

Welcome to

# Electric Machines & Drives

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**Session 12:  
Control of AC  
Motors**

Fall 2011




## Session 12

➤ **Chapter 23 – Control of AC Motors**



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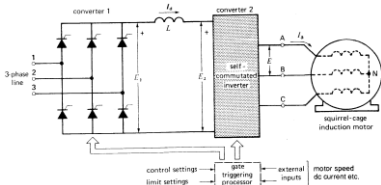

## Chapter 23 – Control of AC Motors



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## Chapter 23

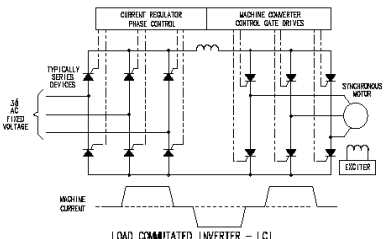

Self Commutated Inverter – (forced commutation) – generate frequency and voltage  
 Internal commutating circuitry – reactive power source to commutate off. VSI and CSI types.

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## Chapter 23

### LCI Load Commutated Inverter





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## Chapter 23

- SCR rectifier
- L Filter
- Synchronous Machines
- Match motor to drive
- PF reflected to line
- Low speed cogging

6



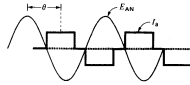
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CSI – Constant Idc – DC link choke  
 CSI – motor current rectangular pulse of 1200  
 Voltage sinusoidal  
 Delay function of motor PF  
 Can operate in quadrant 1 or 4 in fwd or  
 Quadrant 2 or 3 in rev  
 Typical turn down 10:1



Motor



Generator



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**Example 23-3**

A 40 HP, 1165 rpm, 460V, 52A, 60 Hz, 3 phase motor is driven by a current source frequency converter. The efficiency of the motor is 88% and that of the inverter is 99.4%. Referring to Fig 23.24, calculate the approximate value for the following

- The dc power input to converter 2
- The current in the dc link
- The dc voltage E1 produced by converter 1

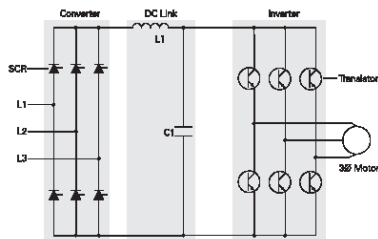


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8

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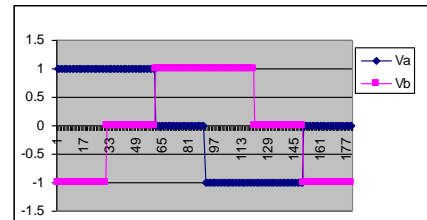
VSI – Voltage source Inverter



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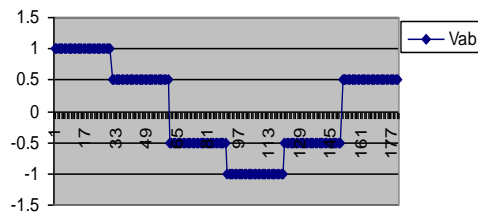
Van and Vbn



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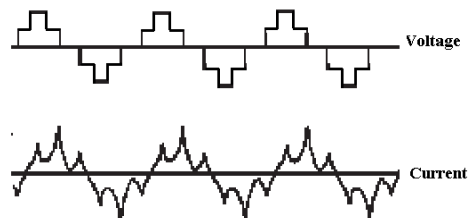
Vab = Va - Vb



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**Chapter 23**

Motor Voltage and Current



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**Chapter 23**

SCR rectifier  
 L/C Filter  
 Vrms out controlled by rectifier  
 Low speed cogging  
 High load harmonic

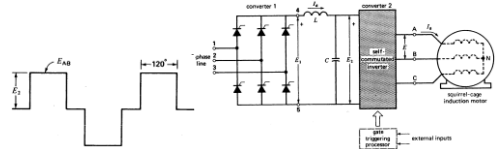
13



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VSI – constant Vdc – DC capacitor  
 Voltage Output square wave 120° pulses  
 Allow for multiple motor / converter 2 to one common DC bus.  
 Six Step Drive – Six steps per cycle (every 60°)



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To adjust output voltage as speed changes, Ed is varied by converter 1  
 Above base speed, Ed constant, P constant, T decreases ( $P \propto T \times \Omega$ )  
 To achieve regen brake, third converter needed as current direction reverses, not Id like CSI  
 Dynamic Brake possible with DC bus resistor

Eline = 0.78 Ed  
 Eline = effective fundamental component of line to line voltage (V)  
 Ed = dc voltage at input to converter (V)

