

Welcome to

Electric Machines & Drives

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Session 11:
 Control of AC & DC Motors

Fall 2011



Session 11

- Chapter 22 – Control of DC Motors
- Chapter 23 – Control of AC Motors

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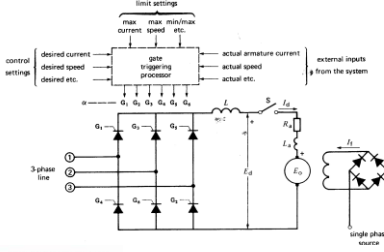
Chapter 22 – Control of DC Motors

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Chapter 22

First Quadrant – speed control



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Chapter 22

Speed varied by changing armature voltage
 α initially 90° , switch closed, α decreased to increase armature Vdc, increasing Id

- 1.No armature resistors needed (no losses)
- 2.Power loss reduced, improved efficiency
- 3.Current limit prevent over current.
- 4.PF poor during start period

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A typically 15° at full conduction
 $E_d > E_o$ by $I_d \cdot R_a$
 To lower speed, α increased, $I_d = 0$, motor coast to lower speed till $I_d \neq 0$
 Ripple voltage large, but L gives smooth Id
 Motor coast to stop (no braking)

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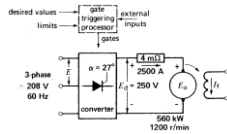
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Example 22-1

A 750 HP, 250V, 1200 rpm, dc motor is connected to a 208V, 3 phase, 60 Hz line using a 3 phase bridge converter Fig 22.2a. The full load armature current is 2500A and the armature resistance is 4 m Ω .

Calculate

- The required firing angle α under rated full load conditions
- The firing angle required so that the motor develops its rated torque at 400 rpm.



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Example 22-2

Referring to Example 22-1, calculate the reactive power absorbed by the converter when the motor develops full torque at 400 rpm.

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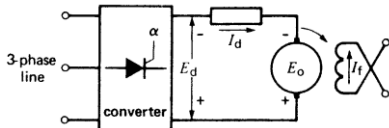


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Chapter 22

Two quadrant control via field reversal –
Dynamic Brake – resistor across armature
Regenerative brake – generate power back to line
Procedure follows:

Motor control by field reversal

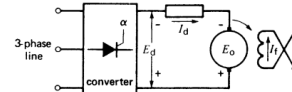


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- 1.Delay gate pulse by 180 $^\circ$ (cause E_d to be neg)
- 2.Reverse I_f (Delayed)
- 3.Reduce α so $|E_d| < |E_o|$
- 4.Once speed lowered, Delay gate pulse again by 180 $^\circ$ (cause E_d to be positive)
- 5.Reverse back I_f (Delay)
- 6.Increase α so $|E_d| > |E_o|$

Motor control by field reversal

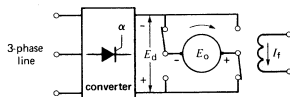


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Two quadrant control via armature reversal (single converter) –
Quicker response – $L_a \ll L_f$
Delay gate pulse by 180 $^\circ$ (cause E_d to be neg)
Reverse E_o to reverse I_o
Reduce α so $|E_d| < |E_o|$

Motor control by field reversal

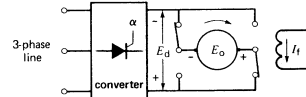


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Once speed lowered, Delay gate pulse again by 180 $^\circ$ (cause E_d to be positive)
Reverse back E_o to reverse back I_o
Increase α so $|E_d| > |E_o|$

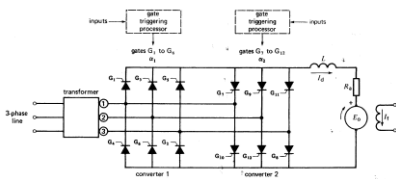
Motor control by field reversal



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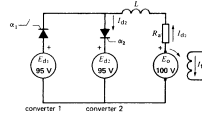
Two quadrant control via armature reversal (two converters) –
Only one operates at a time – quicker response



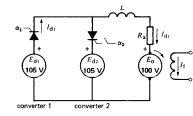
Chapter 22

Only one converter gate at a time, other has gate pulses blocked
Gate circuit for both set to same E_d (converter 1 has α_1 , converter 2 has $\alpha_2 = 180^\circ - \alpha_1$) even though one blocked

Converter 2 operation
Converter 1 blocked.

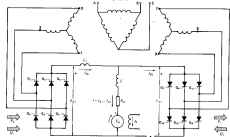


Converter 1 operation
Converter 2 blocked.



Chapter 22

Four quadrant control via armature reversal (two converters with circulating current) –
Low speed (low E_d operation) current may be discontinuous – allow converters to operation simultaneously to overcome
Dc inductors L1 and L2 to limit circulating current.



Example 22-3

The dc motor in Fig 22.8 has an armature voltage of 450V while drawing a current of 1500 A. Converter 1 delivers a current I_{d1} of 1800A and converter 2 absorbs 300A. If the ac line voltage for each converter is 360V, calculate the following;

Example 22-3

- The dc power associated with converters 1 and 2
- The active power drawn from the incoming 3 phase line
- The firing angles for converters 1 and 2
- The reactive power drawn from the incoming 3 phase line

Chapter 22

Two Quadrant (1&2) control – reversing with same torque direction
Raise – Quadrant 1 – motoring – $0^\circ < \alpha < 90^\circ$

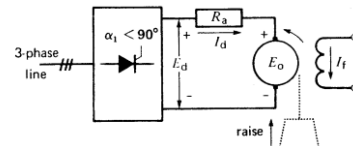


Figure 22.9
Hoist raising a load.

