

Welcome to

Electric Machines & Drives

thomasblairpe.com/EMD



Thomas Blair, P.E.
USF Polytechnic – Engineering
tom@thomasblairpe.com


Session 10:
Power Electronics

Fall 2011




Session 10

➤ **Chapter 21 – Fundamental Elements of Power Electronics (Part 2)**



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

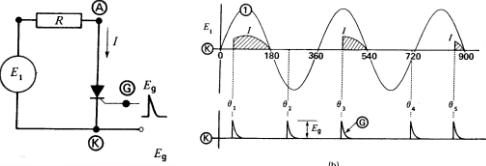

Chapter 21 – Fundamental Elements of Power Electronics (Part 2)



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Example of gating pulses on SCR condition





Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Circuit Operation

Angle or time interval	Explanation of circuit operation
zero to θ_1	Although the anode is positive, conduction is impossible because the gate voltage is zero. The thyristor behaves like an open switch.
angle θ_1	Conduction starts because both the anode and gate are positive.
θ_1 to 180°	Conduction continues even though the gate voltage has fallen to zero. Gate pulses have no further effect once the thyristor conducts. The anode to cathode voltage drop is less than 1.5 V; consequently, we can consider that the anode and cathode are shorted. The thyristor behaves like a closed switch.
angle 180°	The thyristor current is zero, conduction ceases, and the gate regains control.
180° to 360°	Conduction is impossible because the anode is negative. Although the gate is triggered at angle θ_2 , it produces no effect. The thyristor experiences an inverse voltage during this half-cycle.
360° to 540°	Conduction starts at θ_1 and ceases again as soon as the current is zero. The gate pulse is delayed more than during the first positive half-cycle. Consequently, the anode current flows for a shorter time.
720° to 900°	Conduction starts at angle θ_1 , but the resulting anode current is very small because of the long delay in firing the gate.



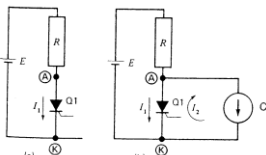

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Natural commutation vs forced commutation

Stop commutation by:

1. Reduce dc supply voltage to zero
2. Open load circuit via switch
3. Force anode current to zero

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

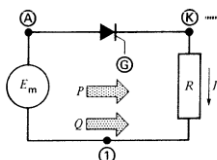
“Power Converter” converts power from one frequency to another frequency (including DC) and may be rectifier, inverter, or rotating machine
Six most common circuit configurations

TABLE 210 SOME BASIC THYRISTOR POWER CIRCUITS

Circuit No.	Thyristor circuit	Typical applications
1	Controlled rectifier supplying a passive load	Electroplating, dc arc welding, electrolysis
2	Controlled rectifier supplying an active load	Battery charger, dc motor control, dc transmission line
3	Line-commutated inverter supplying an active ac load	AC motor control, wound-rotor motor speed control, dc transmission line
4	AC static switch	Spot welding, lighting control, ac motor speed control, ac starter
5	Cycloconverter	Low-speed synchronous motor control, electroslag refining of metals
6	Three-phase converter	High-voltage dc transmission, synchronous motor drive



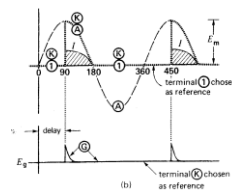
Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)



Reactive power due to lagging current due to lagging gate firing

Chapter 21

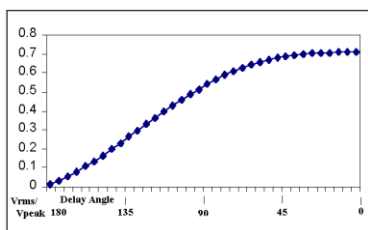
Rectifier – Passive load (no source of energy in load)



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

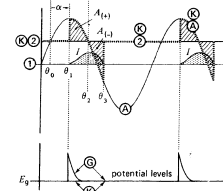
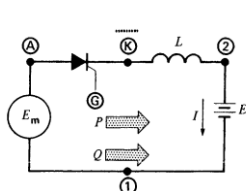
RMS Voltage not linear with conduction angle



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

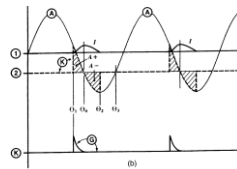
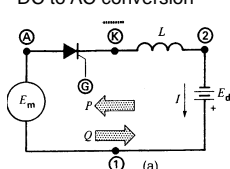
Rectifier – active load (load has energy source)
Peak current = amp*seconds / inductance
Apparent and real power flow to load



