ECE 325 – Electric Energy System Components
8- Fundamental Elements of Power Electronics

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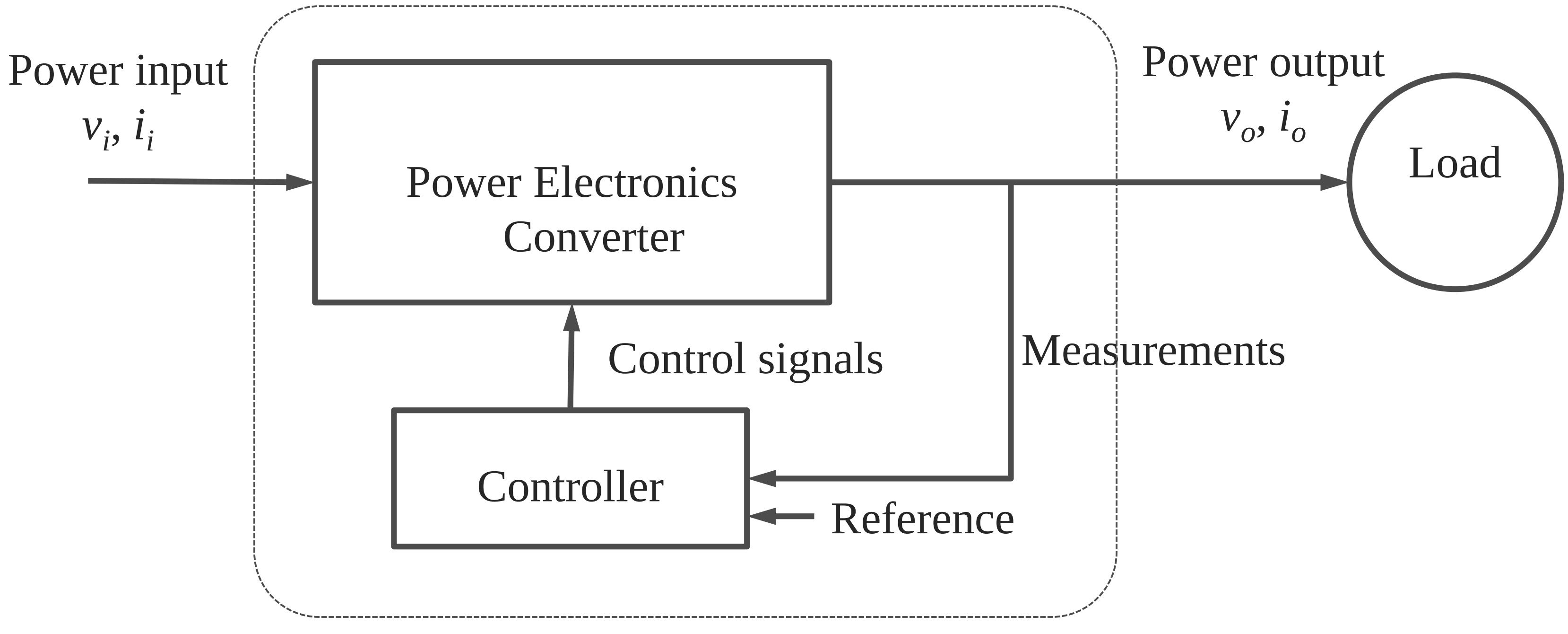
Content

(Selected materials from Chapter 21)

- Power semiconductor switches
  - Diodes, thyristors and controllable switches.
- Principles of AC-to-DC, DC-to-DC and DC-to-AC converters

Introduction

- A power electronics system is to process and control the flow of electric energy by supplying voltages and currents in a form that optimally suits the loads
- A typical power electronics (PE) system:



Applications of PE converters

- For DC voltage/current, a PE converter can regulate and adjust the magnitude to a desired level
- For AC voltage/current, a PE converter can adjust the magnitude and frequency and change the number of phases

- Applications:
  - Switched-mode (DC) power supplies
  - Uninterrupted power supplies (UPS)
  - Adjustable speed motor drives
  - High-voltage DC transmission (HVDC)
  - Battery-based utility energy storage
  - Electric vehicles (EVs) and hybrid electric vehicles (HEVs)
  - Renewable energy integration, e.g. solar PV and wind generation

Classification of PE converters

Four types of PE converters	Examples of application
AC-to-DC (rectifier)	The battery (charging) interface to the power grid and power adapters for electronic devices
DC-to-DC (boost up/step down)	Power supplies for electronic devices
DC-to-AC (inverter, to 1-phase or 3-phase AC)	The battery (discharging) and solar PV interfaces to the power grid
AC-to-AC	Variable-speed motor drive

- Examples of variable-speed motor drives (AC-to-AC converters)

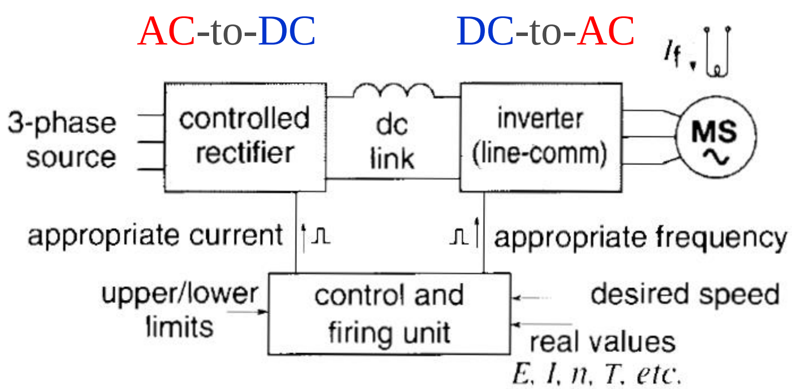


Figure 23.3
Variable-speed synchronous motor drive using a controlled rectifier and a line-commutated inverter fed from a dc link current source (see Section 23.2).

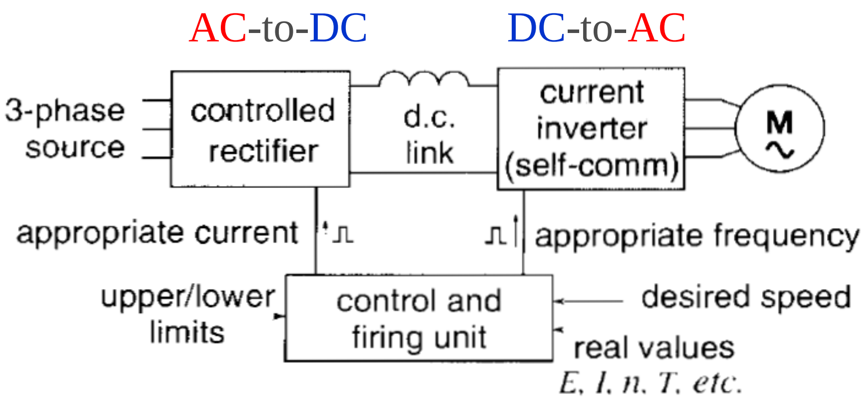


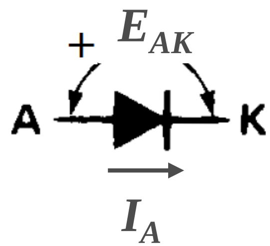
Figure 23.5
Variable-speed drive using a controlled rectifier and a self-commutated inverter fed from a dc link current source (see Section 23.9).