15

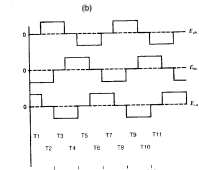
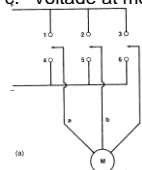


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**Chapter**

- a. Mechanical representation of inverter
- b. Switching sequence of inverter
- c. Voltage at motor terminal

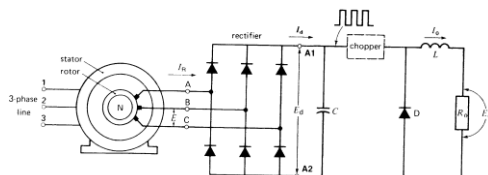
	Time intervals										
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
contacts											
1	x	x	x	x							x
2					x	x	x	x			x
3	x	x	x						x	x	
4				x	x	x	x				x
5	x	x	x					x	x	x	
6				x	x	x					x



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**Chapter 23**

Chopper speed control of wound rotor motor -



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**Chapter 23**

Chopper Speed Control of Wound Rotor Motor –  
 6 pulse rectifier on rotor winding, chopper across Edc with RI on output of chopper.  
 R apparent is :

$$R_d = R_o / D^2$$

(note correction from book – 21.22 that says)

$$R_d = R_o / D_2$$

$$R_d = R_o / D_2$$

18



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**Example 23-4**

The wound rotor motor shown in Fig 23.28 is rated at 30 kW (40 HP), 1170 rpm, 460V, 60 Hz. The open circuit rotor line voltage is 400V, and the load resistor  $R_o$  is  $0.5 \Omega$ . If the chopper frequency is 200 Hz, calculate time  $T_a$  so that the motor develops a torque of 200 Nm at 900 rpm.

19



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**Example 23-5**

In example 23-3, calculate the magnitude of the current pulses drawn from the capacitor.

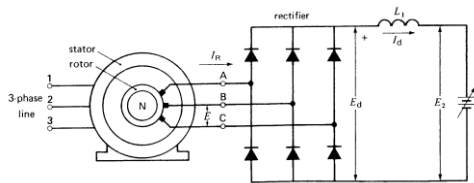
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Recovering power in a wound rotor induction motor – Replace resistor with Battery (reduced losses)



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$$E = s E_{oc}$$

$$E_d = 1.35 E$$

$$S = E_2 / (1.35 E_{oc})$$

$$E_2 = 1.35 E_t \cos \alpha$$

$E_2$  = dc voltage developed by the inverter (V)

$E_t$  = secondary line voltage of transformer T (V)

$\alpha$  = firing angle (degrees)

22



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$E_{oc}$  is fixed, therefore  $S \propto E_2$  (Battery Voltage)  
Synch speed,  $S=0$ ,  $E_2=0$   
Zero speed,  $S=1$ ,  $E_2 = 1.35 * E_{oc}$   
Variable battery in reality is inverter back to line

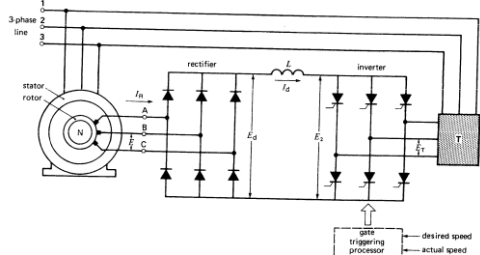
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**Chapter 23**

Inverter back to line



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**Chapter 23**

Inverter fed wound rotor motor Torque / Speed.

Speed control fine  
Efficiency high  
Reactive power absorbed by inverter  
Economical speed control as inverter only fraction of stator ampacity

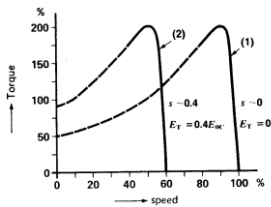


Figure 23.31a Torque-speed characteristics of a wound-rotor motor for two settings of voltage  $E_r$ .



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**Example 23-6**

A 3 phase, 3000 HP, 4000V, 60 Hz, 8 pole, wound rotor induction motor drives a variable speed centrifugal pump. When the motor is connected to a 4160V line, the open circuit rotor line voltage is 1800V. A 3 phase, 4160V/480V transformer is connected between the inverter and line (fig 23.32). If the motor has to develop 800 kW at a speed of 700 rpm, calculate the following;

26



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**Example 23-6**

- The power output of the rotor
- Rotor voltage and line voltage
- Link current  $I_d$  and rotor current
- Firing angle of the inverter
- Current in the primary and secondary lines of the transformer T

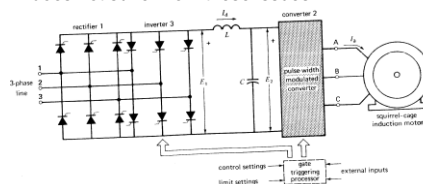
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PWM drives – (note below pertains to motor side)  
LCI / VSI / CSI – high 5<sup>th</sup> / 7<sup>th</sup> harmonic, torque pulsations at 6 \* motor freq  
PWM does not suffer from these issues.



