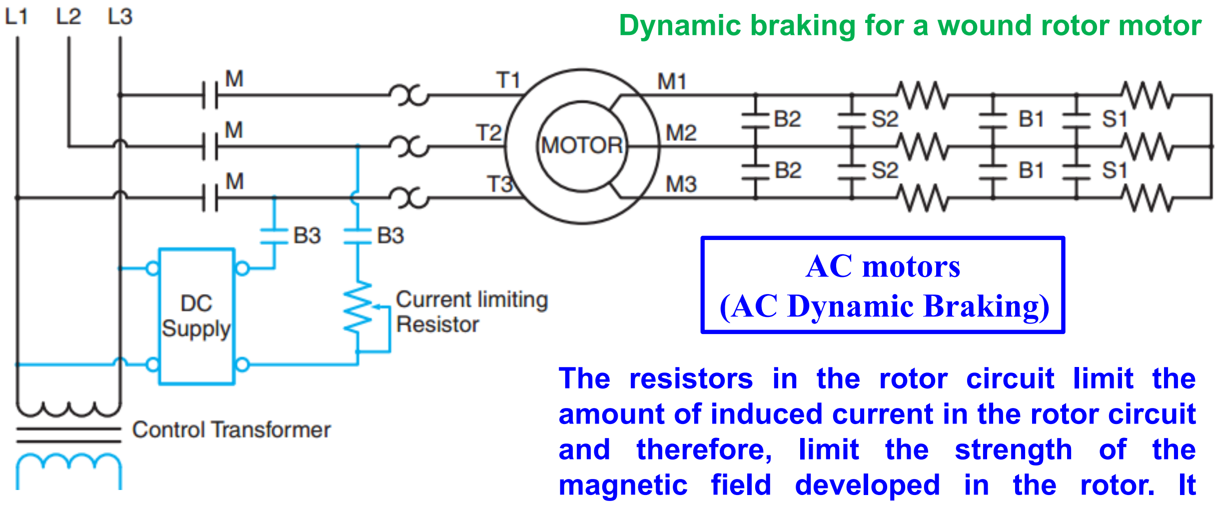
Dynamic braking for a wound rotor motor

AC motors
(AC Dynamic Braking)

This braking is obtained when the motor is run on a single phase supply by disconnecting one phase from the source and either leaving it open or connecting it with another machine phase. When connected to a 1-phase supply, the motor can be considered to be fed by positive and negative sequence three-phase set of voltages. Net torque produced by the machine is sum of torques due to positive and negative sequence voltages. When rotor has a high resistance, the net torque is negative and braking operation is obtained.

Electrical Braking – Dynamic Brk.

Dynamic braking for a wound rotor motor

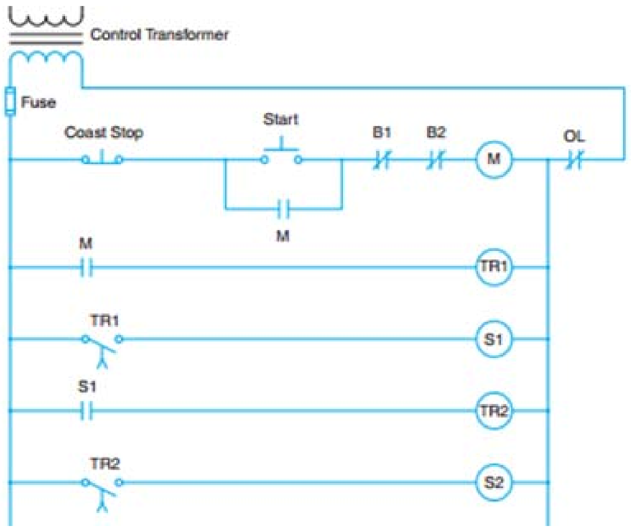


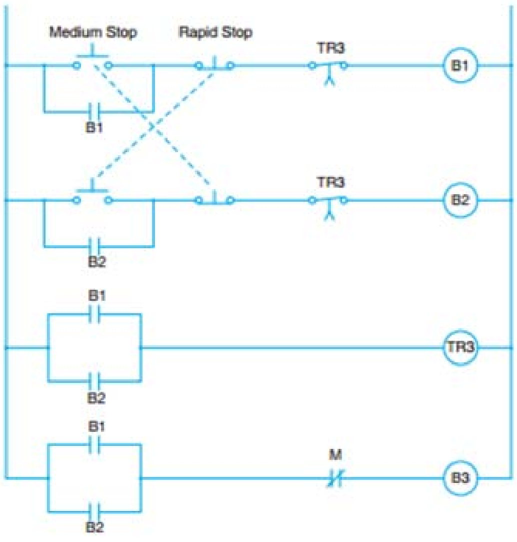
AC motors (AC Dynamic Braking)

The resistors in the rotor circuit limit the amount of induced current in the rotor circuit and therefore, limit the strength of the magnetic field developed in the rotor. It should be noted that if less braking torque is desired, the two B1 load contacts can be disconnected from the circuit. This would permit all the rotor circuit resistors to limit rotor current and further weaken the magnetic field developed in the rotor

---

Electrical Braking – Dynamic Brk.





TR3 limits the amount of time that DC voltage can be applied to the stator winding.

AC motors (AC Dynamic Braking)

Electrical Braking – Dynamic Brk.

- When the medium stop button is pressed, a circuit is supplied to B1 contactor.
- The two B1 load contacts close and shunt out the first set of resistors in the rotor circuit.
- All B1 auxiliary contacts close. One auxiliary contact is connected in parallel with the medium stop button to maintain power to the circuit. A second B1 auxiliary contact provides power to timer coil TR3. TR3 limits the amount of time that DC voltage can be applied to the stator winding. The third B1 auxiliary contact closes and provides power to contactor B3.
- Contactor B3 closes the two B3 load contacts that supply DC voltage to the stator winding

---

Electrical Braking – Dynamic Brk.

- The rapid stop option operates in the same manner as the medium stop option except that the load contacts controlled by contactor B2 directly short the rotor circuit causing maximum rotor current and therefore, maximum magnetic field strength to be developed in the rotor

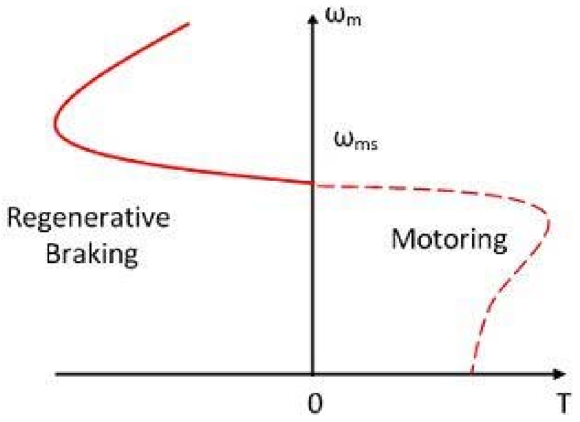
Electrical Braking – Regenerative Brk.

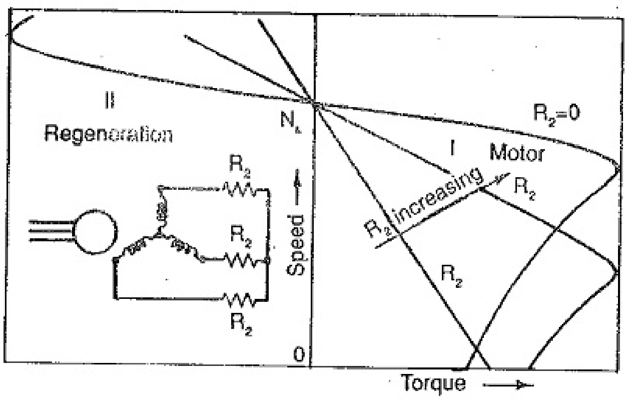
- **Regenerative braking** takes place whenever the speed of the motor exceeds the synchronous speed.
- This baking method is called **regenerative baking** because here the motor works as generator and supply itself (i.e., is given power from the load).
- The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place.

Electrical Braking – Regenerative Brk.

- Due to the effects of stator resistance, the maximum torque developed during regeneration is greater than the maximum torque during motoring.
- The main advantage of regenerative braking is that the generated power is fully used.
- The only disadvantage of this type of braking is that the motor has to run at super synchronous speed which may damage the motor mechanically and electrically, but regenerative braking can be done at sub synchronous speed if the variable frequency source is available.
- In other words, the main drawback is that when fed from a constant frequency source the motor can not employ below synchronous speed.

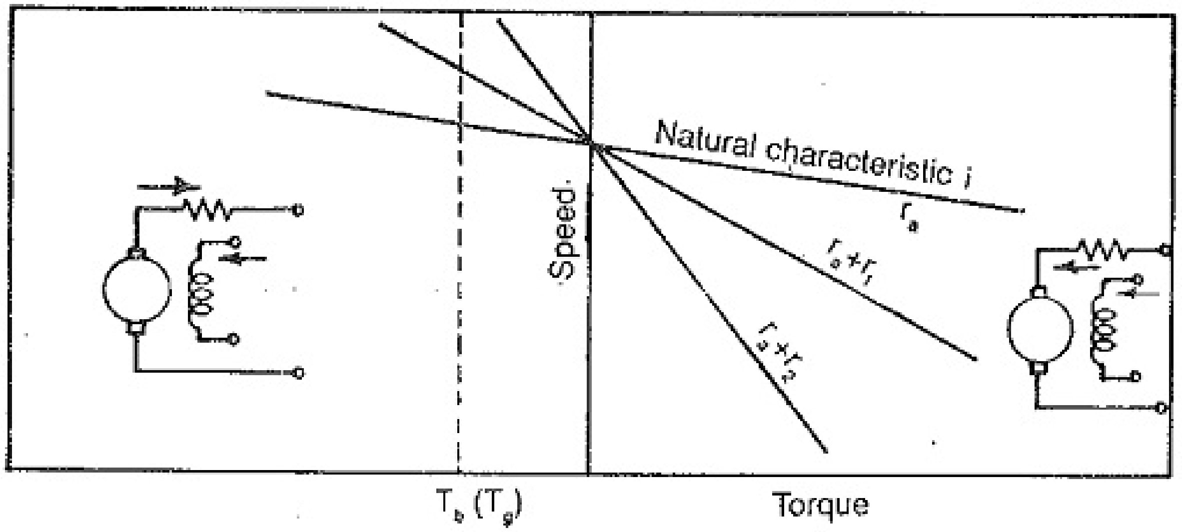
Electrical Braking – Regenerative Brk.



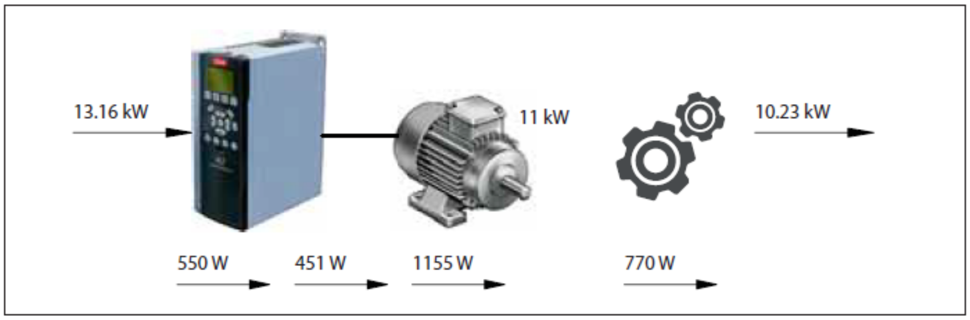


In "super capacitor regenerative braking systems" super capacitor accept and release charge more quickly and can be discharged and recharged many times and with have longer life time than a battery. For example in MAZDA car the unit can accept a full charge in just 8-10 seconds. The capacitor may take up to about 113s for discharging when the load is at minimum at about 18A

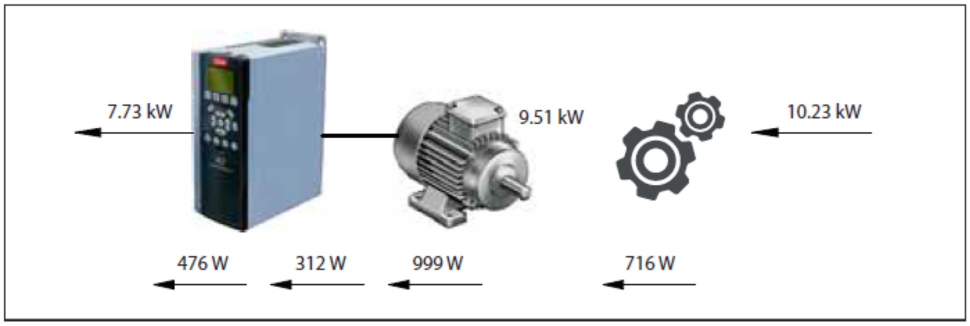
Electrical Braking – Regenerative Brk.



Power Losses – Regen. Brk.



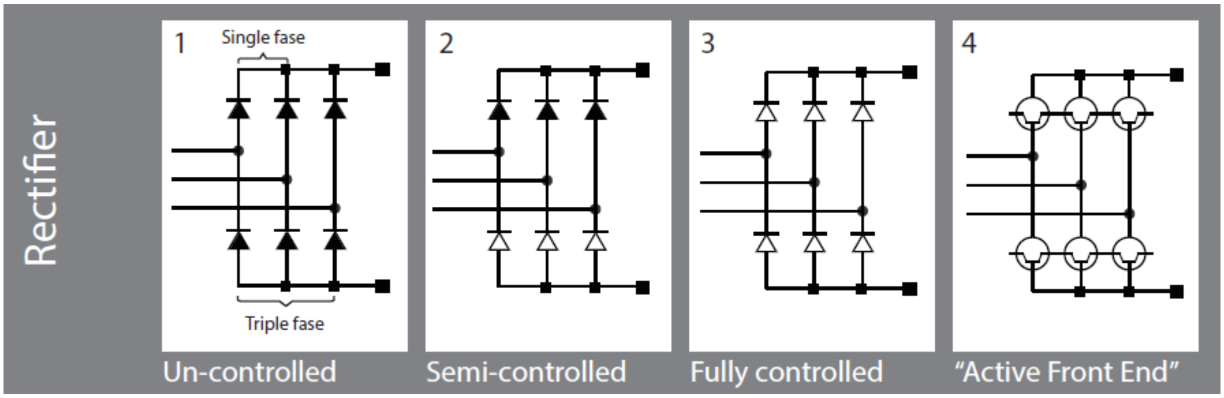
System losses during motor operation



System losses at regenerative operation

The losses caused by the AFE or AIC itself are much higher than for a standard FC due to the active rectifier whose losses can be twice as high in operation but also in standby. Depending on the construction, regenerative FC's without the necessary filters create more harmonic currents, which can also lead to higher losses in the grid.

Power Losses – Regen. Brk.



Frequency convertors (FCs) require a controlled (active) rectifier, which allows energy to flow backwards. Therefore these devices are called Active Front End (AFE) or Active Infeed Converters (AIC).

Introduction to Electric Drives

By

Dr. Mohammad Salah

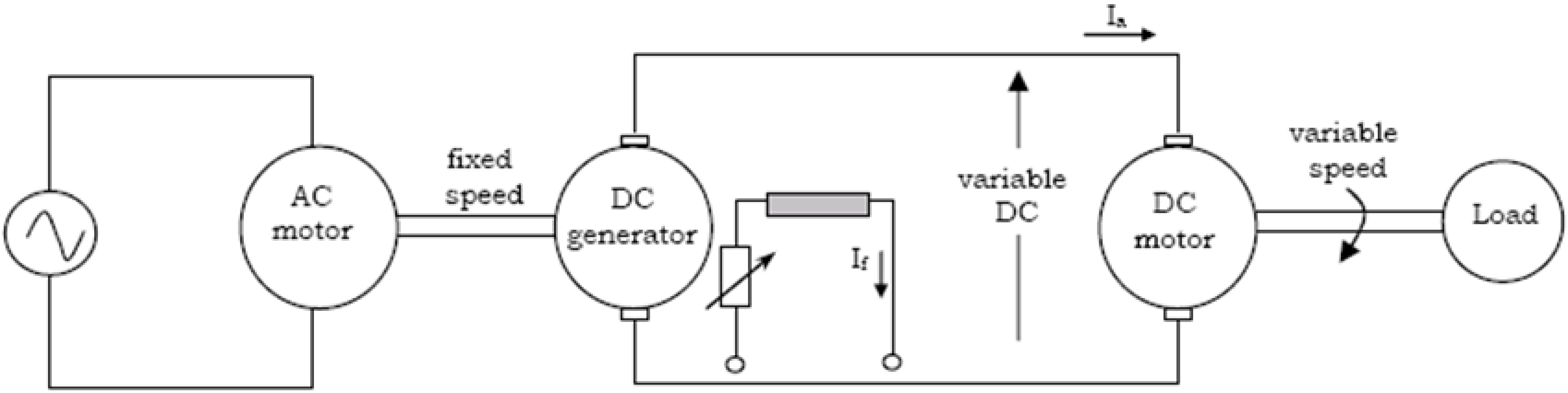
Mechatronics Engineering Department

The Hashemite University

Definition of Electric Drives

- **Drives** – system employed for motion control
- Motion control requires prime movers (motors)
- **Electrical Drives** – Drives that employ Electric Motors as prime movers
- The systems which controls the motion of the electrical machines, are known as **electrical drives**

Conventional Electric Drives

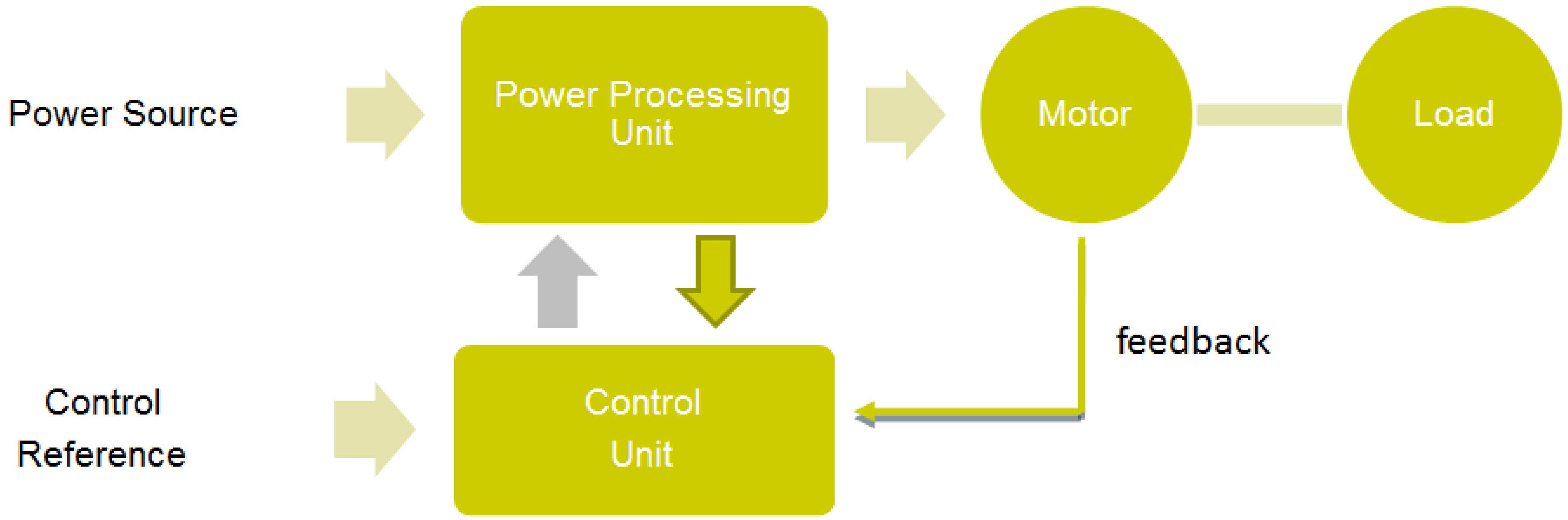


Ward-Leonard system (introduced in 1890s)

Disadvantage :

- Bulky
- Expensive
- Inefficient
- Complex

Modern Electric Drives


Power Source

Power Processing Unit

Motor

Load

feedback

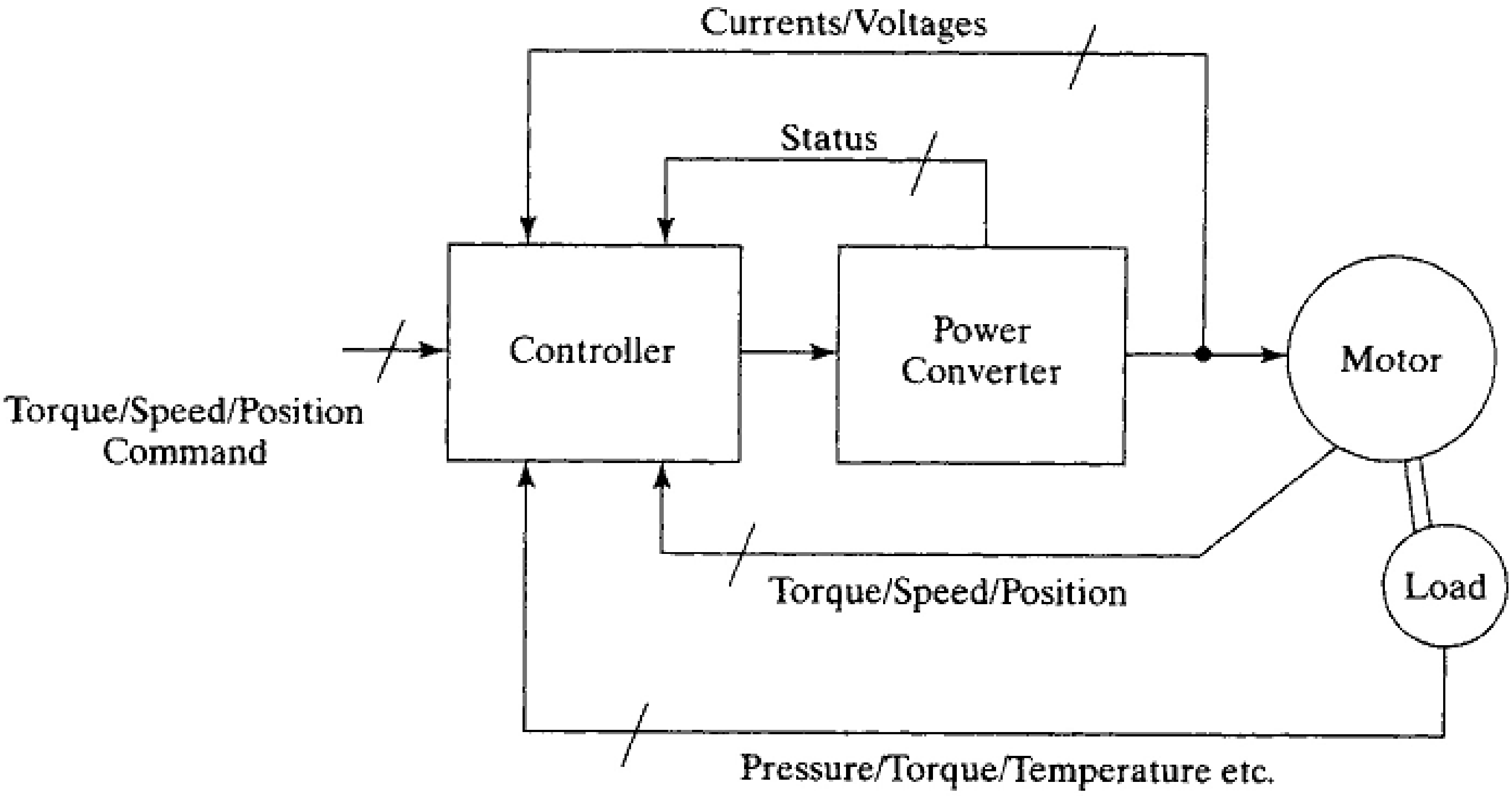
Control Reference

Control Unit

- Small (compact)
- Efficient
- Flexible

- Interdisciplinary (involving more than fields or branch of knowledge)

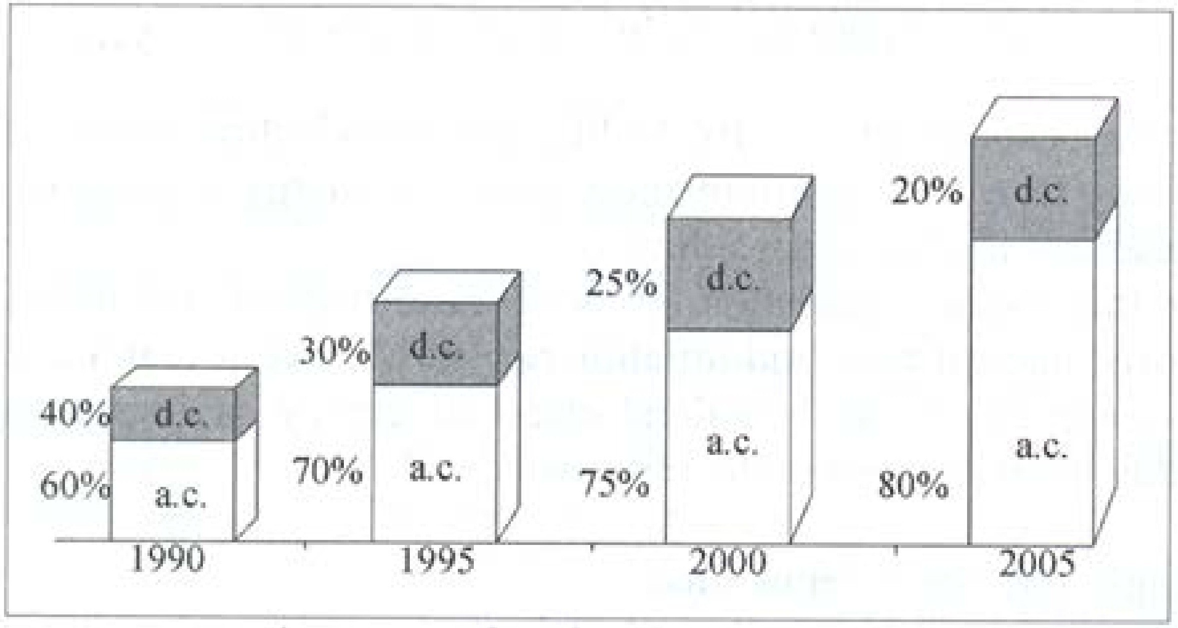
Modern Electric Drives



Motor-drive schematic

Modern Electric Drives

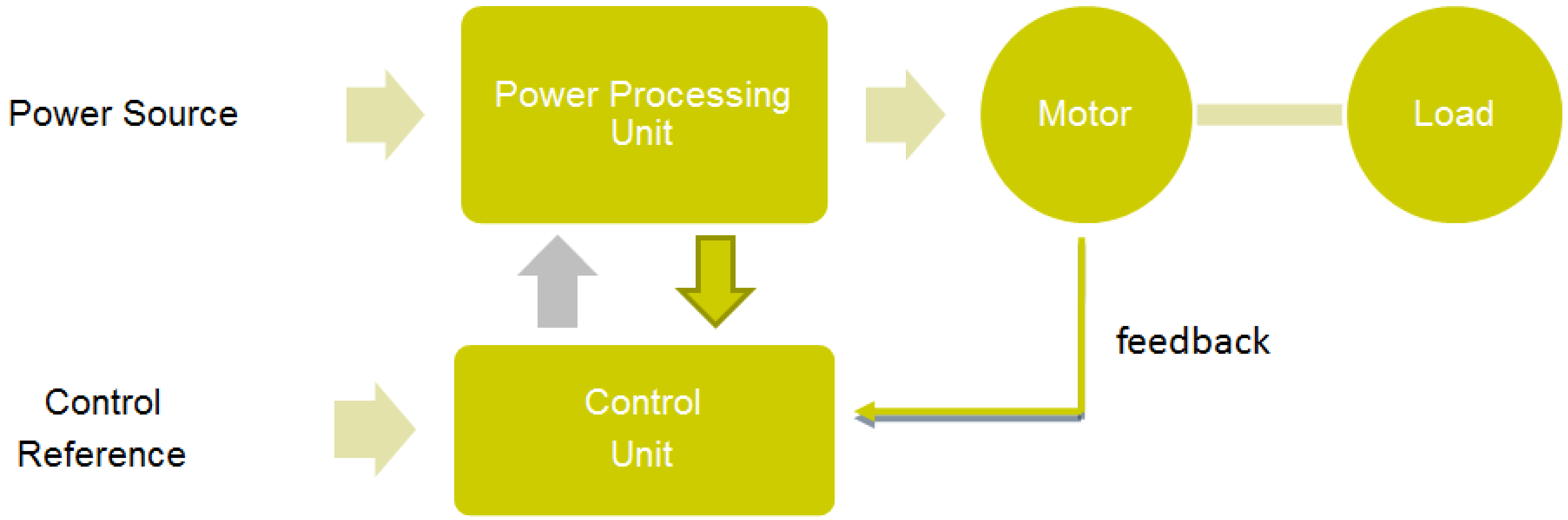
Overview of AC and DC drives



A.c. versus d.c. electric drives market dynamics

Traditionally for variable speed drives, d.c. brush motors have been used for decades. However, a.c. motors started to catch up with variable speed applications since 1990. This radical shift is mainly due to the rapid progress in power electronic converters for a.c. motors.

Basic Components of E.D.



- Power Source
- Motor – AC or DC
- Power Processing Unit (Electronic Converter)
- Control Unit
- Mechanical Load

Basic Components of E.D.

Power Source

- Provides energy to electric motors
- Regulated (e.g., utility) or Unregulated (e.g., renewable energy)
- Unregulated power sources must be regulated for high efficiency – use power electronic converters
- DC source
  - Batteries
  - Fuel cell
  - Photovoltaic
- AC source
  - Single- or three- phase utility
  - Wind generator

Basic Components of E.D.

Motor

Electrical Energy

Motor

Mechanical Energy

- Obtain power from electrical sources
- Could be DC or AC motors
- Selection of machines depends on many factors:

  - Application

  - Cost

  - Efficiency

  - Environment

  - Type of source available

Basic Components of E.D.

Power Processing Unit

- Provides a regulated power supply to motor
- Enables motor operation in reverse, braking and variable speeds
- Supervise operation
- Enhance overall performance and stability
- Complexity depends on performance requirement
- Analog Control – noisy, inflexible, ideally infinite bandwidth
- Digital Control – immune to noise, configurable, smaller bandwidth (depends on sampling frequency)

Basic Components of E.D.