Power semiconductor switches

- They are key functional components in a PE converter besides resistors, inductors and capacitors.
- Two states: ON (conducting) and OFF (open-circuit)
- Three types in terms of the controllability
  - **Not receiving control signal**, e.g.
    - **Diode**: ON and OFF states controlled by the polarity and magnitude of voltage and the magnitude of current.
  - **Partially controlled by a control signal**, e.g.
    - **Thyristor**: turned ON by a control signal and OFF when current goes to zero
  - **Controllable switch**, e.g.
    - **GTO**, **IGBT, BJT**, **MOSFET:** both ON and OFF states are controllable by control signals

Ideal and Practical Diodes

- 2 terminals: A (anode) and K (cathode)
- **Rule 1**: OFF when E_{AK}=0
- **Rule 2**: OFF when E_{AK}<0 (reverse biased)
- **Rule 3**: ON (short-circuited) when E_{AK}>0 (forward biased)
- **Rule 4**: OFF when I becomes 0
- Both ON and OFF switches are instantaneous



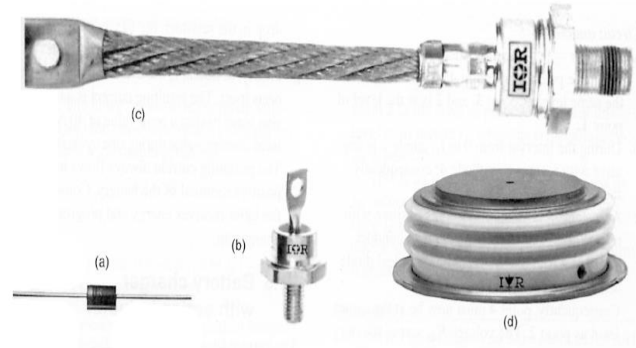
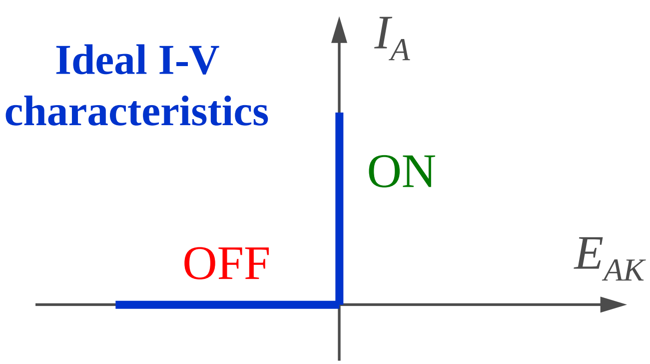
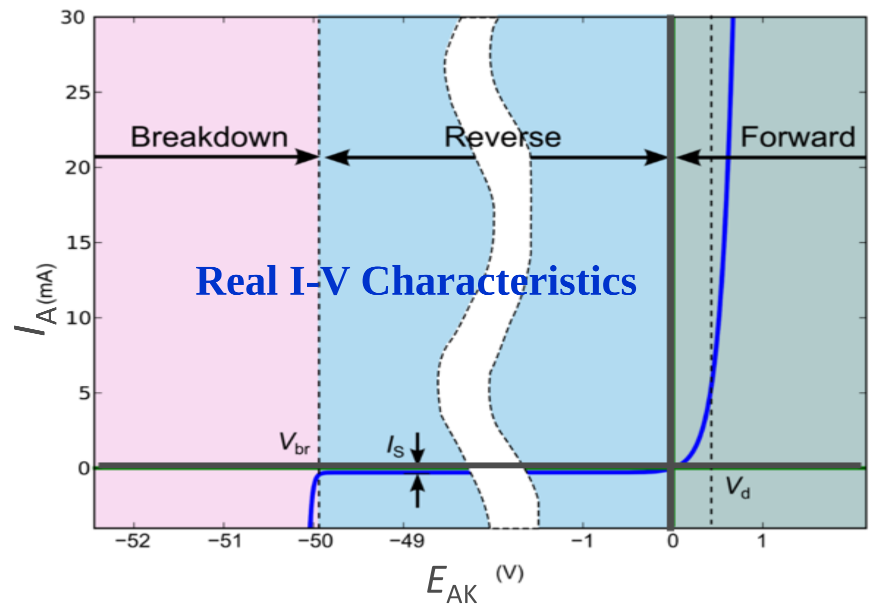


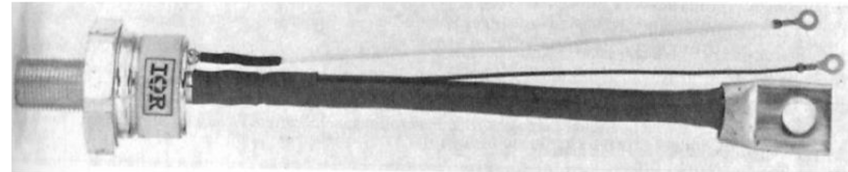
Figure 21.10
a. Average current: 4 A; PIV: 400 V; body length: 10 mm; diameter: 5.6 mm.
b. Average current: 15 A; PIV: 500 V; stud type; length less thread: 25 mm; diameter: 17 mm.
c. Average current: 500 A; PIV: 2000 V; length less thread: 244 mm; diameter: 40 mm.
d. Average current: 2600 A; PIV: 2500 V; Hockey Puk; distance between pole-faces: 35 mm; diameter: 98 mm.
(Photos courtesy of International Rectifier)



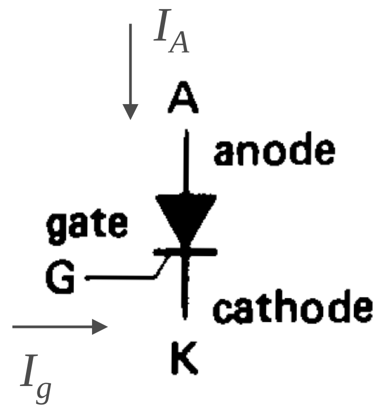


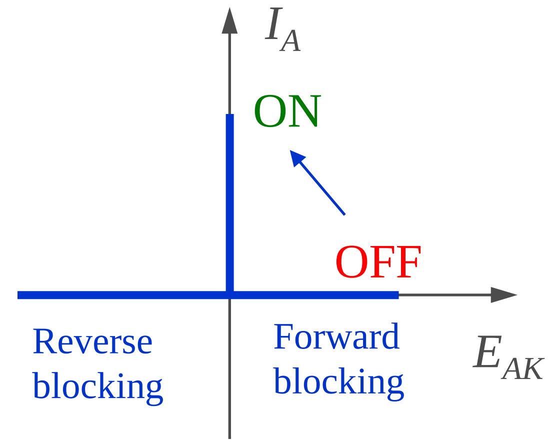
- Practical Diode:
  - Turns ON when forward biased with a voltage V_d about 0.7V or more, and it has a negligible voltage drop <1.5V.
  - When it is OFF (reverse biased), it has a negligible current I_S flowing through.
  - At very large reverse bias beyond its peak inverse voltage (V_{br}=50 to 4000V), it is usually damaged and begins to conduct in reverse.