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Fundamental frequency 0.1hz to 400 hz  
Carrier 200hz to 20khz typical (type of switch)  
Weighted average approaches sine wave.  
Harmonics are carrier and multiples

Waveform of one phase

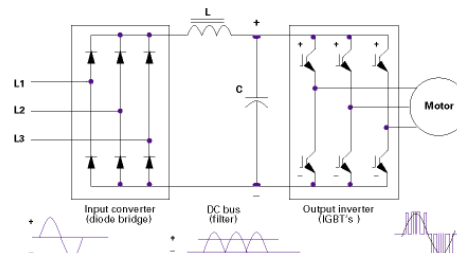
Waveform at 1/2 voltage



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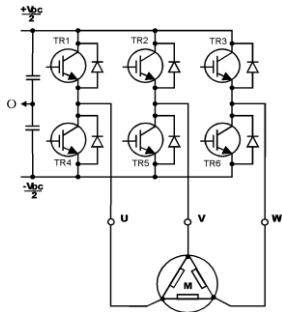
PWM VSI



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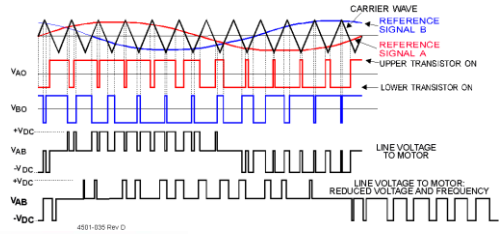
Inverter section



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Sine Coded PWM



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VFD ratings –  
VFD is current rated not HP rated  
Lower RPM motors may have  
higher FLA  
Constant Torque Rated VFD =  
150%, 1min  
Variable Torque Rated VFD =  
110%, 1min

Rise in T decreases rated ampacity  
T increases, rated current  
decreases.

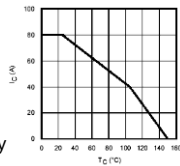


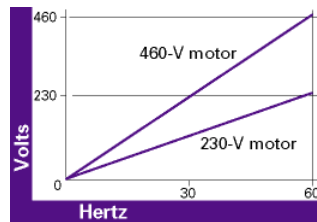
Fig. 1 Maximum DC Collector Current vs. Case Temperature



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Constant Torque to 2\* base speed



$$\frac{460 \text{ V}}{60 \text{ Hz}} = 7.67 \frac{\text{V}}{\text{Hz}}$$

If 230-VAC  
power line:

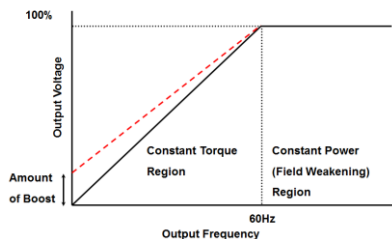
$$\frac{230 \text{ V}}{60 \text{ Hz}} = 3.83 \frac{\text{V}}{\text{Hz}}$$



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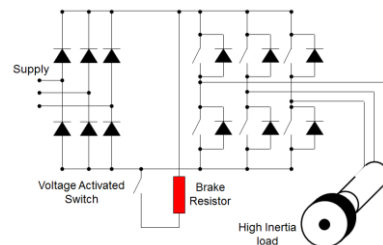
Compensate for stator resistance