Power Processing Unit

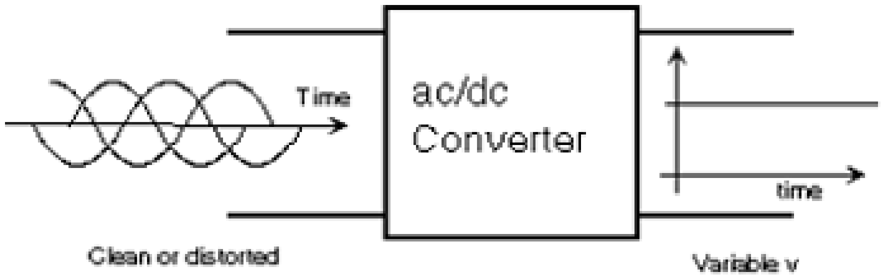
Combination of power electronic converters

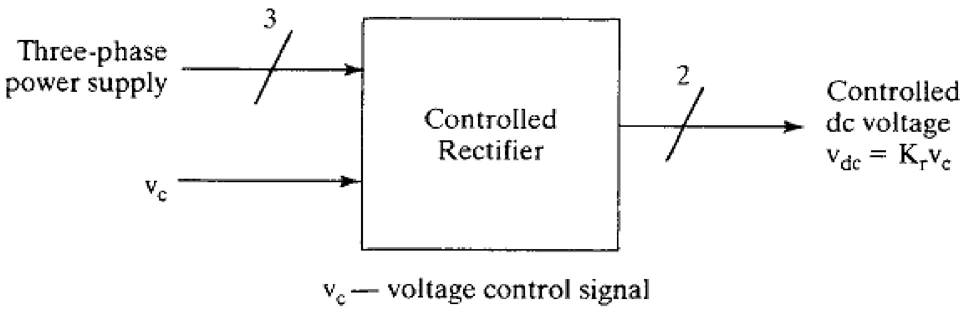
1. Compact
2. More efficient (ideally no losses occur)
3. Flexible (voltage and current easily shaped through switching control)
4. Several conversions possible: AC-DC, DC-AC, DC-DC, AC-AC (treated as ‘black boxes’ with certain transfer function)

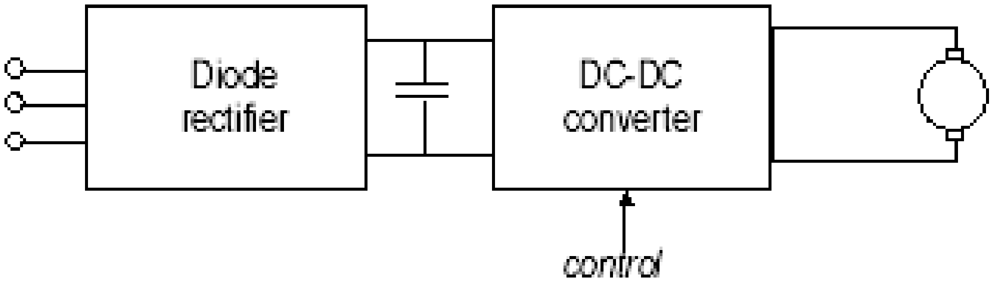
Basic Components of E.D.

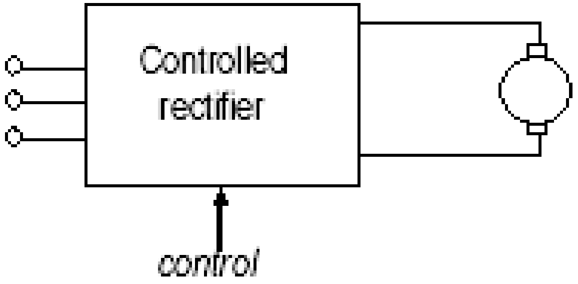
Power Processing Unit

- AC to DC (Rectifier – Uncontrolled/Controlled)





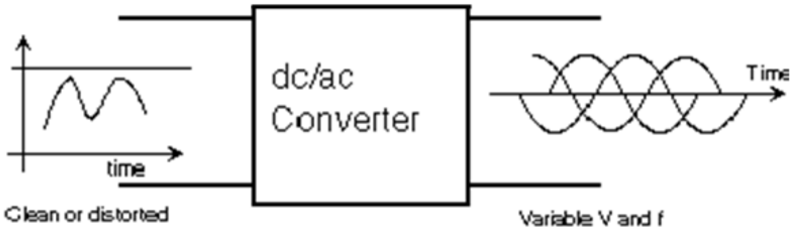


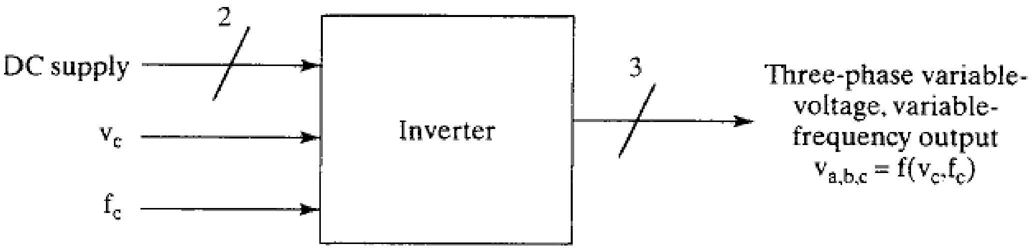


Basic Components of E.D.

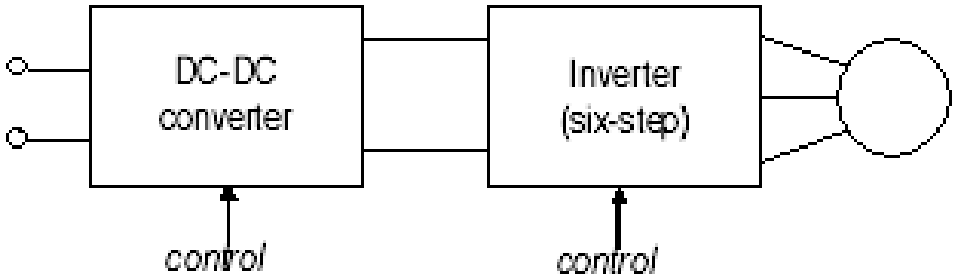
Power Processing Unit

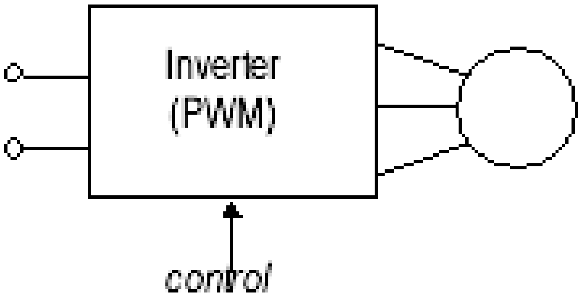
- DC to AC (Inverter)





v_c — voltage magnitude command
f_c — frequency command

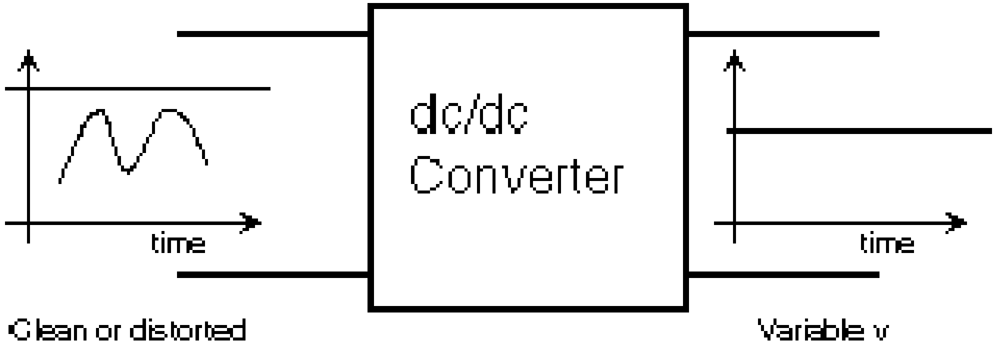


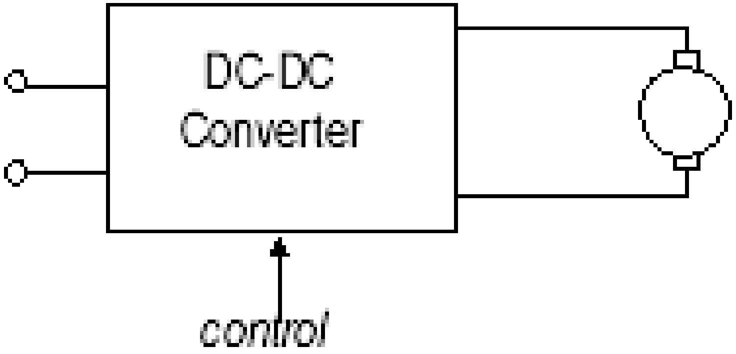


Basic Components of E.D.

Power Processing Unit

- DC to DC (Chopper)

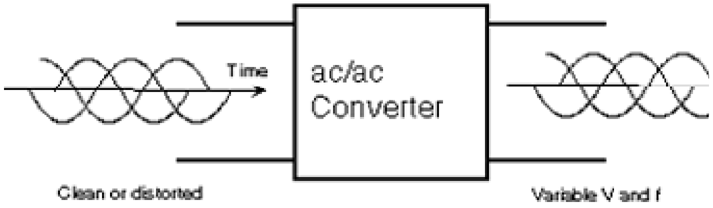


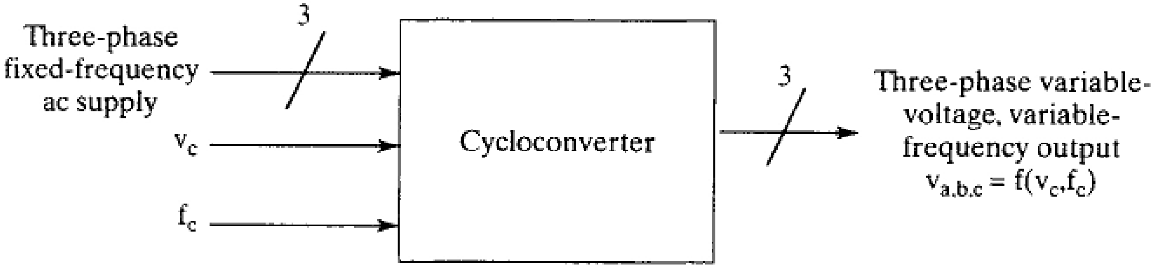


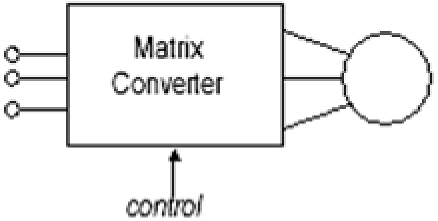
Basic Components of E.D.

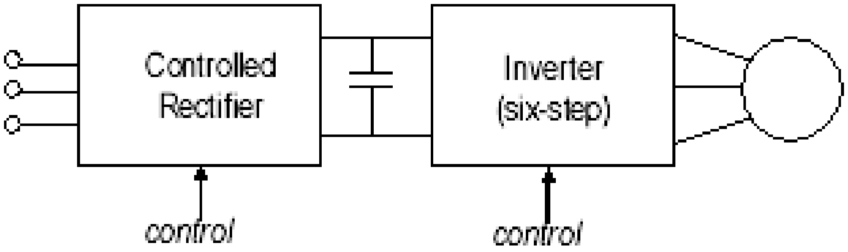
Power Processing Unit

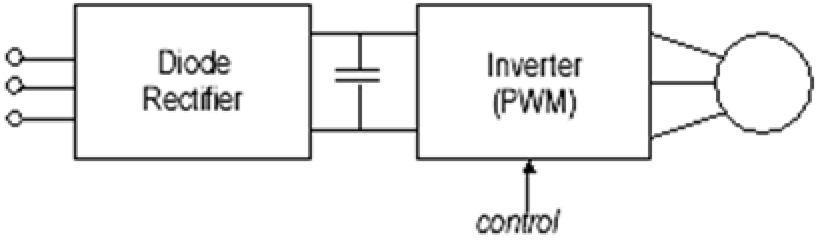
- AC to AC (Cycloconverter)





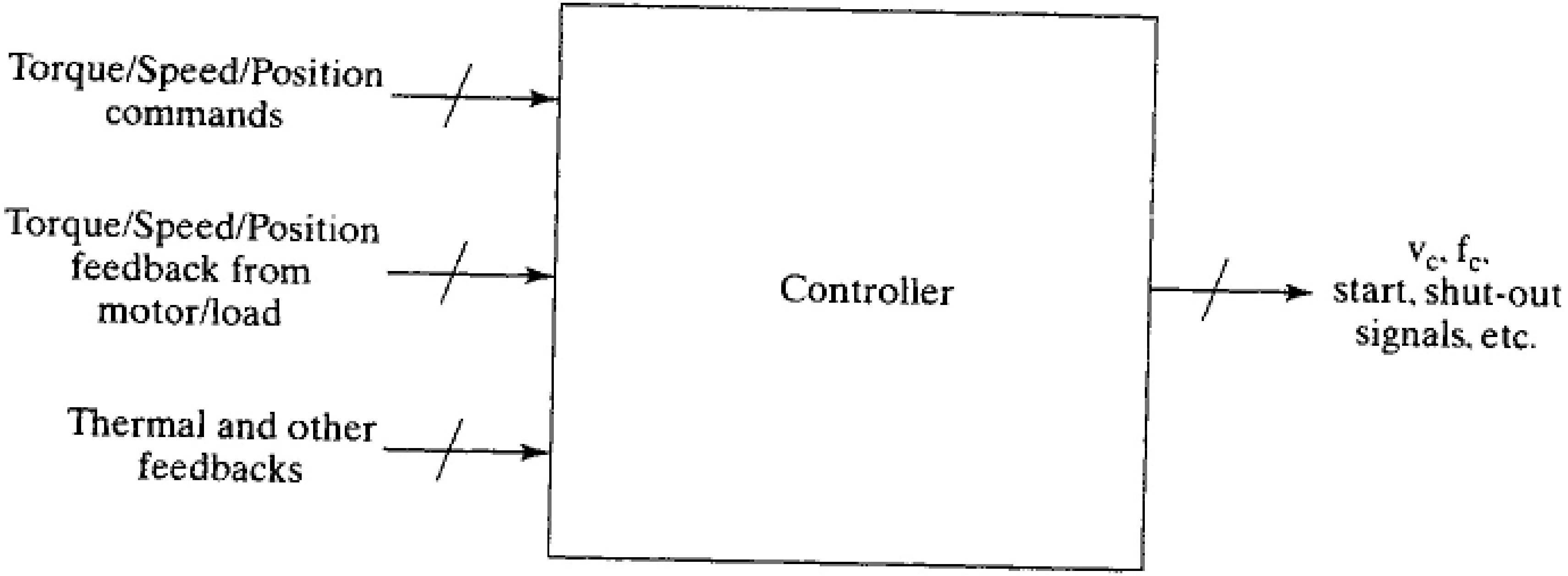






Basic Components of E.D.

Control Unit



Basic Components of E.D.

Mechanical Load

- Load torque is a function of speed $T_L \propto \omega_m^k$
  where k = integer or fraction.

- Mechanical power of load is $P = T_L \omega_m$ and

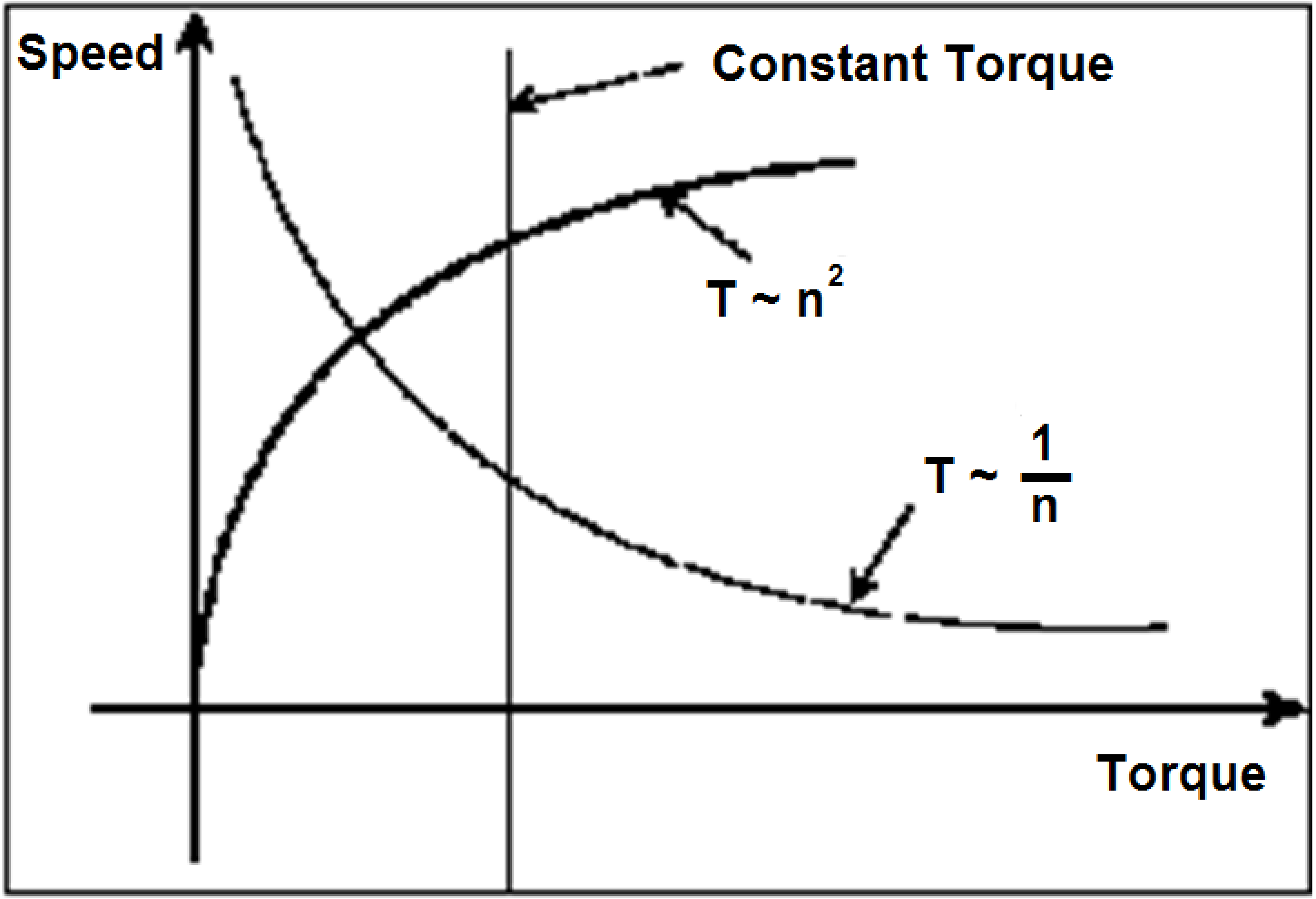
$$\omega_m = \frac{2\pi}{60} n_m$$

Angular speed
in rad/s

Speed
in rpm

Basic Components of E.D.

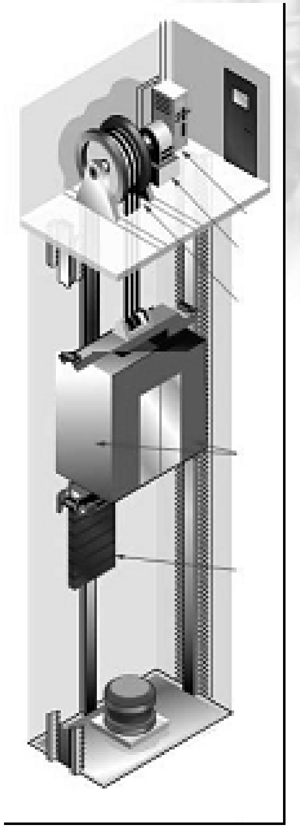
Mechanical Load



Basic Components of E.D.

Mechanical Load

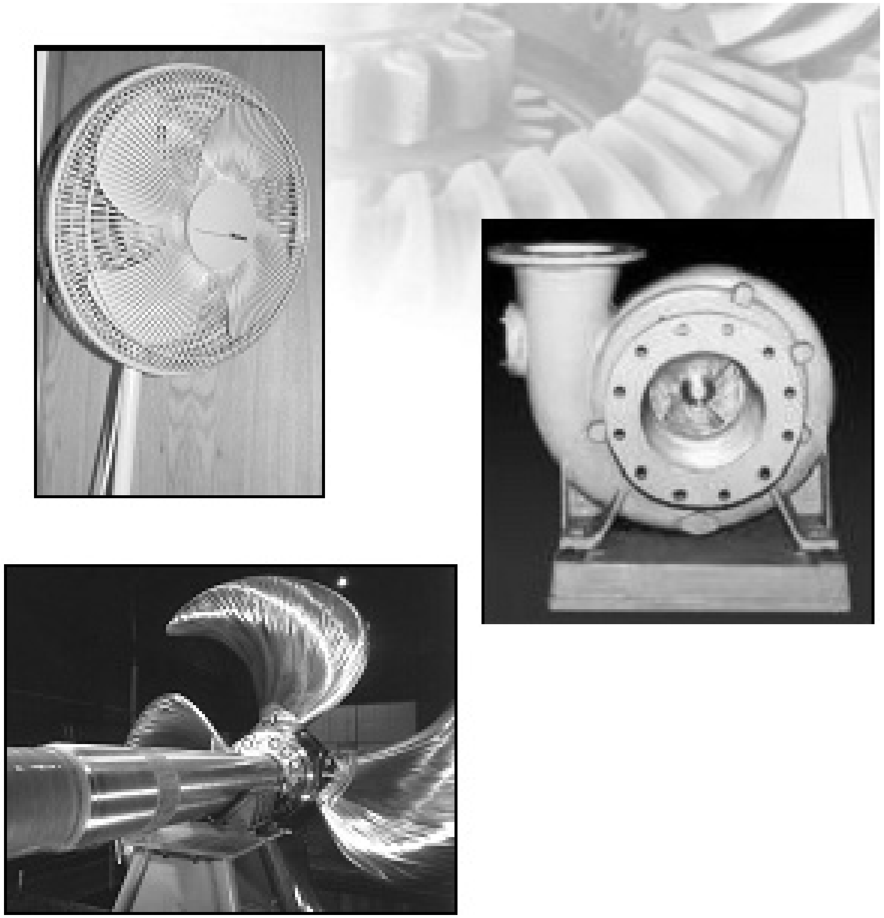
- **Torque independent of speed (*k* = 0)**
    - Hoist
    - Elevator
    - Pumping of water or gas against constant pressure



Basic Components of E.D.

Mechanical Load

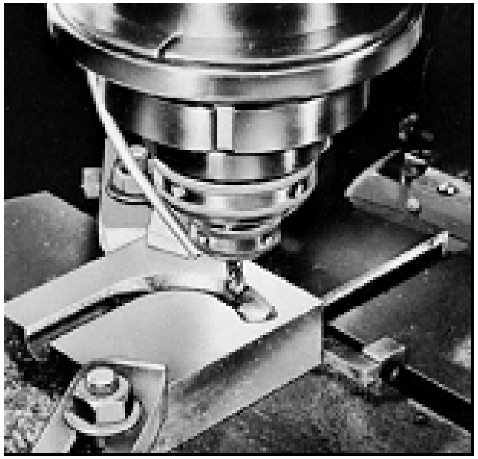
- **Torque proportional to square of speed (k = 2)**
  - Fans
  - Centrifugal pumps
  - Propellers



Basic Components of E.D.

Mechanical Load

- **Torque inversely proportional to speed (**$k = -1$**)**
  - Milling machines
  - Electric drill
  - Electric saw



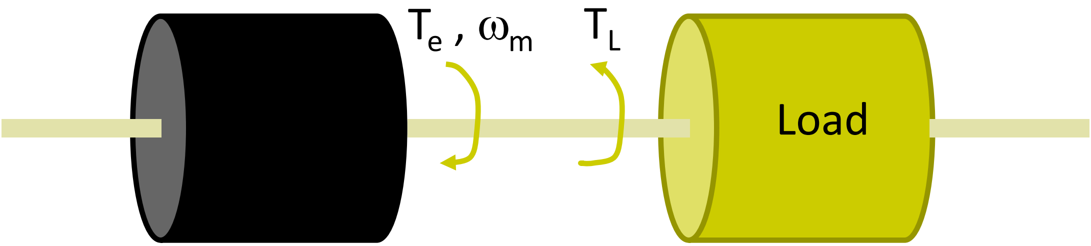
DC Drives vs. AC Drives

	DC Drives	**AC Drives (particularly Induction Motor)**
Motor	• Requires maintenance • Heavy, expensive • Limited speed (due to mechanical construction)	• Less maintenance • Light and cheaper • High speeds achievable (squirrel-cage IM) • Robust
Control Unit	• Simple and cheap even for high performance drives • Decoupled torque and flux control • Possible implementation using single analog circuit	• Depends on required drive performance • Complexity and costs increase with performance • Fast processors required in high performance drives

Torque Equation

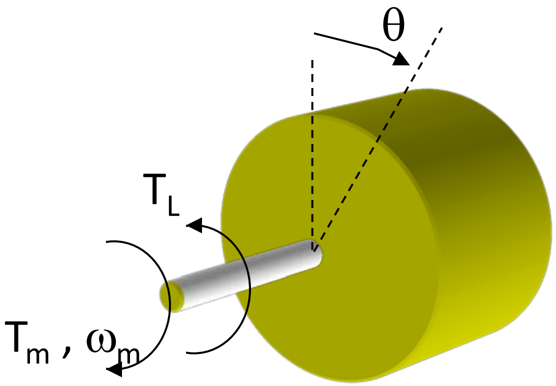
- Motor in systems drives a load through a transmission system (e.g., gears, V-belts, crankshaft and pulleys)
- Load may rotate or undergo translational motion
- Load speed may be different from motor speed
- Systems may also have multiple loads each having different speeds; some may rotate and some may have translational motion

Represent motor-load system as **equivalent rotational system**



Torque Equation

Torque equation for equivalent motor-load system:



$$\boxed{T_m - T_L = \frac{d\left(J\omega_m\right)}{dt}}$$

where:

J = inertia of equivalent motor-load system, kgm^2

ω_m = angular velocity of motor shaft, rads^{-1}

T_m = motor torque, Nm

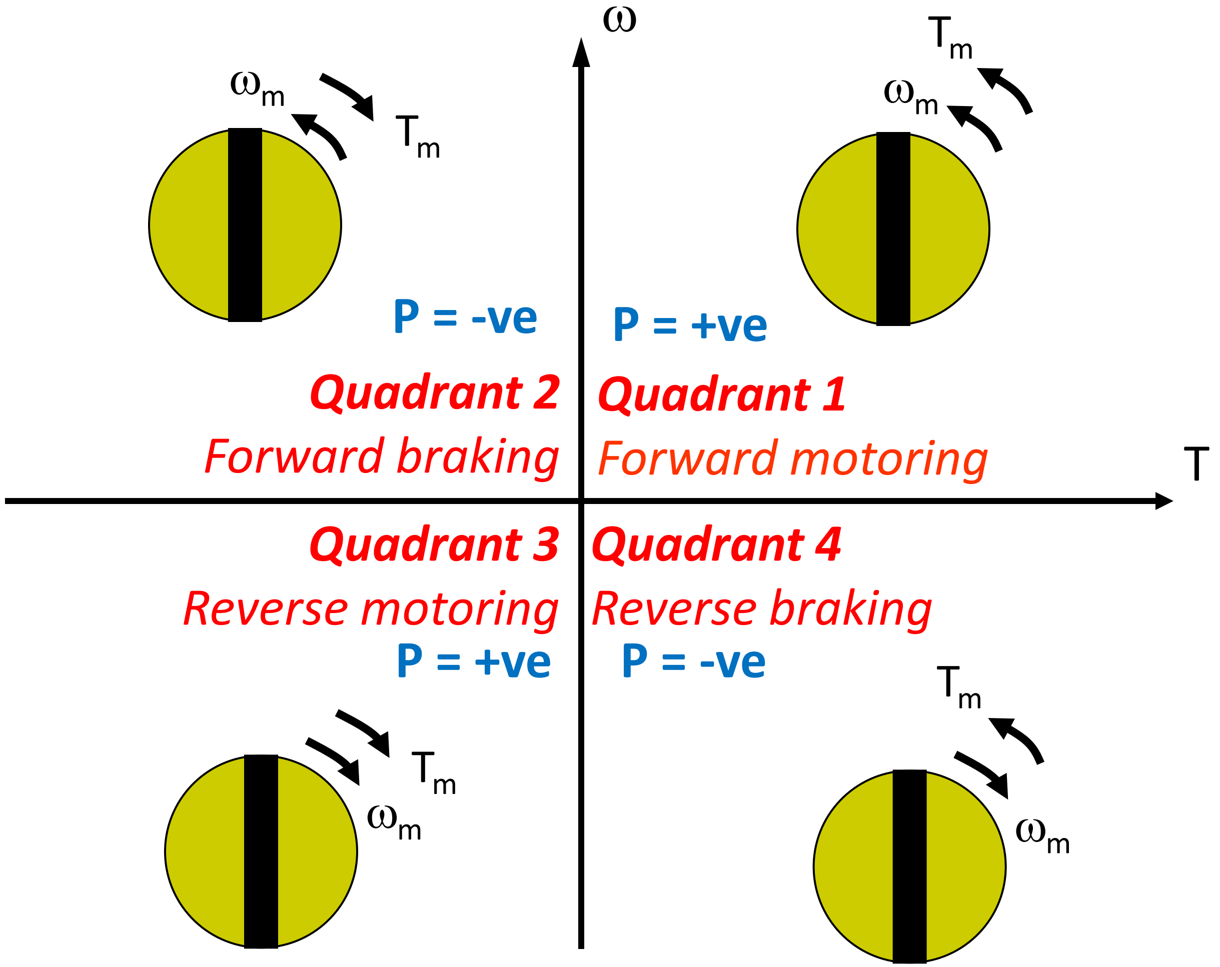
T_L = load torque referred to motor shaft, Nm

with constant inertia *J*,

$$\boxed{T_m - T_L = J\frac{d\omega_m}{dt} = J\frac{d^2\theta_m}{dt^2}}$$

- **First order differential equation for angular frequency (or velocity)**
- **Second order differential equation for angle (or position)**