Thyristors

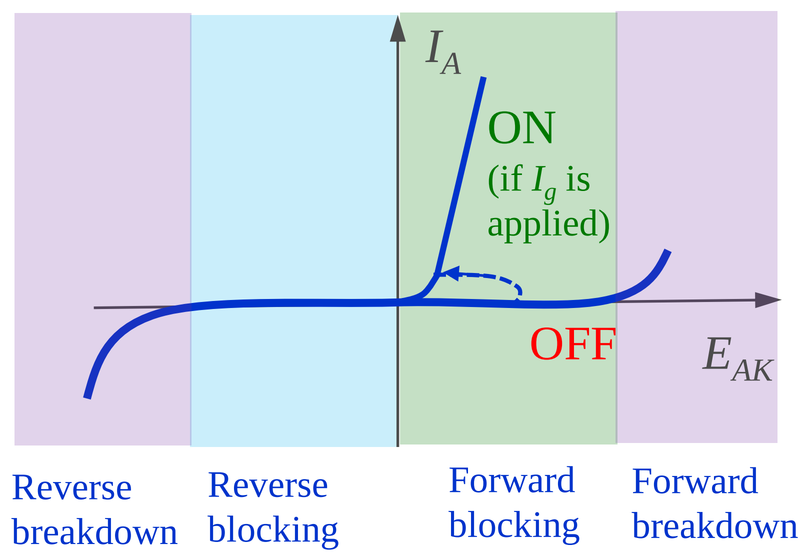


- Usually referred to semiconductor/silicon controlled rectifier (SCR)
- 3 terminals: A (anode), K (cathode) and G (gate)
- A thyristor behaves like a diode except that the instant of conduction can be controlled by "G"; that enables converting DC to AC
- Two conditions to conduct
  1. $E_{AK}>0$
  2. Positive current I_g flows into "G" for at least a few microseconds
- Once conduction starts, "G" will lose control and conduction will continue until the current I_A into "A" falls to zero
- If "G" and "K" are short-circuited, the thyristor is blocked
- A thyristor is **partially controllable**



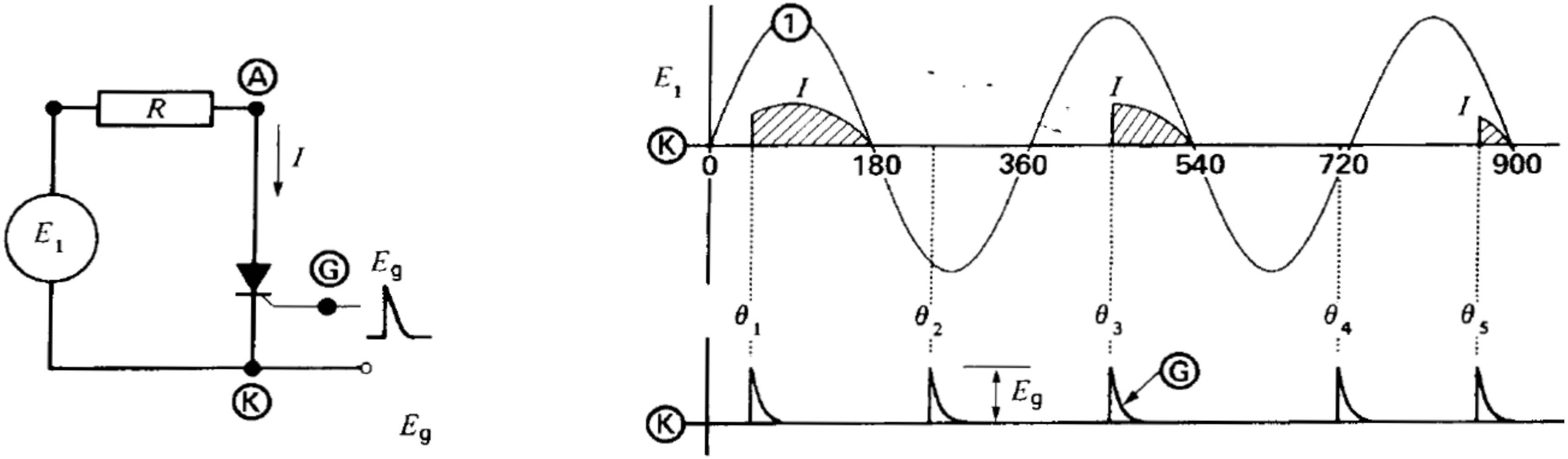


Ideal I-V characteristics



Real I-V characteristics

Principles of gate firing

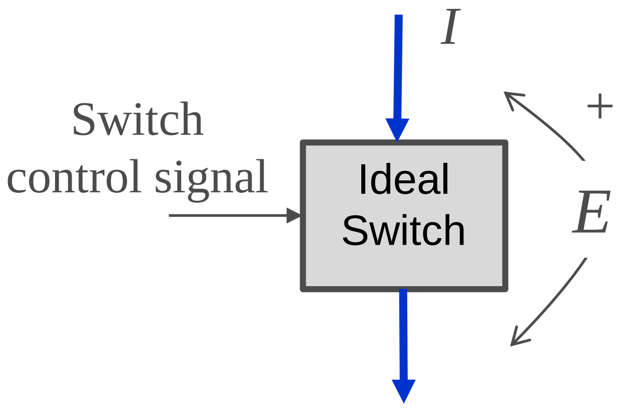


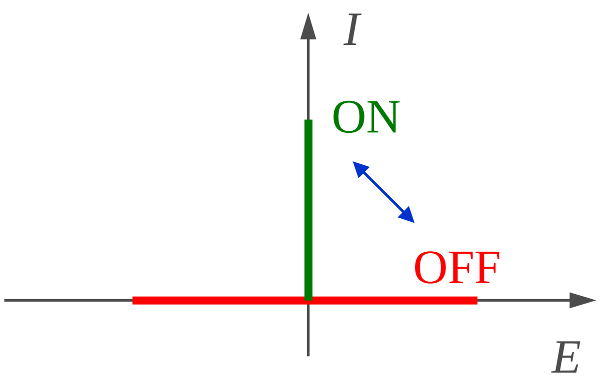
(a) (b)

- We can control the current in an AC circuit by delaying the gate (G) pulses with respect to the start of each positive half-cycle.
  - If the pulses occur at the very beginning of each half-cycle, conduction lasts for 180° like a diode
  - If the pulses are delayed by θ, current only flows during the remaining $180^o-\theta$