Chapter 22

Two Quadrant (1&2) control – reversing with same torque direction – E_o reverses
 Lower – Quadrant 2 – Braking – $90^\circ < \alpha < 180^\circ$

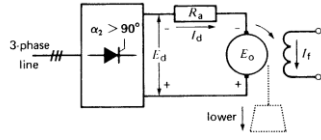


Figure 22.10
Hoist lowering a load.



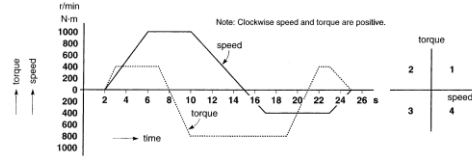
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Four Quadrant Drive – Utilizing 2 converter system

TABLE 22A

Time interval	Operating mode	
	Converter 1	Converter 2
I 2-8 s	rectifier	off
II 8-15 s	off	inverter
III 15-21 s	off	rectifier
IV 21-25 s	inverter	off



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Converter 1 – Rectifier Mode
 Converter 2 – Inverter Mode

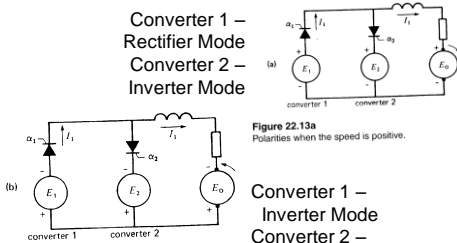


Figure 22.13a
Polarities when the speed is positive.

Figure 22.13b
Interval from 21 s to 25 s.

Converter 1 – Inverter Mode
 Converter 2 – Rectifier Mode



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Example 22-4

An industrial drive has to develop the torque speed characteristic given in Fig 22.11. A dc shunt motor is used, power by two converters operating back to back. The converters function alternately (only one at a time). Determine the state of each converter of the 26 second operating period, and indicate the polarity at the terminals of the dc machine. The speed and torque are considered positive when acting clockwise.

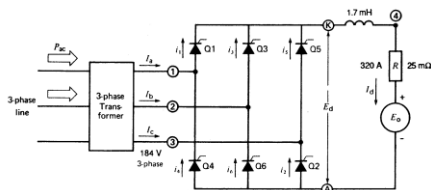
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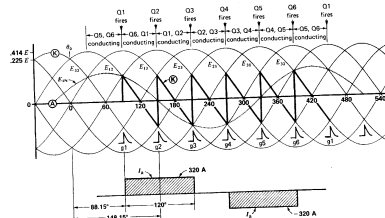
6 pulse converter with freewheeling diode – Without diode, small values of E_d contain negative portions of E_d



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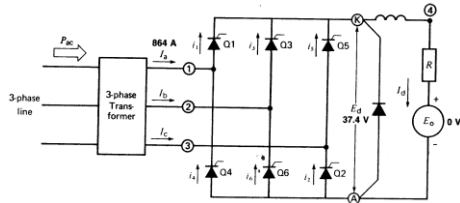
Due to lag, reactive current large. Also, I line 120° regardless of α
 $I = 0.816 I_d$



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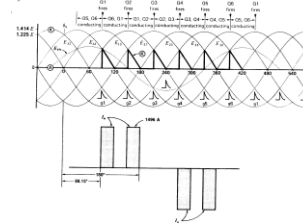
Placing diode prevents E_d from being negative



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For same α , increased I_d – increase α angle for same I_d , note I line no longer 120°



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With Freewheeling diode, calculation of E_d and I become – (note- eqn only apply for reduced voltage ($\alpha > 60^\circ$) where there is neg comp of E_d .)

$$E_d = 1.35 E [1 - \cos (120-\alpha)]$$

$$I = I_d \sqrt{[(120-\alpha)/90]}$$

E_d = dc voltage (V)

E = effective value of line to line voltage (V)

α = firing angle (between 60° and 120°)

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Example from Book (22.8) –

Given:

Rated power = 100 HP

Rated armature voltage = 240 V

Rated armature current = 320 A

Armature resistance = 25 m Ω

Armature inductance = 1.7 mH

$$8 = 1.35 \times 184 (1 - \cos [120 - \alpha])$$

$$\alpha = 120 - 14.6^\circ = 105.4^\circ$$

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Motor at rest and $E_o = 0$

$$E_d = IR = 320A \times 25m \Omega = 8V$$

Firing Angle =

$$8 = 1.35 \times 184 (1 - \cos[120-\alpha])$$

$$\alpha = 120 - 14.6 = 105.4^\circ$$

$$8 = 1.35 \times 184 (1 - \cos [120 - \alpha])$$

$$\alpha = 120 - 14.6^\circ = 105.4^\circ$$

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Line current I , lags V_{ln} by :

$$\phi_d = 30^\circ + \alpha/2$$

ϕ_d = displacement phase angle (degrees)

α = firing angle (must lie between 60° and 120° (degrees))