Torque-Speed Quadrant of Operation



P = -ve

Quadrant 2

Forward braking

P = +ve

Quadrant 1

Forward motoring

Quadrant 3

Reverse motoring

P = +ve

Quadrant 4

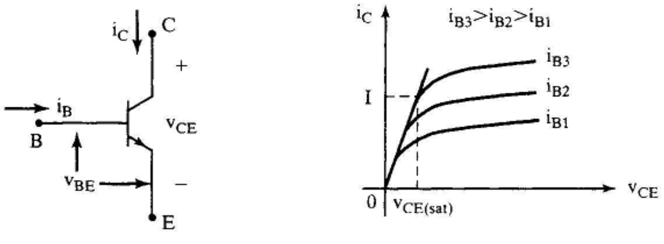
Reverse braking

P = -ve

$$P = T_m \omega_m$$

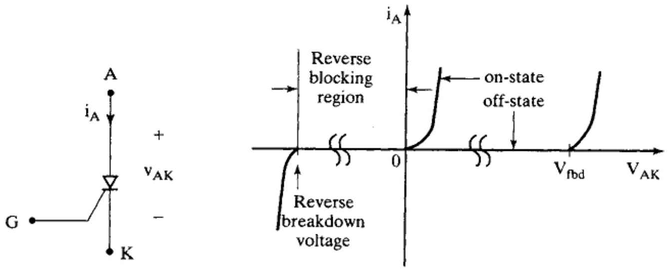
Power Devices

Power Device	Ratings	Switching Frequency	Applications	Notes
Power Diode	- Several 100A at several 100V - On-state drop voltage of 2-3V	Limited to line frequency	- Line rectifier - Inverter	- Can be turned off only by reverse biasing - Has blocking mode
Power Transistor	- Up to 1000A, 1400V - On-state drop voltage of 2V	2-6 kHz	- Not used very much in newer products	- Does not have reverse voltage blocking capabilities
Silicon Controlled Rectifier (SCR)	- 6-8 kA, 12 kV - On-state drop voltage of 1-3V	Limited to 300-400 Hz	- Used only on HVDC rectifiers - Inverters - Motor drive higher than 30MW	- Can be turned off only by reverse biasing - Holds off its conduction in the forward-biased mode until the gate signal is injected
Gate-Turn-Off (GTO) Thyristor	- 6 kA, 6 kV - On-state drop voltage of 2-3V	1 kHz	- Mainly in high power inverters	- Thyristor device with gate turn-on and gate turn-off capability
Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET)	- 100A at 100-200V - 10A at 1000V	30 kHz – 1 MHz	- PWM	- Requires low gate voltage for turn-on and turn-off - Has no reverse voltage blocking capability - It behaves like a resistor when in conduction so used as a current sensor in a drive circuit - Comes always with a parasitic anti-parallel diode
Insulated Gate Bipolar Transistor (IGBT)	- 1.2kA at 3.3kV - 0.6kA at 6.6kV - On-state drop voltage of 5V - Higher A at reduced V with much lower OSDV are available	Around 20 kHz	- PWM	



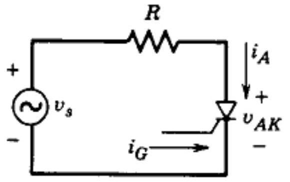
(i) Schematic (ii) Characteristics

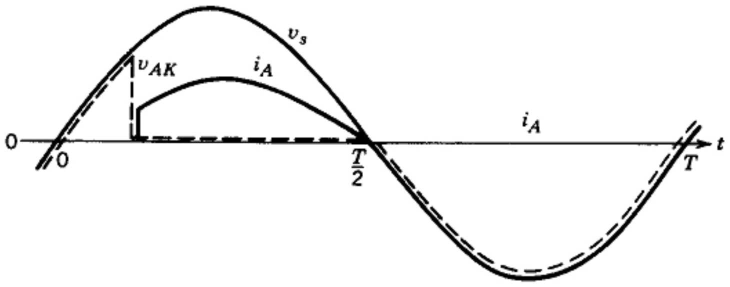
Figure 1.2 Power-transistor schematic and characteristics

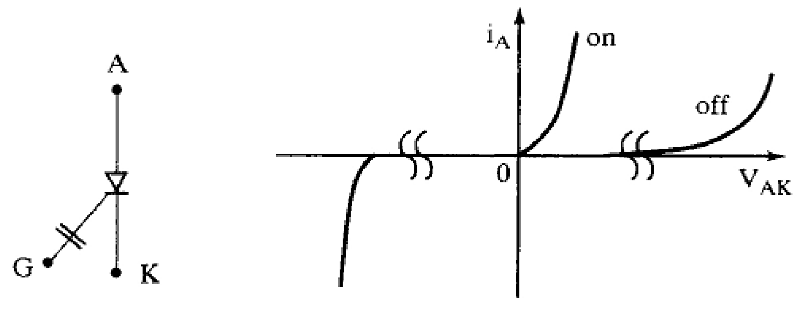


(i) SCR schematic (ii) SCR characteristics

Figure 1.3 SCR schematic and characteristics

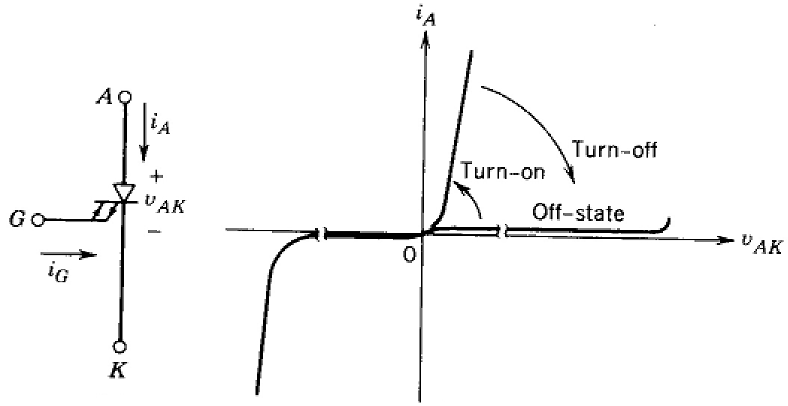






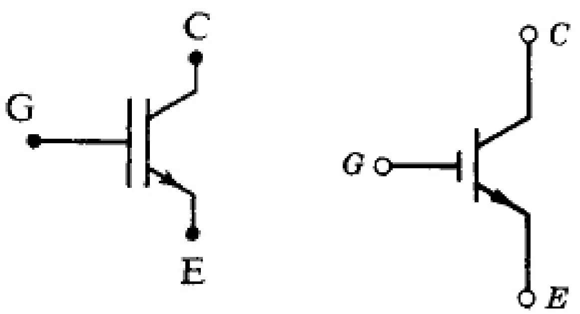
(i) GTO schematic (ii) GTO characteristics

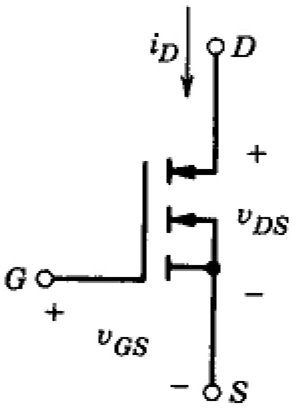
Figure 1.4 The schematic and characteristics of the GTO



(i) N-channel MOSFET schematic (ii) Characteristics

Figure 1.5 Schematic and characteristics of the N-channel MOSFET





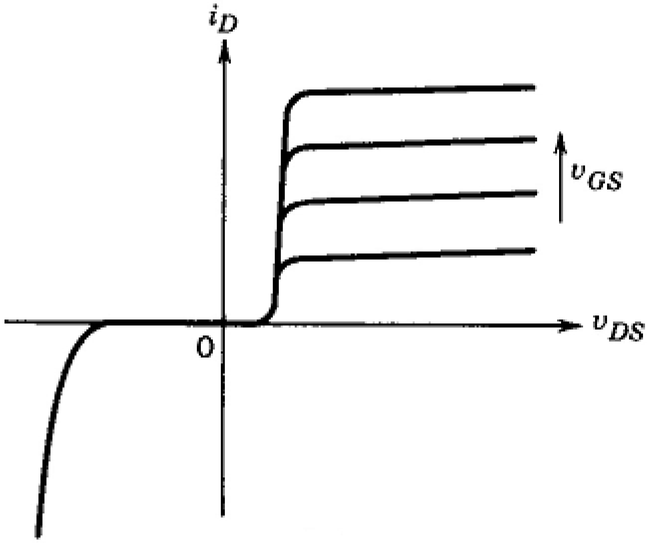
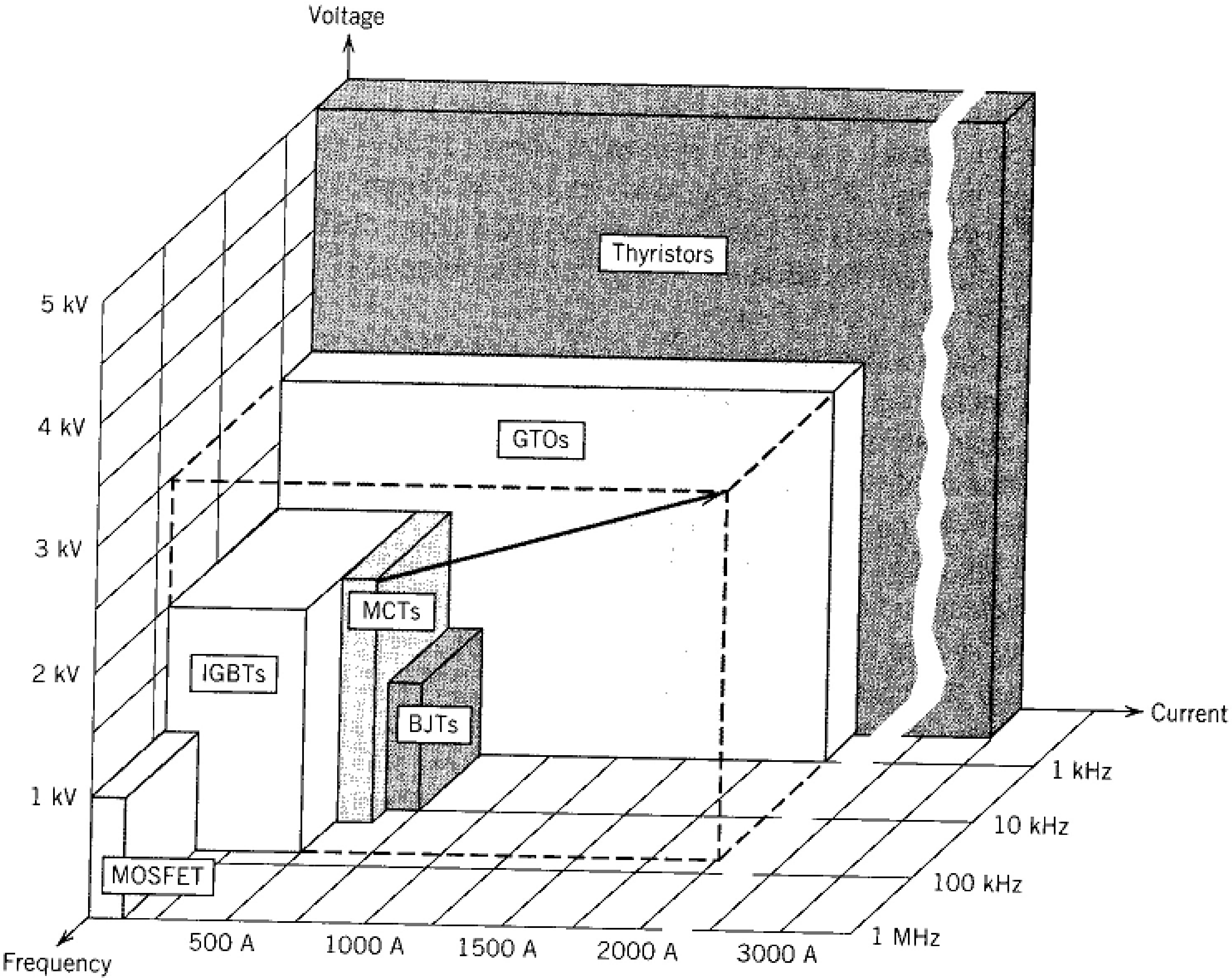


Figure 1.6 IGBT symbol


Voltage
5 kV
4 kV
3 kV
2 kV
1 kV
Thyristors
GTOs
MCTs
IGBTs
BJTs
MOSFET
Current
1 kHz
10 kHz
100 kHz
1 MHz
500 A
1000 A
1500 A
2000 A
3000 A
Frequency

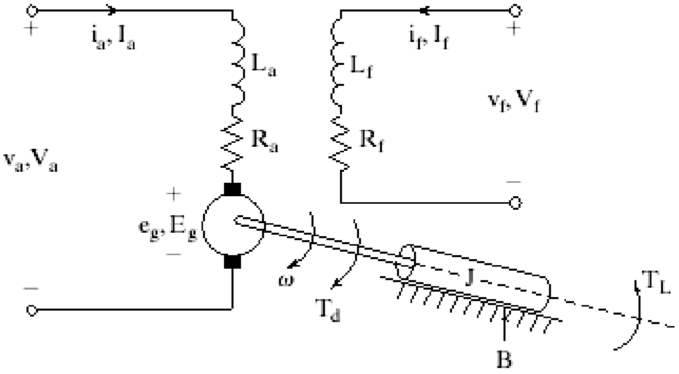
Speed Control of DC Motors

By

Dr. Mohammad Salah

Mechatronics Engineering Department
The Hashemite University

Separately Excited DC Motor



$$T_m = J\frac{d\omega}{dt} + B\omega + T_L$$

where

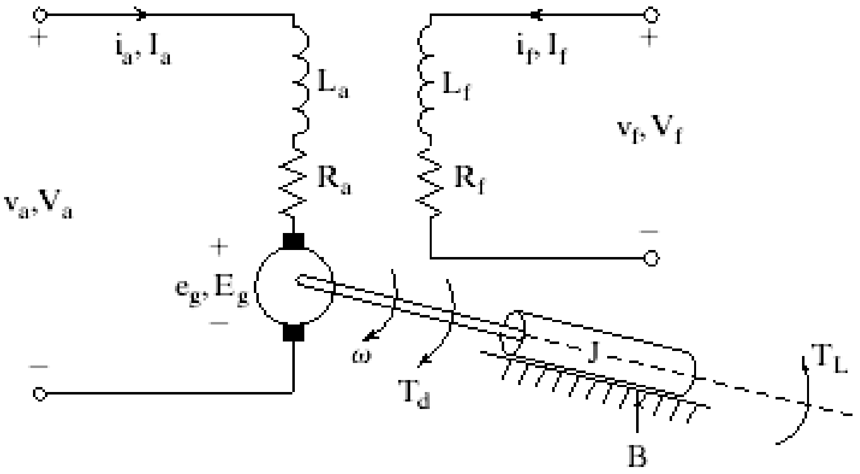
$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

T_L= load torque

J = load inertia (kg/m^2)

B = viscous friction coefficient (Nm/rad/s)

S.E.D.M – Steady State Condition



$$V_f = R_f I_f$$

$$E_a = K_b \varphi \omega$$

$$V_a = R_a I_a + E_a$$

$$= R_a I_a + K_b \varphi \omega$$

$$T_m = K_m \varphi I_a = B\omega + T_L$$

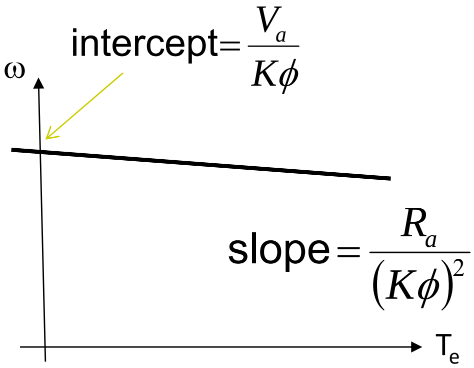
$$P_d = T_e \omega \quad \Rightarrow \quad Developed\ Power$$

S.E.D.M – Speed Control Methods

$$K_b = K_m = K$$

$$\omega = \frac{V_a - R_a I_a}{K\varphi} \quad = \frac{V_a}{K\varphi} - \frac{R_a}{K\varphi}\left(\frac{T_m}{K\varphi}\right)$$

$$\therefore \omega = \frac{V_a}{K\varphi} - \frac{R_a}{(K\varphi)^2} T_m$$



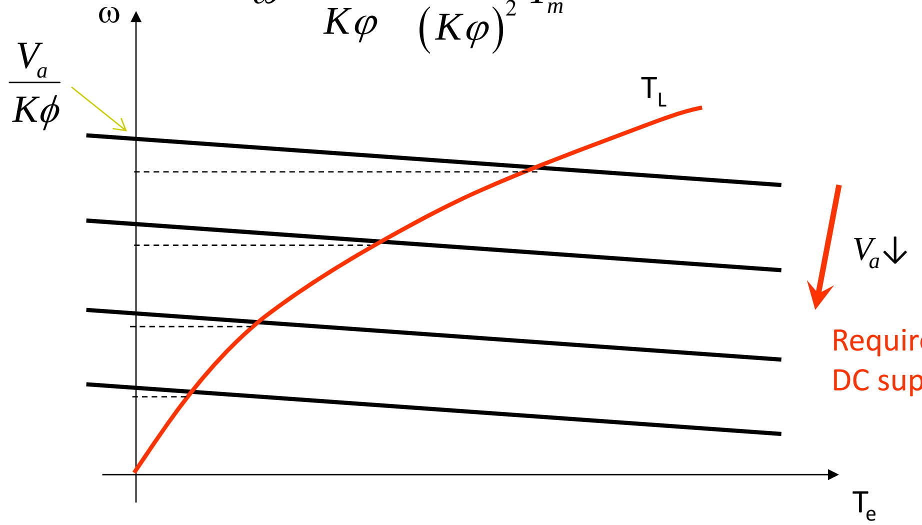
Three possible methods for speed control:

- Armature voltage V_a
- Armature resistance R_a
- Field flux ϕ (by changing field resistance R_f)

S.E.D.M – Speed Control Methods

V_a control method

$$\omega = \frac{V_a}{K\varphi} - \frac{R_a}{(K\varphi)^2} T_m$$

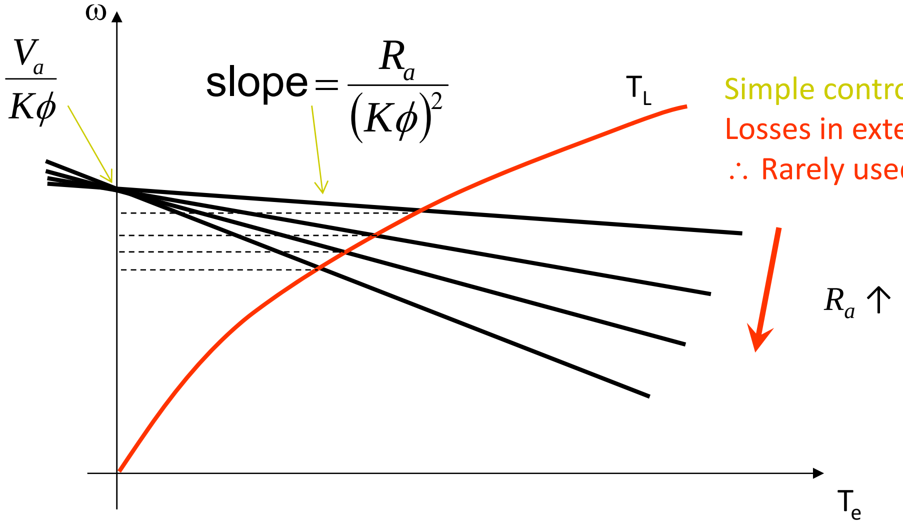


Requires variable
DC supply

S.E.D.M – Speed Control Methods

R_a control method

$$\omega = \frac{V_a}{K\varphi} - \frac{R_a}{(K\varphi)^2} T_m$$



Simple control

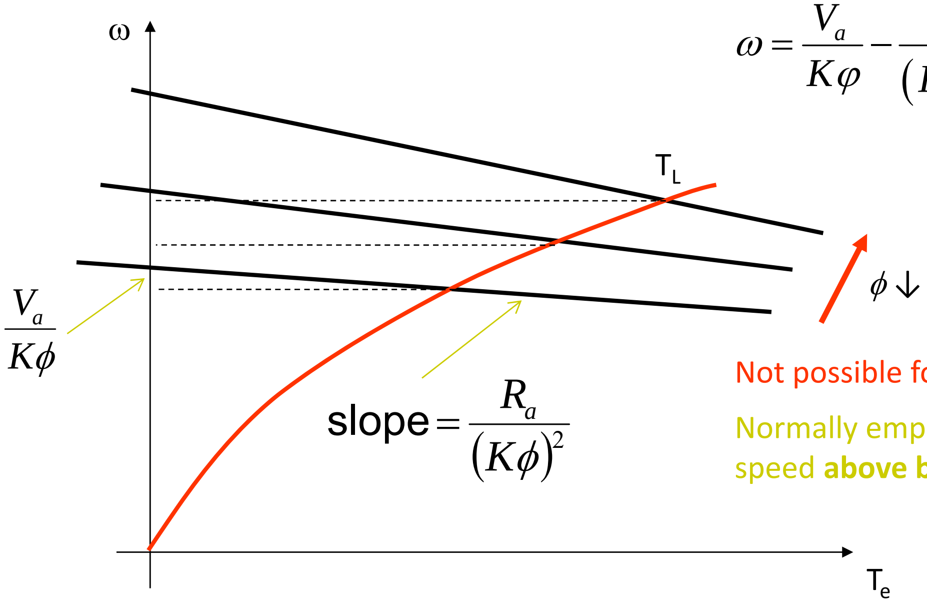
Losses in external resistor

∴ Rarely used.

S.E.D.M – Speed Control Methods

Φ control method

$$\omega = \frac{V_a}{K\varphi} - \frac{R_a}{(K\varphi)^2} T_m$$



Not possible for PM motor

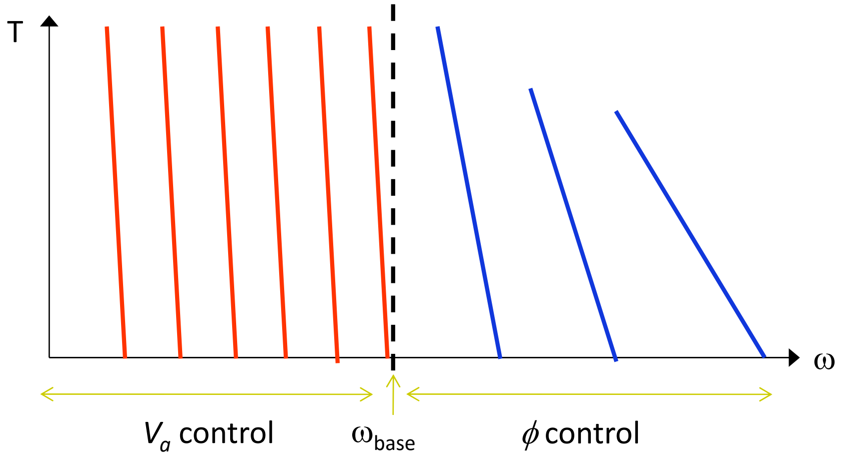
Normally employed for speed **above base speed**

S.E.D.M – Speed Control Methods

Base speed ω_{base} = Speed at rated V_a, I_f and I_a

$\omega = 0$ to $\omega_{base} \Rightarrow$ speed control by V_a

$\omega > \omega_{base} \Rightarrow$ speed control by flux weakening ($\phi\downarrow$)



S.E.D.M – Speed Control Methods

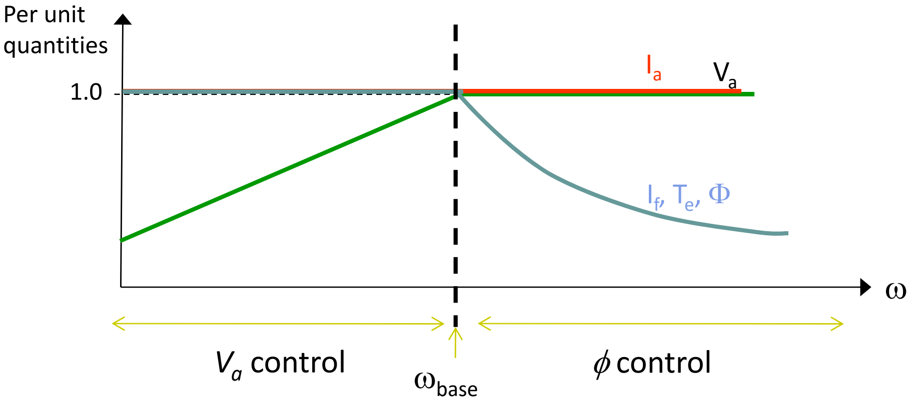
$\omega = 0$ to $\omega_{base} \Rightarrow$ speed control by V_a

$\omega > \omega_{base} \Rightarrow$ speed control by flux weakening ($\phi\downarrow$)

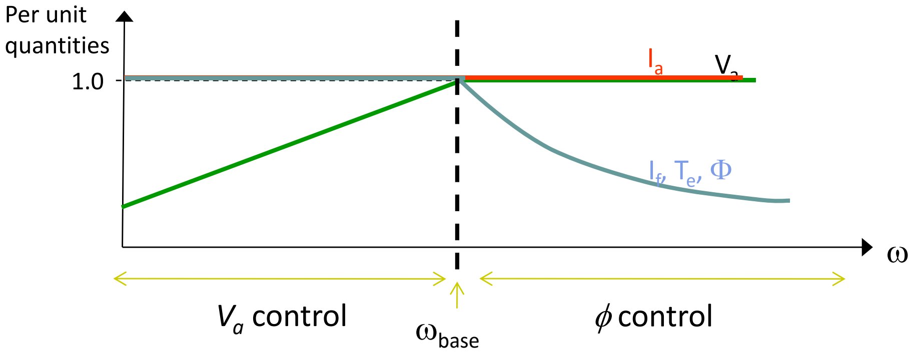
$T \propto I_a\phi \Rightarrow$ For maximum torque capability, $I_a = I_{a\ max}$

$P_d = E_aI_a = (K\phi\omega)I_a =$ constant when $\omega > \omega_{base}$

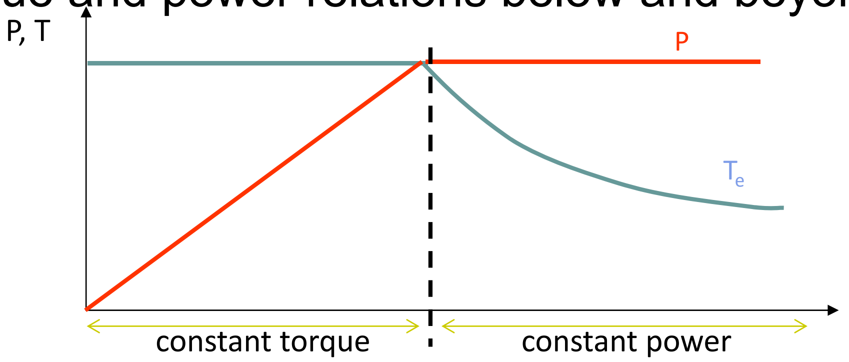
$\therefore$ in order to go beyond ω_{base}, $\phi \propto (1/\omega)$



S.E.D.M – Speed Control Methods



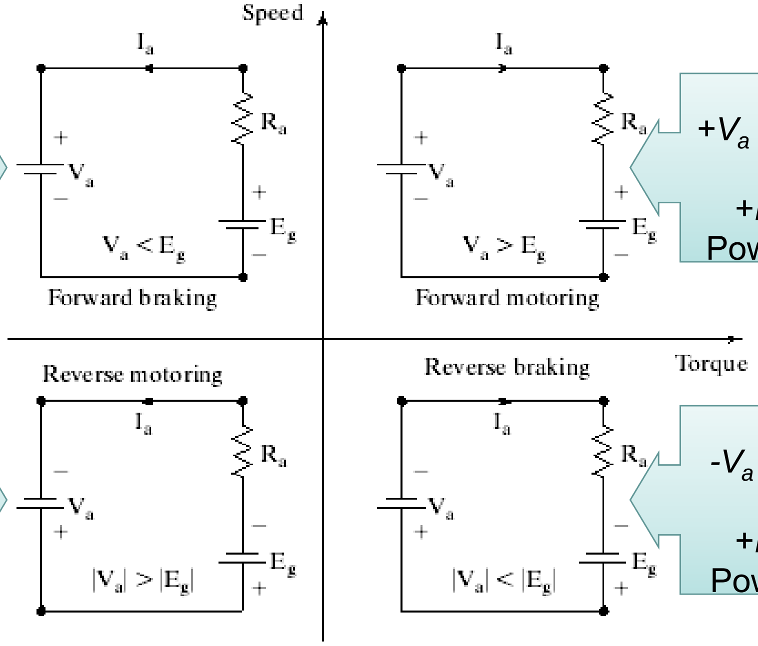
Torque and power relations below and beyond ω_{base}



$P = K\phi\omega$

$T_e = K\phi I_a$

Four Quadrant Operating Modes



Q2

$+V_a$, $+E_a \Rightarrow +\omega$

$-I_a \Rightarrow -T$

Power = -ve

Q1

$+V_a$, $+E_a \Rightarrow +\omega$

$+I_a \Rightarrow +T$

Power = +ve

Q3

$-V_a$, $-E_a \Rightarrow -\omega$

$-I_a \Rightarrow -T$

Power = +ve

Q4

$-V_a$, $-E_a \Rightarrow -\omega$

$+I_a \Rightarrow +T$

Power = -ve

DC Motor Drives

By

Dr. Mohammad Salah

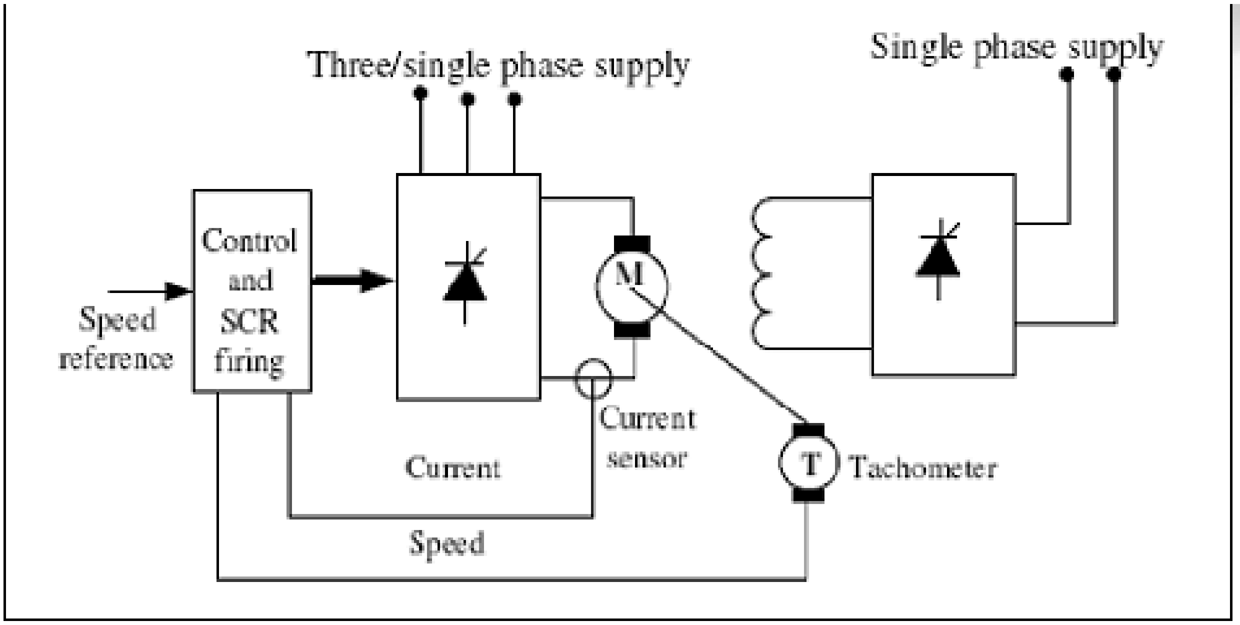
Mechatronics Engineering Department
The Hashemite University

