Welcome to

Electric Machines & Drives

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UNIVERSITY OF SOUTH FLORIDA POLYTECHNIC

Session 9:
Motor Control &
Power Electronics

Fall 2011

Session 9

- **Chapter 20 – Basics of Industrial Motor Control**
- **Chapter 21 – Fundamental Elements of Power Electronics (Part 1)**

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Chapter 20 – Basics of Industrial Motor Control

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Chapter 20

Starting, stopping, direction
Speed, Torque, Power – chapter 22/23
Size accordingly
Switches, breakers, Push Button, relays, contactors (starters), fuses, OL, Lights (annunciator), resistors, inductors, xfmrs, capacitors.
Symbols in Table 20A

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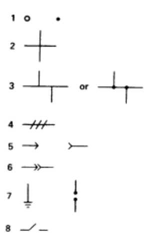
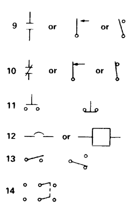


Chapter 20



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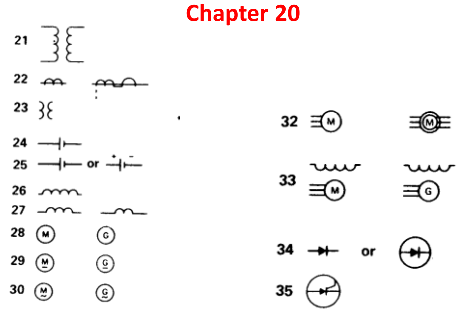
Chapter 20



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Example 20-1

A 3 phase NEMA size 5 magnetic contactor rated at 270A, 460V possesses a 120V, 60Hz relay coil. The coil absorbs an apparent power of 2970 VA and 212 VA, respectively, in the open and closed contactor position. Calculate

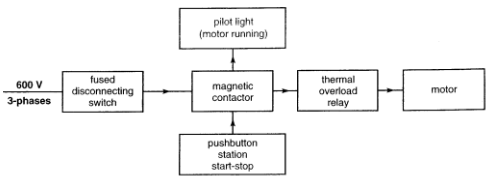
a. The inrush exciting current
b. The normal sealed exciting current
c. The control power needed to actuate the relay coil

Chapter 20

Control Diagrams –
Block Diagram – description of functions and interactions
One Line Diagram – More detail than block diagram –
Wiring Diagram – Detailed connection information in physical representation
Schematic diagram – Detailed connection information in logical sequence

Chapter 20

Block Diagram of Combination Starter



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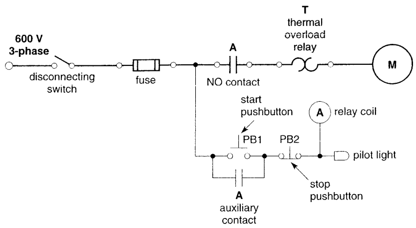
One Line Diagram



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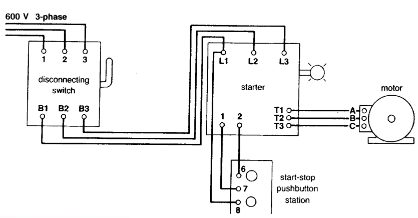
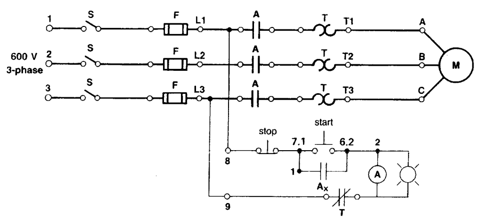
Wiring Diagram



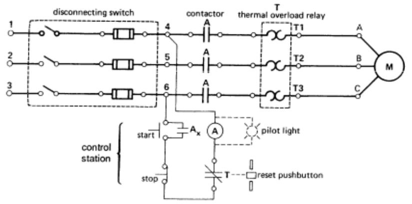
Chapter 20

Schematic Diagram



Chapter 20

ATL start – Simple, Large inrush, Large Torque
Starter = Contactor + OL
Combination starter = Starter + Switch (or CB)
Purpose of OL vs Purpose of fuse?