PF (displacement) = $\cos \phi_d$

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Effective value of line current :

$$I = I_d \sqrt{[(120 - \alpha) / 90]}$$

Reactive Power:

$$Q = P \tan \phi_d$$

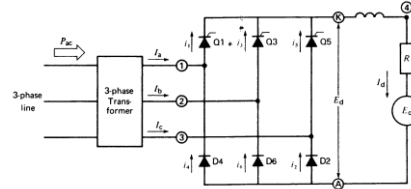
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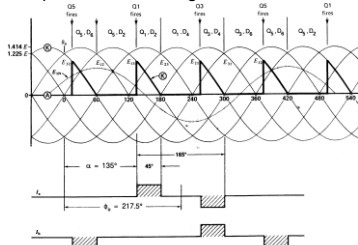
Half Bridge Converter –
3 diode/3 SCR



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Note – 3 pulse rectifier – again $I_{line} < 120^\circ$



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Half Bridge Converter –
 $E_d = 0.675 E (1 + \cos \alpha)$

E_d = dc voltage across the load (V)

E = effective value of line voltage (V)

α = firing angle (angle (must lie between 60° and 180° (degrees)

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Converter A – 3phase, 6 pulse
Converter B – 3phase, 6 pulse w/ FW diode
Converter C – 3phase, 3 pulse half bridge

TABLE 22B PROPERTIES OF SOME RECTIFIER CONVERTERS (RESISTIVE LOAD)

Items	Converter A 3-phase, 6-pulse	Converter B 3-phase, 6-pulse + freewheeling diode	Converter C Half-bridge
firing angle (α) limits	0 to 90°	60° to 120°	60° to 180°
dc output voltage (E_d)	$1.35 E \cos \alpha$	$1.35 E (1 - \cos (120 - \alpha))$	$0.675 E (1 + \cos \alpha)$
displacement angle (Φ_d)	α	$30 + \alpha/2$	$\alpha/2$
PF (displacement) = $\cos \Phi_d$	$\cos \alpha$	$\cos (30 + \alpha/2)$	$\cos \alpha/2$
effective line current (I)	$0.816 I_d$	$I_d \sqrt{(120 - \alpha) / 90}$	$I_d \sqrt{(180 - \alpha) / 180}$
Total apparent power (S)	$E I \sqrt{3}$	$E I \sqrt{3}$	$E I \sqrt{3}$
Total active power (P)	$E_d I_d$	$E_d I_d$	$E_d I_d$
Total reactive power (Q)	$P \tan \Phi_d$	$P \tan \Phi_d$	$P \tan \Phi_d$
PF (total)	P/S	P/S	P/S



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Chapter 22

DC Traction Example of simple DC to DC Chopper:

$$E_o = E_s f T_a = D E_s$$

Note, either F or T_a or both can be varied to vary D and thereby vary E_o

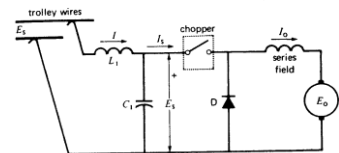


Figure 22.17 Direct-current series motor driven by a chopper. The chopper is not a switch as shown, but a force-commutated SCR.

Example 22-5

A trolley bus is driven by a 150 HP, 1500 rpm, 600V series motor. The nominal full load current is 200A and the total resistance of the armature and field is 0.1Ω . The bus is fed from a 700V dc line. A chopper controls the torque and speed. The copper frequency varies from 50 Hz to 1600 Hz but the on time T_a is fixed at $600 \mu\text{s}$. Calculate

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Example 22-5

- The chopper frequency and the current drawn from the line when the motor is at standstill and drawing a current of 240A.
- The copper frequency when the motor delivers it rated output.

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Example 22-6

Referring to Example 22-5 and fig 22.18a, calculate the peak value of currents I_s and I when the motor is at standstill.

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Chapter 22

Motor Drive via DC to DC switching converter
Operation in all 4 quadrants -

$$E_d = 1.35 E$$

$$E_{LL} = E_h (2 D - 1)$$

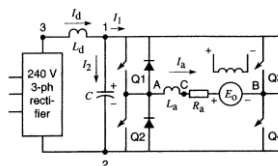


Figure 22.20
DC motor controlled by a 4-quadrant dc-to-dc converter.



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Example 22-7

A 25 HP, 250V, 900 rpm dc motor is connected to a dc to dc converter that operates at a switching frequency of 2 kHz. The converter is fed by a 6 pulse rectifier connected to a 240V, 3 phase, 60 Hz line (Fig 22.21a). A $500 \mu\text{f}$ capacitor C and an inductor L_d act as filters. The armature resistance and inductance are respectively $150 \text{ m}\Omega$ and 4 mH. The rated dc armature current is 80A. We wish to determine the following:

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Example 22-7

- The required duty cycle when the motor develops its rated torque at rated speed
- The waveshape of current I_1 , I_2 , and I_a
- The waveshape of voltages E_{12} and E_{ab} .

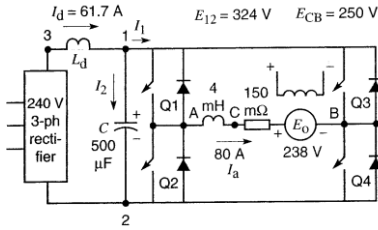
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Example 22-7



Chapter 22

$\Delta I_a = A / L_a$

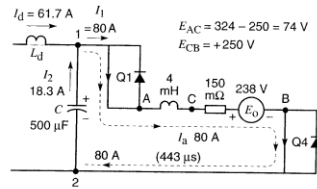


Figure 22.21b
Circuit when Q1 and Q4 are "on." Current I_a is increasing. $E_{CA} = -74$ V.