DC Motor Drives

To obtain variable voltage, efficient drive with ideally no losses, two methods can be used depending on voltage source:

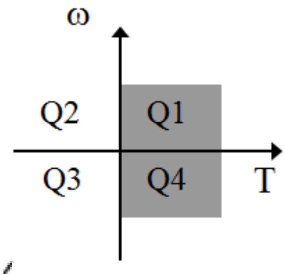
- AC voltage source ⇒ Controlled Rectifiers
- Fixed DC voltage source ⇒ DC-DC converters (Choppers)

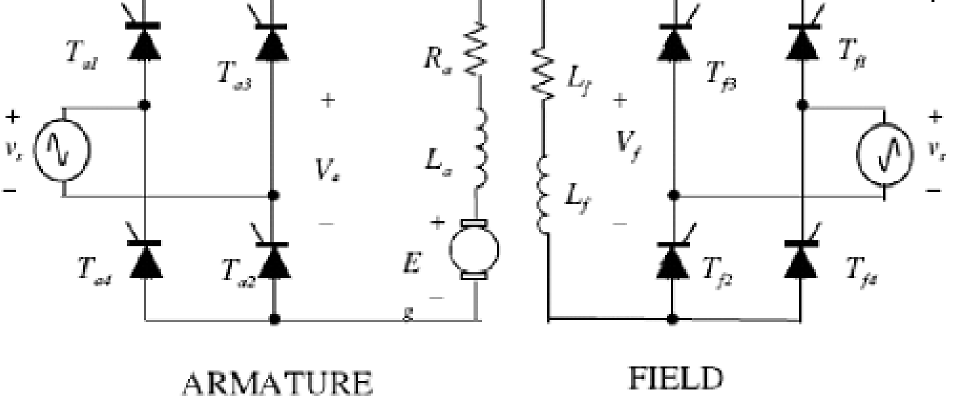
Controlled Rectifier DC Drives



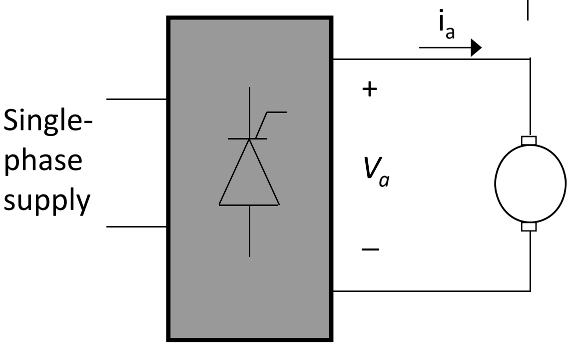
Controlled Rectifier **Single-Phase** DC Drives

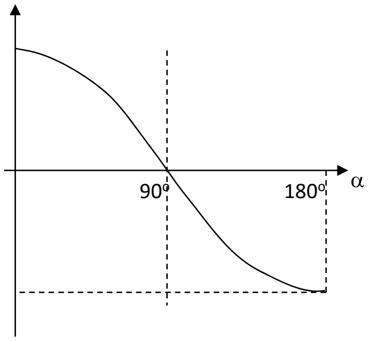
- **Two-quadrant drive**
- Limited to applications up to 15 kW
- Regeneration (Q4) only be achieved with loads that can drive the motor in reverse (-ve ω)





Controlled Rectifier Single-Phase DC Drives





Armature voltage

$$V_a = \frac{2V_m}{\pi}\cos\alpha_a$$

where V_m = peak voltage

Armature current

$$I_a = \frac{V_a - E_a}{R_a}$$

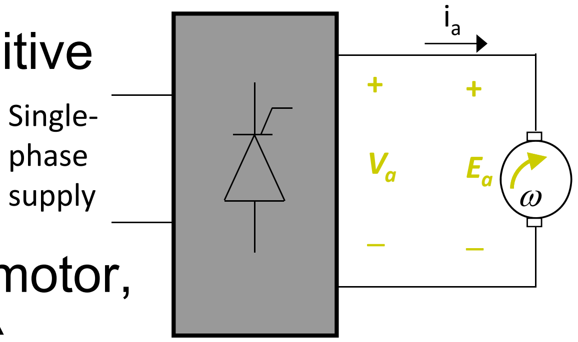
Field voltage

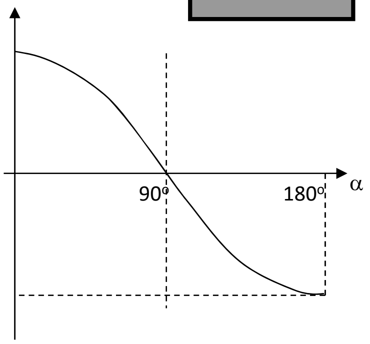
$$V_f = \frac{2V_m}{\pi}\cos\alpha_f$$

Controlled Rectifier Single-Phase DC Drives

For **Quadrant 1** operation:

- ω positive → E_a and V_a positive
- $\alpha_a \leq 90°$
- I_a positive
- Rectifier delivers power to motor, i.e. forward motoring.



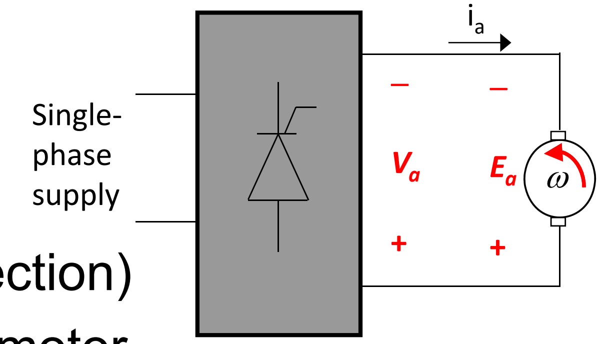


$$V_a = \frac{2V_m}{\pi}\cos\alpha_a$$

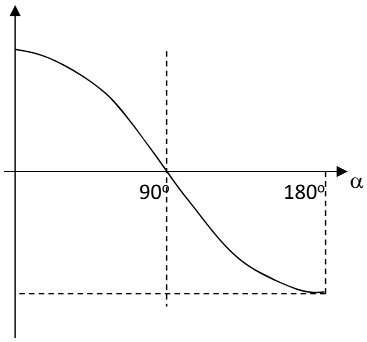
Controlled Rectifier Single-Phase DC Drives

For **Quadrant 4** operation:

- ω negative → E_a negative
- $\alpha_a > 90°$ → V_a negative
- I_a positive (still in same direction)
- Rectifier takes power from motor, i.e. regenerative braking.

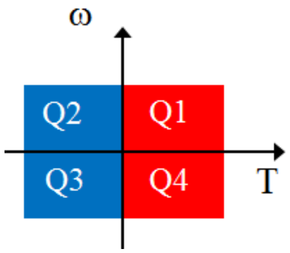


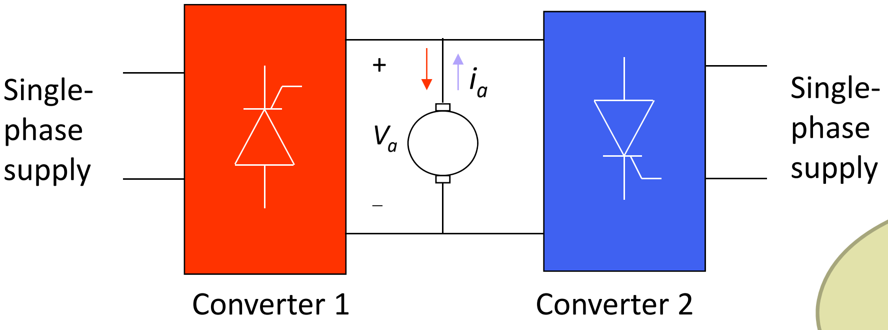
$$V_a = \frac{2V_m}{\pi}\cos\alpha_a$$



Controlled Rectifier Single-Phase DC Drives

- **Four-quadrant drive**
- Converter 1 for operation in 1st and 4th quadrant
- Converter 2 for operation in 2nd and 3rd quadrant
- Limited to applications up to 15 kW





Two rectifiers connected in **anti-parallel** across motor armature

Controlled Rectifier Single Phase DC Drives

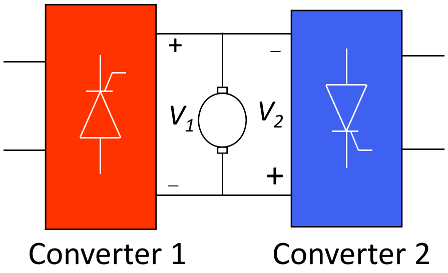
- **Four-quadrant drive**

  For continuous current:
  - Both converters are operated to produce the same dc voltage across the terminal, i.e.: $V_1 + V_2 = 0$

    where $V_1 = \dfrac{2V_m}{\pi}\cos\alpha_{a1}$ and $V_2 = \dfrac{2V_m}{\pi}\cos\alpha_{a2}$

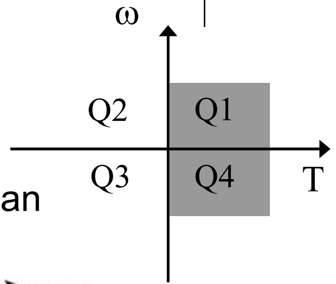
    (V_m = peak supply voltage)
  - Hence, firing angles of both converters must satisfy the following:

$$\boxed{\alpha_{a1} + \alpha_{a2} = \pi}$$

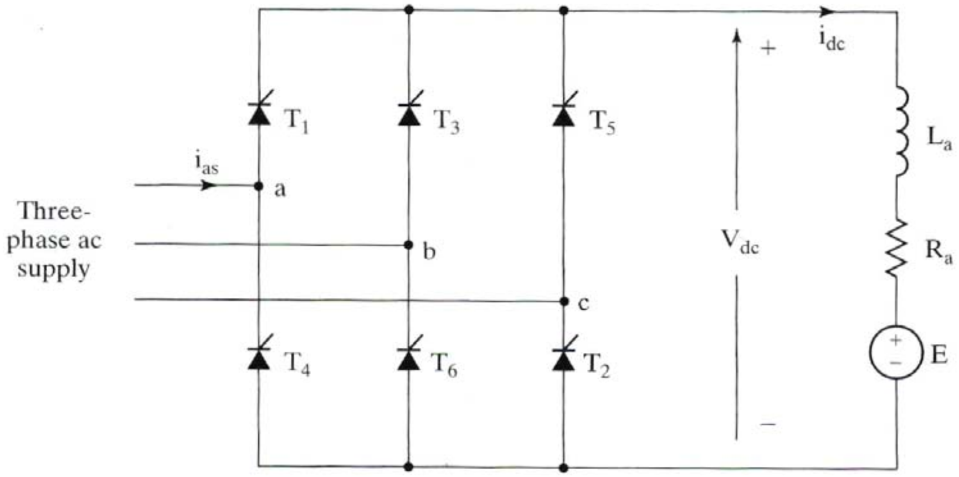


  - Armature current $I_a = \dfrac{V_a - E_a}{R_a}$
  - Field voltage $V_f = \dfrac{2V_m}{\pi}\cos\alpha_f$

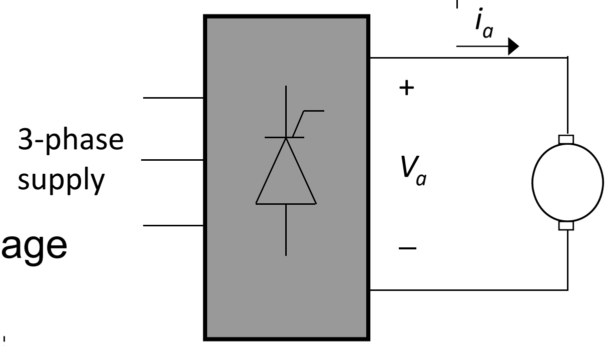
Controlled Rectifier Three-Phase DC Drives



- **Two-quadrant drive**
- Limited to applications up to 1500 kW
- Regeneration (Q4) only be achieved with loads that can drive the motor in reverse (-ve ω)



Controlled Rectifier Three-Phase DC Drives



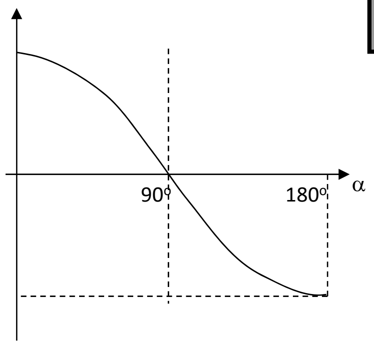
Armature voltage

$$V_a = \frac{3V_{\text{L-L},\,m}}{\pi}\cos\alpha_a$$

where $V_{\text{L-L},\,m}$ = peak line-to-line voltage

Armature current

$$I_a = \frac{V_a - E_a}{R_a}$$



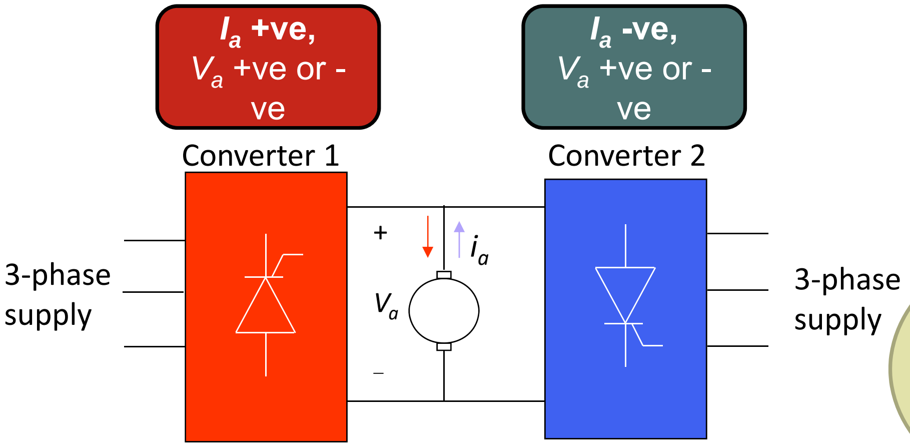
Field voltage

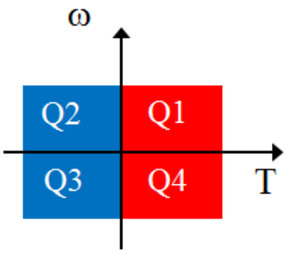
$$V_f = \frac{3V_{\text{L-L},\,m}}{\pi}\cos\alpha_f$$

(assuming a three-phase supply is used for field excitation)

Controlled Rectifier Three-Phase DC Drives

- **Four-quadrant drive**
- Converter 1 for operation in 1st and 4th quadrant
- Converter 2 for operation in 2nd and 3rd quadrant

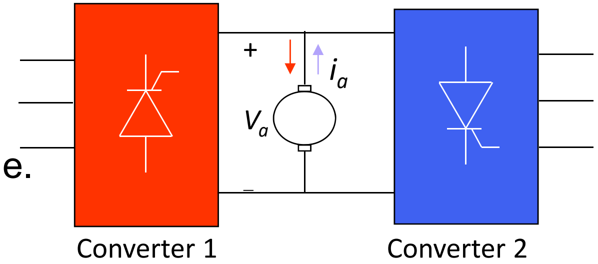




Two rectifiers connected in **anti-parallel** across motor armature

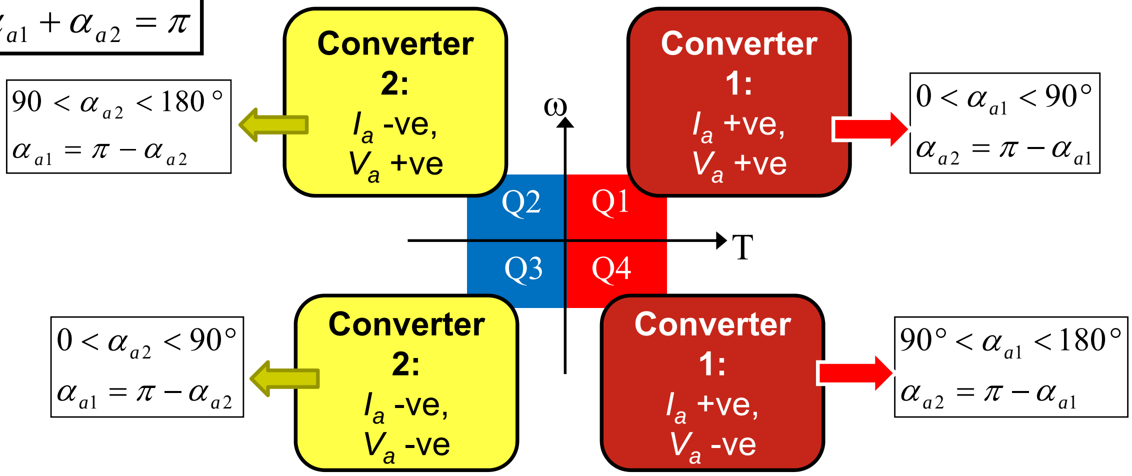
Controlled Rectifier Three-Phase DC Drives

$$\boxed{V_a = \frac{3V_{L-L,m}}{\pi}\cos\alpha_a}$$



where $V_{L\text{-}L,\,m}$ = peak line-to-line voltage.
Similar to single-phase drive:

$$\boxed{\alpha_{a1}+\alpha_{a2}=\pi}$$



Converter 2: I_a -ve, V_a +ve

$90 < \alpha_{a2} < 180°$
$\alpha_{a1} = \pi - \alpha_{a2}$

Converter 1: I_a +ve, V_a +ve

$0 < \alpha_{a1} < 90°$
$\alpha_{a2} = \pi - \alpha_{a1}$

Converter 2: I_a -ve, V_a -ve

$0 < \alpha_{a2} < 90°$
$\alpha_{a1} = \pi - \alpha_{a2}$

Converter 1: I_a +ve, V_a -ve

$90° < \alpha_{a1} < 180°$
$\alpha_{a2} = \pi - \alpha_{a1}$

Controlled Rectifier Three-Phase DC Drives

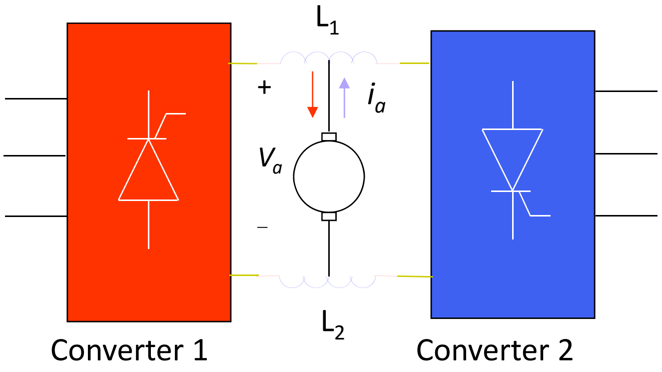
For **continuous current**:

Armature current $I_a = \dfrac{V_a - E_a}{R_a}$

Field voltage $V_f = \dfrac{3V_{L\text{-}L,\,m}}{\pi}\cos\alpha_f$

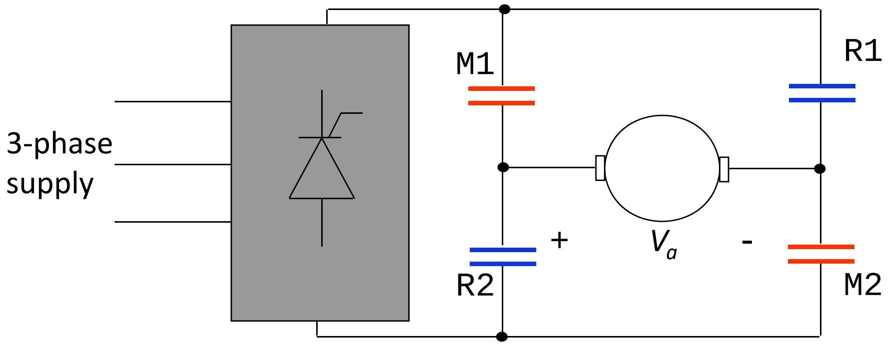
Disadvantages:

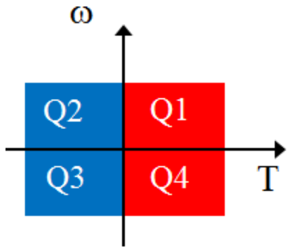
- ❑ Circulating current (Inductors L_1 and L_2 added to reduce circulating currents)
- ❑ Slow response



Controlled Rectifier Three-Phase DC Drives

- **Four-quadrant drive using one rectifier**
- One controlled rectifier with 2 pairs of contactors
- M1 and M2 closed for operation in 1st and 4th quadrant
- R1 and R2 closed for operation in 2nd and 3rd quadrant





Rectifier DC Drives Problems

1. Distortion of Supply
   - Controlled rectifier introduces harmonics to supply currents and voltages which cause:

     (a) heating and torque pulsations in motor

     (b) resonance in power system network – interaction between rectifier RL with capacitor banks in system
   - Solution - eliminate most dominant harmonics by:

     (a) install LC filters at input of converters – tuned to absorb most dominant harmonics (i.e. 5th and 7th harmonics)

     (b) Use 12-pulse converter – consists of two 6-pulse inverters connected in parallel

     (c) Selective switching of supply input using self-commutating devices (e.g., GTOs and IGBTs)

Rectifier DC Drives Problems

2. Low supply power factor
   - Power factor related to firing angle α of rectifier
   - Low power factor especially during low speed operations
   - Solution:

     Employ pulse-width modulated (PWM) rectifiers using GTOs, IGBTs
     - High power factor
     - Low harmonic supply currents
     - Low efficiency - high switching losses (disadvantage)

Rectifier DC Drives Problems

3. Effect on motor
   - Ripple in motor current – harmonics present (most dominant is 6th harmonic)

     (a) causes torque ripple, heating and derating of motor

     solution: extra inductance added in series with L_a
   - Slow response
   - Discontinuous current may occur if

     (a) L_a not large enough

     (b) Motor is lightly loaded
   - Effect of discontinuous current

     (a) Rectifier output voltage increases $\Rightarrow$ motor speed increases

     (poor speed regulation under open-loop operation)

DC-DC Converter DC Drives

Self-commutated devices are preferred (e.g., MOSFETs, IGBTs, GTOs) over thyristors <u>because</u>

- ❑ Commutated by lower power control signal
- ❑ Commutation circuit not needed
- ❑ Can be switched at higher frequency for same rating → Improved motor performance (less ripple, no discontinuous currents, increased control bandwidth) and Suitable for high performance applications
- ❑ Regenerative braking possible up to very low speeds even when fed from fixed DC voltage source

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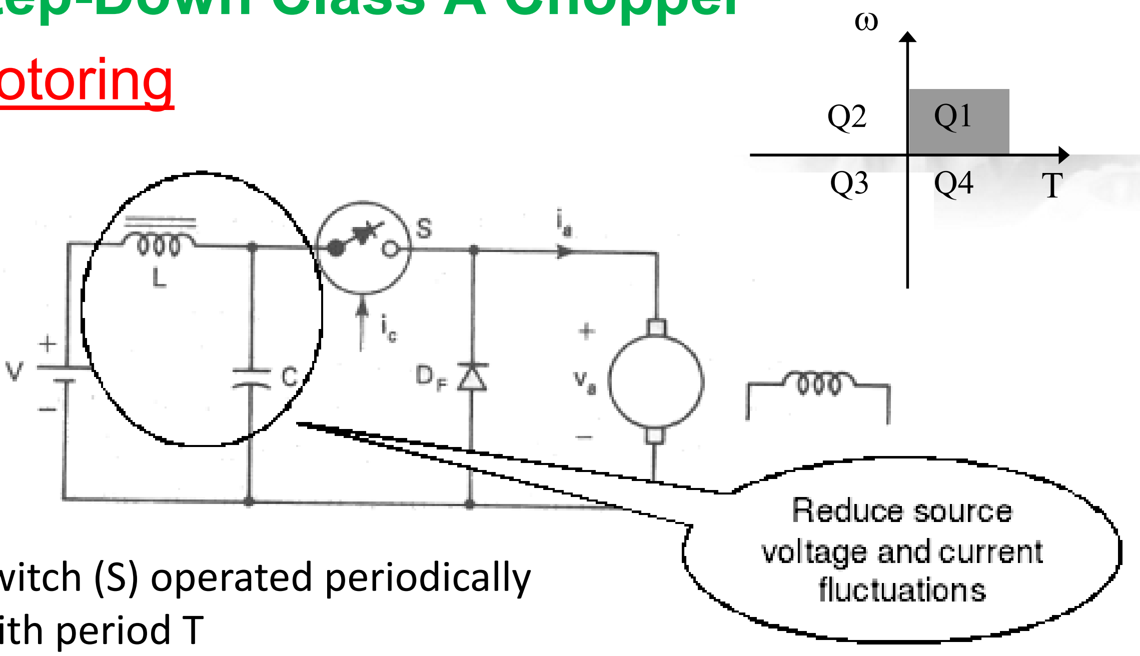
DC-DC Converter DC Drives

Step-Down Class A Chopper

<u>Motoring</u>



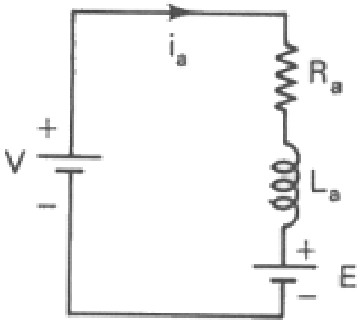
Switch (S) operated periodically with period T

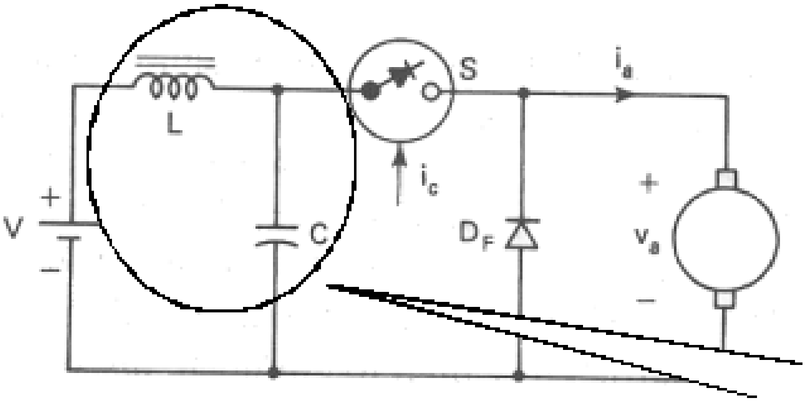
DC-DC Converter DC Drives

Step-Down Class A Chopper

Motoring

S is ON ($0 \le t \le t_{on}$)





$$R_a i_a + L_a \frac{di_a}{dt} + E \; = V$$

- V_a = V
- I_a flows to motor
- $|I_a|$ increases

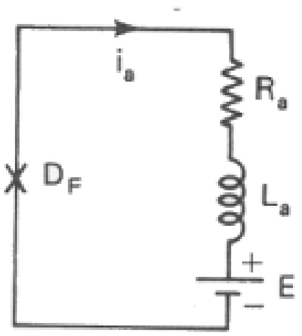
Duty Interval ($i_a \uparrow$)

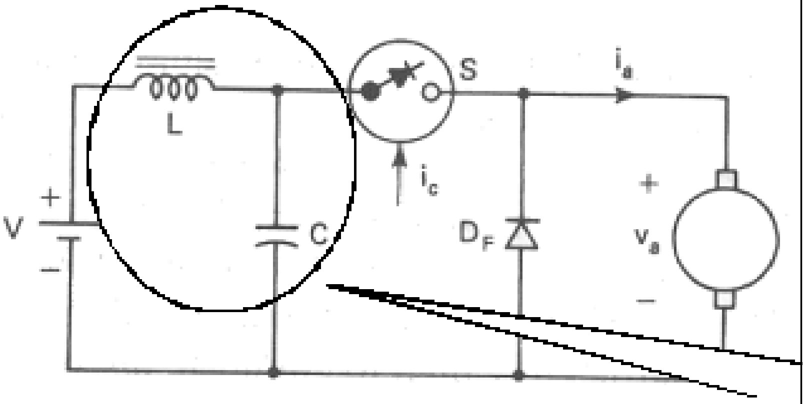
DC-DC Converter DC Drives

Step-Down Class A Chopper

Motoring

S if OFF ($t_{on} \le t \le T$)





$$R_a i_a + L_a \frac{di_a}{dt} + E \; = 0$$

- V_a = 0
- I_a freewheels through diode D_F
- $|I_a|$ decreases

Freewheeling Interval ($i_a \downarrow$)

DC-DC Converter DC Drives

Step-Down Class A Chopper

Motoring

- Duty cycle $\boxed{\delta = \frac{t_{on}}{T} \text{ where } T = \text{chopper period}}$
- Under steady-state conditions:

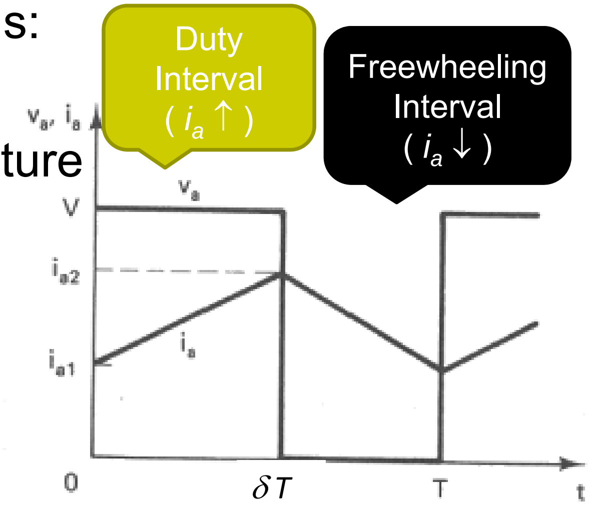
  Motor side: $V_a = R_a I_a + E$

  Chopper side, average armature voltage: $V_a = \delta V$ Therefore,

$$\boxed{\delta V = V_a = R_a I_a + E}$$

- Average armature current:

$$\boxed{I_a = \frac{\delta V - E}{R_a}}$$


Duty Interval ($i_a \uparrow$)