Chapter 20

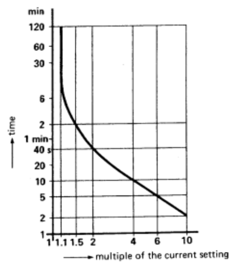
Higher voltage starters – CPT – reduce control voltage
Manual ATL starter vs Magnetic ATL starter?
Simplicity
Safety

Chapter 20

OL curve –
From cold condition
Reduce about 30% if from hot condition
Class 10 – @ 6X PU, trips in 10 sec from cold condition
Class 20 – @ 6X PU, trips in 20 sec from cold condition
Class 30 – @ 6X PU, trips in 30 sec from cold condition
NEC requirements, conductor size, fuse size, etc

Chapter 20

Overload Curve



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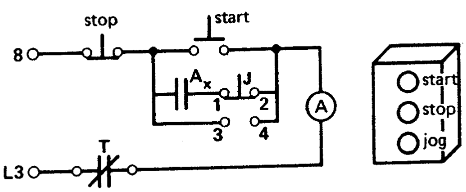
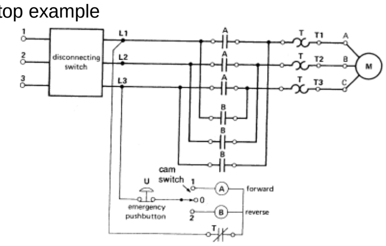
Inching / Jogging
Severe contact duty –make/break currents
Contactor oversized



Chapter 20

Reversing – change 2 lines
Mechanical / electrical interlocks
E-stop example



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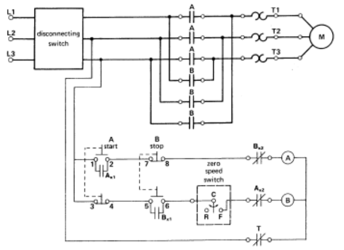
Plugging – Stop Motor



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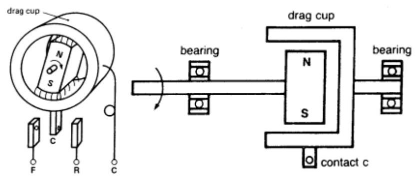
Zero Speed Switch –
PM drags cup in direction of rotation



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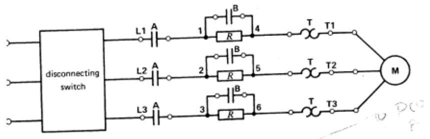
Chapter 20

Reduced Voltage Starting (softstart)
Primary Resistance
Primary Reactance
Wye – Delta
Auto Xfmr
Partial winding start
Solid state



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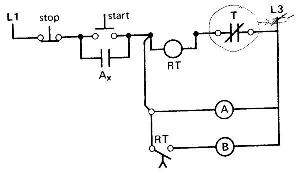
Chapter 20

Control circuit for primary resistance start
T typically on common return
Larger size contactors use circuit C for inrush
Torque ∝ voltage^2



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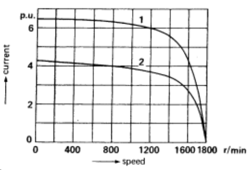
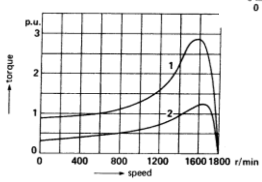
Chapter 20

Torque ∝ voltage^2
Current ∝ voltage





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Example 20-2

A 150 kW (200HP), 460V, 3 phase, 3520 rpm, 60 Hz induction motor has a locked rotor torque of 600 Nm and a locked rotor current of 1400 A. Three resistor are connected in series with the line so as to reduce the voltage across the motor to 0.65 pu. Calculate

a. The apparent power absorbed by the motor under full voltage, locked rotor conditions
b. The apparent power absorbed y the motor when the resistors are in the circuit.
c. The apparent power drawn from the line, with the resistor in the circuit
d. The locked rotor torque developed by the motor

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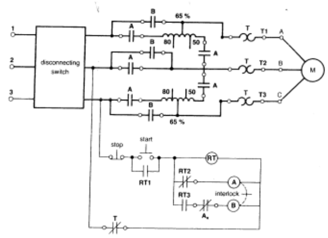
Example 20-3

From Example 20-2, fi the locked rotor power factor of the motor alone is 0.35, calculate the value of the series resistor and the power they dissipate.