Controllable power semi-conductor switches

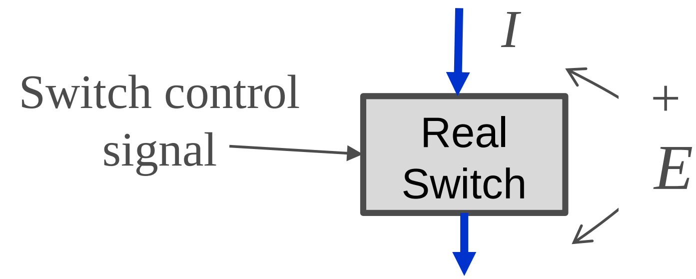
- **Examples:**
  - **GTO** (Gate-turn-off thyristor)
  - **IGBT** (Insulated gate bipolar transistor)
  - **BJT** (Bipolar junction transistor)
  - **MOSFET** (Metal-oxide-semiconductor field effect transistor)
- **Ideal switch**
  - Vanishingly small power required from the control signal to trigger the switch
  - Switch between ON and OFF instantaneously when triggered by the control signal
  - When OFF, block arbitrarily large forward and reverse voltages with zero current flow
  - When ON, conduct arbitrarily large currents with zero voltage drop

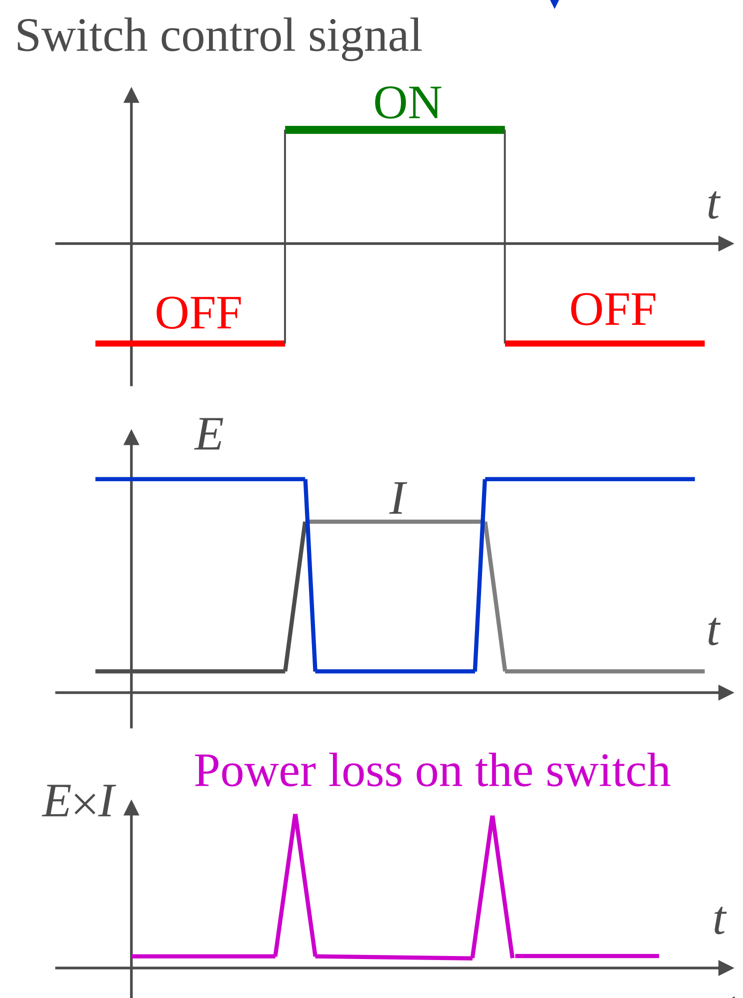




Controllable power semi-conductor switches (cont'd)

- **Real switches:**
  - Requiring control power for switches (the less control power the simpler the control circuit)
  - Limited switching frequency
  - Having OFF-state leakage current
  - Having ON-state voltage (relevant to conducting losses)
  - Limited forward- & reverse-voltage blocking capability (the higher voltage blocking capability, the fewer switches in series)
  - Limited ON-state current rating (the higher current rating, the fewer switches in parallel)
  - Limited *dE/dt* and *dI/dt* ratings (requiring additional circuit to limit |*EI*|)





AC-to-DC converter: single-phase, diode bridge rectifier

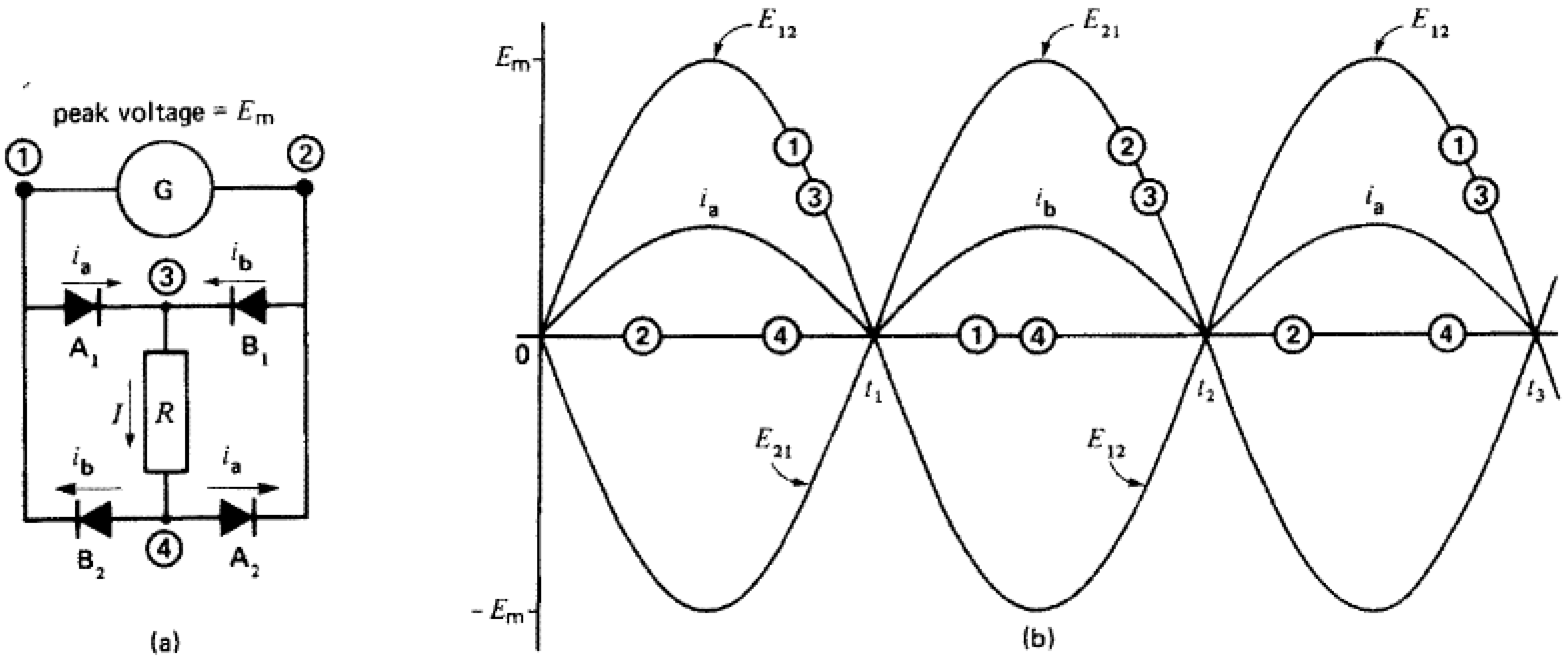


Figure 21.13
a. Single-phase bridge rectifier.
b. Voltage levels.