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Dynamic Braking



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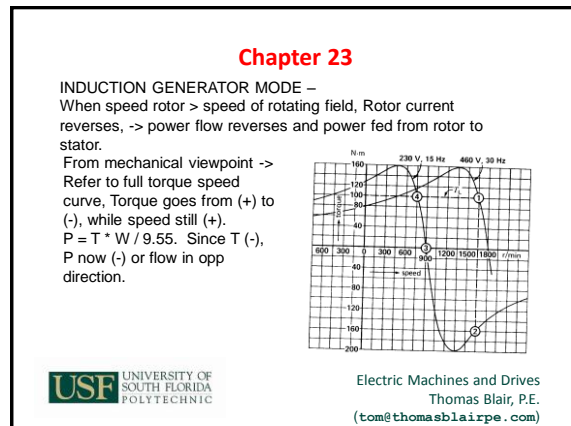
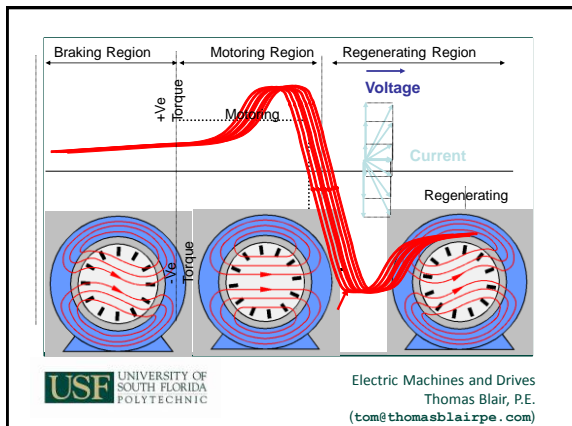
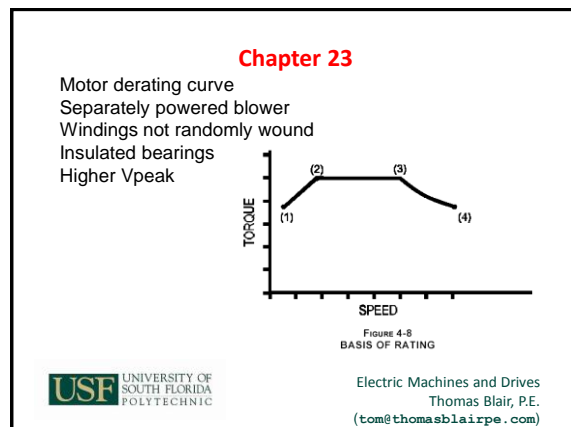


Table 5-1  
 MAXIMUM SAFE OPERATING SPEED FOR STANDARD DESIGN A AND B DIRECT DRIVE IFS SHAFTS FOR MOTORS ABOVE THE 20 FRAME SQUARE-CAGE INDUCTION MOTORS  
 (Data Excludes Full-Cage Open-Drum)

Motor Frame	Maximum Speed of 60 Hz					
	3000	1800	1200	900	720	600
14	7200	3600	2400	1800	1440	1200
15	7200	3600	2400	1800	1440	1200
16	7200	3600	2400	1800	1440	1200
17	7200	3600	2400	1800	1440	1200
18	7200	3600	2400	1800	1440	1200
19	7200	3600	2400	1800	1440	1200
20	7200	3600	2400	1800	1440	1200
21	7200	3600	2400	1800	1440	1200
22	7200	3600	2400	1800	1440	1200
23	7200	3600	2400	1800	1440	1200
24	7200	3600	2400	1800	1440	1200
25	7200	3600	2400	1800	1440	1200
26	7200	3600	2400	1800	1440	1200
27	7200	3600	2400	1800	1440	1200
28	7200	3600	2400	1800	1440	1200
29	7200	3600	2400	1800	1440	1200
30	7200	3600	2400	1800	1440	1200
31	7200	3600	2400	1800	1440	1200
32	7200	3600	2400	1800	1440	1200
33	7200	3600	2400	1800	1440	1200
34	7200	3600	2400	1800	1440	1200
35	7200	3600	2400	1800	1440	1200
36	7200	3600	2400	1800	1440	1200
37	7200	3600	2400	1800	1440	1200
38	7200	3600	2400	1800	1440	1200
39	7200	3600	2400	1800	1440	1200
40	7200	3600	2400	1800	1440	1200
41	7200	3600	2400	1800	1440	1200
42	7200	3600	2400	1800	1440	1200
43	7200	3600	2400	1800	1440	1200
44	7200	3600	2400	1800	1440	1200
45	7200	3600	2400	1800	1440	1200
46	7200	3600	2400	1800	1440	1200
47	7200	3600	2400	1800	1440	1200
48	7200	3600	2400	1800	1440	1200
49	7200	3600	2400	1800	1440	1200
50	7200	3600	2400	1800	1440	1200

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**CONSTANT TORQUE OPERATION -** To develop same torque, slip (in RPM) must be same regardless of applied frequency (or direction) -> for constant torque V/F must be same to maintain same flux density (B).

41

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Where slip ->  
 $S = (n_s - n) / n_s$

42

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#### CONSTANT POWER OPERATION –

Above base speed, V constant (there is exception to this)

V/F reduced as F increased. This reduced flux density (B). Torque is reduced as speed increase.

$P \propto T \cdot \text{speed} = \text{constant}$  in this area.