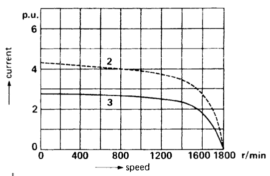
Chapter 20

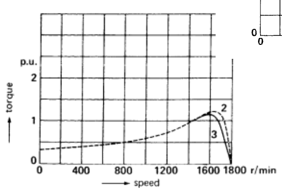
Auto Transformer Starter
For given Torque – lower line current
Open transition
Closed transition



Chapter 20

Autotransformer start (3) vs primary resistance start (2)





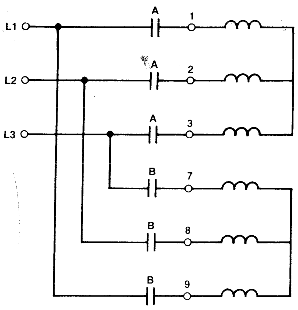
Example 20-4

A 200 HP (150 kW, 460V 3 phase, 3520 rpm, 60 Hz induction motor has a locked rotor torque of 600 Nm and a locked rotor current of 1400 A (Same motor as example 20-2). Two autotransformers connected in open delta and having a 65% tap, are employed to provide reduced voltage starting. Calculate

a. The apparent power absorbed by the motor
b. The apparent power supplied by the 460V line
c. The current supplied by the 460V line
d. The locked rotor torque

Chapter 20

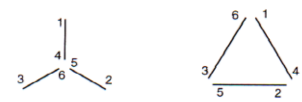
Part winding starter



Chapter 20

Wye delta starter
Start V = Vll / √3
Torque = T / 3

SINGLE AND DUAL VOLTAGE
WYE-DELTA CONNECTIONS



SINGLE VOLTAGE

OPERATING MODE	CONNECTION	L1	L2	L3	JOIN
START	WYE	1	2	3	4&5&6
RUN	DELTA	1,6	2,4	3,5	---

Chapter 20

Drive Fundamentals – 4 quadrants of operation
More info in Chapters 20 - 22

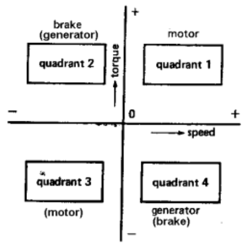


Figure 20.36
Electric drives can operate in four distinct quadrants.
FIGURE MODIFIED FROM BOOK

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Chapter 20

Motor – Generator - Brake

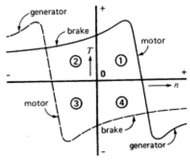

Figure 20.37
Typical torque-speed curve of a squirrel-cage induction motor operating at fixed voltage and frequency.

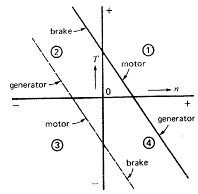

Figure 20.38
Typical torque-speed curve of a dc motor.

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Chapter 20

Torque / speed curve AC induction machine

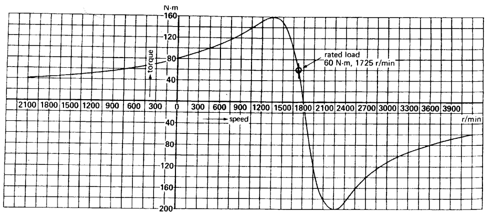

Figure 20.39
Torque-speed curve of a 15 hp, 460 V, 60 Hz, 3-phase, squirrel-cage induction motor.