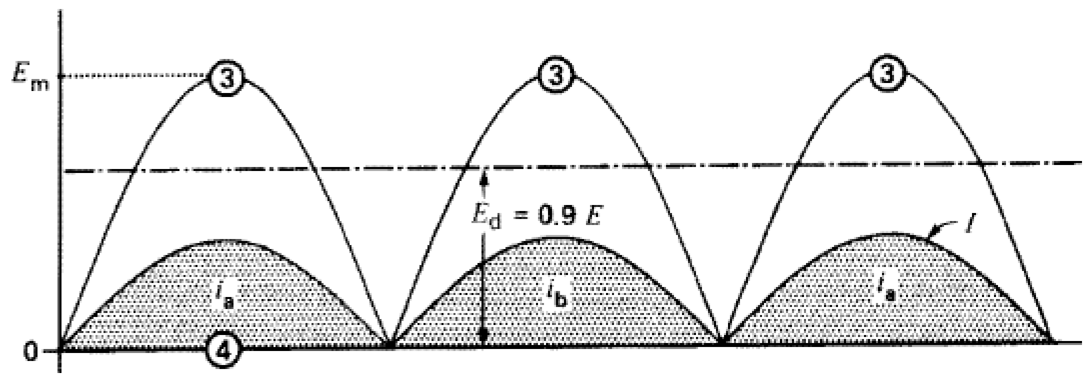
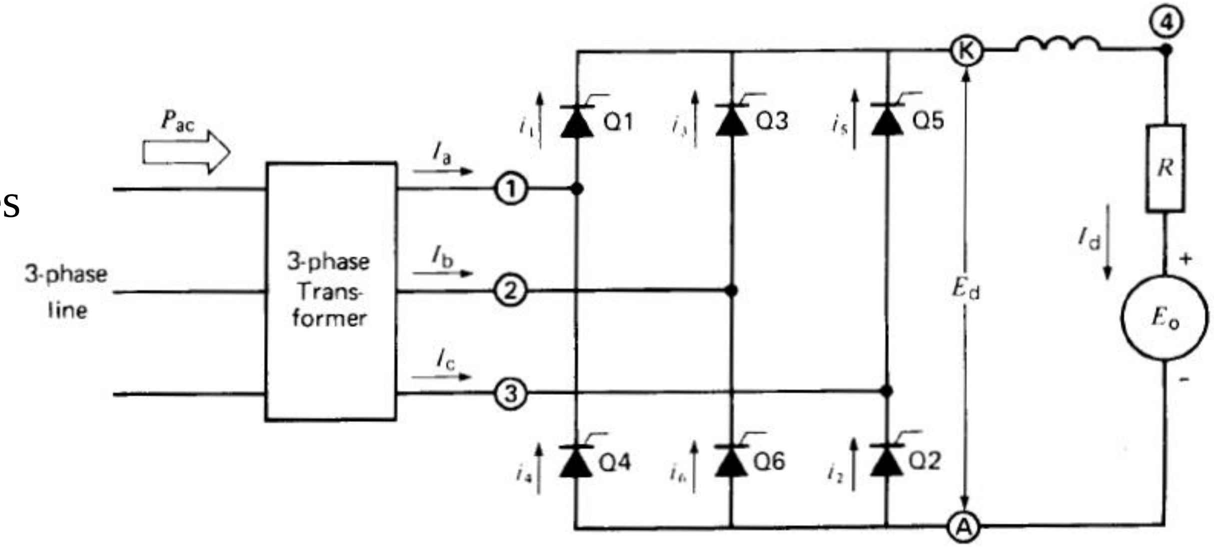


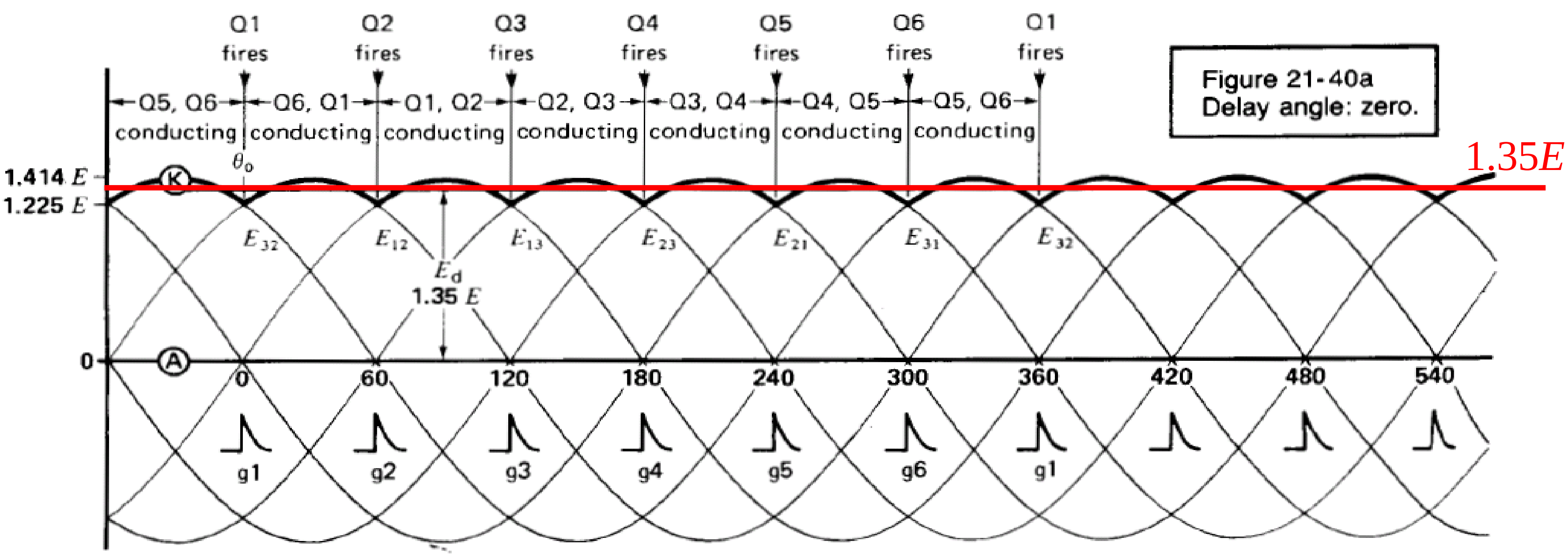
Figure 21.13c
Voltage and current waveforms in load R.