Chapter 22

$\Delta I_a = A / L_a$

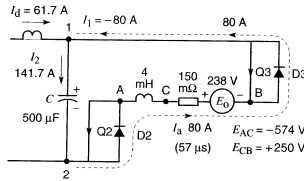
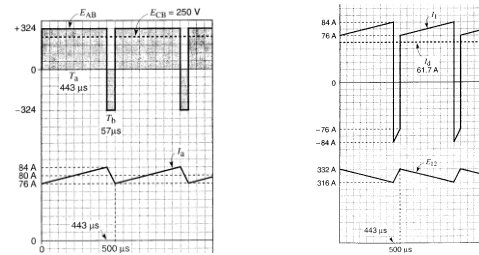


Figure 22.21c
Circuit when D2 and D3 are conducting. Current I_a is decreasing.

Chapter 22

Waveshapes of current / voltage in example 22- 7



Example 22-8

We now consider the question of dynamic braking. The same motor is used in example 22-7 and we assume it is running at 900 rpm at the moment that braking is applied. Further assume that the inertia of the motor and its load is very large. As a result the speed can not change quickly. The connection between the convert and 6 pulse rectifier is removed and a braking resistance of 20Ω is connected between terminals 1 and 2 along with the $500\mu\text{F}$ capacitor (fig 22.22).

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Example 22-8

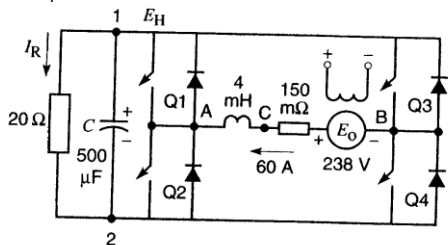
We assume that a braking torque equal to 75% of nominal torque is sufficient. Consequently, the required armature current is $0.75 \times 70\text{A} = 60\text{A}$
The switching frequency remains unchanged at 2 kHz. We wish to determine the following

- The voltage across the resistor
- The duty cycle required
- The braking behavior of the system

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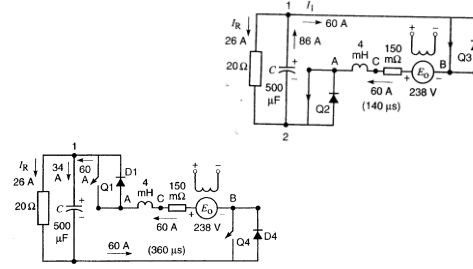
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Example 22-8



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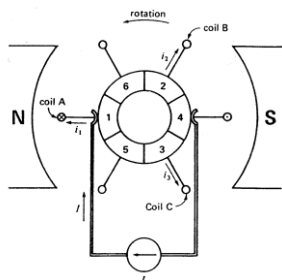
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Chapter 22

Special Current Fed DC Motor



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Chapter 22

Brushless DC Motor
DC current source ->
Torque in direction shown ->
Commutator - DC->AC
6 segments -> 60° conduction
 $T = k I B$
 T = motor torque (N m)
 I = current in conductor (A)
 B = average flux density surrounding conductor
 k = constant dependent on # of turns per coil and size of armature

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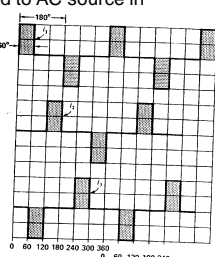


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DC current in source converted to AC source in armature winding, frequency is;
 $f = p n / 120$

Commutator generates AC current in armature to cause rotation
Speed is balance between T_I and T_m



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Replace Commutator with slip rings - Reversing switch between source and ring
Synchronize switching to rotation
Same effect as commutators

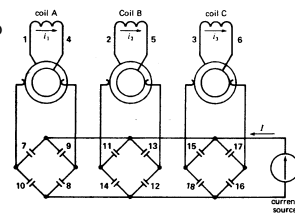


Figure 22.27 The commutator can be replaced by an array of mechanical switches and a set of slip-rings.



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Slip Rings would be maintenance –
If put Field on rotor, Armature on stator, reduced slip ring maintenance requirements

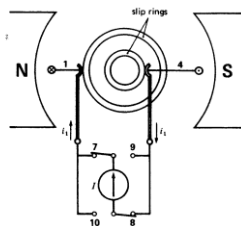


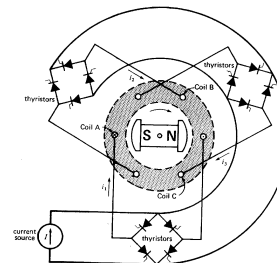
Figure 22.28
Circuit showing how current is controlled in coil A.



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Armature on stator
GTO switches
GTO synched to rotor speed
Reduce switches by using converter
The armature is now stator and switches are thyristors.

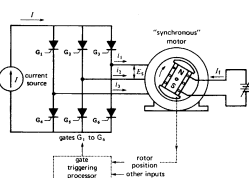


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Important properties:
Never “pull out” when triggering related to rotor position
GTO device PF lead, lag or unity (not for LCI)
Can be motor or generator

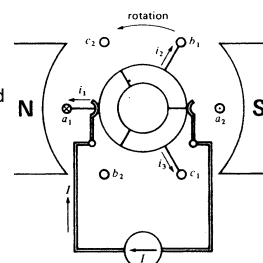
Brushless motor driven by converter.