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Chapter 20

Varying Volts and Hertz on AC machines

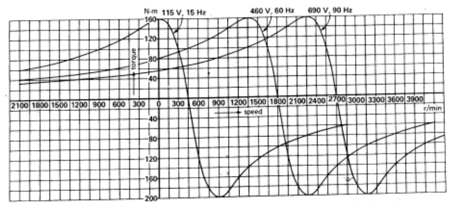

Figure 20.40
Torque-speed curve at three different frequencies and voltages.

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Chapter 20

DC effect on Torque speed curve

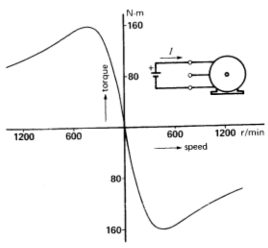

Figure 20.41
Stator excited by dc current.

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Examle 20-5

A standard 3 phase, 10 HP, 575V, 1750 rpm, 60 Hz, NEMA class D squirrel cage induction motor develops a torque of 110 Nm at a speed of 1440 rpm. If the motor is excited at a frequency of 25 Hz, calculate the following:

a. The required voltage to maintain the same flux in the machine
b. The new speed at a torque of 110 Nm

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Chapter 20

Current vs Speed

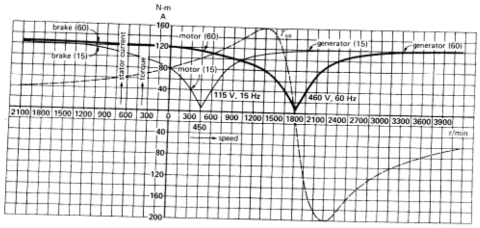


Figure 20.42
Current-speed curve at 60 Hz and 15 Hz. Also T-n curve at 460 V 60 Hz

Example 20-6

Using the information revealed by the 60Hz torque speed and current speed curves of figure 20.42, calculate the voltage and frequency required so that the machine will run at 3200 rpm while developing a torque of 100 Nm. What is the corresponding stator current?

Chapter 20

If freq changed
F 60hz -> 30 hz
Motor speed still 1650RPM
1 – 2 – 3 – 4
Final motor speed 750
Note slip still 150 RPM for same torque

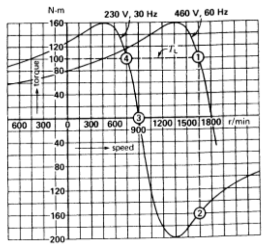


Figure 20.44
Effect of suddenly changing the stator frequency.

Chapter 21 – Fundamental Elements of Power Electronics (Part 1)

Chapter 21

Power Electronics -> control of electric machine parameters such as Torque, Speed, Power.
Due to importance, deserves some study of subject for EMD.

Chapter 21

$V_{56} = L * di/dt$

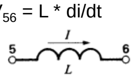


Figure 21.7
Potential across an inductor.

$V_{78} = 1/C \int Ic * dt$

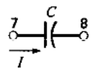


Figure 21.8
Potential across a capacitor.

Switch open – $V_{12} \neq 0$
Switch closed – $V_{12} = 0$

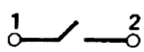


Figure 21.5
Potential across a switch.

$V_{34} = I * R$

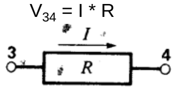
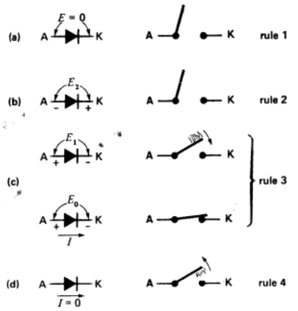


Figure 21.6
Potential across a resistor.