Since Torque is reduced, slip is increased (in RPM)

43



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Determine AIC of drive and SCA of system

If SCA of system > AIC of drive, install current limiting fusing

May need to add reactor

UL508C requirements listed below

Horsepower	AIC Ratings
1.5 – 50	5000
51 – 200	10000
201- 400	18000
401 – 600	30000
601 – 900	42000



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#### Load Characteristics

Constant HP

Constant Torque

Variable Torque

HP =  $\frac{\text{Torque (lb. ft)} \times \text{RPM}}{5250}$

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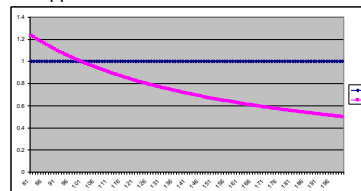
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Torque inverse to speed

Power independent of speed

V/F inverse to speed

High inertia applications



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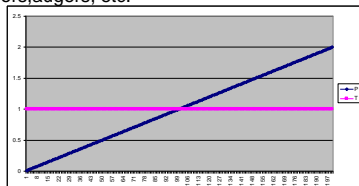
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Torque independent of speed

HP proportional to speed

V/F independent of speed

Conveyors, augers, etc.



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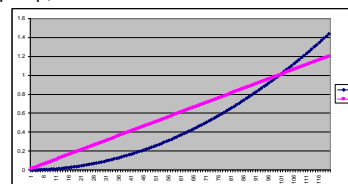
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Torque proportional to speed

Power proportional to square of speed

V/F proportional to speed

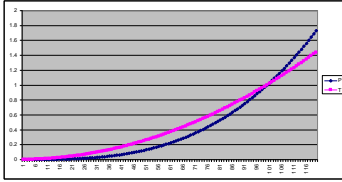
PD pump, mixer



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Torque proportional to square of speed  
 Power proportional to cube of speed  
 V/F proportional to square of speed  
 Centrifugal pump, blower



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**Chapter 23**

$$HP = \frac{CFM \times PSI}{229 \times \text{Efficiency of Fan}}$$

CENTRIFUGAL AFFINITY LAWS

$\frac{Flow_1}{Flow_2}$	=	$\frac{RPM_1}{RPM_2}$
$\frac{Pres_1}{Pres_2}$	=	$\frac{(RPM_1)^2}{(RPM_2)^2}$
$\frac{HP_1}{HP_2}$	=	$\frac{(RPM_1)^3}{(RPM_2)^3}$



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**Chapter 23**

Power  $\propto$  Q x H

Power =  $\rho g H Q / \eta$

- $\rho$  = Density
- $g$  = Gravity const
- $H$  = Head
- $Q$  = Flow Rate
- $\eta$  = Pump Efficiency

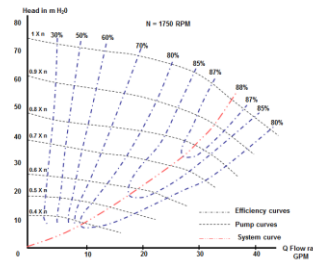
51



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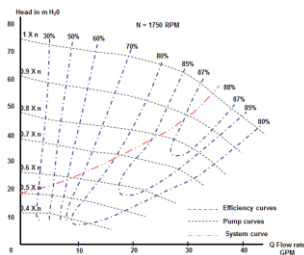
PUMP EFFICIENCY CURVES



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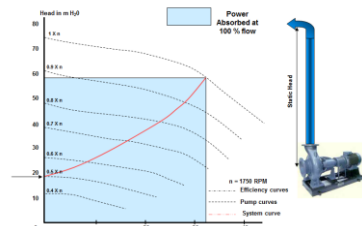
PUMP EFFICIENCY CURVES vs SYSTEM CURVE



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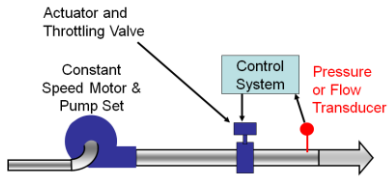
CONSTANT FLOW PUMP



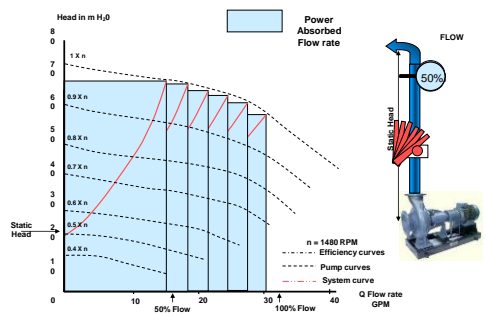
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**Chapter 23**