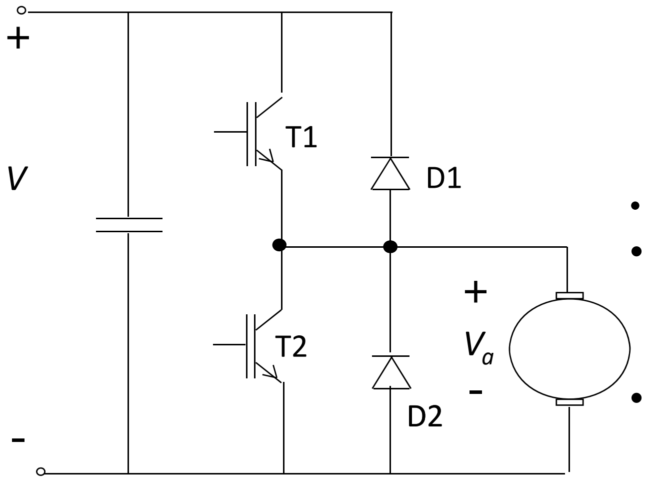
Freewheeling Interval ($i_a \downarrow$)

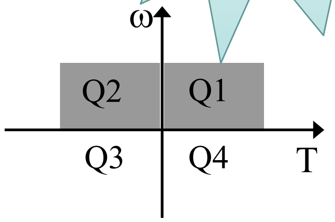
DC-DC Converter DC Drives

Two Quadrant Control

- Combination of Class A & B choppers
- Forward motoring **Q1 - T1 and D2 (Class A)**
- Forward braking **Q2 – T2 and D1 (Class B)**

No Speed Reversal





- V_a always +ve ⇒ ω always +ve
- **T1 and T2 turned on alternately**

  ⇒ if T1 on, T2 off

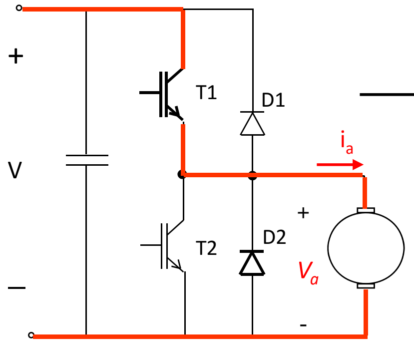
  ⇒ if T1 off, T2 on
- **Do not fire both switches together** ⇒ short circuit at supply

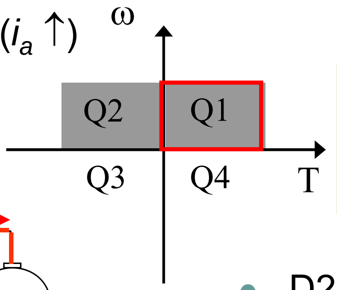
DC-DC Converter DC Drives

Two Quadrant Control

Forward motoring Q1 - T1 and D2 (Class A)

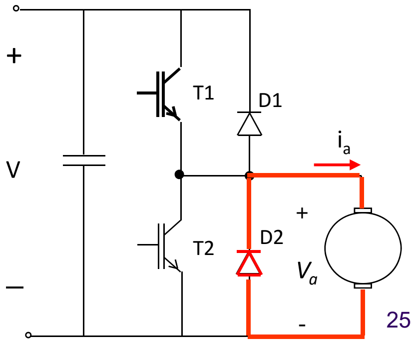
- T1 conducting: $V_a = V$ (i_a ↑)



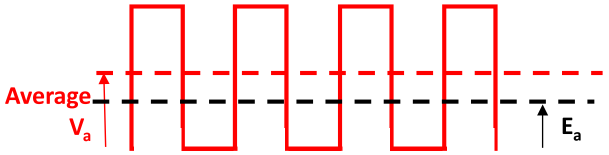


•Average V_a positive
•Average V_a made **larger** than back emf E_a
•I_a positive

- D2 conducting: $V_a = 0$ (i_a ↓)



Average $V_a = \delta V$,
$\delta = (t_{on\ T1} / T)$

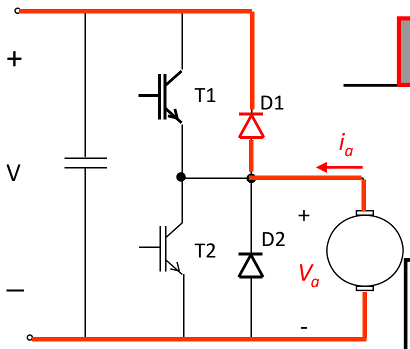


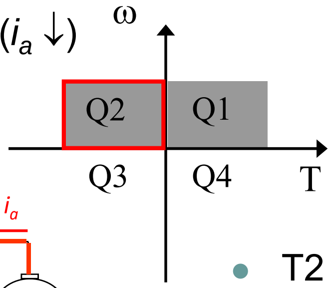
DC-DC Converter DC Drives

Two Quadrant Control

Forward braking Q2 – T2 and D1 (Class B)

- D1 conducting: $V_a = V$ (i_a ↓)

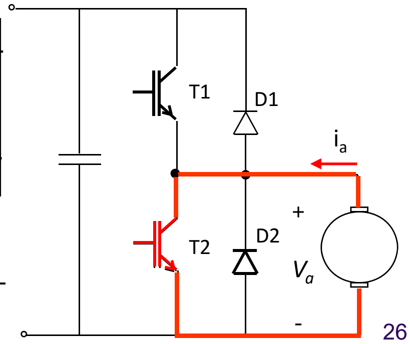


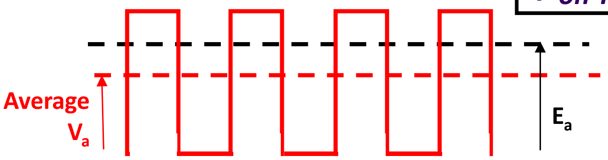


•Average V_a positive
•Average V_a made **smaller** than back emf E_a
•I_a negative (motor acts as generator)

- T2 conducting: $V_a = 0$ (i_a ↑)

Average $V_a = \delta V$,
$\delta = (t_{off\ T2} / T) = (t_{on\ T1} / T)$

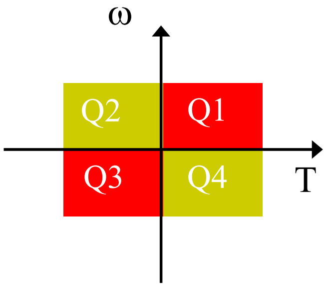


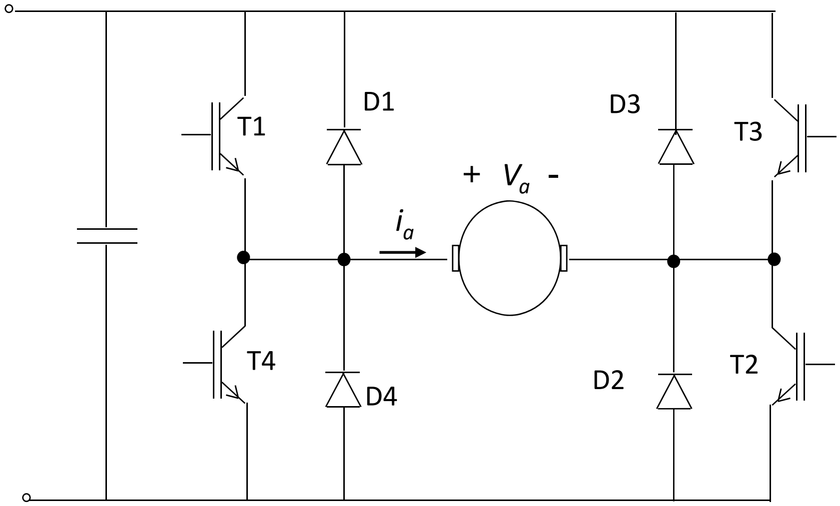


DC-DC Converter DC Drives

Four Quadrant Control

- Operation in all quadrants
- Speed can be reversed





Note:
Polarity of V_a and direction of I_a indicated are assumed positive.

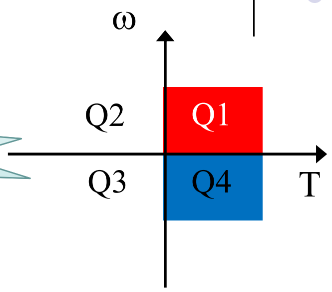
DC-DC Converter DC Drives

Four Quadrant Control

Forward Motoring Q1

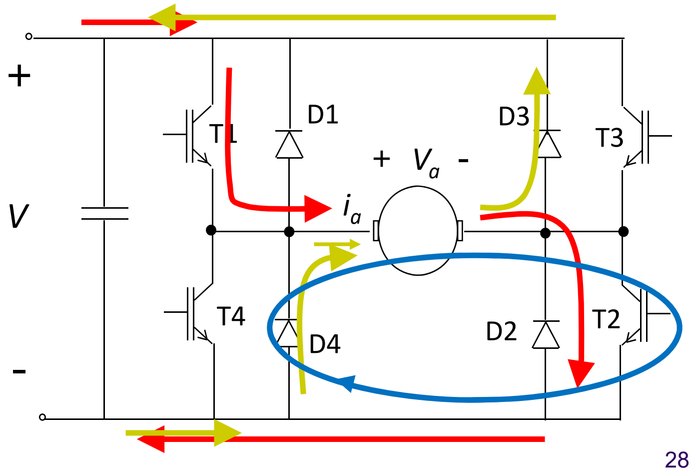
- T1 and T2 on
  - $V_a = V$
  - I_a increases

T3 and T4 off



Reverse Braking Q4 (Regeneration)

- T1 off but T2 still on
  - $V_a = 0$
  - I_a decays thru T2 and D4
- T1 and T2 off
  - $V_a = -V$
  - I_a decays thru D3 and D4
  - Energy returned to supply



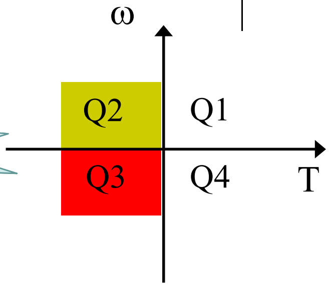
DC-DC Converter DC Drives

Four Quadrant Control

Reverse Motoring Q3

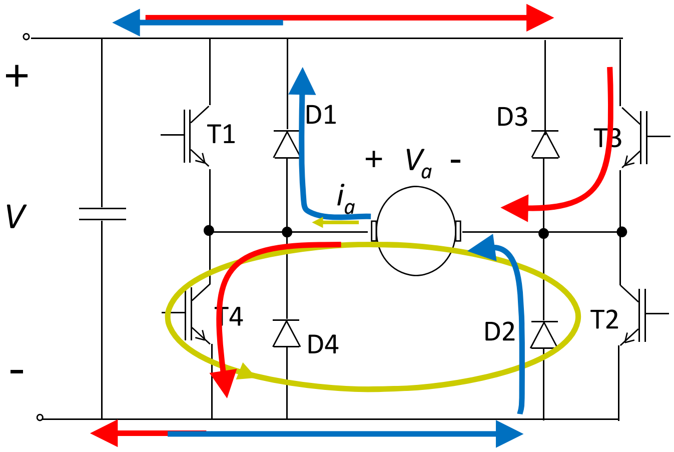
- T3 and T4 on
  - $V_a = -V$
  - I_a increases in reverse direction

T1 and T2 off



Forward Braking Q2 (Regeneration)

- T3 off but T4 still on
  - $V_a = 0$
  - I_a decays thru T4 and D2
- T3 and T4 off
  - $V_a = V$
  - I_a decays thru D1 and D2
  - Energy returned to supply



AC Motor Drives

By

Dr. Mohammad Salah

Mechatronics Engineering Department
The Hashemite University

Introduction – Induction Motors

- Induction motors (IM) mainly used in applications requiring constant speed.
- Conventional speed control of IM expensive or highly inefficient.
- IM drives replace DC drives in a number of variable speed applications due to:
  - ❑ Improvement in power devices capabilities
  - ❑ Reduction in cost of power devices

Introduction – Induction Motors

- Motor stator is supplied by balanced 3-phase AC source (frequency f [Hz] or ω [rad/sec])
- Magnetic field is produced and rotates at synchronous speed ω_s [rad/sec]

$$\boxed{\omega_s = \frac{2}{P}\omega = \frac{4}{P}\pi f} \qquad \boxed{n_s = \frac{120}{P} f}$$

where P = number of poles

- Rotor rotates at speed ω_m [rad/sec]
- Slip speed, ω_{sl} – relative speed between rotating field and rotor.

$$\boxed{\omega_{sl} = \omega_s - \omega_m}$$

Introduction – Induction Motors

- Slip, *s* – ratio between slip speed and synchronous speed

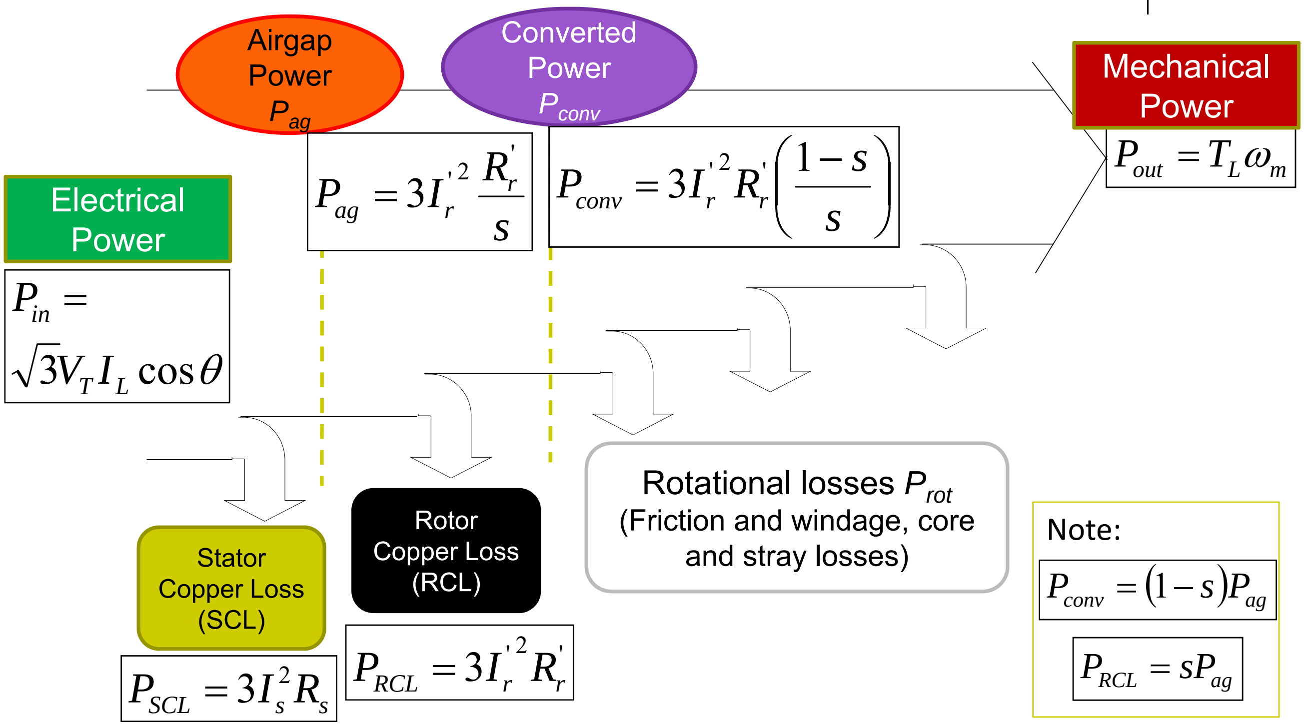
$$\boxed{s = \frac{\omega_s - \omega_m}{\omega_s}}$$

- Frequency of rotor voltages and currents:

$$\boxed{f_r = sf}$$

- Torque is produced due to interaction between rotor magnetic field (due to induced current) and stator magnetic field

Introduction – Power Flow



Electrical Power

$$P_{in} = \sqrt{3} V_T I_L \cos\theta$$

Airgap Power P_{ag}

$$P_{ag} = 3 I_r'^2 \frac{R_r'}{s}$$

Converted Power P_{conv}

$$P_{conv} = 3 I_r'^2 R_r' \left(\frac{1-s}{s} \right)$$

Mechanical Power

$$P_{out} = T_L \omega_m$$

Stator Copper Loss (SCL)

$$P_{SCL} = 3 I_s^2 R_s$$

Rotor Copper Loss (RCL)

$$P_{RCL} = 3 I_r'^2 R_r'$$

Rotational losses P_{rot} (Friction and windage, core and stray losses)

Note:

$$P_{conv} = (1-s) P_{ag}$$

$$P_{RCL} = s P_{ag}$$

Introduction – Power Flow

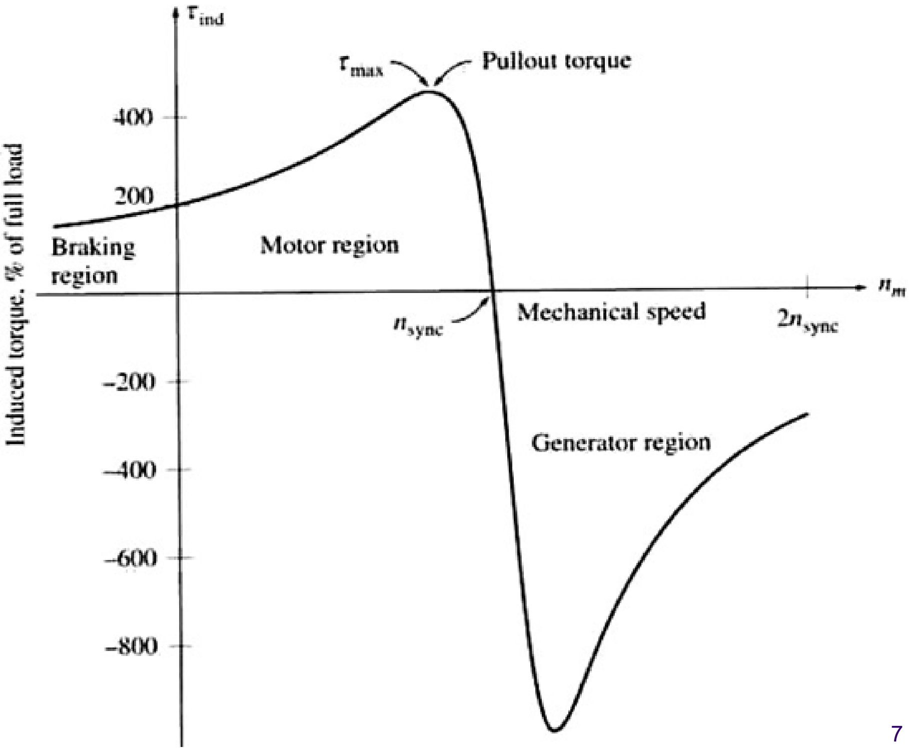
- Motor induced torque is related to converted power by:

$$T_m = \frac{P_{conv}}{\omega_m}$$

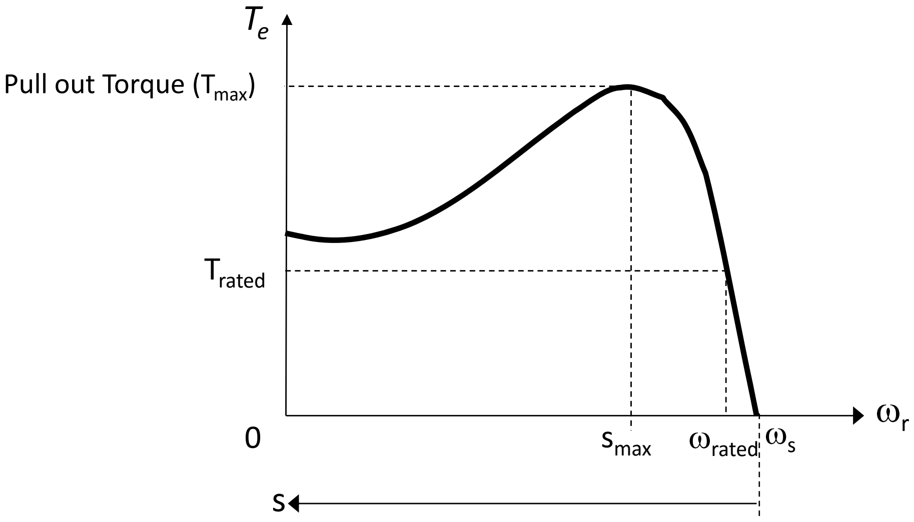
- Note that $P_{conv} = (1-s) P_{ag}$ and $\omega_r = (1-s)\omega_s$

Introduction – Characteristic Curve

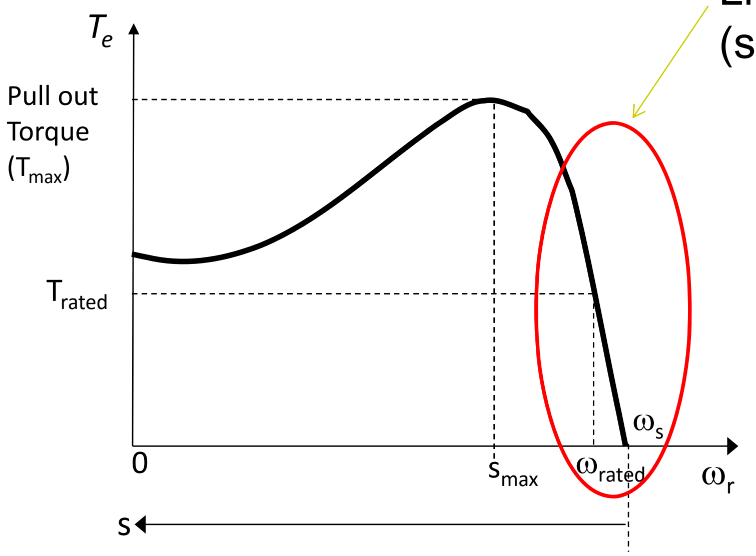
T-ω characteristic of IM during generating, motoring, and braking



Introduction – Characteristic Curve



Introduction – Characteristic Curve



Linear region of operation (small s)

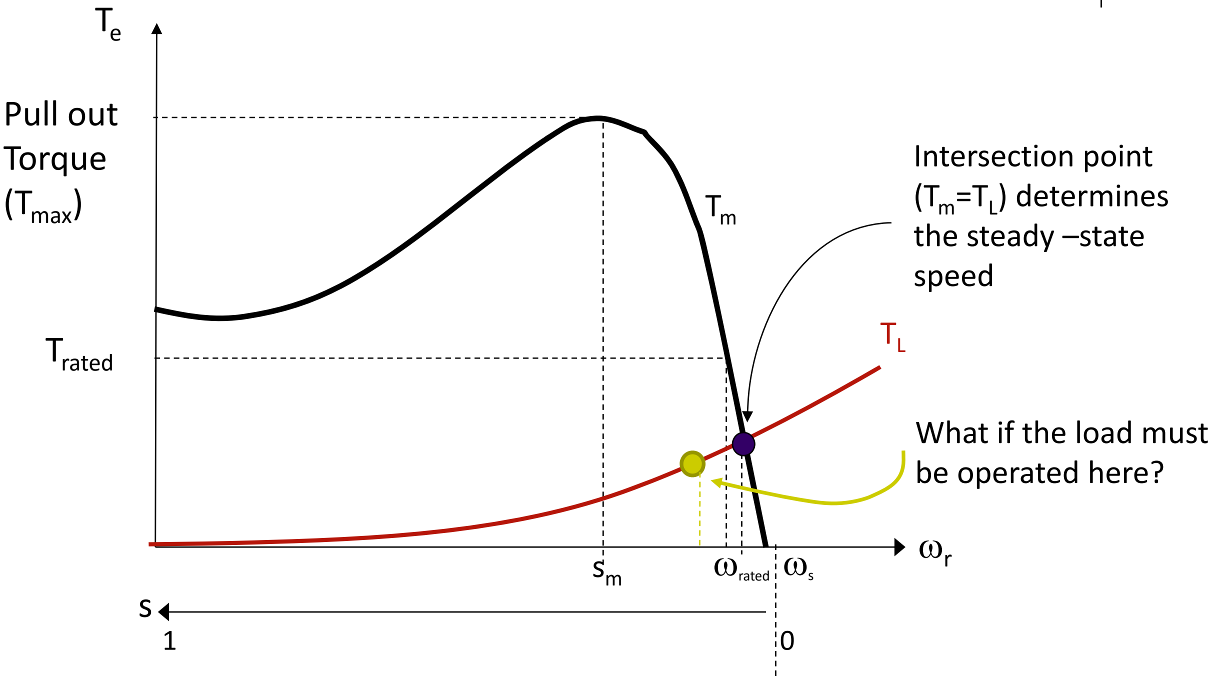
$T_e \propto s$

High efficiency

- $P_{out} = P_{conv} - P_{rot}$
- $P_{conv} \uparrow = (1- s\downarrow)P_{ag}$

Stable motor operation

Speed Control

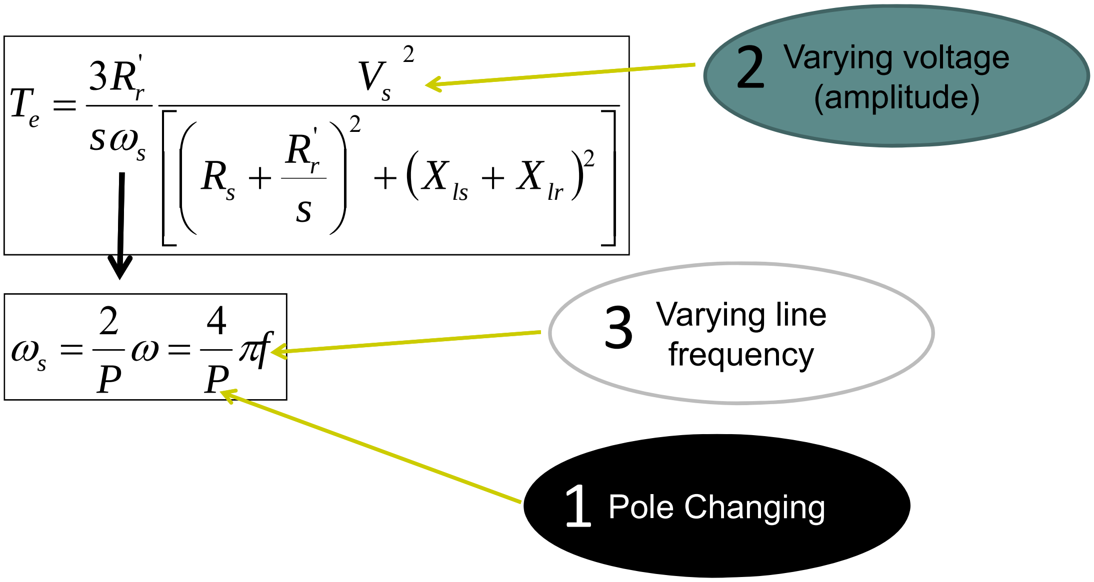


Intersection point (T_m=T_L) determines the steady –state speed

What if the load must be operated here?

Speed Control

Given a load T–ω characteristic, the steady-state speed can be changed by **altering the T–ω curve** of the motor



$$T_e = \frac{3R_r'}{s\omega_s}\frac{V_s^{\,2}}{\left[\left(R_s+\frac{R_r'}{s}\right)^2+\left(X_{ls}+X_{lr}\right)^2\right]}$$

$$\omega_s = \frac{2}{P}\omega = \frac{4}{P}\pi f$$

2 Varying voltage (amplitude)

3 Varying line frequency

1 Pole Changing

Speed Control

Pole Changing

- Machines must be specially manufactured (i.e. called pole changing motors or multi-speed motors)

- Need special arrangement of stator windings

- Only used with squirrel-cage motors (because number of poles induced in squirrel cage rotor will follow number of stator poles) and this method is expensive

Speed Control

Variable Voltage (Amp) - Constant Frequency

Controlled using:

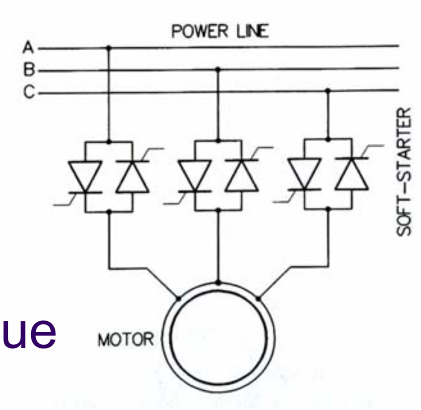
1. Transformer (rarely used)
2. Thyristor voltage controller
   - ❑ Thyristors connected in anti-parallel (motor can be star or delta connected)
   - ❑ Voltage control by firing angle control (gating signals are synchronized to phase voltages and are spaced at 60° intervals)
   - ❑ Only for operations in Quadrant 1 and Quadrant 3 (requires reversal of phase sequence)
   - ❑ Also used in soft starts

Speed Control

Variable Voltage (Amp) - Constant Frequency

From torque equation

$T_m \propto V_s^2$ hence $V_s \downarrow$, T_m and speed reduce.