Chapter 21

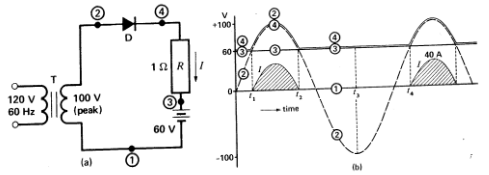
Diode Behavior
Vak = 0 -> open
Vak < 0 -> open
Vak > 0 -> short
I > Ihold -> short
I < Ihold -> open
PIV ->
Iav(max) -> max avg
T(max) -> max Temp
Max di/dt (turnon)
Max dv/dt (turnoff)



Chapter 21

Resistive Battery Charger
I^2R losses in resistor
$I = E_{43}/R$

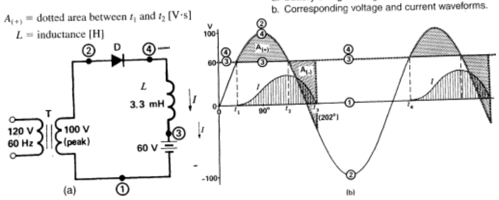
Figure 21.11
a. Simple battery charger circuit.
b. Corresponding voltage and current waveforms.



Chapter 21

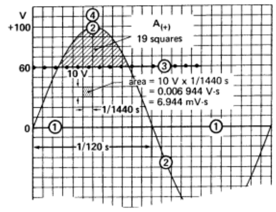
Inductive Battery Charger
Stored Energy example
$I_{max} = A_{(+)}/L$

Figure 21.12
a. Battery charger using a series inductor.
b. Corresponding voltage and current waveforms.



Example 21-1

The coil below has an inductance of 3.3 mH and the battery voltage is 60V. Calculate the peak current if the line frequency is 60 Hz.



Chapter 21

Single Phase Bridge Rectifier
2 pulse rectifier
Fripple = #pulse*fline
 = 2 * fline
Ripple = 2*f(line)
Ripplep-p = Epeak

Ed = 0.9 E   Id = Ed/R = 0.9 E / R
Ed = dc voltage of single phase bridge rectifier (V)
E = effective value of ac line voltage (V)

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Chapter 21

Single phase rectifier

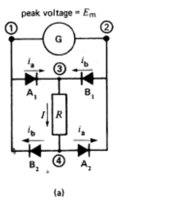


Figure 21.13
a. Single-phase bridge rectifier.
b. Voltage levels.

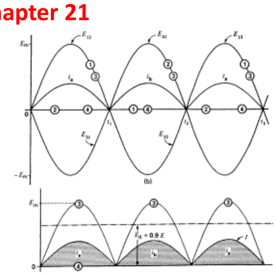


Figure 21.13c
Voltage and current waveforms in load R.

Example 21-2

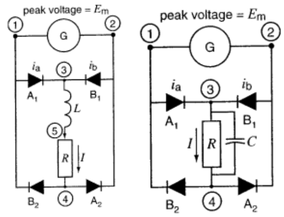
The ac source in fig 21.13a has an effective voltage of 120V, 60Hz. The load draws a dc current of 20A. Calculate

a. The dc voltage across the load
b. The average dc current in each diode

Chapter 21

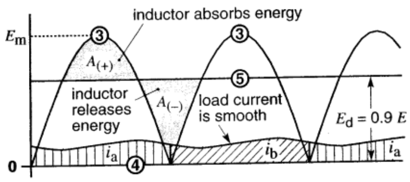
Filters –
L – constant current
Series w/ load
Line current square wave
C – constant voltage
Parallel w/ load
Line current spike

a. Rectifier with inductive filter
b. Rectifier with cap filter



Chapter 21

L – constant current - Series
C – constant voltage - Parallel
Voltage and current waveforms in inductive filter



Chapter 21

Ripple in single phase rectifier with filter

Ripple = (5.5 P) / (f Wl)

Ripple = peak to peak current as % of dc current (%)
Wl = dc energy stored in the smoothing inductor (J)
P = dc power drawn by the load (W)
f = frequency of the source