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Line commutated inverter – active load (load has energy source, note polarity)
Peak current = amp*seconds / inductance
Apparent power to load, real power to source
DC to AC conversion



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Line Commutated Inverter –
DC to AC real power conversion
Forced Commutated – commutation by current reversal within power bridge
Line Commutated – Commutation current provided by line.
Due to polarity of E_d, Power flows to source.
Source side voltage must be present to provide needed VAR



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

AC static switch – back to back SCRs
 Reactive power draw
 Phase angle. zero fired. on/off

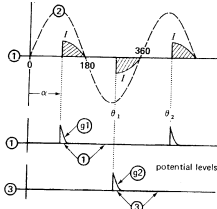
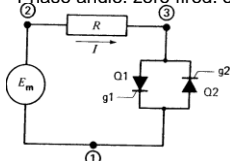


Figure 21.33

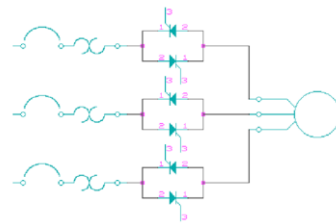
- a. Electronic contactor.
- b. Waveforms with a resistive load.



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

3 phase, back to back

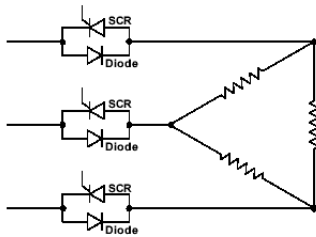


Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

14

Chapter 21

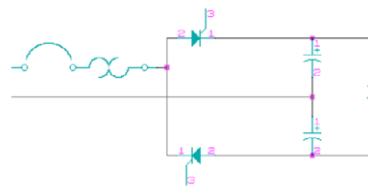
3 phase hybrid



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Voltage Doubler

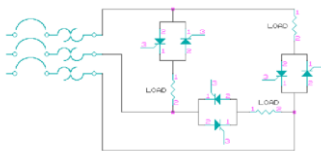


Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

16

Chapter 21

Inside Delta –
 $I_d = 58\% I_{line}$
 $P_{loss} = 58\%$ of in line device
 $PIV = 173\%$ of in line device

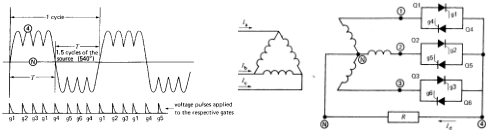


Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

17

Chapter 21

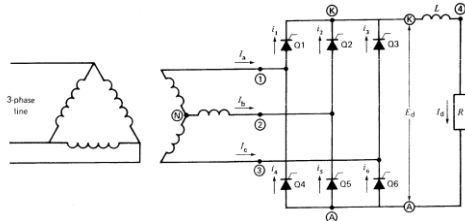
Cycloconverter – $F_{source} > F_{load}$
 Each successive sinewave delay angle adjusted



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

3 phase, 6 pulse, converter –
If Eka (+), rectifier, if Eka (-), inverter



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Note Source / Load Voltage polarity

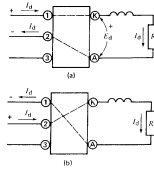


Figure 21.37
Rectifier mode (see Fig. 21.36)
a. Q1 and Q5 conducting.
b. Q2 and Q4 conducting.

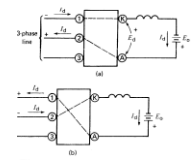
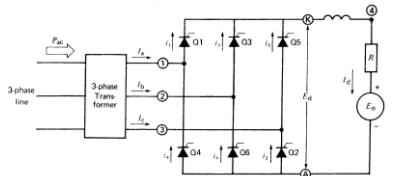


Figure 21.38
Inverter mode (see Fig. 21.36)
a. Q1 and Q5 conducting.
b. Q2 and Q4 conducting.

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

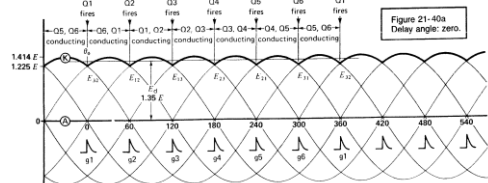
3 Phase, 6 pulse rectifier – to active load
 $V_d = 1.35 \cdot V \cdot \cos \alpha$
 $E_d > E_o$ for current flow, $E_d < E_o$ zero current flow
 $I_d = (E_d - E_o) / R$



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

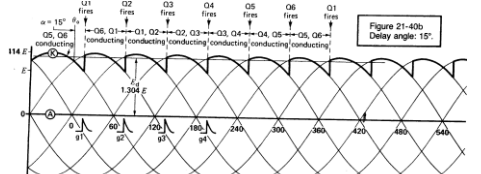
Trigger point critical –
Trigger late, reduced output,
Trigger early, no conduction