**THROTTLED SYSTEM**



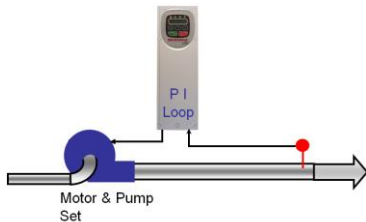
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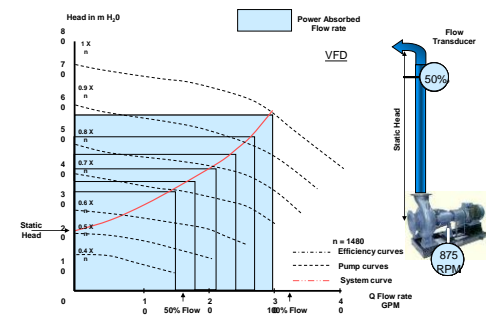
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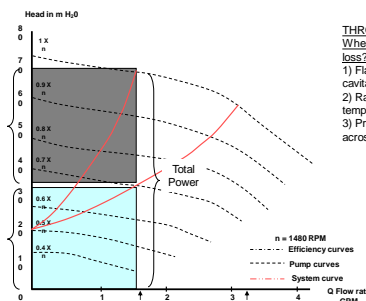
**VARIABLE SPEED SYSTEM**



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**THROTTLED**  
Where is the power loss?

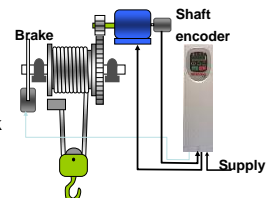
- 1) Flashing and cavitation
- 2) Raising liquid temperature
- 3) Pressure drop across valve



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**Hoist**

- Vector drive required
- Constant torque
- Full torque at zero speed
- Hoist regenerative on lowering load
- Motor oversized for cooling
- Drive oversized for peak torque



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### Lift

Vector drive required  
 Constant torque  
 Full torque at zero speed  
 Lift regenerative on raising empty car  
 Motor oversized for cooling  
 Drive oversized for peak torque

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### Trolley

Dynamic brake or Regenerative rectifier required  
 Constant torque (load dependant)  
 Vector drive required  
 May require rapid Acc/Dec

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### Winder / Unwinder

Vector drive required (Torque app)  
 Regen continuously  
 Dynamic brake  
 Motor oversized or forced cooled  
 Speed & torque limits used

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High Inertia Loads  
 Variable torque (cube)  
 Low Acc/Dec rates  
 Dynamic or DC braking for rapid deceleration rates  
 Spin starting sometimes required  
 Can present instability problems under light loads

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### Chapter 23

Conveyors

Constant torque  
 High brake away torque  
 Regen if vertical section  
 Low speed motor heating possible

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### Chapter 23

Screw Conveyor (Auger)

Constant torque  
 High brake away torque  
 Low speed motor over heating possible

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Variable torque (square)  
Often overloaded  
High start torque  
Torque increase with time  
Bypass common for LRT

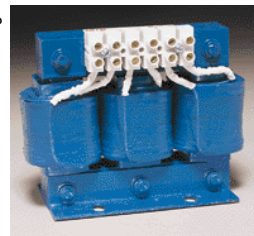


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3 Phase Reactor

IEEE Std 519, THDI < 5%  
Act to reduce the peak current seen by rectifier  
Reduce THDI  
Required if SCA>AIC  
Required if Voltage imbalance > 3%



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**Chapter 23**

Critical Lead Length

Pulse Rise Time uS	Critical Lead Length Meters	Critical Lead Length Feet
6	300	984.3
2	100	328.1
1	50	164.1
0.5	25	82
0.1	5	16.4
0.05	2.5	8.2

CLL = 100 m/u sec x Rise Time (u sec) / 2

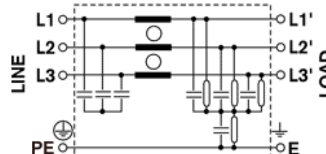
69



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**Chapter 23**

LINE SIDE HARMONIC FILTER



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**Chapter 23**

IEEE 519 THDI (TDD) REQUIREMENTS

Maximum Harmonic Current Distortion in % of I <sub>L</sub>						
Individual Harmonic Order (Odd Harmonics)						
I <sub>sc</sub> / I <sub>L</sub>	< 11	11 < h < 17	17 < h < 23	23 < h < 35	35 < h	TDD
< 20*	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	#0
50-100	10.0	4.5	4.0	1.5	0.7	15.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 35% of the odd harmonic limits. TDD refers to Total Demand Distortion and is based on the average maximum demand current at the fundamental frequency, taken at the PCC.

\*All power generation equipment is limited to these values of current distortion regardless of I<sub>sc</sub> / I<sub>L</sub>.