Suitable for applications where torque demand reduces with speed

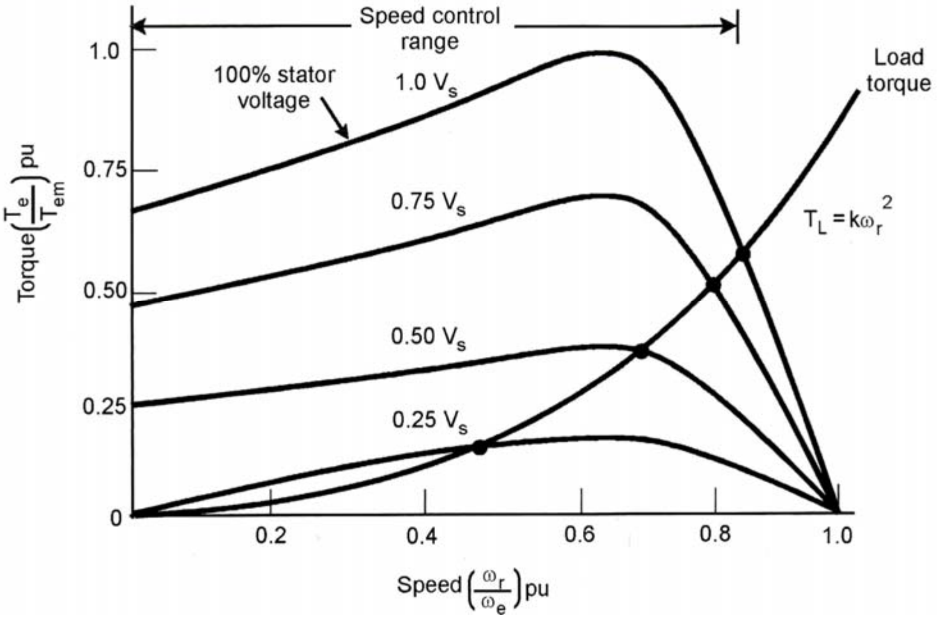
(e.g.: fan and pump drives where $T_L \propto \omega_m^2$)

Suitable for high-slip, high R_r type motors (High rotor copper loss, low efficiency motors)

Speed Control

Variable Voltage (Amp) - Constant Frequency

If terminal voltage is reduced to (bV_s) where $b \leq 1$



Speed Control

Variable Voltage (Amp) - Constant Frequency

<u>Disadvantages:</u>

- limited speed range ⇒ when applied to low-slip motors
- Excessive stator currents at low speeds ⇒ high copper losses
- Distorted phase current in machine and line (harmonics introduced by thyristor switching)
- Poor line power factor (power factor proportional to firing angle). Hence, only used on low-power, appliance-type motors where efficiency is not important (e.g. small fan or pumps drives)

Speed Control

Variable Frequency

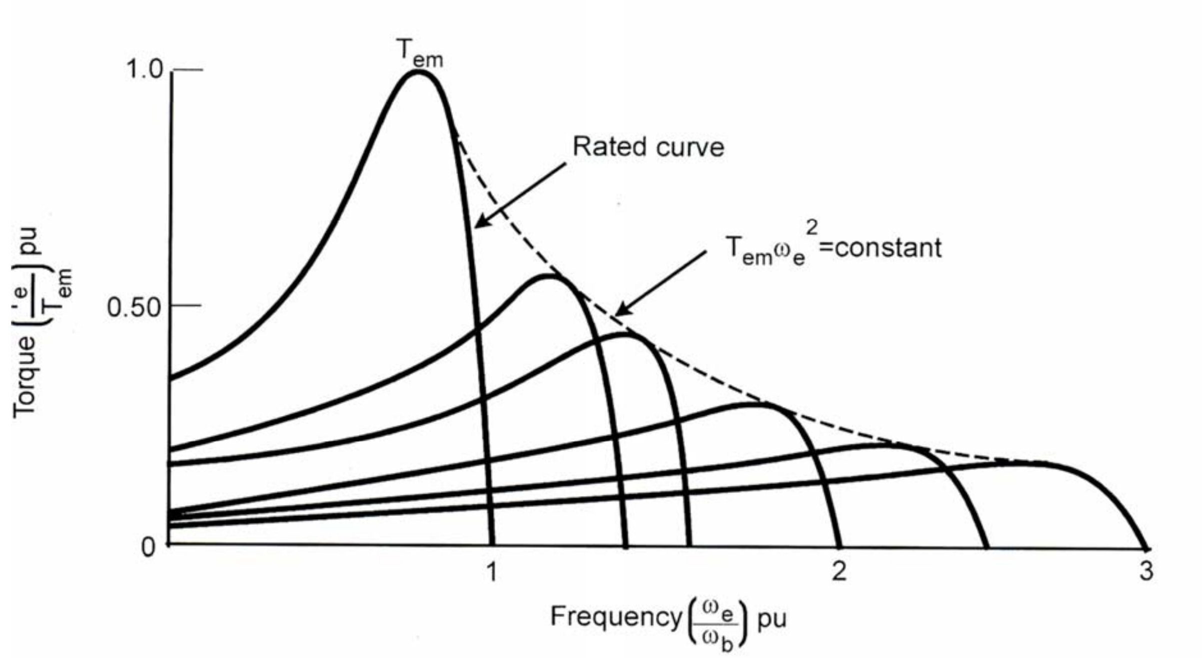
Speed control above rated (base) speed

- Requires the use of PWM inverters to control frequency of motor
- Frequency increased (i.e. ω_s increased)
- Stator voltage held constant at rated value
- Airgap flux and rotor current decreases
- Developed torque decreases $T_e \propto (1/\omega_s)$

For control below base speed – use Constant Volts/Hz method

Speed Control

Variable Frequency



Speed Control

Constant V/f [Volts/Hz] Control

Airgap flux in the motor is related to the induced stator voltage

$$\varphi_{ag} \approx \frac{V_s}{f}$$

Assuming **small** voltage drop across R_s and L_s

For **below base speed** operation, frequency reduced at rated V_s - airgap flux saturates ($f \downarrow$, $i_s \uparrow$,$\phi_{ag} \uparrow$ and enters saturation region of B-H curve):

- excessive stator currents flow
- distortion of flux wave
- increase in core losses and stator copper loss

Speed Control

Constant V/f [Volts/Hz] Control

Need to keep ϕ_{ag} **= rated flux = constant,** Hence, stator voltage V_s must be reduced proportional to reduction in f (*i.e.* maintaining V_s / f ratio to a constant value)

Speed Control

Constant V/f [Volts/Hz] Control

Max. torque remains almost constant

$$\phi_{ag} = \frac{E_1}{f} \neq \frac{V_s}{f}$$

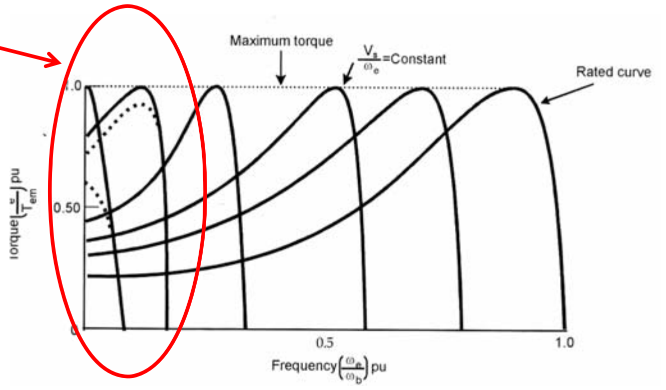
$$\boxed{T_{\max} \propto \frac{V_s}{\omega_s}^2}$$

For **low speed** operation:

- can't ignore voltage drop across R_s and L_{ls} (i.e. $E_1 \neq V_s$)
- poor torque capability (i.e. torque decreased at low speeds shown by dotted lines)
- stator voltage must be boosted – to compensate for voltage drop at R_s and L_{ls} and maintain constant ϕ_{ag}

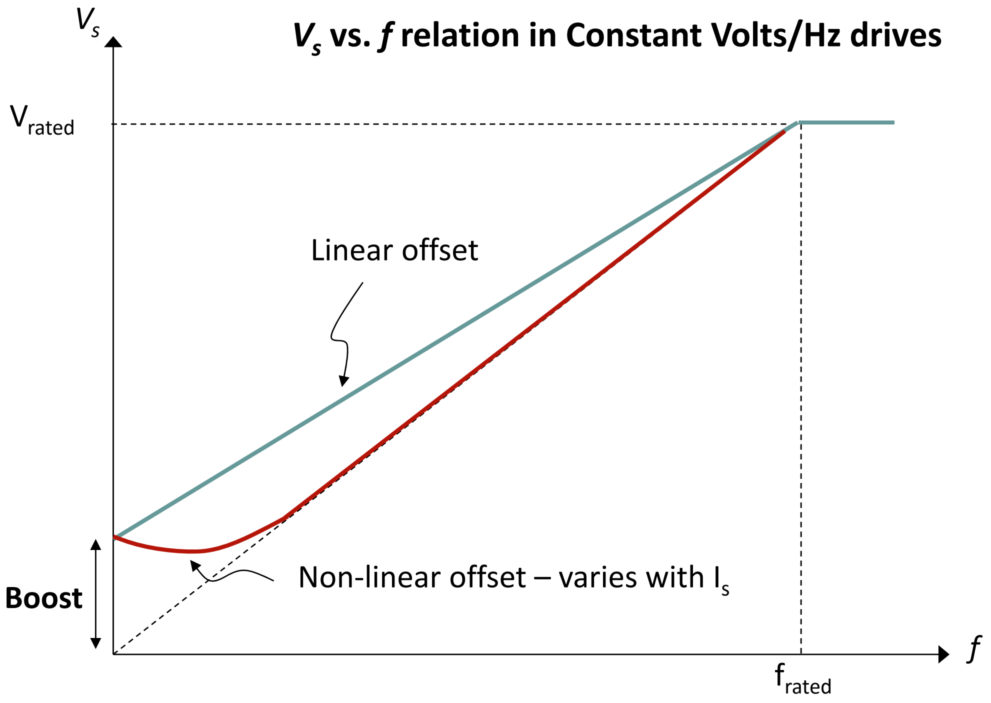
For **above base speed** operation ($f > f_{rated}$):

- stator voltage maintained at rated value
- Same as **Variable Frequency** control



Speed Control

Constant V/f [Volts/Hz] Control



Boost - to compensate for voltage drop at R_s and L_{ls}

Linear offset curve –

- for high-starting torque loads
- **employed for most applications**

Non-linear offset curve –

- for **low-starting torque loads**

Speed Control

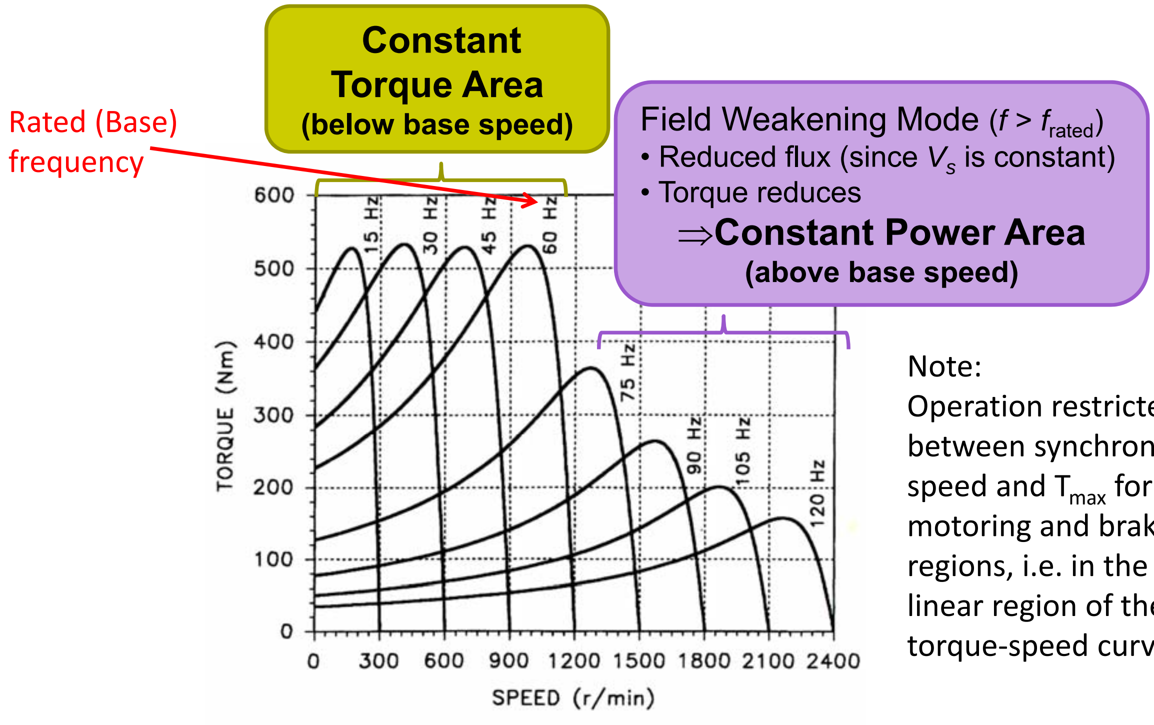
Constant V/f [Volts/Hz] Control

- For **operation at frequency *K* times rated frequency:**
  - $f_s = Kf_{s,\text{rated}} \Rightarrow \omega_s = K\omega_{s,\text{rated}}$
    (Note: speed is given as mechanical speed)
  - Stator voltage: $\boxed{V_s = \begin{cases} KV_{s,\text{rated}}, & \text{when } f_s < f_{s,\text{rated}} \\ V_{s,\text{rated}}, & \text{when } f_s > f_{s,\text{rated}} \end{cases}}$
  - Voltage-to-frequency ratio = *d* = constant

$$\boxed{d = \frac{V_{s,\text{rated}}}{\omega_{s,\text{rated}}}}$$

Speed Control

Constant V/f [Volts/Hz] Control



Rated (Base) frequency

Constant Torque Area (below base speed)

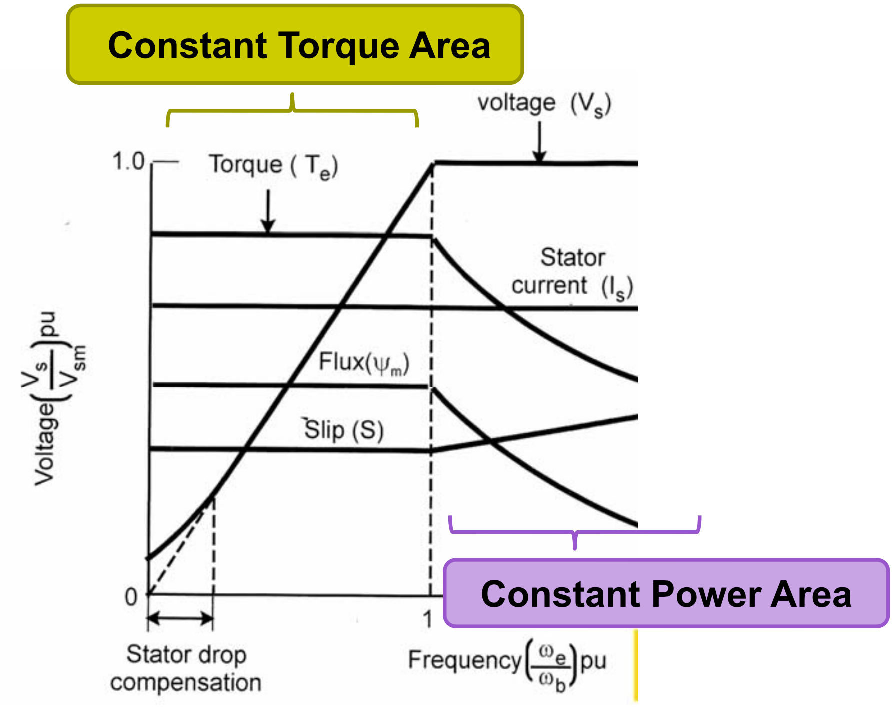
Field Weakening Mode ($f > f_{\text{rated}}$)
- Reduced flux (since V_s is constant)
- Torque reduces

$\Rightarrow$Constant Power Area (above base speed)

Note:
Operation restricted between synchronous speed and $T_{\max}$ for motoring and braking regions, i.e. in the linear region of the torque-speed curve.

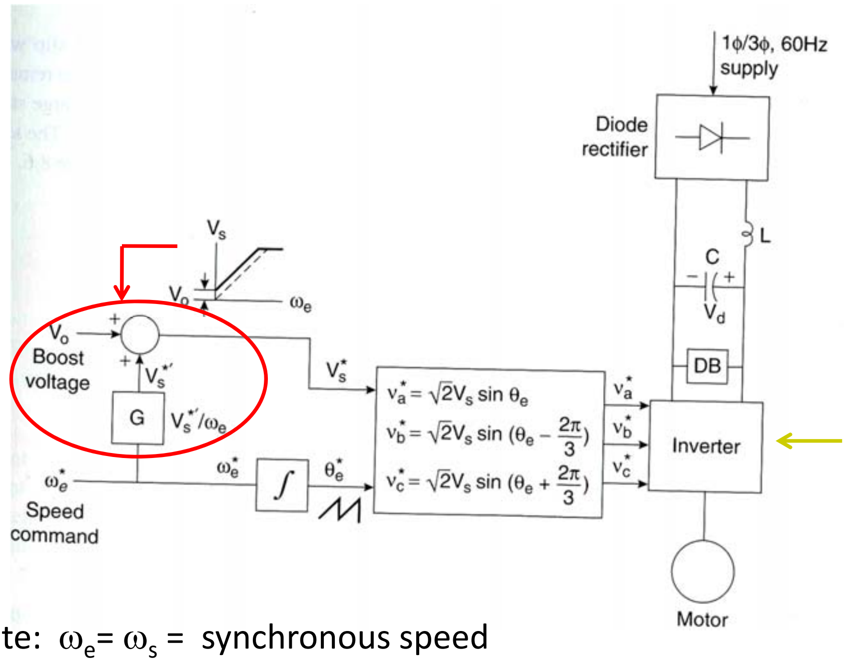
Speed Control

Constant V/f [Volts/Hz] Control



Speed Control

Constant V/f [Volts/Hz] Control – <u>Open Loop</u>



PWM
Voltage-Source
Inverter
(VSI)

Note: $\omega_e = \omega_s =$ synchronous speed

Speed Control

Constant V/f [Volts/Hz] Control – Open Loop

- Most popular speed control method because it is easy to implement
- Used in low-performance applications where precise speed control unnecessary
- Speed command ω_s^* - primary control variable
- Phase voltage command V_s^* generated from V/f relation (shown as the 'G')
  - ➢ Boost voltage V_o is added at low speeds
  - ➢ Constant voltage applied above base speed

Speed Control

Constant V/f [Volts/Hz] Control – Open Loop

- Sinusoidal phase voltages (v_{abc}^*) is then generated from V_s^* & Θ_s^* where Θ_s^* is obtained from the integral of ω_s^*
- v_{abc}^* employed in PWM inverter connected to motor

Speed Control

Constant V/f [Volts/Hz] Control – Open Loop

Problems in open-loop drive operation:

1. Motor speed is not controlled precisely
   - primary control variable is synchronous speed ω_s
   - actual motor speed ω_r *is* less than ω_s due to ω_{sl}
   - ω_{sl} depends on load connected to motor
2. ω_{sl} cannot be maintained since ω_r not measured
   - can lead to operation in unstable region of T-ω characteristic
   - stator currents can exceed rated value – endangering inverter-converter combination

---

Speed Control

Constant V/f [Volts/Hz] Control – Open Loop

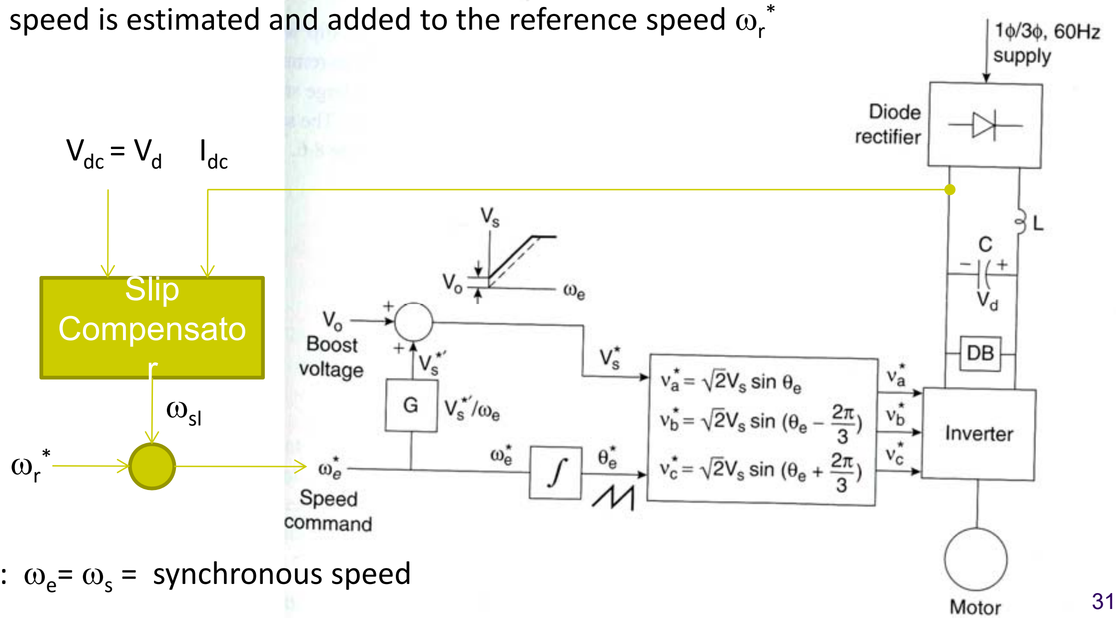
Problems (to an extent) can be overcome by:

1. Open-loop Constant Volts/Hz Drive with Slip Compensation
2. Closed-loop implementation - having outer speed loop with slip regulation

Speed Control

Constant V/f [Volts/Hz] Control – <u>Open Loop with slip compensation</u>

- Slip speed is estimated and added to the reference speed ω_r^*



Note: $\omega_e = \omega_s =$ synchronous speed

Speed Control

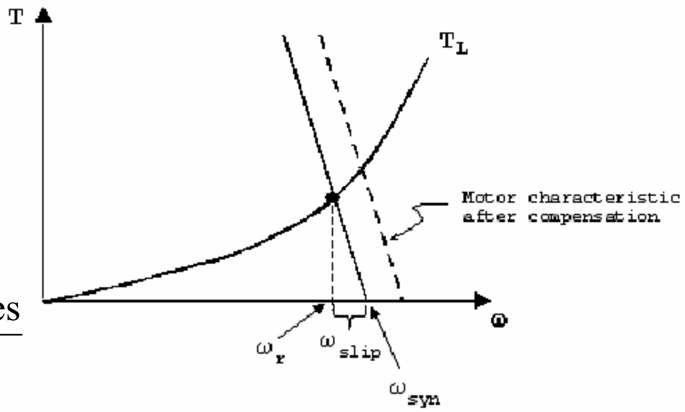
Constant V/f [Volts/Hz] Control – <u>Open Loop with slip compensation</u>

- How is ω_{sl} estimated in the Slip Compensator?
- Using T-ω curve, $\omega_{sl} \propto T_e$
- ω_{sl} can be estimated by estimating torque where:

$$T_e = \frac{P_{ag}}{\omega_s} = \frac{P_{in} - P_{SCL} - \text{inverter losses}}{\omega_s}$$

$$P_{in} = V_{dc} I_{dc}$$

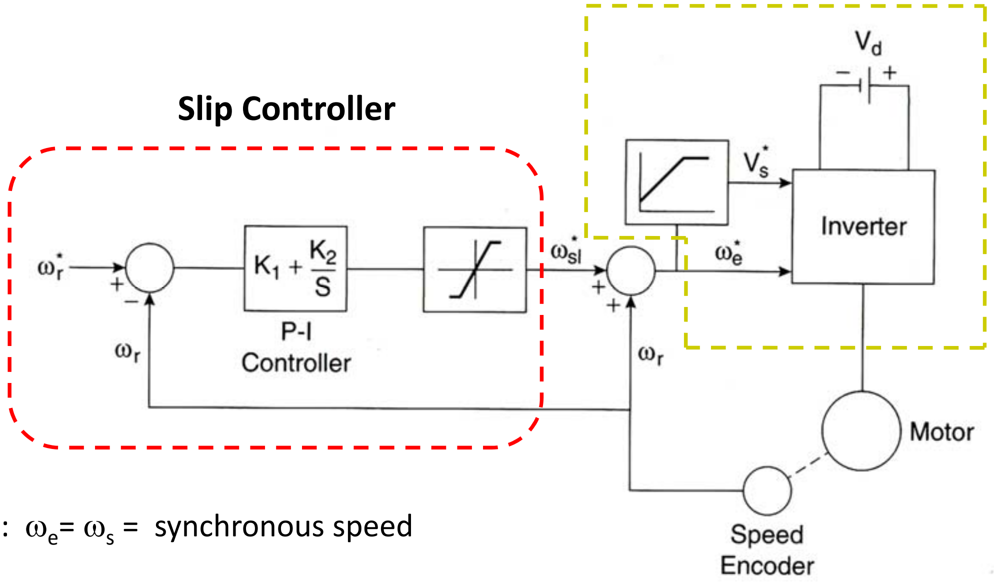
$$\omega_{sl} = \left(\frac{T_e}{T_{e,rated}} \right) \omega_{sl,rated}$$



Note: In the figure,
$\omega_{slip} = \omega_{sl} =$ slip speed
$\omega_{syn} = \omega_s =$ synchronous speed

Speed Control

Constant V/f [Volts/Hz] Control – Closed Loop


Open-loop system
(as in slide 23)

Slip Controller

Note: $\omega_e = \omega_s =$ synchronous speed

Speed Control

Constant V/f [Volts/Hz] Control – Closed Loop

- Reference motor speed ω_r^* is compared to the actual speed ω_r to obtain the speed loop error
- Speed loop error generates slip command ω_{sl}^* from PI controller and limiter (Limiter ensures that the ω_{sl}^* is kept within the allowable slip speed of the motor (i.e. $\omega_{sl}^* \leq$ slip speed for maximum torque))
- ω_{sl}^* is then added to the actual motor speed ω_r to generate synchronous speed command ω_s^* (or frequency
- ω_s^* generates voltage command V_s^* from V/f relation

1. Boost voltage is added at low speeds
2. Constant voltage applied above base speed

- Scheme can be considered open loop torque control (since $T \propto s$) within speed control loop heater element and overload contacts. Under normal conditions, the overload contacts are shut. However, when the temperature of the heater elements rises far enough, the OL contacts open, deenergizing the M relay, which in turn opens the normally open M contacts and removes power from the motor.

When an induction motor is overloaded, it is eventually damaged by the excessive heating caused by its high currents. However, this damage takes time, and an induction motor will not normally be hurt by brief periods of high currents (such as starting currents). Only if the high current is sustained will damage occur. The overload heater elements also depend on heat for their operation, so they will not be affected by brief periods of high current during starting, and yet they will operate during long periods of high current, removing power from the motor before it can be damaged.

Undervoltage protection is provided by the controller as well. Notice from the figure that the control power for the M relay comes from directly across the lines to the motor. If the voltage applied to the motor falls too much, the voltage applied to the M relay will also fall and the relay will deenergize. The M contacts then open, removing power from the motor terminals.

An induction motor starting circuit with resistors to reduce the starting current flow is shown in Figure 7–38. This circuit is similar to the previous one, except that there are additional components present to control removal of the starting resistor. Relays 1TD, 2TD, and 3TD in Figure 7–38 are so-called time-delay relays, meaning that when they are energized there is a set time delay before their contacts shut.

When the start button is pushed in this circuit, the M relay energizes and power is applied to the motor as before. Since the 1TD, 2TD, and 3TD contacts are all open, the full starting resistor is in series with the motor, reducing the starting current.

When the M contacts close, notice that the 1TD relay is energized. However, there is a finite delay before the 1TD contacts close. During that time, the motor partially speeds up, and the starting current drops off some. After that time, the 1TD contacts close, cutting out part of the starting resistance and simultaneously energizing the 2TD relay. After another delay, the 2TD contacts shut, cutting out the second part of the resistor and energizing the 3TD relay. Finally, the 3TD contacts close, and the entire starting resistor is out of the circuit.

By a judicious choice of resistor values and time delays, this starting circuit can be used to prevent the motor starting current from becoming dangerously large, while still allowing enough current flow to ensure prompt acceleration to normal operating speeds.

7.9 SPEED CONTROL OF INDUCTION MOTORS

Until the advent of modern solid-state drives, induction motors in general were not good machines for applications requiring considerable speed control. The normal operating range of a typical induction motor (design classes A, B, and C)

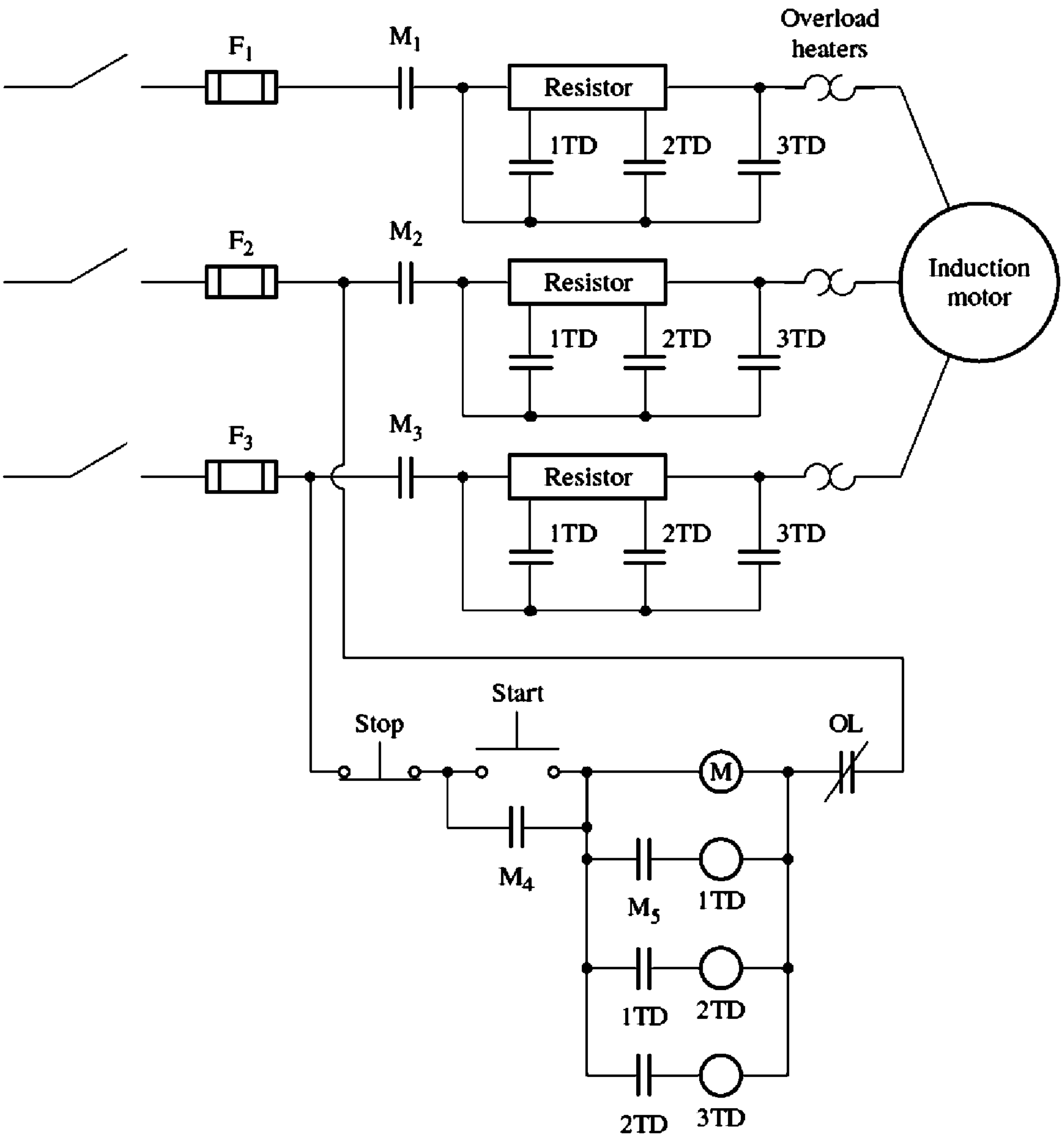


FIGURE 7-38
A three-step resistive starter for an induction motor.

is confined to less than 5 percent slip, and the speed variation over that range is more or less directly proportional to the load on the shaft of the motor. Even if the slip could be made larger, the efficiency of the motor would become very poor, since the rotor copper losses are directly proportional to the slip on the motor (remember that $P_{\mathrm{RCL}} = sP_{\mathrm{AG}}$).