AC-to-DC converter: 3-phase, 6-pulse thyristor rectifier

- Control the DC output voltage E_d by the delay angle α of triggering pulses

$$E_d = 1.35 E \cos\alpha$$





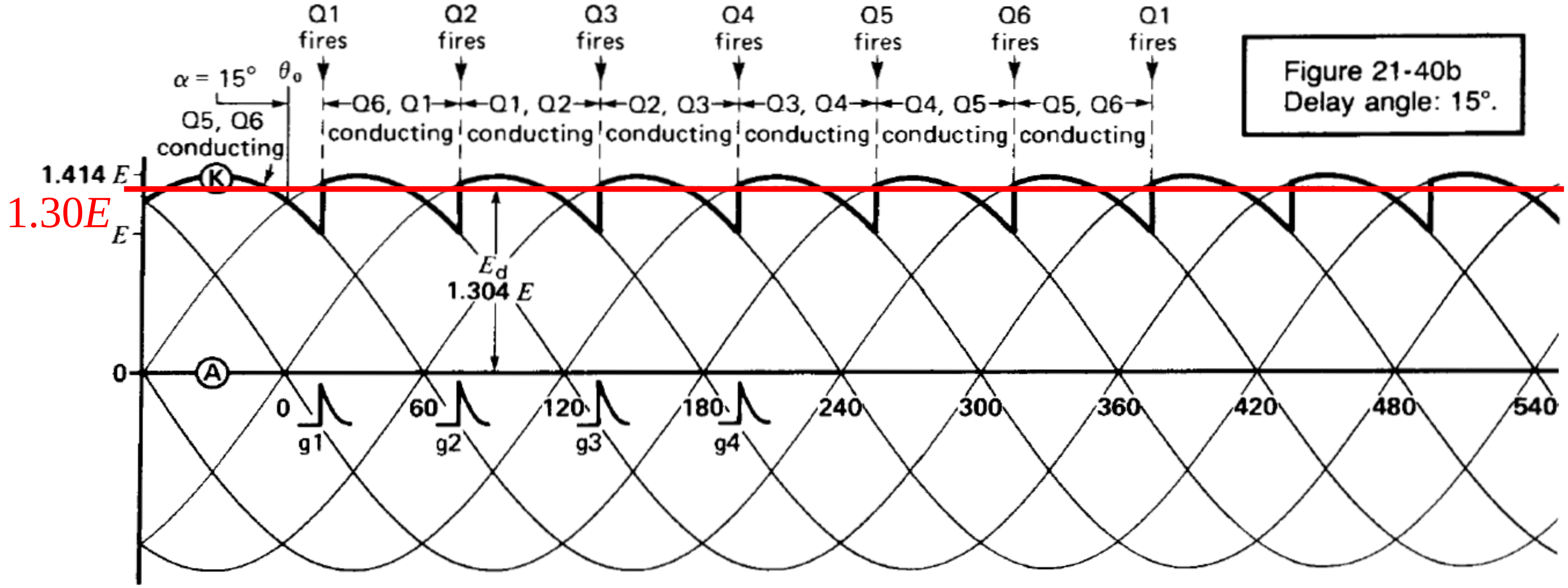


Figure 21-40b
Delay angle: 15°.
Q1 fires
Q2 fires
Q3 fires
Q4 fires
Q5 fires
Q6 fires
Q1 fires
α = 15°
θo
Q5, Q6 conducting
Q6, Q1 conducting
Q1, Q2 conducting
Q2, Q3 conducting
Q3, Q4 conducting
Q4, Q5 conducting
Q5, Q6 conducting
1.414 E
1.30E
E
K
Ed
1.304 E
0
A
0
60
120
180
240
300
360
420
480
540
g1
g2
g3
g4

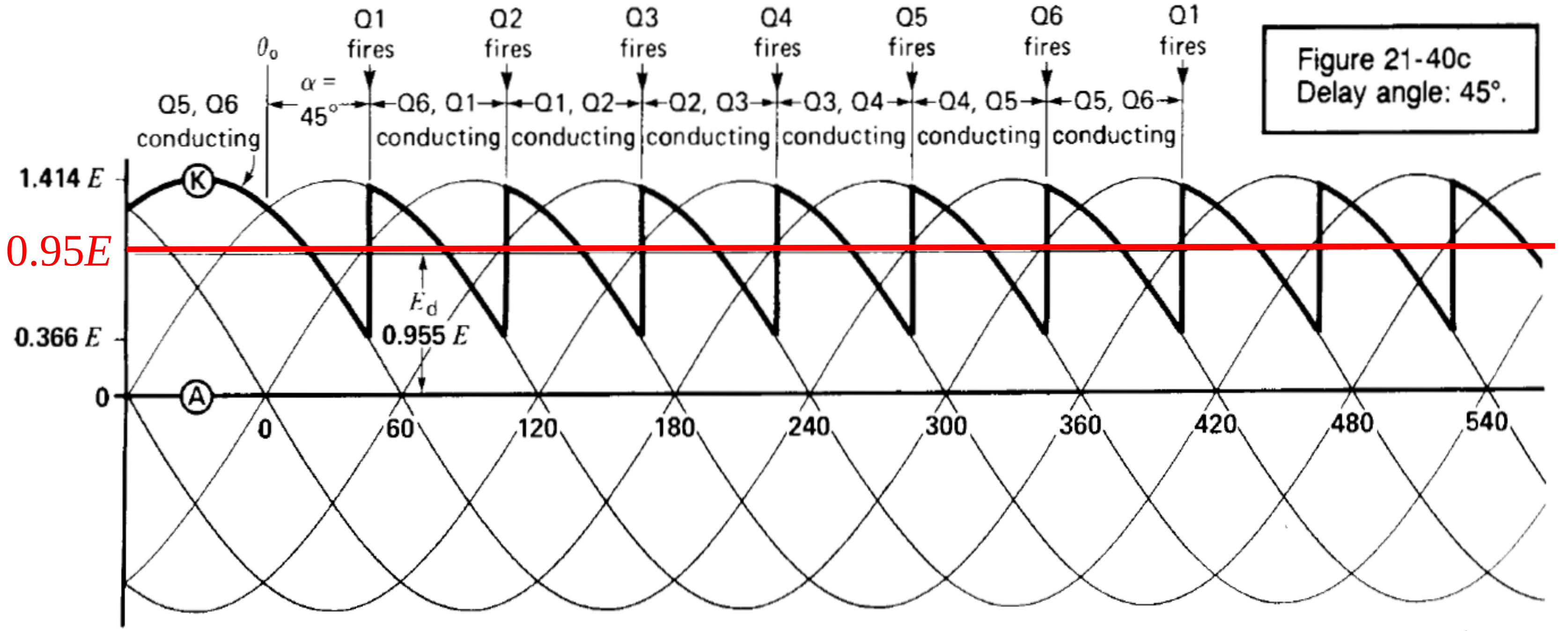


Figure 21-40c
Delay angle: 45°.
Q1 fires
Q2 fires
Q3 fires
Q4 fires
Q5 fires
Q6 fires
Q1 fires
θo
α = 45°
Q5, Q6 conducting
Q6, Q1 conducting
Q1, Q2 conducting
Q2, Q3 conducting
Q3, Q4 conducting
Q4, Q5 conducting
Q5, Q6 conducting
1.414 E
K
0.95E
Ed
0.955 E
0.366 E
0
A
0
60
120
180
240
300
360
420
480
540