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If AC source frequency Fixed, speed fixed.
Now can “slip pole” (when switching related to rotor position – closed loop
When switching fixed, open loop)



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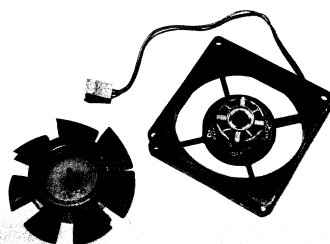


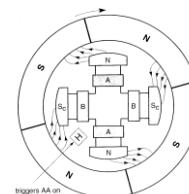
Figure 22.32
This miniature blower, rated at 1 W, 12 V dc, 2500 r/min, is driven by a brushless dc motor. The 7-blade impeller on the left contains a circular 4-pole permanent magnet that constitutes the revolving field. The stationary armature on the right consists of four coils that are commutated by an electronic switch. The switch is timed by a position-sensing detector; together they behave like a pair of brushes riding on a 4-segment commutator.



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Example of Brushless DC motor
12V, 1W brushless DC motor. Coil stationary. Hall detector H triggers coils A on and B off



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H pickup provides trigger signal to Q1 and Q2

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AC synchronous motor / generator natural transition between DC motor control theory and AC motor control theory

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Chapter 23 – Control of AC Motors

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Chapter 23

Where DC motors controlled by controlling Voltage and Current, AC motors controlled with Voltage and Frequency

Types of AC drives –

- Static Frequency Changers
- Static Voltage Changers
- Rectifier / Inverter Systems with Line Commutation
- Rectifier / Inverter Systems with Self Commutation
- PWM Systems

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VFD standards –

NEMA “Application Guide For AC Adjustable Speed Drive Systems”

Available Free at: <http://www.nema.org/>

IEEE Std 958 “Guide for Application of AC Adjustable-Speed Drives for Electric Power Generating Stations”

IEEE Std 1566 “Standard for Performance of Adjustable Speed AC Drives Rated 375 kW and Larger”

Available at: <http://www.ieee.org/standards>

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IEEE Std 1566 – sample datasheet (purchaser)

Annex A – Technical Data Sheet
(To Be Completed By Purchaser)

Project Reference: Spec. Reference: _____ Date: _____

System of units: SI SI plus US standard

Power System One-Line Diagram Provided Yes No Details

Supply system voltage:

2400 V 3300 V 4160 V 6900 V 13800 V Other _____ V +/- _____ %

Short circuit level _____ MVA Line frequency: 60 Hz 50 Hz

Point of common coupling (PCC) _____ Required Telephone Influence (TI) at PCC _____

Average Demand Current (I_d) _____ Other harmonic requirements: _____

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IEEE Std 1566 – sample datasheet (Vendor)

Annex B – Technical Data Sheet

(To Be Completed By Vendor)

Project Reference: _____ Spec. Reference: _____

General Information:

Vendor: _____ Manufacturing location: _____

Nearest available service reps location from customer site? _____

Weight of heaviest component removable for maintenance/troubleshooting _____ kg

Drive weight _____ kg Drive dimensions (WxDxH) _____ mm

Transformer/reactor weight _____ kg Transformer / reactor dimensions (WxDxH) _____ mm

Other auxiliary equipment (list) _____

Device _____ Weight _____ kg Dimensions (WxDxH) _____ mm

_____ kg Dimensions (WxDxH) _____ mm

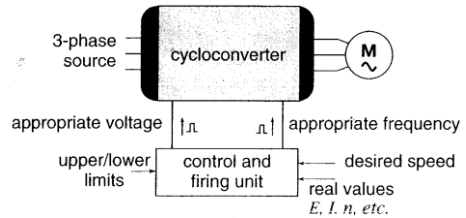
_____ kg Dimensions (WxDxH) _____ mm



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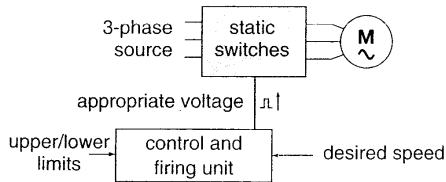
Static Frequency Changer - convert f_{line} to f_{load}



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Static Voltage Controller – Vary AC voltage to motor to control torque / speed (also used to softstart)



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Chapter 23

Rectifier / Inverter w/ line commutation – AC to DC to AC conversion. Rectifier uses Line to commutate. Inverter uses Motor to commutate (LCI). Used on Synchronous and Wound Rotor Motors. (why not induction machines?)

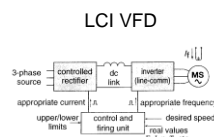


Figure 23.3 Variable-speed synchronous motor drive using a controlled rectifier and a line-commutated inverter fed from a dc link current source (see Section 23.2).

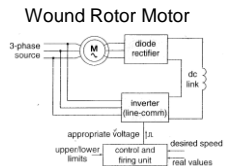
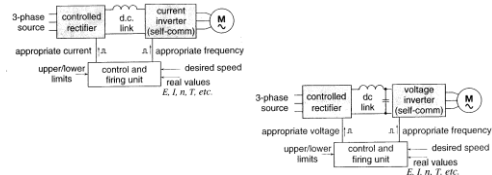


Figure 23.4 Variable-speed drive for a wound-rotor induction motor (see Section 23.12).

Chapter 23

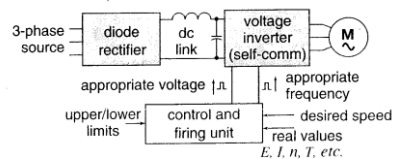
Rectifier / Inverter w/ self commutation – AC to DC to AC conversion. Rectifier uses self commutation. Used on squirrel cage induction motors that can not provide commutation energy.