There are really only two techniques by which the speed of an induction motor can be controlled. One is to vary the synchronous speed, which is the speed of the stator and rotor magnetic fields, since the rotor speed always remains near n_{sync}. The other technique is to vary the slip of the motor for a given load. Each of these approaches will be taken up in more detail.

The synchronous speed of an induction motor is given by

$$n_{\text{sync}} = \frac{120 f_e}{P} \tag{7-1}$$

so the only ways in which the synchronous speed of the machine can be varied are (1) by changing the electrical frequency and (2) by changing the number of poles on the machine. Slip control may be accomplished by varying either the rotor resistance or the terminal voltage of the motor.

Induction Motor Speed Control by Pole Changing

There are two major approaches to changing the number of poles in an induction motor:

1. The method of consequent poles
2. Multiple stator windings

The *method of consequent poles* is quite an old method for speed control, having been originally developed in 1897. It relies on the fact that the number of poles in the stator windings of an induction motor can easily be changed by a factor of 2:1 with only simple changes in coil connections. Figure 7–39 shows a

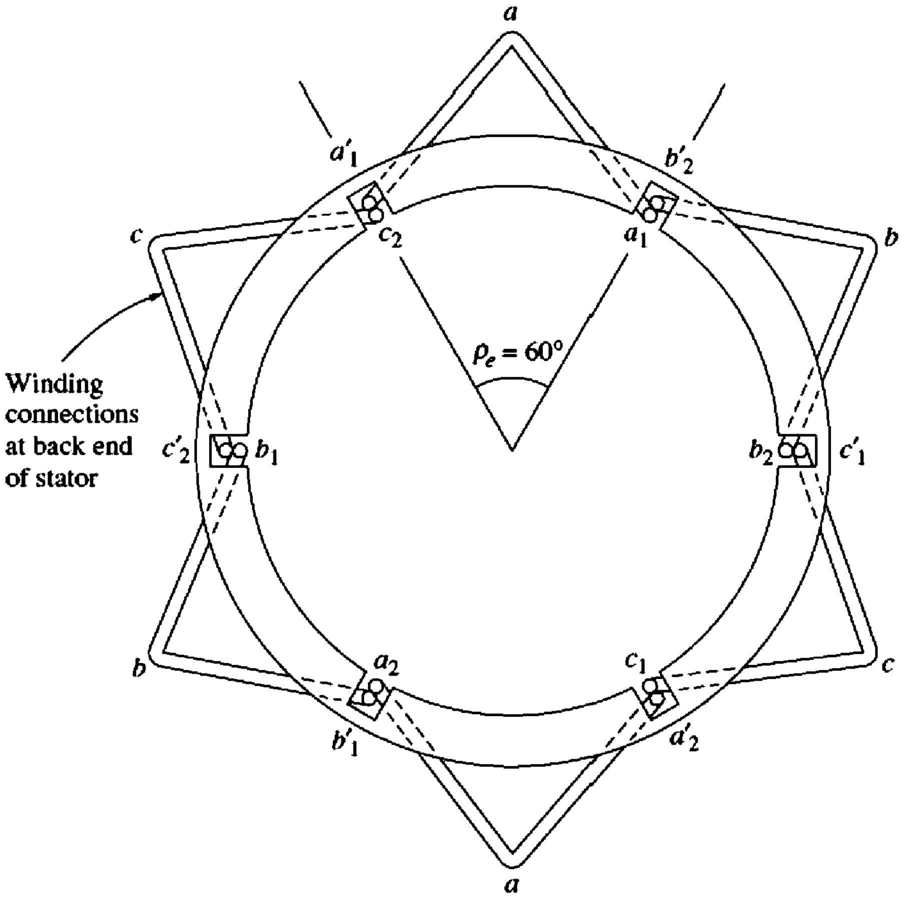


FIGURE 7–39
A two-pole stator winding for pole changing. Notice the very small rotor pitch of these windings.

simple two-pole induction motor stator suitable for pole changing. Notice that the individual coils are of very short pitch (60 to 90°). Figure 7–40 shows phase *a* of these windings separately for more clarity of detail.

Figure 7–40a shows the current flow in phase *a* of the stator windings at an instant of time during normal operation. Note that the magnetic field leaves the stator in the upper phase group (a north pole) and enters the stator in the lower phase group (a south pole). This winding is thus producing two stator magnetic poles.

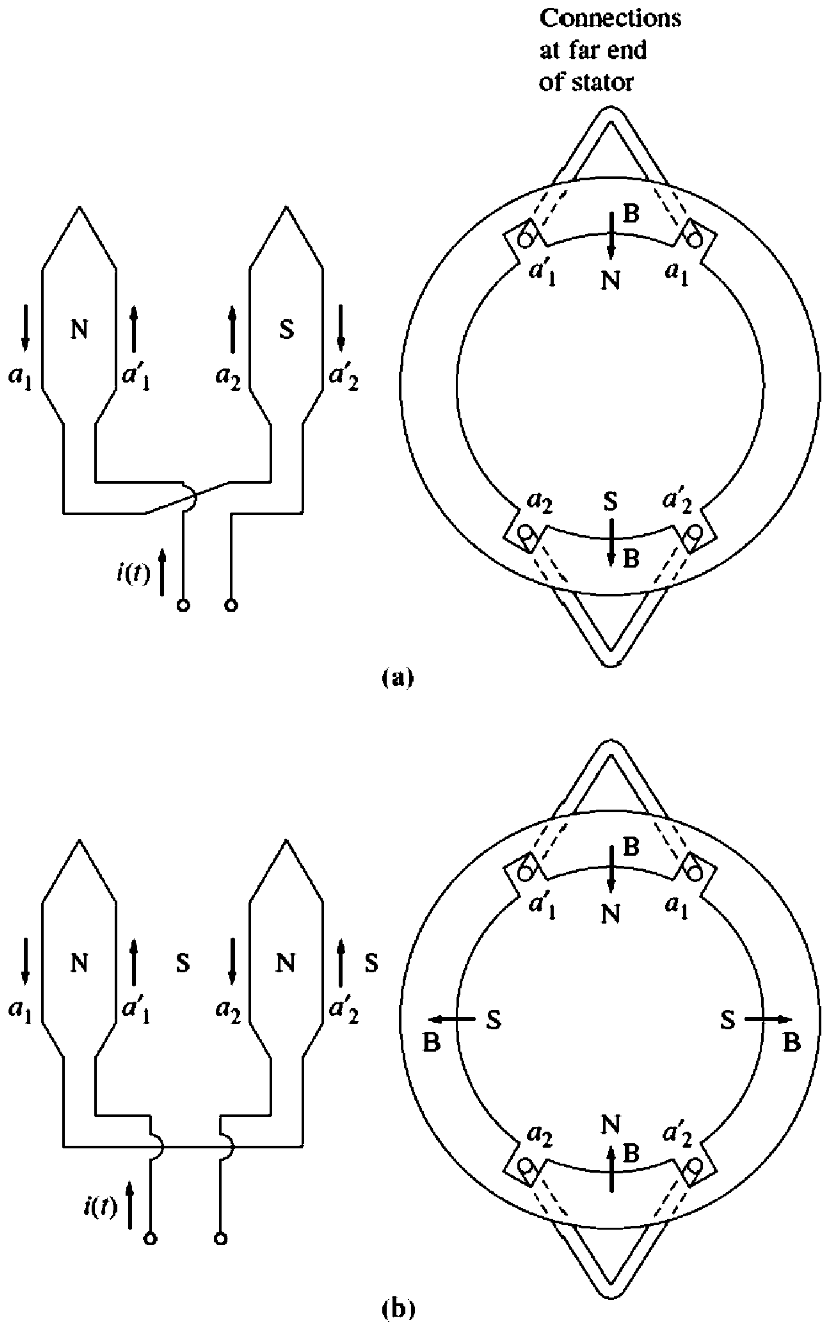


FIGURE 7–40

A close-up view of one phase of a pole-changing winding. (a) In the two-pole configuration, one coil is a north pole and the other one is a south pole. (b) When the connection on one of the two coils is reversed, they are both north poles, and the magnetic flux returns to the stator at points halfway between the two coils. The south poles are called *consequent poles*, and the winding is now a four-pole winding.

Now suppose that the direction of current flow in the *lower* phase group on the stator is reversed (Figure 7–40b). Then the magnetic field will leave the stator in *both* the upper phase group *and* the lower phase group—each one will be a north magnetic pole. The magnetic flux in this machine must return to the stator *between* the two phase groups, producing a pair of *consequent* south magnetic poles. Notice that now the stator has four magnetic poles—twice as many as before.

The rotor in such a motor is of the cage design, since a cage rotor always has as many poles induced in it as there are in the stator and can thus adapt when the number of stator poles changes.

When the motor is reconnected from two-pole to four-pole operation, the resulting maximum torque of the induction motor can be the same as before (constant-torque connection), half of its previous value (square-law-torque connection, used for fans, etc.), or twice its previous value (constant-output-power connection), depending on how the stator windings are rearranged. Figure 7–41 shows the possible stator connections and their effect on the torque–speed curve.

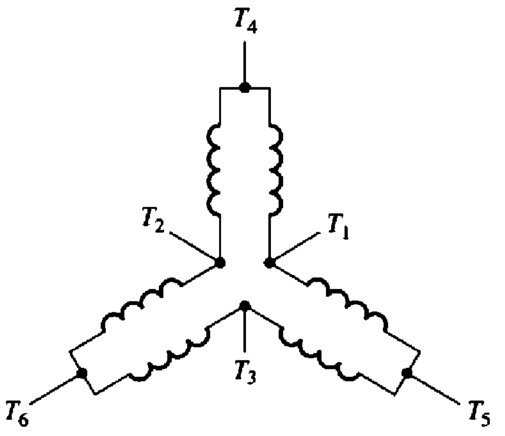
The major disadvantage of the consequent-pole method of changing speed is that the speeds *must* be in a ratio of 2:1. The traditional approach to overcoming this limitation was to employ *multiple stator windings* with different numbers of poles and to energize only one set at a time. For example, a motor might be wound with a four-pole and a six-pole set of stator windings, and its synchronous speed on a 60-Hz system could be switched from 1800 to 1200 r/min simply by supplying power to the other set of windings. Unfortunately, multiple stator windings increase the expense of the motor and are therefore used only when absolutely necessary.

By combining the method of consequent poles with multiple stator windings, it is possible to build a four-speed induction motor. For example, with separate four- and six-pole windings, it is possible to produce a 60-Hz motor capable of running at 600, 900, 1200, and 1800 r/min.

Speed Control by Changing the Line Frequency

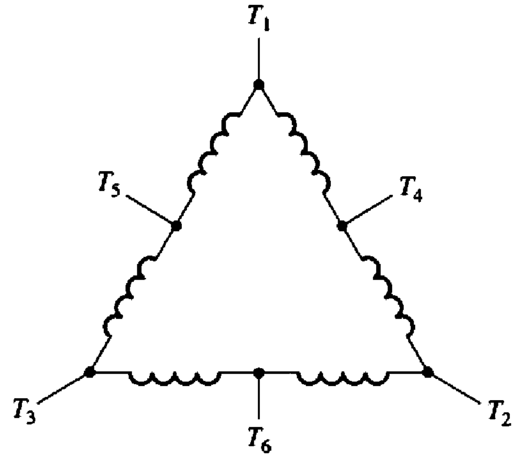
If the electrical frequency applied to the stator of an induction motor is changed, the rate of rotation of its magnetic fields n_{sync} will change in direct proportion to the change in electrical frequency, and the no-load point on the torque–speed characteristic curve will change with it (see Figure 7–42). The synchronous speed of the motor at rated conditions is known as the *base speed*. By using variable frequency control, it is possible to adjust the speed of the motor either above or below base speed. A properly designed variable-frequency induction motor drive can be *very* flexible. It can control the speed of an induction motor over a range from as little as 5 percent of base speed up to about twice base speed. However, it is important to maintain certain voltage and torque limits on the motor as the frequency is varied, to ensure safe operation.

When running at speeds below the base speed of the motor, it is necessary to reduce the terminal voltage applied to the stator for proper operation. The terminal voltage applied to the stator should be decreased linearly with decreasing



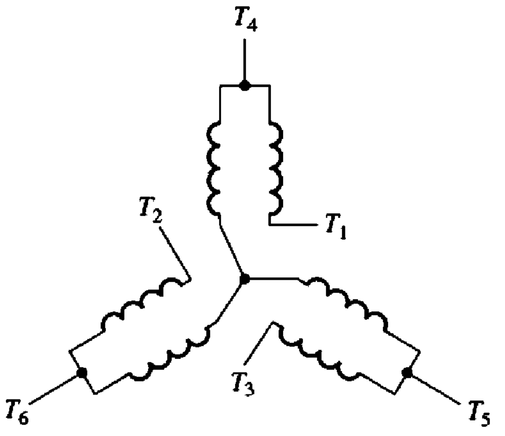
Speed	Lines			
	L_1	L_2	L_3	
Low	T_1	T_2	T_3	T_4, T_5, T_6 open
High	T_4	T_5	T_6	$T_1 - T_2 - T_3$ together

(a)



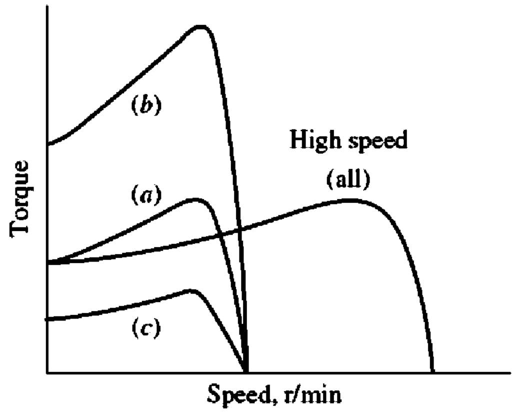
Speed	Lines			
	L_1	L_2	L_3	
Low	T_4	T_5	T_6	$T_1 - T_2 - T_3$ together
High	T_1	T_2	T_3	T_4, T_5, T_6 open

(b)



Speed	Lines			
	L_1	L_2	L_3	
Low	T_1	T_2	T_3	T_4, T_5, T_6 open
High	T_4	T_5	T_6	$T_1 - T_2 - T_3$ together

(c)



(d)

FIGURE 7–41

Possible connections of the stator coils in a pole-changing motor, together with the resulting torque–speed characteristics: (a) *Constant-torque connection*—the torque capabilities of the motor remain approximately constant in both high-speed and low-speed connections. (b) *Constant-horsepower connection*—the power capabilities of the motor remain approximately constant in both high-speed and low-speed connections. (c) *Fan torque connection*—the torque capabilities of the motor change with speed in the same manner as fan-type loads.

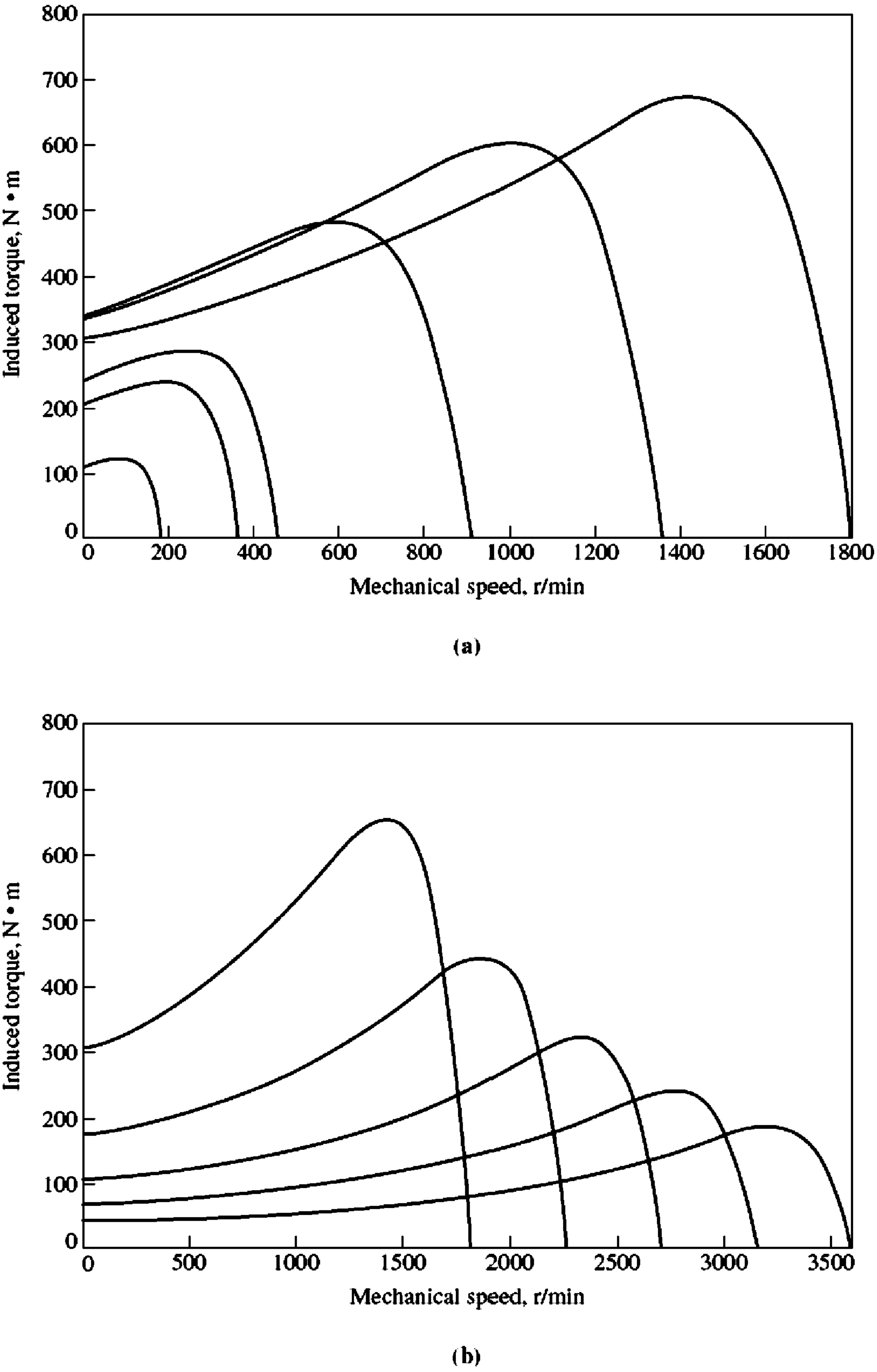
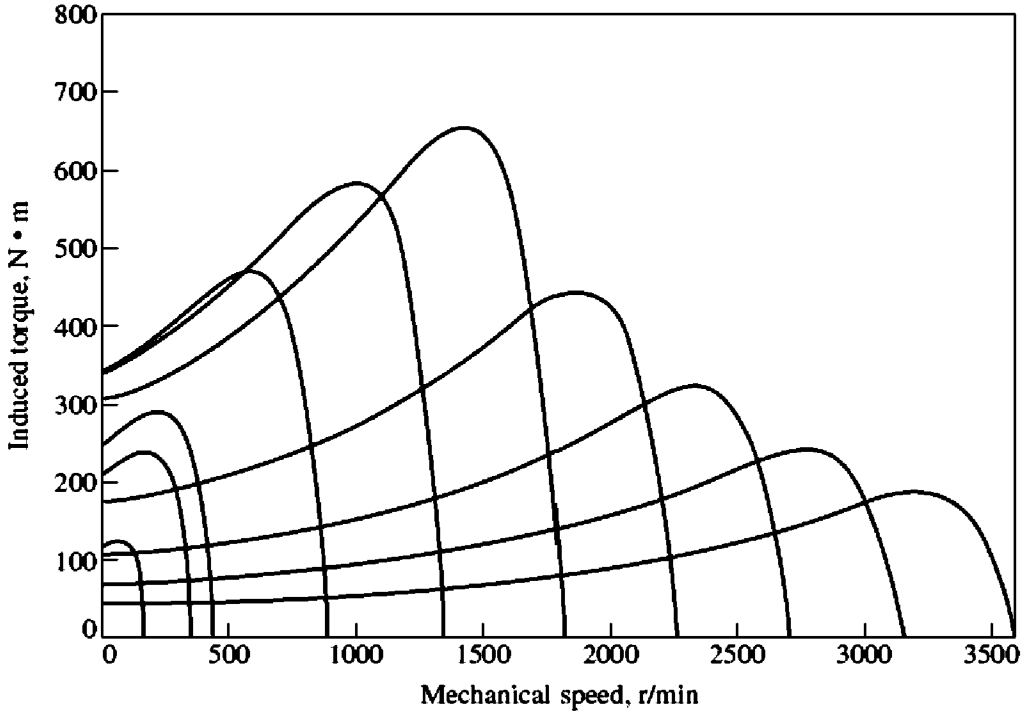


FIGURE 7–42
Variable-frequency speed control in an induction motor: (a) The family of torque–speed characteristic curves for speeds below base speed, assuming that the line voltage is derated linearly with frequency. (b) The family of torque–speed characteristic curves for speeds above base speed, assuming that the line voltage is held constant.



(c)

FIGURE 7–42 (concluded)
(c) The torque–speed characteristic curves for all frequencies.

stator frequency. This process is called *derating*. If it is not done, the steel in the core of the induction motor will saturate and excessive magnetization currents will flow in the machine.

To understand the necessity for derating, recall that an induction motor is basically a rotating transformer. As with any transformer, the flux in the core of an induction motor can be found from Faraday's law:

$$v(t) = -N\frac{d\phi}{dt} \tag{1–36}$$

If a voltage $v(t) = V_M \sin \omega t$ is applied to the core, the resulting flux ϕ is

$$\phi(t) = \frac{1}{N_P}\int v(t)\,dt$$

$$= \frac{I}{N_P}\int V_{\mathrm{M}} \sin \omega t\,dt$$

$$\boxed{\phi(t) = -\frac{V_M}{\omega N_P}\cos \omega t} \tag{7–57}$$

Note that the electrical frequency appears in the *denominator* of this expression. Therefore, if the electrical frequency applied to the stator *decreases* by 10 percent while the magnitude of the voltage applied to the stator remains constant, the flux in the core of the motor will *increase* by about 10 percent and the magnetization current of the motor will increase. In the unsaturated region of the motor's magnetization curve, the increase in magnetization current will also be about 10 percent. However, in the saturated region of the motor's magnetization curve, a 10 percent increase in flux requires a much larger increase in magnetization current. Induction motors are normally designed to operate near the saturation point on their magnetization curves, so the increase in flux due to a decrease in frequency will cause excessive magnetization currents to flow in the motor. (This same problem was observed in transformers; see Section 2.12.)

To avoid excessive magnetization currents, it is customary to decrease the applied stator voltage in direct proportion to the decrease in frequency whenever the frequency falls below the rated frequency of the motor. Since the applied voltage v appears in the numerator of Equation (7–57) and the frequency ω appears in the denominator of Equation (7–57), the two effects counteract each other, and the magnetization current is unaffected.

When the voltage applied to an induction motor is varied linearly with frequency below the base speed, the flux in the motor will remain approximately constant. Therefore, the maximum torque which the motor can supply remains fairly high. However, the maximum power rating of the motor must be decreased linearly with decreases in frequency to protect the stator circuit from overheating. The power supplied to a three-phase induction motor is given by

$$P = \sqrt{3} V_L I_L \cos \theta$$

If the voltage V_L is decreased, then the maximum power P must also be decreased, or else the current flowing in the motor will become excessive, and the motor will overheat.

Figure 7–42a shows a family of induction motor torque–speed characteristic curves for speeds below base speed, assuming that the magnitude of the stator voltage varies linearly with frequency.

When the electrical frequency applied to the motor exceeds the rated frequency of the motor, the stator voltage is held constant at the rated value. Although saturation considerations would permit the voltage to be raised above the rated value under these circumstances, it is limited to the rated voltage to protect the winding insulation of the motor. The higher the electrical frequency above base speed, the larger the denominator of Equation (7–57) becomes. Since the numerator term is held constant above rated frequency, the resulting flux in the machine decreases and the maximum torque decreases with it. Figure 7–42b shows a family of induction motor torque–speed characteristic curves for speeds above base speed, assuming that the stator voltage is held constant.

If the stator voltage is varied linearly with frequency below base speed and is held constant at rated value above base speed, then the resulting family of torque–speed characteristics is as shown in Figure 7–42c. The rated speed for the motor shown in Figure 7–42 is 1800 r/min.

In the past, the principal disadvantage of electrical frequency control as a method of speed changing was that a dedicated generator or mechanical frequency changer was required to make it operate. This problem has disappeared with the development of modern solid-state variable-frequency motor drives. In

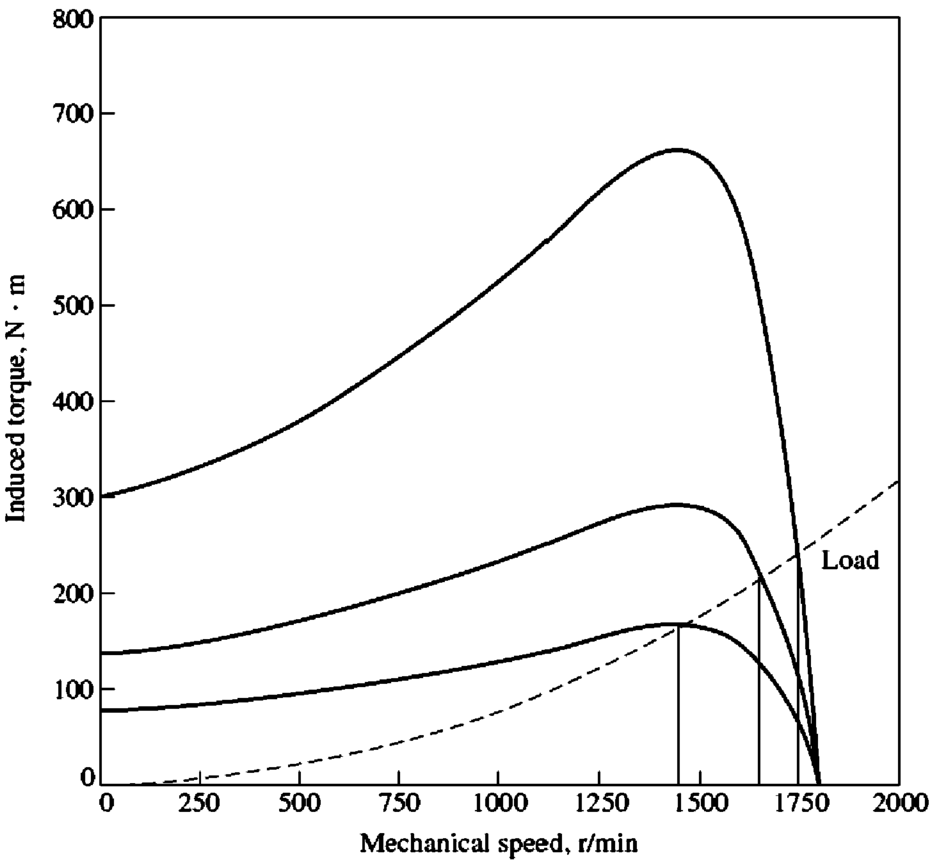


FIGURE 7–43
Variable-line-voltage speed control in an induction motor.

fact, changing the line frequency with solid-state motor drives has become the method of choice for induction motor speed control. Note that this method can be used with *any* induction motor, unlike the pole-changing technique, which requires a motor with special stator windings.

A typical solid-state variable-frequency induction motor drive will be described in Section 7.10.

Speed Control by Changing the Line Voltage

The torque developed by an induction motor is proportional to the square of the applied voltage. If a load has a torque–speed characteristic such as the one shown in Figure 7–43, then the speed of the motor may be controlled over a limited range by varying the line voltage. This method of speed control is sometimes used on small motors driving fans.

Speed Control by Changing the Rotor Resistance

In wound-rotor induction motors, it is possible to change the shape of the torque–speed curve by inserting extra resistances into the rotor circuit of the machine. The resulting torque–speed characteristic curves are shown in Figure 7–44.

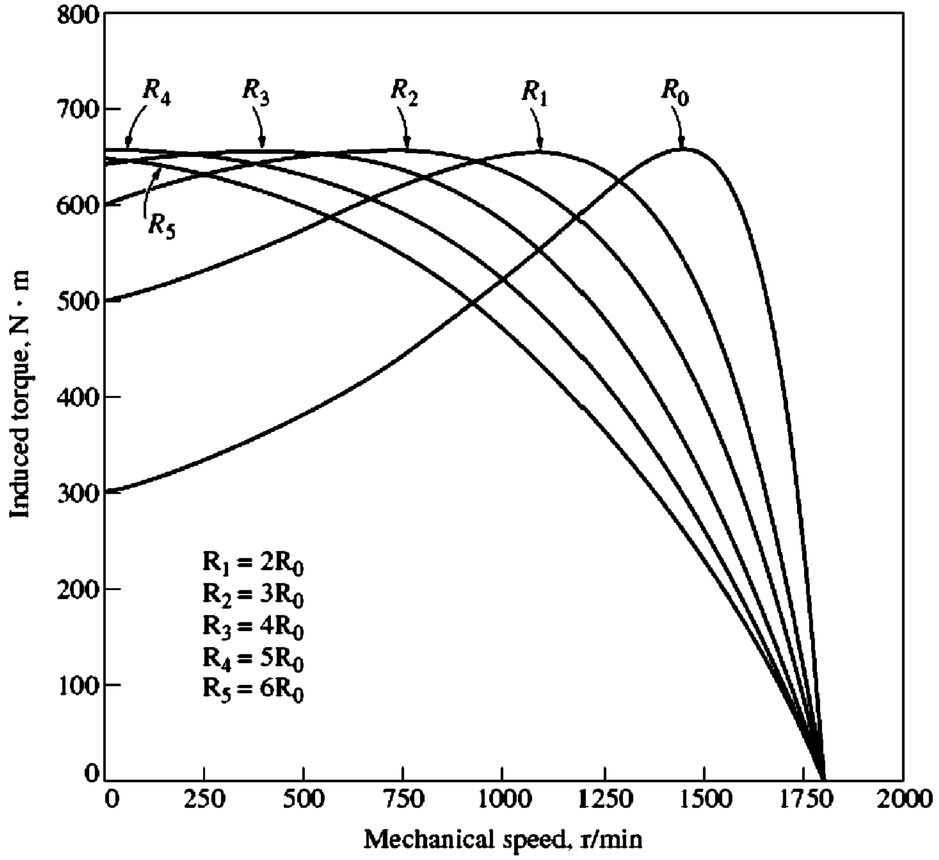


FIGURE 7–44
Speed control by varying the rotor resistance of a wound-rotor induction motor.