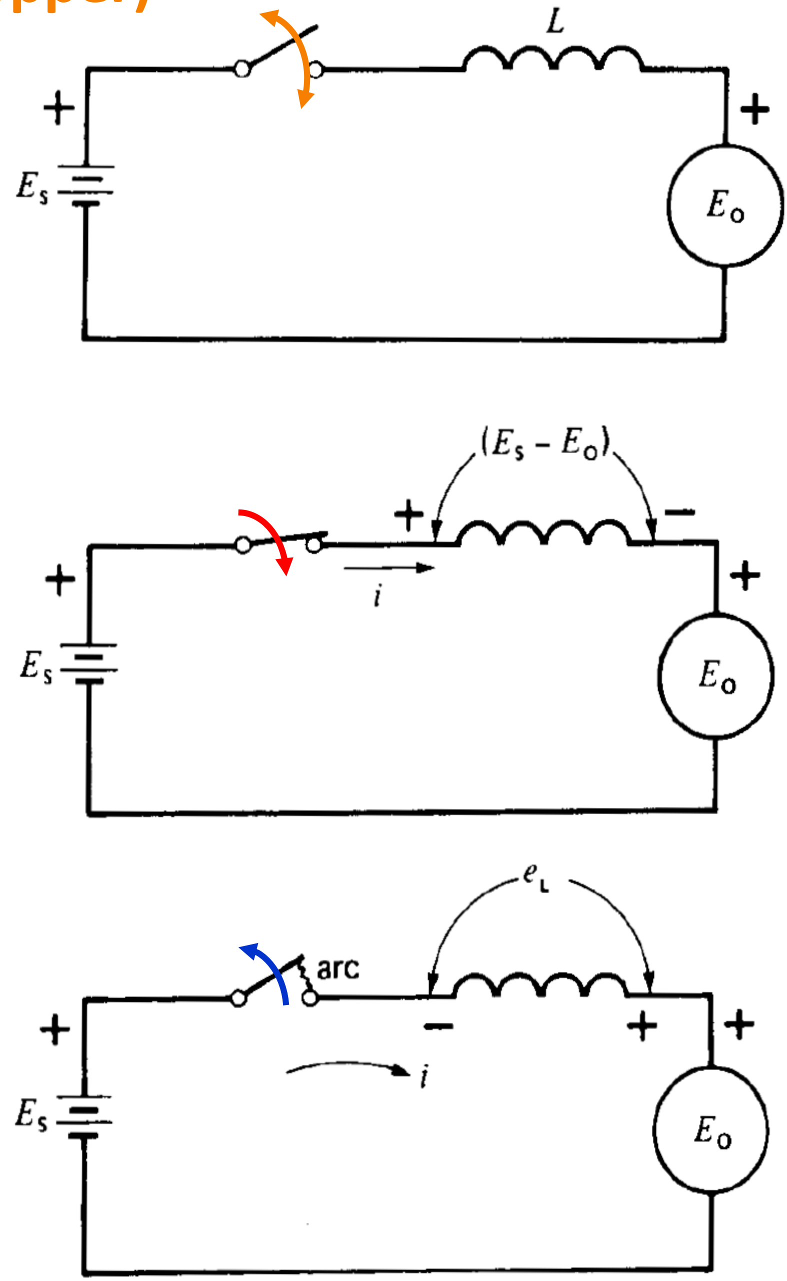
Step-down DC-to-DC converter (buck chopper)

- To transfer power from a high-voltage DC source E_S to a lower-voltage DC load E_o, one solution is to connect them by an inductor and to open and close the circuit periodically
  - When switch closes, energy is transferred from E_S to E_o during time of closure T_1

$$E_S - E_o = L\frac{di}{dt} \quad \xrightarrow{\text{Integration}} \quad i = \frac{E_S - E_o}{L}t$$

$$I_a \triangleq i(T_1) = \frac{E_S - E_o}{L}T_1 \qquad W = \frac{1}{2}LI_a^2$$

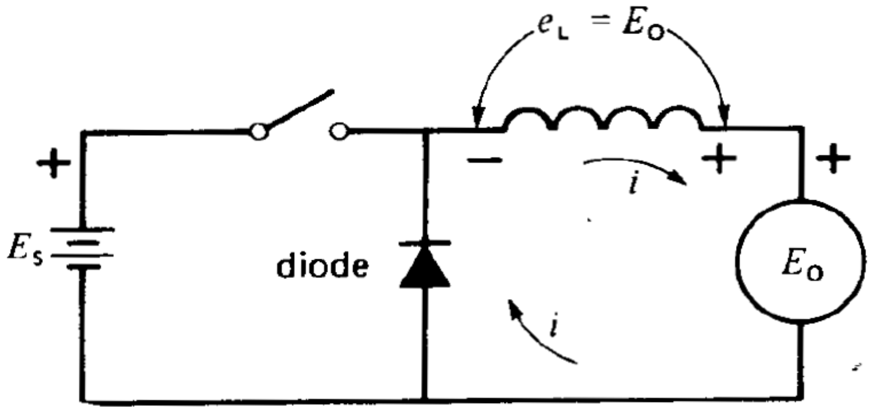
  - When the switch opens, magnetic energy W stored in the inductor is dissipated in the arc across the switch, so efficiency of power transfer is poor