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Delayed trigger – rectifier mode
Increased delay angle, reduced Ed
Conduction angle still 60°
Each thyristor still conducts for 120°



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

$E_d = 1.35 E \cos \alpha$
Excel Spreadsheet showing calculation
Also available on web page



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

$E_d = 1.35 E \cos \alpha$

E_d = dc voltage produced by the 3 phase 6 pulse converter (V)
 E = effective value of the ac line to line voltage (V)
 α = firing angle (degree)

Note: if $E_d < E_o$, I_d forced to 0 – Forced commutation mode – Important mode to LCI drive.

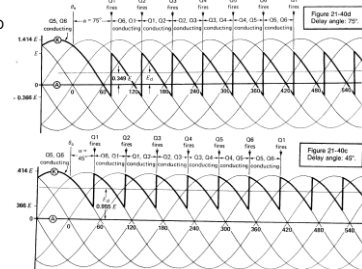
25



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Conduction angles of 45° and 75°



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Example 21-7

The 3 phase converter of Fig. 21.39 is connected to a 3 phase, 480V, 60 Hz source. The load consists of a 500V dc source having an internal resistance of 2Ω. Calculate the power supplied to the load for triggering delays of (a) 15° and (b) 75°.

27

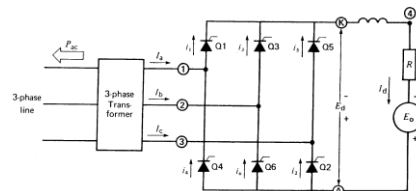


Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Delayed Trigger – Inverter Mode
 Note Polarity of E_o and E_d

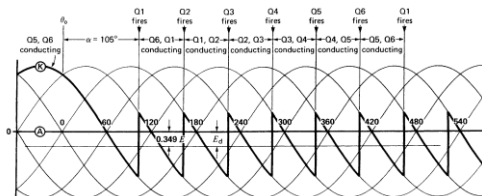
$I = (E_o - E_d) / R$



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

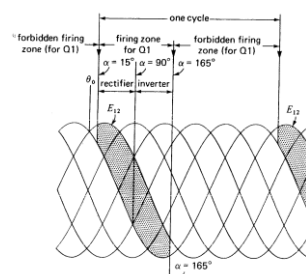
Inverter mode, $90^\circ < \alpha < 180^\circ$
 $E_o > E_d$ current flow, $E_d > E_o$, zero current flow
 Power flow to source



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

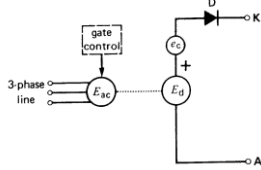
Firing Angle typically 15° to 165° to ensure controlled firing



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

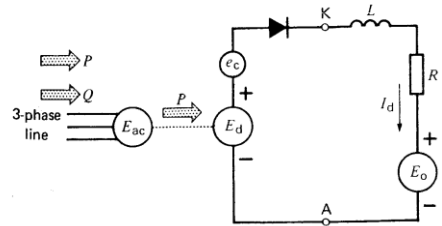
MG set with Vdc out
 Current unidirectional
 Vdc magnitude /
 polarity tied to phase
 angle
 Ripple increases as
 Vdc decreases
 $V_{dc} = E_d + e_c(\text{ripple})$



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

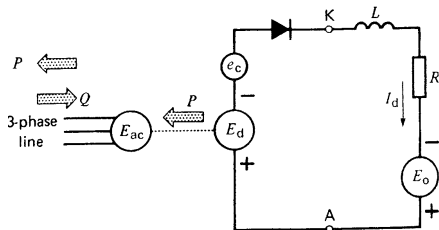
3 phase converter in rectifier mode



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

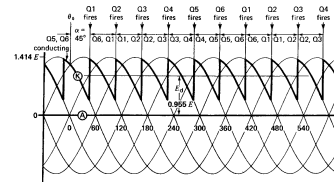
3 phase converter in inverter mode



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

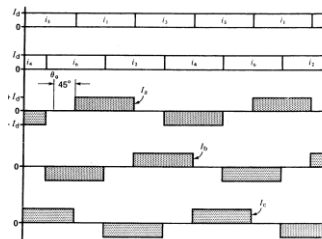
Real Power flow either direction – reactive power
 always absorbed
 No Electric isolation like MG set would provide (without
 isolation xfmr)



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Current flow: $I = \sqrt{(2/3)} I_d = 0.816 I_d$