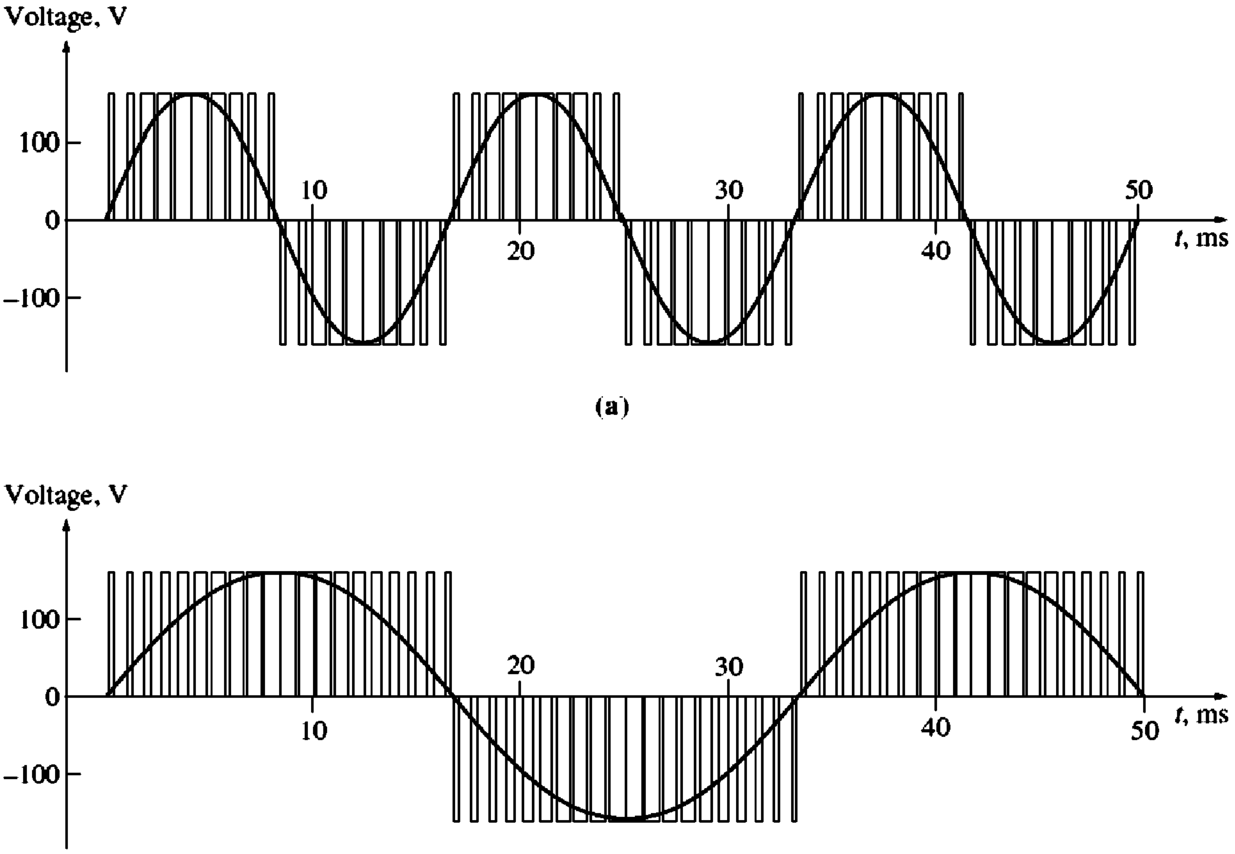
If the torque–speed curve of the load is as shown in the figure, then changing the rotor resistance will change the operating speed of the motor. However, inserting extra resistances into the rotor circuit of an induction motor seriously reduces the efficiency of the machine. Such a method of speed control is normally used only for short periods because of this efficiency problem.

7.10 SOLID-STATE INDUCTION MOTOR DRIVES

As mentioned in the previous section, the method of choice today for induction motor speed control is the solid-state variable-frequency induction motor drive. A typical drive of this sort is shown in Figure 7–45. The drive is very flexible: its input power can be either single-phase or three-phase, either 50 or 60 Hz, and anywhere from 208 to 230 V. The output from this drive is a three-phase set of voltages whose frequency can be varied from 0 up to 120 Hz and whose voltage can be varied from 0 V up to the rated voltage of the motor.

The output voltage and frequency control is achieved by using the pulse-width modulation (PWM) techniques described in Chapter 3. Both output frequency and output voltage can be controlled independently by pulse-width modulation. Figure 7–46 illustrates the manner in which the PWM drive can control the output frequency while maintaining a constant rms voltage level, while Figure 7–47 illustrates

FIGURE 7–45
A typical solid-state variable-frequency induction motor drive. (*Courtesy of MagneTek, Inc.*)



(a)

(b)

FIGURE 7–46
Variable-frequency control with a PWM waveform: (a) 60-Hz, 120-V PWM waveform; (b) 30-Hz, 120-V PWM waveform.

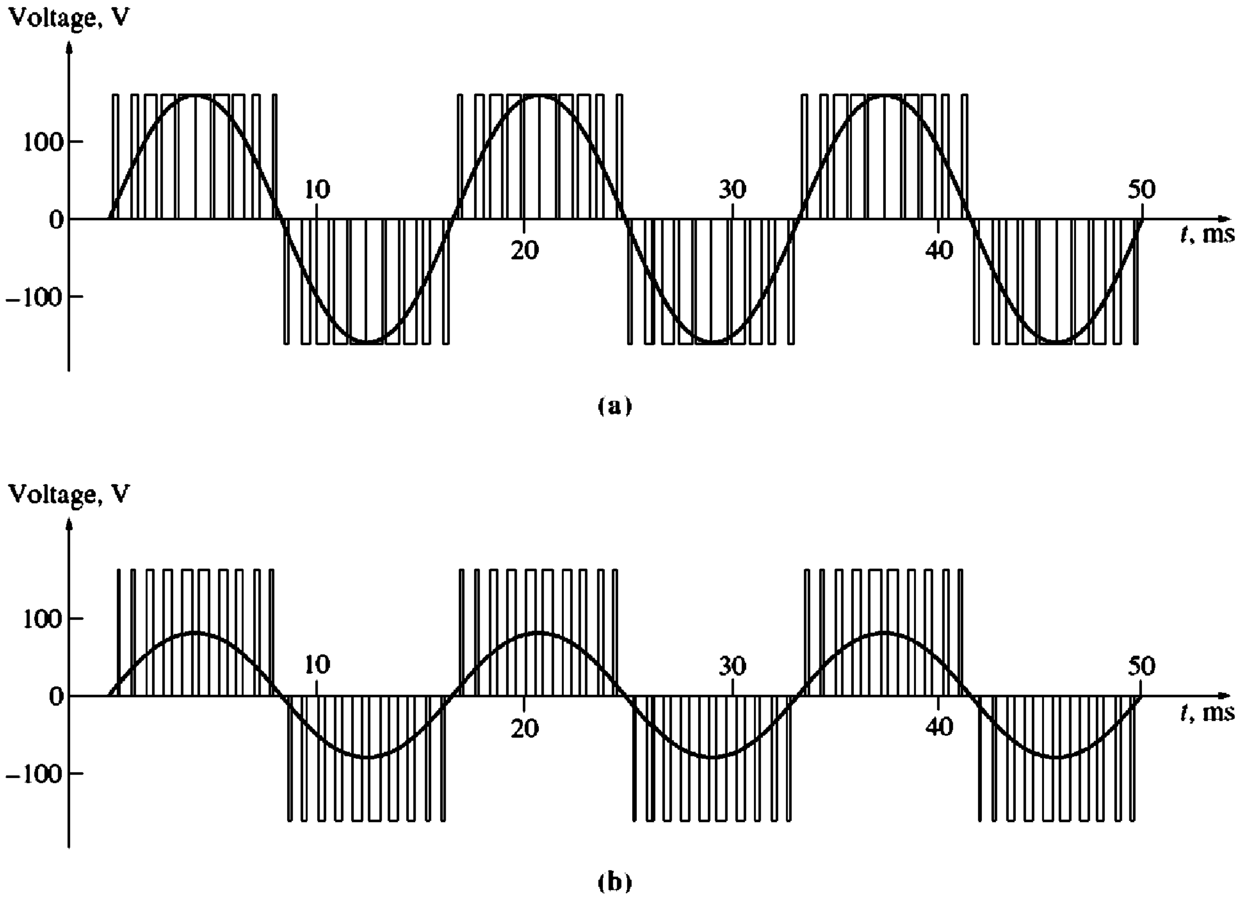


FIGURE 7–47
Variable voltage control with a PWM waveform: (a) 60-Hz, 120-V PWM waveform; (b) 60-Hz, 60-V PWM waveform.

the manner in which the PWM drive can control the rms voltage level while maintaining a constant frequency.

As we described in Section 7.9, it is often desirable to vary the output frequency and output rms voltage together in a linear fashion. Figure 7–48 shows typical output voltage waveforms from one phase of the drive for the situation in which frequency and voltage are varied simultaneously in a linear fashion.* Figure 7–48a shows the output voltage adjusted for a frequency of 60 Hz and an rms voltage of 120 V. Figure 7–48b shows the output adjusted for a frequency of 30 Hz and an rms voltage of 60 V, and Figure 7–48c shows the output adjusted for a frequency of 20 Hz and an rms voltage of 40 V. Notice that the peak voltage out of the drive remains the same in all three cases; the rms voltage level is controlled by the fraction of time the voltage is switched on, and the frequency is controlled by the rate at which the polarity of the pulses switches from positive to negative and back again.

The typical induction motor drive shown in Figure 7–45 has many built-in features which contribute to its adjustability and ease of use. Here is a summary of some of these features.

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*The output waveforms in Figure 7–47 are actually simplified waveforms. The real induction motor drive has a much higher carrier frequency than that shown in the figure.

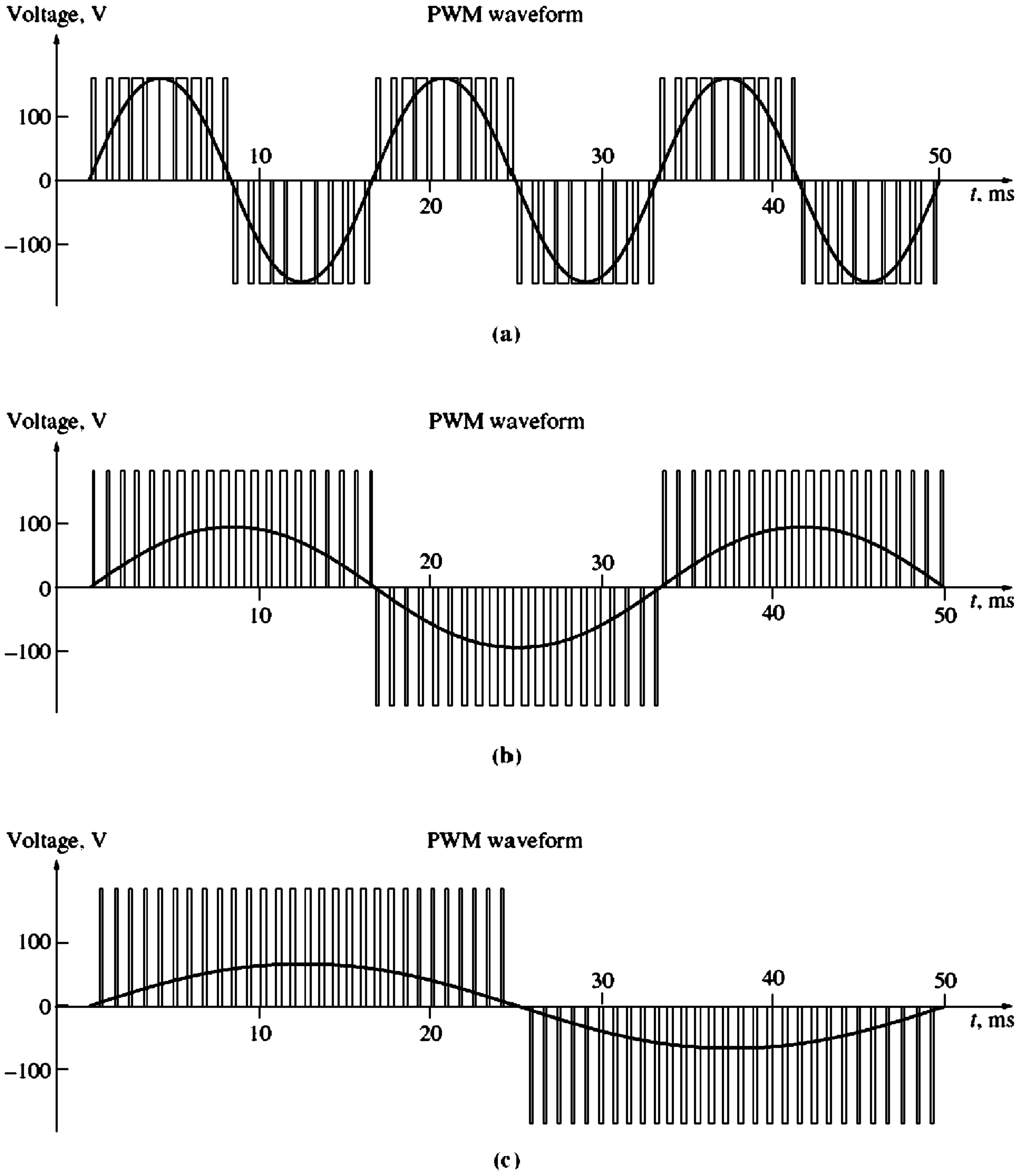


FIGURE 7–48
Simultaneous voltage and frequency control with a PWM waveform: (a) 60-Hz, 120-V PWM waveform; (b) 30-Hz, 60-V PWM waveform; (c) 20-Hz, 40-V PWM waveform.

Frequency (Speed) Adjustment

The output frequency of the drive can be controlled manually from a control mounted on the drive cabinet, or it can be controlled remotely by an external voltage or current signal. The ability to adjust the frequency of the drive in response to some external signal is very important, since it permits an external computer or process controller to control the speed of the motor in accordance with the overall needs of the plant in which it is installed.

A Choice of Voltage and Frequency Patterns

The types of mechanical loads which might be attached to an induction motor vary greatly. Some loads such as fans require very little torque when starting (or running at low speeds) and have torques which increase as the square of the speed. Other loads might be harder to start, requiring more than the rated full-load torque of the motor just to get the load moving. This drive provides a variety of voltage-versus-frequency patterns which can be selected to match the torque from the induction motor to the torque required by its load. Three of these patterns are shown in Figures 7–49 through 7–51.

Figure 7–49a shows the standard or general-purpose voltage-versus-frequency pattern, described in the previous section. This pattern changes the output voltage linearly with changes in output frequency for speeds below base speed and holds the output voltage constant for speeds above base speed. (The small constant-voltage region at very low frequencies is necessary to ensure that there will be some starting torque at the very lowest speeds.) Figure 7–49b shows the resulting induction motor torque–speed characteristics for several operating frequencies below base speed.

Figure 7–50a shows the voltage-versus-frequency pattern used for loads with high starting torques. This pattern also changes the output voltage linearly with changes in output frequency for speeds below base speed, but it has a shallower slope at frequencies below 30 Hz. For any given frequency below 30 Hz, the output voltage will be *higher* than it was with the previous pattern. This higher voltage will produce a higher torque, but at the cost of increased magnetic saturation and higher magnetization currents. The increased saturation and higher currents are often acceptable for the short periods required to start heavy loads. Figure 7–50b shows the induction motor torque–speed characteristics for several operating frequencies below base speed. Notice the increased torque available at low frequencies compared to Figure 7–49b.

Figure 7–51a shows the voltage-versus-frequency pattern used for loads with low starting torques (called *soft-start loads*). This pattern changes the output voltage parabolically with changes in output frequency for speeds below base speed. For any given frequency below 60 Hz, the output voltage will be lower than it was with the standard pattern. This lower voltage will produce a lower torque, providing a slow, smooth start for low-torque loads. Figure 7–51b shows the induction motor torque–speed characteristics for several operating frequencies below base speed. Notice the decreased torque available at low frequencies compared to Figure 7–49.

Independently Adjustable Acceleration and Deceleration Ramps

When the desired operating speed of the motor is changed, the drive controlling it will change frequency to bring the motor to the new operating speed. If the speed change is sudden (e.g., an instantaneous jump from 900 to 1200 r/min), the drive

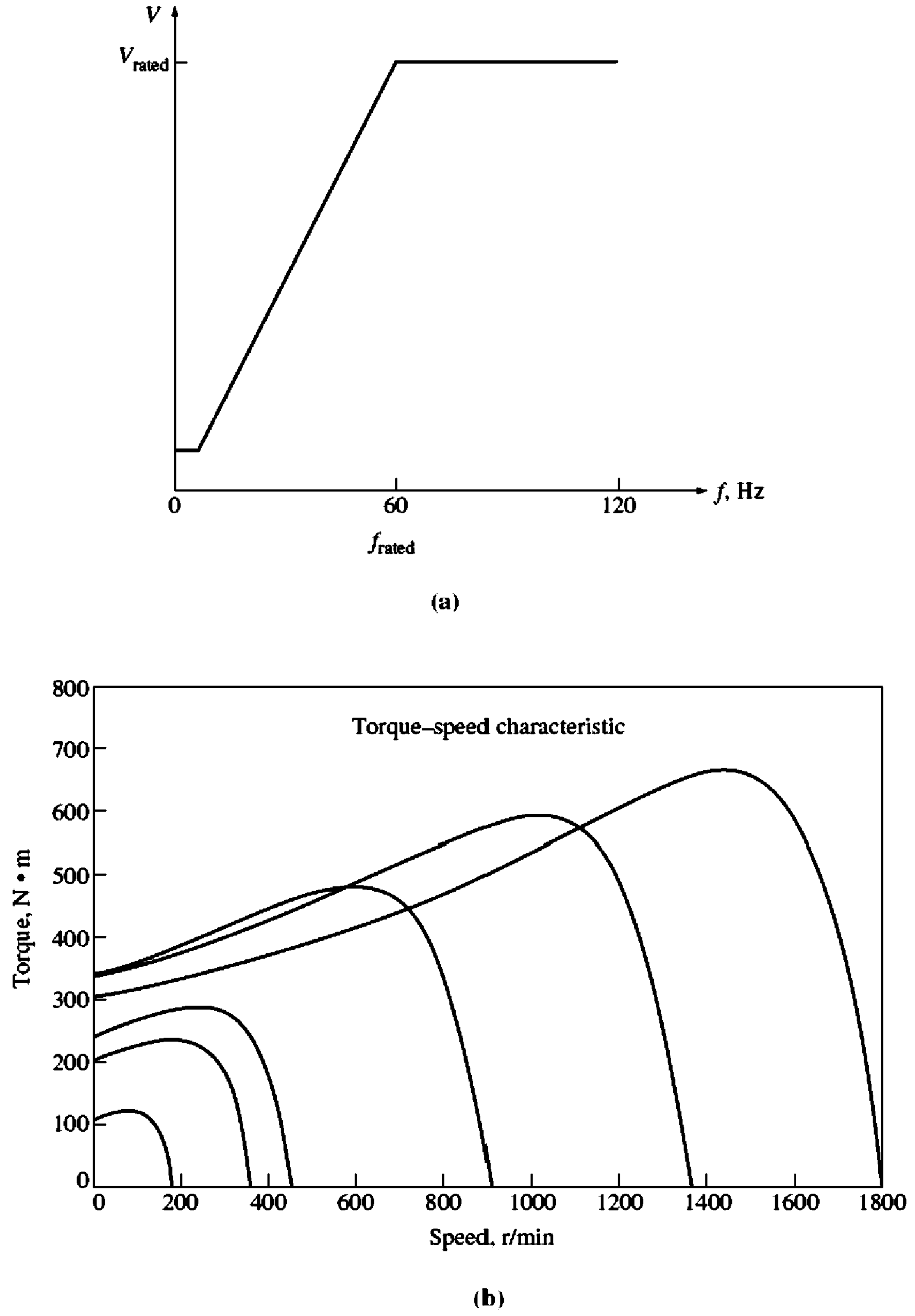


FIGURE 7–49

(a) Possible voltage-versus-frequency patterns for the solid-state variable-frequency induction motor drive: *general-purpose pattern.* This pattern consists of a linear voltage–frequency curve below rated frequency and a constant voltage above rated frequency. (b) The resulting torque–speed characteristic curves for speeds below rated frequency (speeds above rated frequency look like Figure 7–41b).

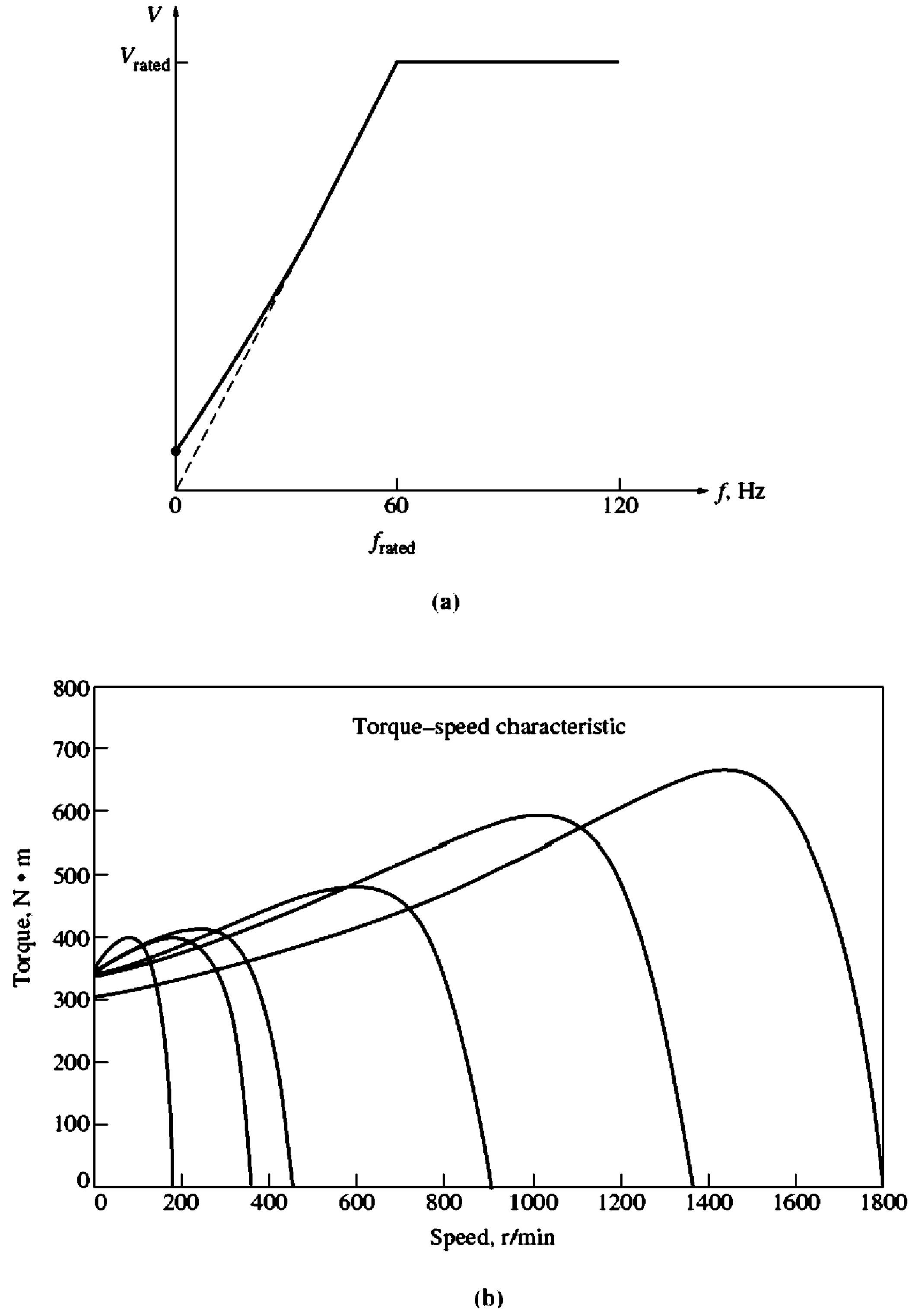
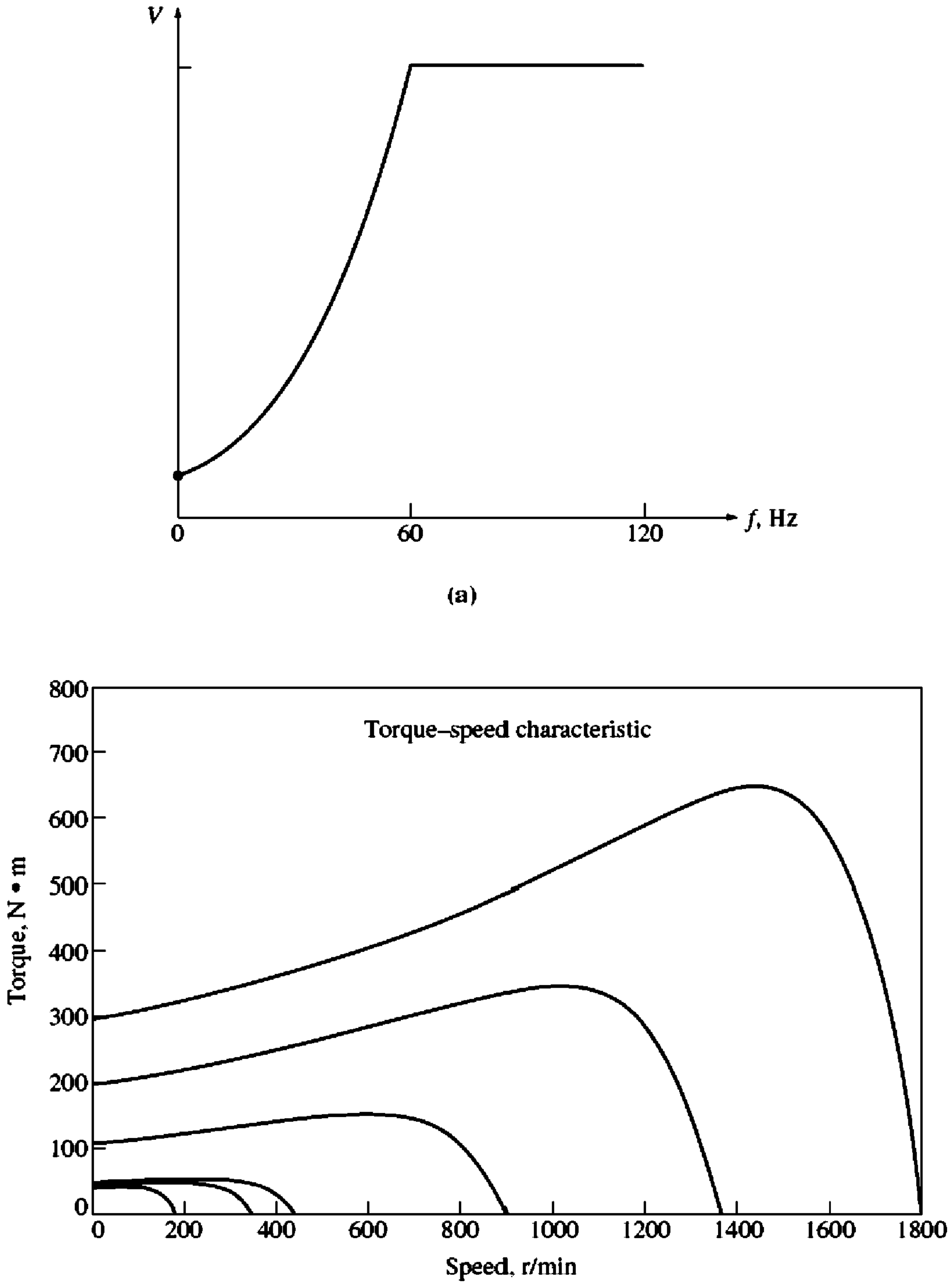


FIGURE 7–50

(a) Possible voltage-versus-frequency patterns for the solid-state variable-frequency induction motor drive: *high-starting-torque pattern.* This is a modified voltage-frequency pattern suitable for loads requiring high starting torques. It is the same as the linear voltage–frequency pattern except at low speeds. The voltage is disproportionately high at very low speeds, which produces extra torque at the cost of a higher magnetization current. (b) The resulting torque–speed characteristic curves for speeds below rated frequency (speeds above rated frequency look like Figure 7–41b).



(a)

(b)

FIGURE 7–51

(a) Possible voltage-versus-frequency patterns for the solid-state variable-frequency induction motor drive: *fan torque pattern*. This is a voltage–frequency pattern suitable for use with motors driving fans and centrifugal pumps, which have a very low starting torque. (b) The resulting torque–speed characteristic curves for speeds below rated frequency (speeds above rated frequency look like Figure 7–41b).

does not try to make the motor instantaneously jump from the old desired speed to the new desired speed. Instead, the rate of motor acceleration or deceleration is limited to a safe level by special circuits built into the electronics of the drive. These rates can be adjusted independently for accelerations and decelerations.

Motor Protection

The induction motor drive has built into it a variety of features designed to protect the motor attached to the drive. The drive can detect excessive steady-state currents (an overload condition), excessive instantaneous currents, overvoltage conditions, or undervoltage conditions. In any of the above cases, it will shut down the motor.

Induction motor drives like the one described above are now so flexible and reliable that induction motors with these drives are displacing dc motors in many applications which require a wide range of speed variation.

7.11 DETERMINING CIRCUIT MODEL PARAMETERS

The equivalent circuit of an induction motor is a very useful tool for determining the motor's response to changes in load. However, if a model is to be used for a real machine, it is necessary to determine what the element values are that go into the model. How can R_1, R_2, X_1, X_2, and X_M be determined for a real motor?

These pieces of information may be found by performing a series of tests on the induction motor that are analogous to the short-circuit and open-circuit tests in a transformer. The tests must be performed under precisely controlled conditions, since the resistances vary with temperature and the rotor resistance also varies with rotor frequency. The exact details of how each induction motor test must be performed in order to achieve accurate results are described in IEEE Standard 112. Although the details of the tests are very complicated, the concepts behind them are relatively straightforward and will be explained here.

The No-Load Test

The no-load test of an induction motor measures the rotational losses of the motor and provides information about its magnetization current. The test circuit for this test is shown in Figure 7–52a. Wattmeters, a voltmeter, and three ammeters are connected to an induction motor, which is allowed to spin freely. The only load on the motor is the friction and windage losses, so all P_{conv} in this motor is consumed by mechanical losses, and the slip of the motor is very small (possibly as small as 0.001 or less). The equivalent circuit of this motor is shown in Figure 7–52b. With its very small slip, the resistance corresponding to its power converted, $R_2(1 - s)/s$, is much much larger than the resistance corresponding to the rotor copper losses R_2 and much larger than the rotor reactance X_2. In this case, the equivalent circuit reduces approximately to the last circuit in Figure 7–52b. There,