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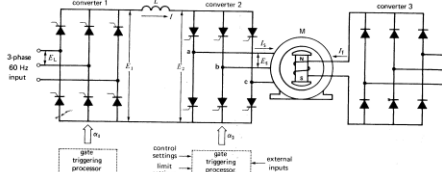
PWM system – AC to DC to AC conversion. Used on induction motors.



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Synchronous motor current source drive –
 Operate like brushless DC motor (control Ia & If)
 $E_s \propto \text{speed} \& I_f$. Gate controlled by rotor position.
 Speed controlled by Ia or If.



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Converter 2 in inverting mode –
 $E_2 = 1.35 E_s \cos \alpha_2$

E_2 = dc voltage generated by converter 2 (V)
 E_s = effective line to line stator voltage (V)
 α_2 = firing angle of converter 2 (degree)

Converter 1 in rectifying mode -
 $E_1 = 1.35 E_L \cos \alpha_1$

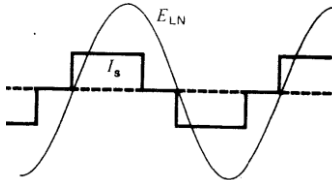


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Chapter 23

Triggered to provide leading PF – provide var for reactive power needed by converter 2 –
 Regen brake by Converter 1 invert, Converter 2 rect, inverting E1 and E2 (Idc same direction)



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Example 23-1

A 3 phase synchronous motor rated at 200 kW, 480V, 60 Hz, 450 rpm is connected to a drive similar to that shown in fig 23.8. The three phase electric utility voltage is 600V, 60 Hz. The motor runs at a speed of 535 rpm. The effective terminal voltage is 511V and the motor draws an effective line current Is of 239A at a power factor of 95%. The motor has an efficiency of 93%. Neglecting the losses in the converts, calculate;



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Example 23-1

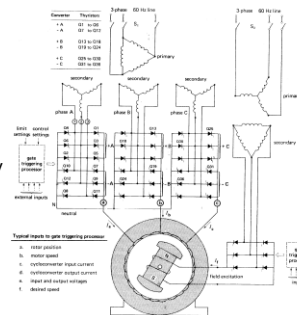
- The frequency applied to the stator
- The fundamental component of the stator current Is
- The current I flowing in the dc link.
- The firing angle α_2 of converter 2
- The voltage E_2 of the dc link
- The firing angle α_1 of converter 1
- The reactive power supplied to converter 1
- The mechanical power developed by the motor



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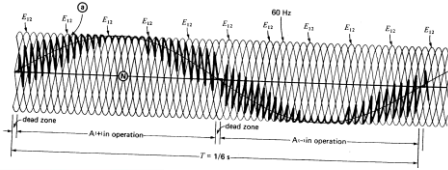
Cycloconverter –
 each leg has 2 converters
 $F_o < F_{line}$
 Input PF lagging, output around unity
 Firing angle varied for each line cycle
 Isolation transformer to isolate each phase



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Chapter 23

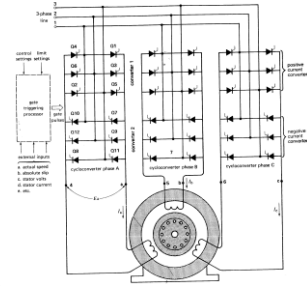
Line voltage typically based on max op freq, not line freq – improves PF by reducing α
Voltage between line A and N



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Chapter 23

Instead of isolation transformers, isolated windings can be used
Only 1 converter on at a time.
Separate cooling typical.



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Example 23-2

A 3 phase, squirrel cage induction motor has a full load rating of 25 HP, 480V, 1760 rpm, 60 Hz. The three independent windings each carry a rated current of 20A.
This motor is connected as shown in Fig 23.15. The cycloconverter is connected to a 3 phase, 60 Hz line and generates a frequency of 8 Hz. Calculate the approximate value of the following.

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Example 23-2

- a. The effective voltage across each winding
- b. The no load speed
- c. The speed at rated torque
- d. The effective current in the windings at rated torque
- e. The effective voltage of the 60 Hz line

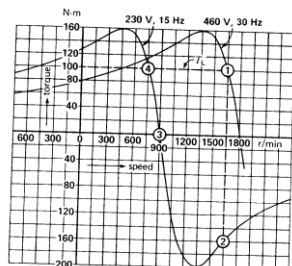
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Chapter 23

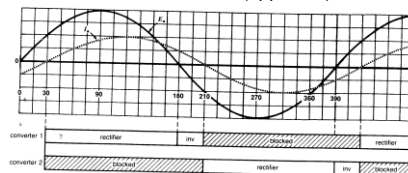
Torque speed curve for variable speed
If V/F constant, flux constant, peak torque same



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Chapter 23

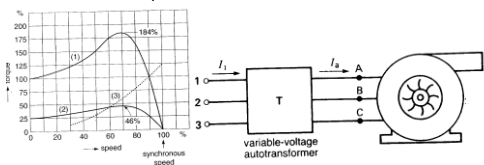
Converter 1 on when I +, Converter 2 on when I –
Converter 1 rectifier when Ea +
Converter 1 inverter when Ea –
Converter 2 rectifier when Ea – (same as Ia)
Converter 2 inverter when Ea + (opp as Ia)