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Reactive Power draw of bridge dependent on Real
 Power draw and delay angle

$$Q = P \tan \alpha$$

Q = reactive power absorbed by converter (var)
 P = dc power of the converter (positive for rectifier,
 negative for inverter) (W)
 α = triggering angle (degree)



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Example 21-8

In Example 21-7, and for a triggering angle of 15°, calculate;

- a. The displacement power factor
- b. The reactive power absorbed by the converter
- c. The total power factor

37



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 21-9

A 16kV dc source having an internal resistance of 1 W supplies 900A to a 12kV, 3 phase, 6 pulse, 60 Hz inverter. Calculate

- a. The dc current carried by each SCR
- b. The dc voltage generated by the inverter
- c. The required firing angle α
- d. The effective value of the ac line currents
- e. The reactive power absorbed by the inverter

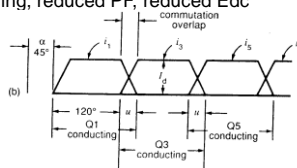
38



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

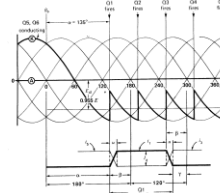
Commutation Overlap period,
 μ – commutation angle
Light load $\mu=5^\circ$, large load $\mu=20^\circ$
Conduction = $120^\circ + \mu$
Delayed firing, reduced PF, reduced Edc



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Extinction angle (γ) – allow SCR to recover blocking ability before anode becomes (+)



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Conduction begin somewhere between 0-180°
Extinction $180^\circ + 120^\circ < 300^\circ$
Aka margin angle adequate time for reverse bias of SCR
Advance angle is Commutation + Extinction
 $\beta = \mu + \gamma = 180 - \alpha$
 μ = Commutation Angle
 α = Delay Angle
 β = Advance Angle
 γ = Extinction Angle

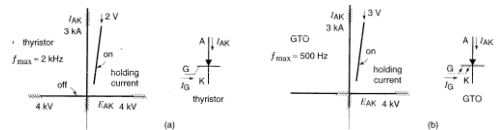
41



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

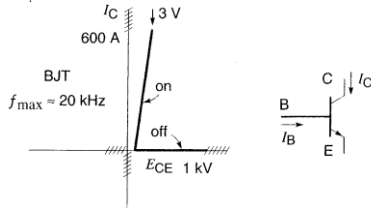
SCR limits – turn off via commutation current
Max fc 2kHz due to commutation time
GTO – No Blocking capability, $V_{AK(on)}$ higher
Negative current in gate commutate off



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

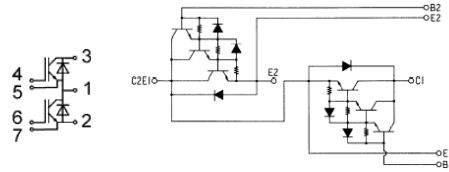
BJT – $i_e = i_c + i_b$, used in saturated region
 i_b large enough to drive into saturation
 Can not tolerate negative V_{ce}



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

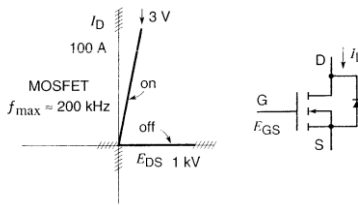
Darlington Configuration – higher base to emitter current gain – reduced base current requirements



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

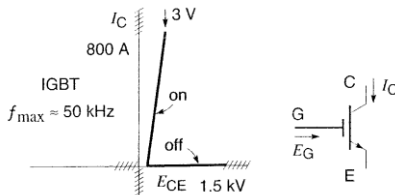
MOSFET – voltage controlled gate
 V_g on = +12vdc, V_g off = -5vdc



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

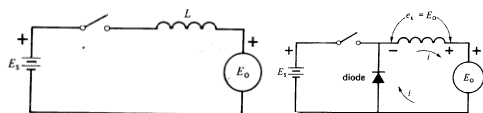
IGBT – FET gated BJT
 Fast switching



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

DC to DC converter – voltage level conversion
 Switching converter (chopper)
 During charge, $di = V \cdot dt / L$
 When switch opened:
 $W = \frac{1}{2} L i_a^2$
 $i_a = (E_s - E_o) T_1 / L$



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

$E_i = E_o \rightarrow di/dt$ constant
 $(V = L \cdot di/dt)$
 i decays at constant rate of:

$i = i_a - (E_o t) / L$
 At time T_2 , current = 0,
 diode commutates off
 $T_2 = (E_s - E_o) T_1 / E_o$

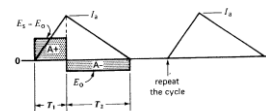


Figure 21.59
 E and i in the inductor of Fig. 21.58.