Example 21-3

We wish to build a 135V, 20A dc power supply using a single phase bridge rectifier and an inductive filter. The peak to peak current ripple should be about 10%. If a 60 Hz ac source is available, calculate the following;

a. The effective value of the ac supply voltage
b. The energy stored in the inductor
c. The inductance of the inductor
d. The peak to peak current ripple

Chapter 21

3 phase, 3 pule rectifier

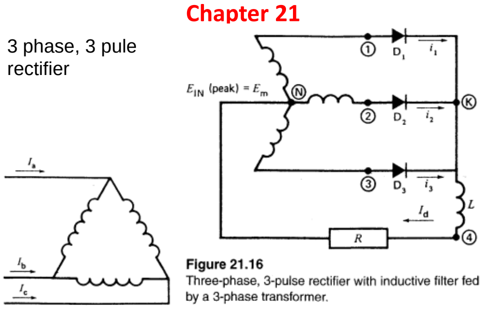


Figure 21.16
Three-phase, 3-pulse rectifier with inductive filter fed by a 3-phase transformer.

Chapter 21

3 pulses per cycle – Filter element L
Conduction period 360^O / 3 pulses = 120^O per pulse

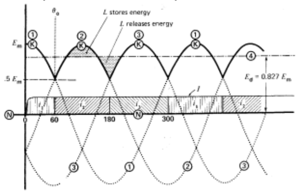


Figure 21.17
Voltage and current waveforms in a 3-phase, 3-pulse rectifier.

Chapter 21

Commutation – change of diode state from on to off
Natural or Line commutation – Line voltage forces commutation
Ripple voltage less than single phase
F_{ripple} = #pulse*f_{line} = 3 * f_{line}

Ed = 0.675 E
Ed = average or dc voltage of a 3 pulse recitifer (V)
E = effective ac line voltage (V)

Chapter 21

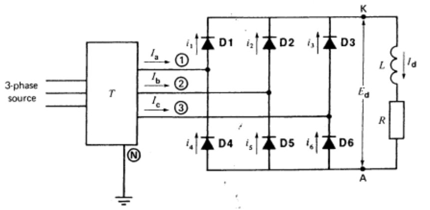
3 Phase, 6 pulse rectifier – 1.225 < Ed < 1.414
Peak to Peak 1.414 – 1.225 = 0.189 E
Fripple = Fline * Pulse #
Fripple = Fline * 6

Ed = 1.35 E
Ed = dc voltage of 6 pulse rectifier (V)
E = effective line voltage (V)

Chapter 21

3 phase, 6 pulse rectifier

$$I_a = i_1 - i_4$$
$$I_b = i_2 - i_5$$
$$I_c = i_3 - i_6$$



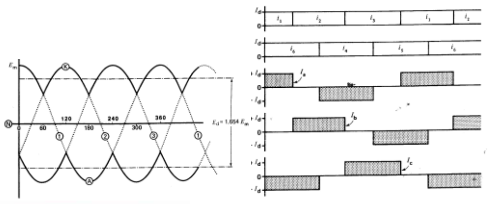
Chapter 21

Ripple - PIV = Epeak
Conduction 360^O / #pulse = 360^O/6 = 60^{O}e
Ripple = (0.17 P) / (f Wl)

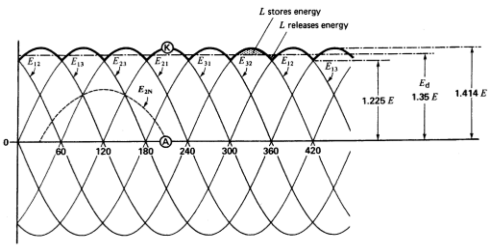
Ripple = peak to peak current as % of the dc current (%)
Wl = dc energy stored in the inductor (J)
P = dc power drawn by the load (W)
f = frequency of the 3 phase, 6 pulse source)