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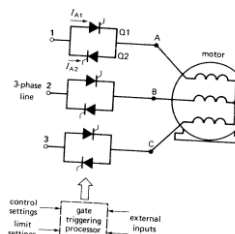
Static voltage controller – adjust voltage (not freq)
 $T \propto V^2$
 Greater slip.
 Increased rotor heating
 Small motor only



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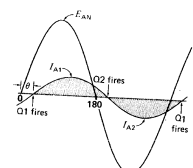
Solidstate voltage reduction
 Adjusting delay angle –
 Reduced Vac to motor
 Vrms not linear to angle



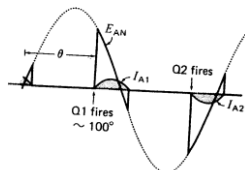
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Chapter 23

Waveform at full conduction



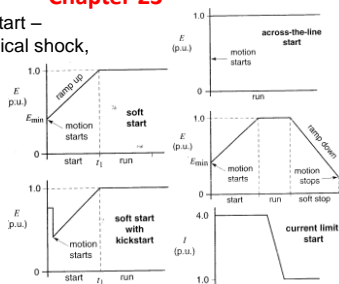
Waveform at partial conduction



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Chapter 23

Solidstate softstart –
 reduce mechanical shock,
 reduced peak
 start current.
 5 basic type
 Ramp down vs
 DC injection.



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Chapter 23

Terminology –
 Soft start
 Reduced Voltage Starter (RVS)
 Solid State Reduced Voltage Starter (SSRVS)
 Purpose of softstart
 Reduce the inrush current during start
 Reduce peak torque during start.
 Brief review of motor theory for how soft start
 effects these parameters

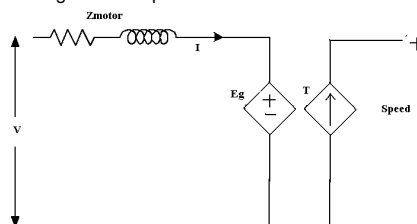
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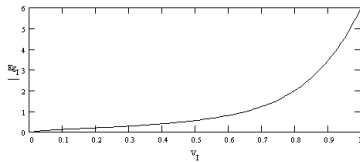
Simplified SLE -
 Power = $E_g \cdot I = T \cdot \text{Speed}$



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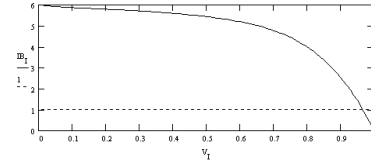
How does E_g vary as motor accelerates to full speed?
 At low speed, E_g changes little = constant impedance device.
 At high speed, E_g changes greatly = constant HP device.



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$I_{running} = (V - E_g) / Z_{motor}$
 At locked rotor, $E_g = 0$
 $I_{starting} = V / Z_{motor}$
 As motor increases speed, E_g increases
 Motor current decays as E_g increases



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LRA

HP	RATED VOLTAGE					
	200V	230V	460V	575V	2300V	4000V
5	23	28	10	8		
7.5	29	35	12	10		
10	34	38	15	12		
15	46	48	20	16		
20	57	58	25	20		
25	74	84	30	26		
30	106	92	46	37		
35	146	127	63	51		
40	188	162	81	66		
50	267	232	116	93		
75	333	298	145	116		
100	478	365	187	146		
150	688	426	257	174		
200	867	589	348	232		
300	1314	725	362	258		
400	1800	870	435	348	87	50
500	2250	1085	547	434	108	62
750	3365	1550	725	580	145	83
1000	4480	1915	907	726	181	104
1500	6700	2710	1365	1068	271	152
2000	8920	3505	1823	1410	358	197
2500	11140	4300	2281	1752	445	242
3000	13360	5095	2739	2094	532	287
4000	17800	6880	3652	2796	716	381
5000	22240	8665	4565	3498	900	475

The locked-rotor current of Design B, C and D constant speed induction motors, when measured with rated voltage and frequency applied and with rotor locked, shall not exceed the above values.
 Reference: NEMA Standards MG-1 12.35.



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NEMA design E
 LRA

MAXIMUM LOCKED-ROTOR CURRENTS THREE-PHASE SQUARE FLUX MOTORS NEMA DESIGN E

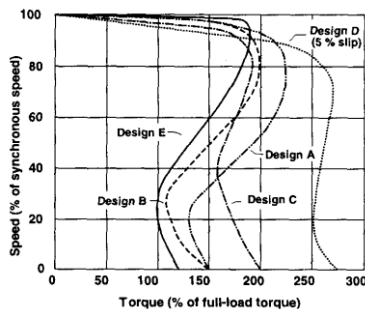
HP	RATED VOLTAGE					
	200V	230V	460V	575V	2300V	4000V
5	33	35	10	8		
7.5	39	38	13	10		
10	48	40	16	12		
15	68	50	20	16		
20	84	58	25	20		
25	110	73	30	26		
30	140	92	40	34		
35	180	110	50	43		
40	210	130	60	51		
50	280	160	80	68		
75	360	200	100	90		
100	480	260	130	120		
150	640	340	170	160		
200	800	420	210	200		
250	960	500	250	240		
300	1120	580	300	280		
400	1440	760	400	380		
500	1760	940	500	480		
750	2640	1400	750	720		
1000	3520	1860	1000	960		
1500	4800	2520	1500	1320		
2000	6080	3180	2000	1680		
2500	7360	3840	2500	2040		
3000	8640	4500	3000	2400		
4000	11520	5920	4000	3200		
5000	14400	7340	5000	4000		

The locked-rotor current of Design E constant speed induction motors, when measured with rated voltage and frequency applied and with rotor locked, shall not exceed the above values.
 Reference: NEMA Standards MG-1 12.35A.