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Rapid Switching – DC current $I_0 \rightarrow$

$$I_0 = (I_a + I_b)/2$$

Source current is \rightarrow

- $I_s = I_0 D$ Where $D = T_a / T$
- $I_s =$ dc current drawn from the source (A)
- $I_0 =$ dc current absorbed by the load (A)
- $T_a =$ on time of the switch (s)
- $T =$ period of one cycle (s)
- $D =$ duty cycle = T_a / T

49



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Rapid Switching –

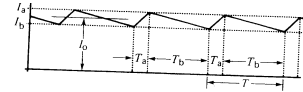


Figure 21.60b
Current in the load.

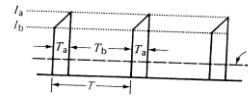


Figure 21.60c
Current pulses provided by the source.

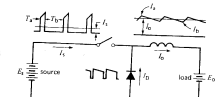


Figure 21.60a
Currents in a chopper circuit.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

$$E_s * I_s = E_o * I_0, \text{ but}$$

$$I_s = I_0 * D \rightarrow$$

$$E_o = D E_s$$

- $E_o =$ dc output voltage of the converter (V)
- $E_s =$ dc voltage of the source (V)
- $D =$ duty cycle

51



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 21-10

The switch in Fig 21.60a opens and closes at a frequency of 20 Hz and remains closed for 3 ms per cycle. A dc ammeter connected in series with the load E_o indicates a current of 70A.

- a. If a dc ammeter is connected in series with the source, what current will it indicate?
- b. What is the average current per pulse?

52



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 21-11

We wish to charge a 120V battery from a 600 Vdc source using a dc chopper. The average battery current should be 20 A, with a peak to peak ripple of 2A. If the chopper frequency is 200 Hz, calculate the following;

- a. The dc current drawn from the source.
- b. The dc current in the diode
- c. The duty cycle
- d. The inductance of the inductor

53

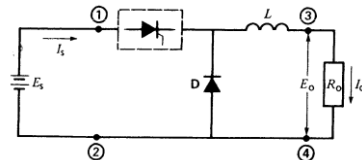


Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

$$R_o = E_o / I_0 = E_s * D^2 / I_s \rightarrow$$

$$R_s = F_o / D^2$$



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 21-12

The copper in Fig 21.62 operates at a frequency of 4 kHz and the on time is 20 μ s. Calculate the apparent resistance across the source, knowing that $R_o = 12\Omega$.

55



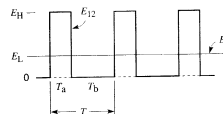
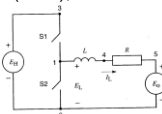
Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

2 quadrant DC to DC converter
 $S1 = D = T_a/T$, $S2 = 1-D = T_b/T$

$E_I = D E_H$ $I_L = (E_I - E_o) / R$

If, $E_L > E_o$, P flow to E_o (boost), if $E_L < E_o$, P flow to E_L (buck), controlled by D



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 21-13

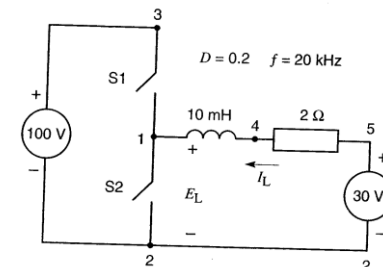
The following data is given on a buck/boost converter (Fig 21.65):
 $E_h = 100V$ $E_o = 30V$ $R = 2\Omega$ $L = 10\text{ mH}$
Switching frequency = 20 kHz with a duty cycle D of 0.2 for S1. Determine the following:
a. The value and direction of the dc current I_L
b. The peak to peak ripple superposed on the dc current

57



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

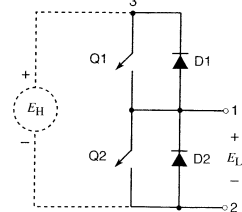
Chapter 21



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

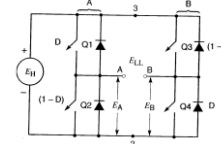
Diodes required to allow for reverse current flow
Dead time for one switch to turn off before gating second switch



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

4 quadrant DC to DC converter – bidirectional E_H , E_o
(2 quad converter, unidirectional E_H , E_o)
Q1 & Q4 operate in pair for $T_a/T = D$, Q2 & Q3 operate in pair for $T_b/T = 1-D$
When $D = 0.5$, $E_{II} = 0$ (note there is still ac component)
When $D = 1$, $E_{II} = E_H$
When $D = 0$, $E_{II} = -E_H$
 $E_{LL} = E_H (2D - 1)$



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

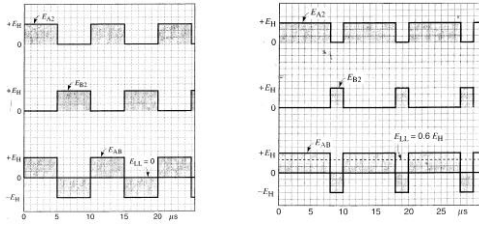


Figure 21.71 Voltage output when $D = 0.5$. The average voltage is $\approx 0.5 E_H$.