Chapter 21

Voltage and current waveforms

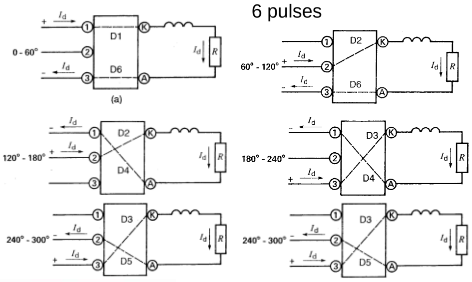


Chapter 21



Chapter 21

6 pulses



Example 21-4

A 3 phase bridge rectifier has to supply power to a 360 kW, 240V dc load. If the 600V, 3 phase, 60 Hz feeder is available, calculate the following

a. Voltage rating of the 3 phase transformer
b. DC current per diode
c. PIV across each diode
d. Peak to peak ripple in the output voltage and its frequency

Chapter 21

a. Calculate the inductance of the smoothing choke required in example 21-4 if the peak to peak ripple in the current is not to exceed 5%.
b. Does the presence of the choke modify the peak to peak ripple in the output votlage Eka?

Chapter 21

Relationship between Id and Iline

I = $\sqrt{(120/180)}$ Id = 0.816 Id

Pd = Ed Id
Pac = $\sqrt{3}$ E If
If = 0.78 Id = 0.955 I

I is effective value of line current
If is fundamental value of line current

Chapter 21

Total PF = PF Displacement & PF Distortion

PF = active power/apparent power

PF dist = If/I but If = 0.955 I

PF dist = 95.5% due to line current being rectangular

Chapter 21

Total PF = PF Displacement & PF Distortion

Total PF = P / (E IL)

Displacement PF = P / (E If)

P = active power per phase (W)
E = effective value of voltage per phase (V)
IL = effective value of line current including fundamental and harmonics (A)
If = effective value of the fundamental component of line current (A)

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Chapter 21

Harmonic Content and THD
N +/- 1
Amplitude = IF Amplitude / harmonic number
$I_2 = I_F^2 + I_H^2$
$I_H^2 = I_{HA}^2 + I_{HB}^2 + I_{HC}^2 + I_{HD}^2 + \ldots$
THD = IH / IF
I = rms value of the line current
I_F = rms value of the fundamental component of line current
I_H = rms value of all the harmonic components combined.

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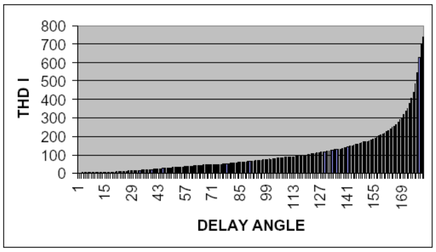
Chapter 21

Harmonic Content and delay angle



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Example 21-6

The 3 phase, 6 pulse rectifier in figure 21.19 furnishes a dc current of 400A to the load. Estimate, for line 1

a. The effective value of the line current measured by an rms hook on ammeter
b. The effective value of the fundamental component of line current
c. The peak value of the 7th harmonic
d. The rms value of the 7th and 11th harmonics combined.

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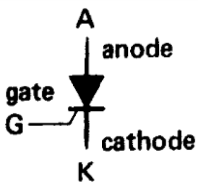
Chapter 21

Solid state switch – point of conduction controlled
a.Anode positive
b.Gate current injected
c.Anode to cathode current remain positive



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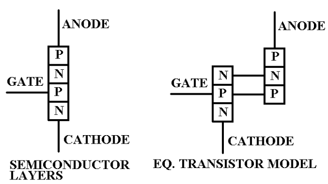
Chapter 21

Vg = (+)
NPN pulling the N substrate low
PNP is gated
Current to flow from cathode to gate



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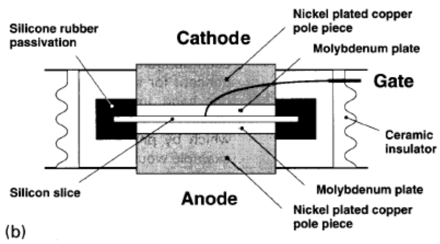
Chapter 21

Construction of “hockey puck”