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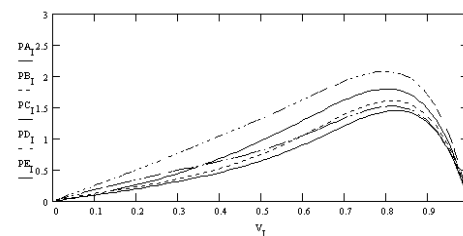
Speed/
 Torque



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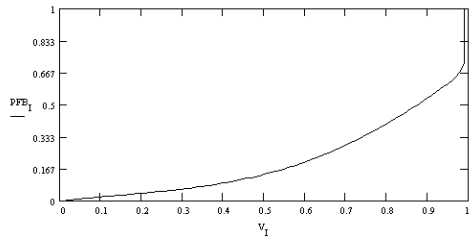
Power vs Speed



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PF vs Speed



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Reduction of current proportional to reduction of voltage.
Reduction of torque proportional to square of reduction of voltage.

Voltage	Starting Current	Starting Torque
100%	600%	100%
90%	540%	81%
80%	480%	64%
70%	420%	49%
60%	360%	36%
50%	300%	25%



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Ensure sufficient motor available torque to start the motor.

Acceleration Time (Tacc) is defined as:

$$T_{acc} = [WK^2 \times RPM] / [308 \times Avg \text{ Acc Trq}]$$

Average Acceleration Torque (Avg Acc Trq) is defined as:

This definition does not account for load:

$$Avg \text{ Acc Trq} = (((FLT+BDT)/2) + BDT + LRT)/3$$

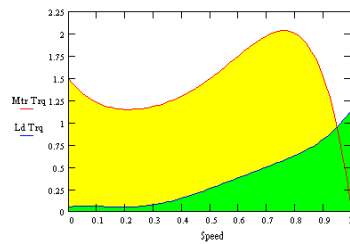
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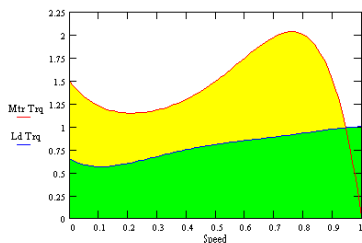
ATL start, variable torque load



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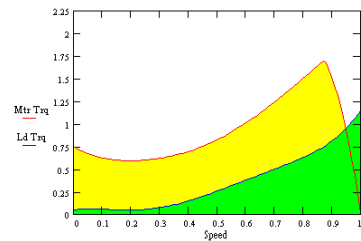
ATL start – constant torque load



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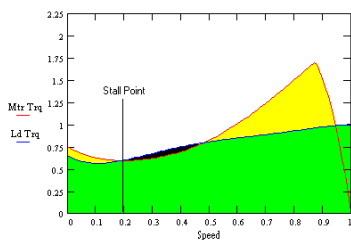
RVS (I limit) – variable torque load



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RVS (Limit) – constant torque load



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Chapter 23

Required = Tmotor + Tload
Evaluate motor and load torque curves.
Ensure sufficient motor accelerating torque exists throughout acceleration curve.
API 841 recommends Tmotor > 1.1 * Tload throughout the speed range.

$$\text{Required} = \left[\frac{WK^2 \times \Delta RPM}{308 \times \text{Avg Acc Trq}} \right] + T \text{ load}$$



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Chapter 23

Motor heating of ATL vs RVS

Dependent on load torque during start.
Motor Ploss is proportional to I².
Total energy in motor during start is Ploss * time.
Motor available torque is proportional to I².
Accelerating time is inversely proportional to AAT.



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Chapter 23

Heating example (No Load Start)–

If current 1/2
Ploss = 1/4
Tmotor = 1/4
Taccel = Tmotor = 1/4
t_start = 4
Energy = Ploss * T_start = same



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Heating Example (under load start) –

If current 1/2
Ploss = 1/4
Tmotor = 1/4
Taccel = Tmotor - Tload < 1/4
t_start > 4
Energy = Ploss * Time > ATL
Reduce Load to Reduce Mtr Heating or shorten accel time and raise I limit.

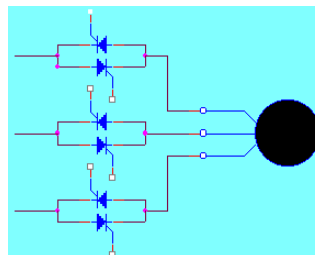


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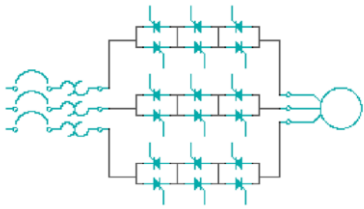
2300V or less



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> 2300 V



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Adjustments –
Torque point
Accel time / Decel time
Boost time/level
Current limit level
Shear pin level
Overload setting
DC brake time

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Applications for reduced voltage start
Pump Applications; prevent water hammer
Mech. transmission issues; reduce torque (electronic shear pin)
Weak distribution lines; limit voltage dip during start
Electronic braking; actively stop loads
Damp applications; motor heating

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**Next Week – Chapter 22 continued -
Control of AC Motors**

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**End of Session 11:
Control of AC
& DC Motors**

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