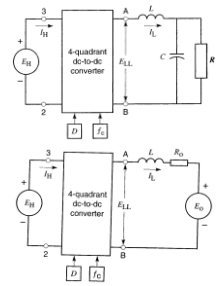
Figure 21.72 Voltage output when $D = 0.8$. The average voltage E_{LL} is $0.6 E_H$.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

L & C filter out ac component
R could also be active source, thereby sinking or sourcing power



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Switching Losses –

Four distinct operations:

1. Turn-on time T_1 – Current increases, voltage decreases
2. On-state time T_2 – Current flowing, V_t 2-3 VDC
3. Turn-off time T_3 – Current decreases, Voltage increases
4. Off-state time T_4 – Current zero, Voltage high.

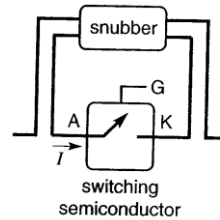
63



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Snubber – During turnoff – controls dv/dt across device



- T_1 = turn-on time
- T_2 = on-state time
- T_3 = turn-off time
- T_4 = off-state time
- D = duty cycle = $\frac{T_2}{T}$



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

$T = T_1 + T_2 + T_3 + T_4 = 1/fc$

$P_{avg\ loss} = \{E(T_1) + E(T_2) + E(T_3)\} / T$

$Energy = P_1T_1 + P_2T_2 + P_3T_3 + P_4T_4$

$Power\ loss = P_1T_1fc + V_{tI}D + P_3T_3fc$

	T_1	T_2	T_3	T_4	
instant. voltage	V_1	V_T	V_3	V_4	
instant. current	I_1	I_T	I_3	0	
average power	P_1	$V_T I_T$	P_3	0	
energy	$P_1 T_1$	$V_T I_T T_2$	$P_3 T_3$	0	P

Figure 21.75b Four stages of a GTO switching operation.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

DC to AC rectangular converter

$E = 0.9 * E_H$

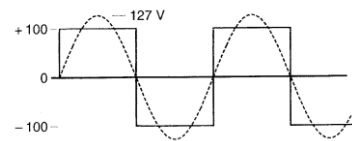


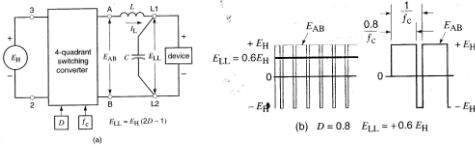
Figure 21.76a The square wave contains a fundamental sinusoidal component.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

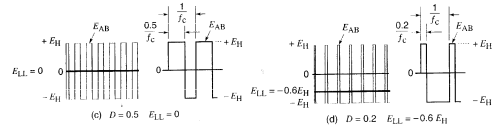
DC to AC converter with PWM
 Adjust D waveform, adjust ELL Magnitude and waveform – fc must be 10 times > f out
 $E_{LL} = E_H (2D - 1)$



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

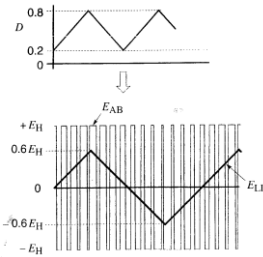
DC to AC converter with PWM
 Adjust D waveform, adjust ELL Magnitude and waveform – fc must be 10 times > f out
 $E_{LL} = E_H (2D - 1)$



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

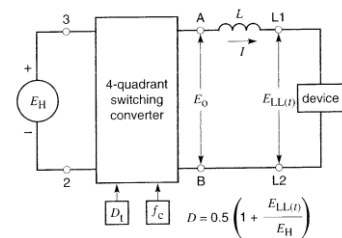
Varying D, varies ELL
 Generate any frequency (as long as $f_c > 10 \cdot f_{out}$), any waveshape.
 Real power flow bidirectional