I<sub>sc</sub> = Maximum short circuit current at the PCC  
I<sub>L</sub> = Maximum demand load current (fundamental) at the PCC  
h = Harmonic number



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IEEE 519 THDI (TDD) REQUIREMENTS

$$THD I := \sqrt{\sum_{M=2}^Z (I_M)^2} / I_1$$



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Other methods of improving THDI

- Phase multiplication (6 pulse system)
- Use 12 or 18 pulse systems (H=kn+/-1)
- Phase Shift = 360 degrees/(# Pulse)
- Line Reactor
- Drive Isolation Transformer (K-factor rated), 3% imp minimum.

73



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Harmonics and Power Factor

- PF\_disp = Displacement Power Factor
- PF\_dist = Distortion Power Factor
- V1rms = Fundamental RMS voltage
- I1rms = Fundamental RMS current

$$pf_{true} = \frac{P_{avg}}{V_{I_{rms}} I_{I_{rms}}} \cdot \frac{1}{\sqrt{1 + (THD_V / 100)^2}} \cdot \frac{1}{\sqrt{1 + (THD_I / 100)^2}}$$

$$pf_{true} = pf_{dsp} \cdot pf_{dist}$$



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K-Factor of Transformer

- Defined in UL 1561
- Ih = rms current value (pu) at harmonic h
- Harmonic currents = additional heating
- K-factor Xfmr > K-factor System

$$K = \sum_{h=1}^{h=h_{max}} I_h^2 \cdot h^2$$



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**Chapter 23**

RECOMMENDED K-FACTOR

TYPICAL LOAD k-FACTORS	
Electric discharge lighting	K-4
UPS with input filtering	K-4
Welders	K-4
Induction heating	K-4
PLCs / SS controls (other than VFDs)	K-4
Telecommunications equipment	K-13
UPS without input filtering	K-13
Multewire receptacle circuits in general care areas	
Health care facilities and classrooms of schools, etc.	K-13
Multewire receptacle circuits supplying inspection or testing equipment on an assembly or production line	K-13
Mainframe computer loads	K-20
Solid state motor drives (variable speed drives)	K-20
Multewire receptacle circuits in critical care areas	K-20
And operating/recovery rooms of hospitals	K-20



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K-FACTOR vs HARMONIC LOSS FACTOR

- Fhl defined in IEEE C57.110
- Ih = rms current value at harmonic h
- IR = rated current of xfmr
- Current effort – use Fhl not K factor

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} \left[ \frac{I_h}{I_1} \right]^2 h^2}{\sum_{h=1}^{h=h_{max}} \left[ \frac{I_h}{I_1} \right]^2} \quad K\text{-factor} = \left[ \frac{\sum_{h=1}^{h=h_{max}} I_h^2}{I_R^2} \right] F_{HL}$$

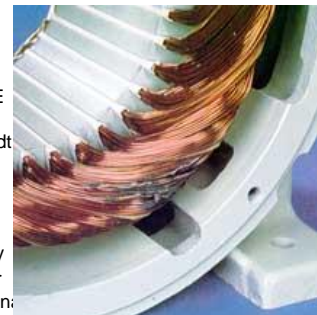


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**Chapter 23**

ISSUES WITH UNFILTERED MOTOR VOLTAGE

- PD due to high dv/dt
- More common on 480V and 600V motors
- General Purpose Motor Vpeak = 1KV
- Inverter Duty motor Vpeak = 3.1 \* nomin.



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**ISSUES W/ UNFILTERED MOTOR VOLTAGE**

Bearing currents due to capacitive coupling  
Insulated bearings and grounding strap will help to minimize damage

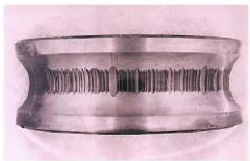


FIGURE 5-8  
FLUTED BEARING DAMAGE CAUSED BY ELECTRICAL CURRENT FLOW



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**ISSUES WITH UNFILTERED MOTOR VOLTAGE**

As shaft voltage increases, Bearing grease breaks down shorting out Cr.