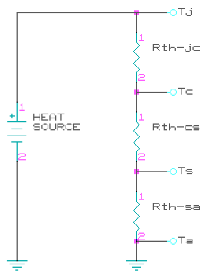


Chapter 21

Packaging:

Chapter 21

Steady state model
Goal = Minimize Tj



Where

Rth-jc = Thermal resistance junction to case

Rth-cs = Thermal resistance case to sink

Rth-sa = Thermal resistance sink to ambient

Tj = Junction temp
Tc = Case temp
Ts = Sink temp
Ta = Ambient temp

Chapter 21

Tj(max) = 125C
HS Thermostat = 90C

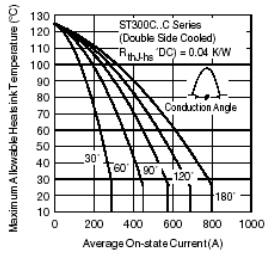


Fig. 3 - Current Ratings Characteristics

Ploss = Vak * I
* # phases
Data sheet = P
* # devices

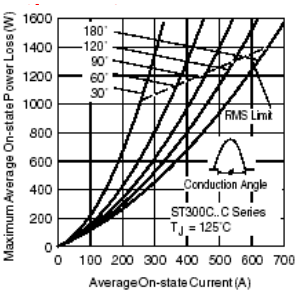
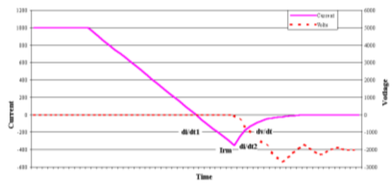


Fig. 5 - On-state Power Loss Characteristics

Chapter 21

SCR Critical Ratings:
PIV = Peak Inverse Voltage
RMS = Current rating (at Tj)
Di/dt = Rate of change of current
Qrr = Peak reverse recovery charge



Chapter 21

Typical PIV ratings

Vrms	PIV
120	300
208	12:00 AM
240	600
380	1000
415	1000
440	1200
480	1200
575	1600
2300	6000
4160	12000
6600	18000
7200	18000
13800	36000

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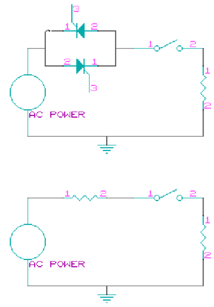
Chapter 21

!!!SAFETY!!!
SCR output = input voltage



Chapter 21

Two Types of control

COMPARISON OF PHASE-ANGLE AND ZERO-CROSS		
PARAMETER	PHASE-ANGLE	ZERO-CROSS
Cost: 1-phase	Slightly more	Slightly less
Cost: 3-phase	Appreciably higher	2-leg control is appreciably less due to lower circuit cost and because only 2 of the 3 supply lines require SCR's. 3-leg control is slightly less because of circuit cost.
Type of loads:	Transformer coupled loads, fast responding loads, loads with large resistance changes, loads requiring current limiting, or soft start.	Resistive loads only. Power can not be applied to a transformer. Moderately fast loads can be controlled with distributive control.
RFI and Harmonics: (Ref Section 5)	Higher harmonics are generated and the potential for RFI is higher.	Harmonics and RFI are very low.
Reliability:	Lower than zero-cross	Higher than phase-angle because fewer components are required and because the SCR turns on when the voltage and current are zero.
Serviceability:	More complex	Easier because of fewer components.

Chapter 21

Applications of control

ELEMENT TYPE	HOT / COLD RATIO	CONTROL TYPE
Molybdenum	15:01	Phase
Tungsten	20:1	Phase
Graphite	20:1	Phase
Nichrome	1.1:1	Zero
Tungsten	20:1	Phase
Iron Chromium	1.1:1	Zero
80/20 Nichrome	1.1:1	Zero
35/20 Nichrome	1.2:1	Zero
Silicon Carbide	0.8:1	Phase

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Chapter 21 next session

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End of Session 9: Motor Control & Power Electronics

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