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

DC to AC sine wave converter –



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

From Equation – $E_{LL}(t) = E_H (2D-1)$

We rewrite as – $D(t) = \frac{1}{2} [1 + (E_{LL}(t)/E_H)]$

If waveform wanted is – $E = E_m \sin(360ft + \theta)$

Duty Cycle waveform is –

$$D(t) = \frac{1}{2} [1 + (E_m/E_H)\sin(360ft + \theta)]$$

71



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Duty Cycle waveform is –

$$D(t) = \frac{1}{2} [1 + (E_m/E_H)\sin(360ft + \theta)]$$

or simply, DC is –

$$D(t) = \frac{1}{2} [1 + (m)\sin(360ft + \theta)]$$

$$M = E_m/E_H$$

$$Mf = f_c/f \text{ (must be at least 10)}$$

72



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Example 21-14

A 200Vdc source is connected to a 4 quadrant switching converter operating at a carrier frequency of 8 kHz. It is desired to generate a sinusoidal voltage having an effective value of 120V at a frequency of 97 Hz and phase angle of 35° lagging. Calculate the value of the amplitude modulation ratio, the frequency modulation ratio, and derive an expression for the duty cycle.

73



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Example of PWM calculation – Given:
Peak ac voltage required = 100V
Frequency required = 83.33 Hz
Carrier frequency = 1000 Hz
DC supply voltage $E_h = 200V$

Duration of one cycle is
 $T = 1/f = 1/83.33 = 0.012 \text{ S} = 12\,000 \mu\text{S}$

74



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Duration of one cycle is
 $T = 1/f = 1/83.33 = 0.012 \text{ S} = 12\,000 \mu\text{S}$

Carrier Frequency period is
 $T_c = 1/f_c = 1/1000\text{s} = 1 \text{ mS} = 1000 \mu\text{S}$

of carrier cycles per fundamental cycle is
 $12\,000 \mu\text{S} / 1000 \mu\text{S} = 12$

75



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

If 12 carrier cycles per fund cycle, then 6 carrier cycle per ½ fund cycle (other half cycle mirror image) – using equation –
 $D(t) = \frac{1}{2} [1 + (ELL/Eh)]$

Period 1 –
 $D(t) = \frac{1}{2} [1 + (ELL/Eh)] = \frac{1}{2} [1 + (0/200)]$
 $D(t) = 0.5$

76



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Period 2 –
 $D(t) = \frac{1}{2} [1 + (ELL/Eh)] = \frac{1}{2} [1 + (50/200)]$
 $D(t) = 0.625$

Period 3 –
 $D(t) = \frac{1}{2} [1 + (ELL/Eh)] = \frac{1}{2} [1 + (86.6/200)]$
 $D(t) = 0.716$

77



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Extending this out for ½ cycle and inverting for other ½ cycle we develop Table 21E

angle [deg]	E_{AB} [V]	D	Q1, Q4 on [μs]	Q2, Q3 on [μs]	interval
0	0	0.5	500	500	A
30	50	0.625	625	375	B
60	86.6	0.716	716	284	C
90	100	0.75	750	250	D
120	86.6	0.716	716	284	E
150	50	0.625	625	375	F
180	0	0.5	500	500	G
210	-50	0.375	375	625	H
240	-86.6	0.284	284	716	I
270	-100	0.250	250	750	J
300	-86.6	0.284	284	716	K
330	-50	0.375	375	625	L
360	0	0.5	500	500	M

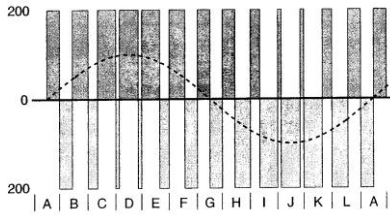
Electric Machines and Drives



Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

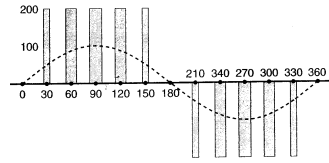
Resultant waveform – Bipolar PWM
 Duty cycle continuously changing, reason for PWM name



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

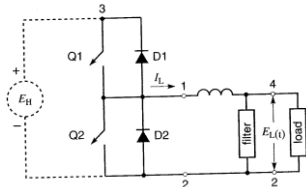
Example of unipolar PWM – same resultant fundamental value
 Higher f_c easier to filter, but high switching loss
 Limit to max f_c , loss and turn-on/turn-off time



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Two quadrant PWM chopper and load. The filter eliminates carrier frequency component.