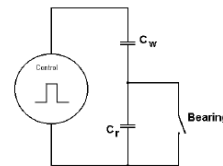
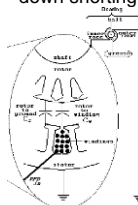


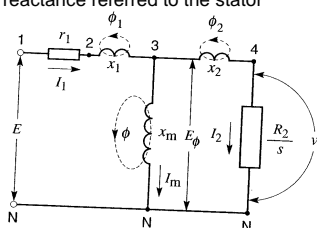
FIGURE 5-11  
COMMON MODE BASIC CIRCUIT



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**Equivalent circuit – Chapter 23**

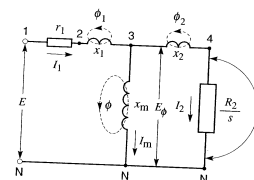
- R1 = stator resistance
- X1 = stator leakage reactance
- X2 = rotor leakage reactance referred to the stator
- R2 = rotor resistance referred to the stator
- Xm = stator magnetizing reactance
- S = slip (not slip speed)



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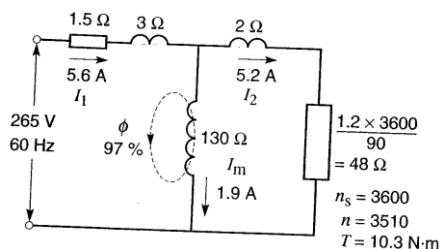
- Im is magnetizing current
- I2 reflection of torque producing current (rotor)
- I1 = Im + I2
- q links stator to rotor and produces B
- B and S produce Eq
- q1 and q2 are leakage
- qstator = q + q1 -> E2N
- qrotor = q + q2 -> E4N
- Pr (air gap power) = I2<sup>2</sup> \* R2/s
- Power resistance = R2/s = R2 Ns / S



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**Torque Boost – compensate for Rs at low frequency**



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**Chapter 23**

- Vector analysis of motor parameters –
- Im – magnetizing – maintain constant for constant B -> constant torque
- I2 – defines power transfer
- Open vector drive Measures I1 and, based on values of Rs, Xs, Xr, Xm, calculates I2 & Im
- Very low speed operation or full torque, zero speed, encoder used.



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### Chapter 23

Carrier Frequency –  
 Higher frequency, reduced audible noise  
 Higher switching losses (reduced current handling capability)  
 Switch Rise time ->  
 1. Voltage doubling at motor terminals  
 2. Uneven voltage distribution across coils

Use of inductors / filters to filter out carrier

85



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Control of 3 phase motors –  
 (for 2 pole motor), windings displaced 120°  
 7 combinations (7<sup>th</sup> is shorted windings)



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Flux distribution –  
 Starting at  $\theta_{s,0}$  initial condition A(+),B(-),C(-)  
 Change to A(+),B(-),C(+)  
 $\theta_s$  rotates to  $\theta_{s,20}$

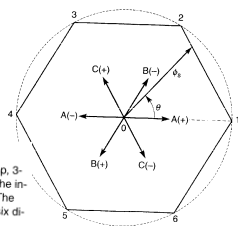


Figure 23.74b  
 Hexagonal path followed by the flux  $\phi_s$  in a 6-step, 3-phase converter. The amplitude and position of the instantaneous flux are indicated by the vector  $\phi_s$ . The six arrows emanating from the center show the six directions in which the flux can be moved.



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Flux distribution & Torque –  
 Torque limited between  $T_a, T_b$  defines switching order.  
 If  $T_m < T_b$ , - C(+) provides increase in Torque  
 If  $T_b < T_m < T_a$ , - B(-), provides smaller T increase  
 If  $T_m > T_a$ , A(+), provides reduction in Torque

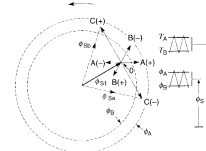


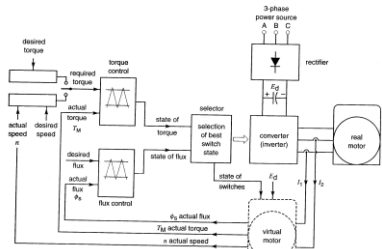
Figure 23.76  
 When  $\phi_{s1}$  is less than  $\phi_{s0}$ , the flux can be increased by selecting one of the following options: A (+), B (-), C (+), or C (-).



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Torque or speed control – load defines other parameter



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Common application, two drives on one motor / system –  
 One drive in control of speed (primary). Send signal from primary drive to secondary drive of torque and secondary drive control point is torque.

Ensure sharing of torque (current) between drives.

90



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VFD Benefits –  
 Starting current reduced to at or below motor FLA.  
 Motor starting torque available to 150% FLT.  
 Control characteristics easily adjusted.  
 Gain speed control of motor.  
 Elimination of mechanical control devices.  
 Motor protection circuit integrated.  
 Potential energy savings for VT loads

91



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VFD Limitations –  
 Current harmonics on line side and voltage harmonics on load side.  
 Cost  
 Torque < 150% FLT unless drive oversized  
 Setup more complex than starter  
 Heat generation

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**End of Electric Machines and Drives**



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## Electric Machines & Drives

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End of Session 12:  
 Control of AC  
 Motors

Spring 2011