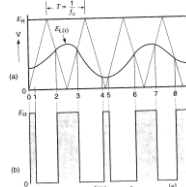
Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Triangular generation of PWM waveform

When $V > E_L$ – off
 When $V < E_L$ – on

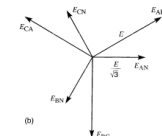
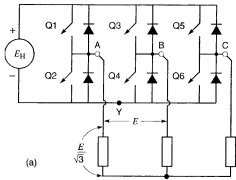
NOTE: Technology has application past power – example, fiberoptic converters
 Transmit real time waveform via FO



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

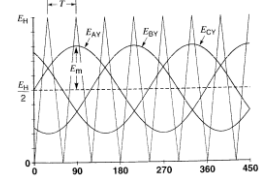
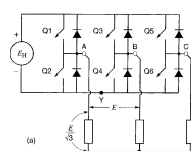
3 phase, DC to AC converter
 3 single phase converter shifted 120°
 $E_{an}, E_{bn}, E_{cn} = E/\sqrt{3}$, $E_m = E^* \sqrt{2}$, \rightarrow
 $E_m = E^* \sqrt{6}$



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

Chapter 21

Q1 closed when $E_{ay} > E_{fc}$
 Q3 closed when $E_{by} > E_{fc}$
 Q5 closed when $E_{cy} > E_{fc}$
 Q2 closed when $E_{ay} < E_{fc}$
 Q4 closed when $E_{by} < E_{fc}$
 Q6 closed when $E_{cy} < E_{fc}$



Electric Machines and Drives
 Thomas Blair, P.E.
 (tom@thomasblairpe.com)

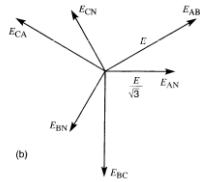
Chapter 21

Line to Line vs Line to neutral values
Neutral is floating – switching between phase to phase.

$$E_{AN} = \frac{1}{3}(E_{AB} + E_{AC})$$

$$E_{BN} = \frac{1}{3}(E_{BA} + E_{BC})$$

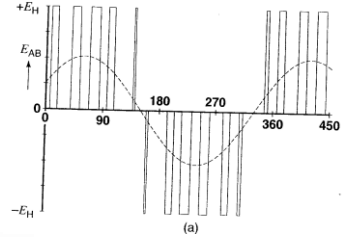
$$E_{CN} = \frac{1}{3}(E_{CA} + E_{CB})$$



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

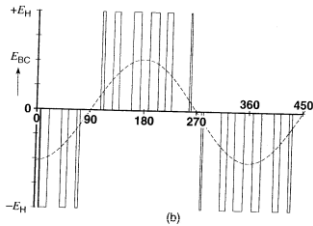
a. PWM pulses between terminal A and B and the fundamental E_{ab} component of the pulses.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

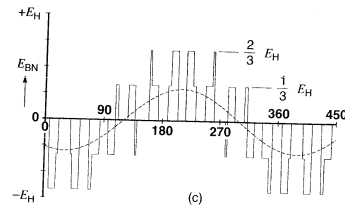
b. PWM pulses between terminal B and C and the fundamental E_{bc} component of the pulses.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

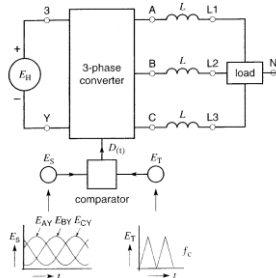
c. PWM pulses between terminal B and neutral of load. Dotted sine wave is fundamental component "buried" in the PWM pulses.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Block diagram of 3 phase PWM converter.



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 21-15

We wish to generate a 3 phase, 245V, 60 Hz source using the converter of Fig 21.93. The dc supply voltage E_H is 500V and the carrier frequency f_c is 540 Hz. Determine

- The peak value of the fundamental voltage between terminal L1 and the floating neutral N of the load
- The period T of the triangular wave and the corresponding angular interval in degrees
- The PWM program

90



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Example 21-15

- d. The waveshape for the PWM voltage between terminals A and Y during one cycle
- e. The waveshapes of the PWM voltage between terminals A-Y, B-Y, and C-Y
- f. The waveshapes for the PWM voltages between terminals A-B, B-C, and C-A

91

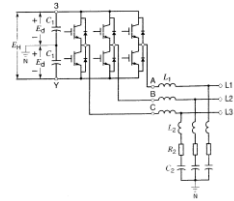


Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 21

Converter as Universal
Generator –

Fast response,
Small impedance
No isolation without
transformer
RLC to filter out f_c
C1 to filter DC bus



Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Chapter 22 & 23 next session

Electric Machines and Drives
Thomas Blair, P.E.
(tom@thomasblairpe.com)

Electric Machines & Drives

thomasblairpe.com/EMD

Thomas Blair, P.E.
USF Polytechnic – Engineering
tom@thomasblairpe.com



End of Session 10:
Power Electronics

Spring 2011