1-Quadrant DC-to-DC converter

- Add an diode in order to deliver energy W to load E_o also when the switch opens:

$$L\frac{di}{dt}+E_o=0 \quad \Rightarrow \quad i-I_a=-\frac{E_o}{L}t$$



If i takes T_2 to become zero

$$I_a=\frac{E_o}{L}T_2$$

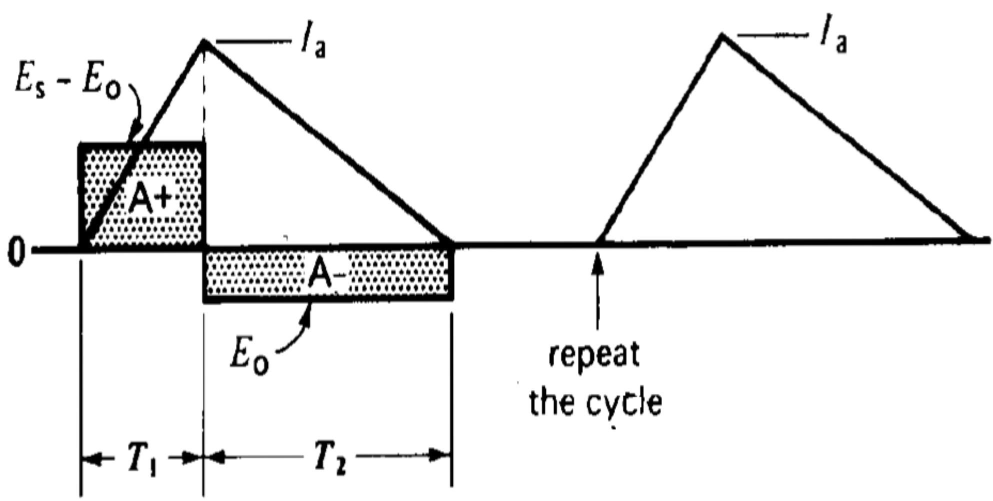
$$I_a=\frac{E_S-E_o}{L}T_1 \quad \Rightarrow \quad E_oT_2=(E_S-E_o)T_1$$

A- = A+

(from previous the slide)

$$\frac{T_2}{T_1}=\frac{E_S-E_o}{E_o}$$

- The inductor absorbs energy at a relatively high voltage (E_S-E_o) and delivers it at a lower voltage E_o
- This circuit enables us to transfer energy without incurring any losses
- In reality, the mechanical switch is replaced by a controllable semi-conductor switch (GTO, MOSFET or IGBT).



Rapid switching

- Open and close the switch rapidly so that the current increases and decreases in a narrow range between I_a and I_b
  - When the current falls to I_b (after T_b), the switch recloses
  - When the current rises to I_a (after T_a), the switch reopens
- Duty cycle:

$$D=T_a/(T_a+T_b)=T_a/T \ <1$$

- Average DC current to the load:

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

- Average DC current from the source:

$$I_S=I_o(T_a/T)=I_oD \quad \Rightarrow I_o=I_S/D$$

- If there is no power loss

$$E_SI_S=E_oI_o=E_oI_S/D \quad \Rightarrow \ E_o=DE_S$$

DC output voltage can simply be controlled by varying the duty cycle

- See Example 21-11

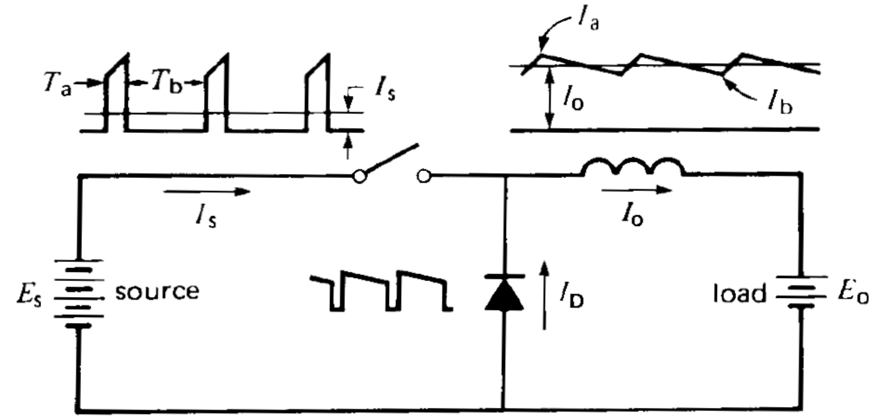


Figure 21.60a
Currents in a chopper circuit.

$$I_a-I_b=\frac{E_S-E_o}{L}T_a=\frac{E_o}{L}T_b$$

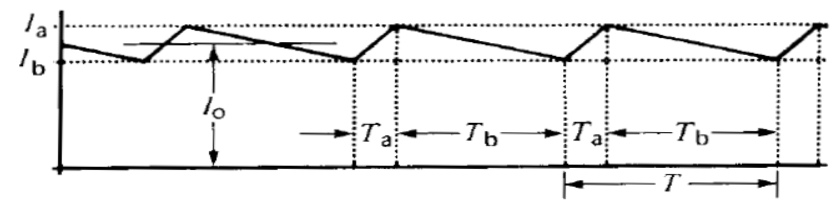


Figure 21.60b
Current in the load.

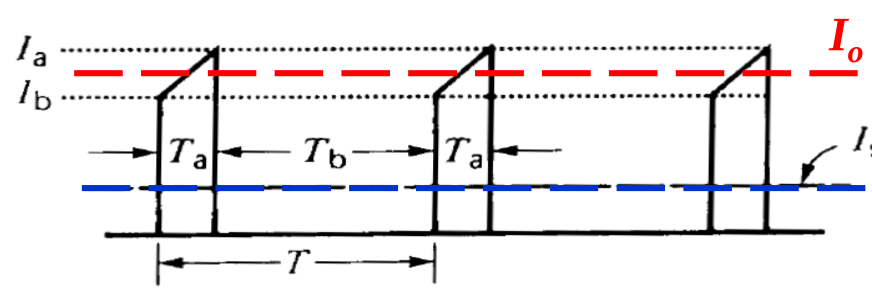


Figure 21.60c
Current pulses provided by the source.

Impedance transformation

Duty cycle $D<1$

$I_o=I_S/D$ $E_o=DE_S$

$R_o=E_o/I_o$

$R_S=E_S/I_S=(E_o/D)/(I_oD)$

$=R_o/D^2$

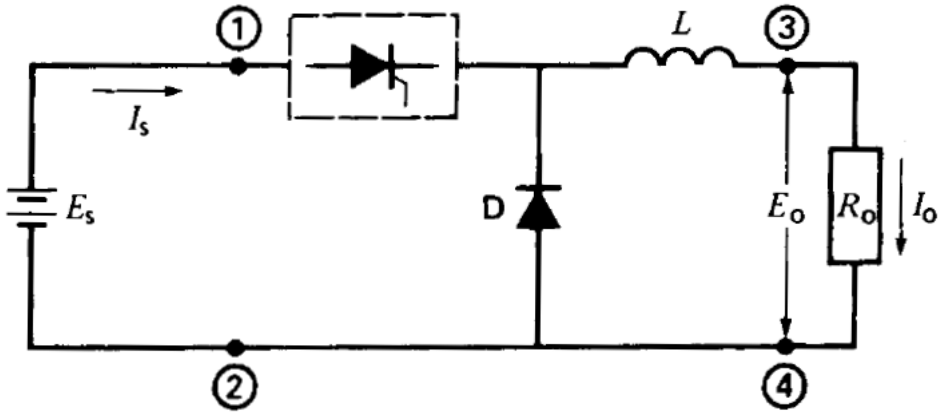
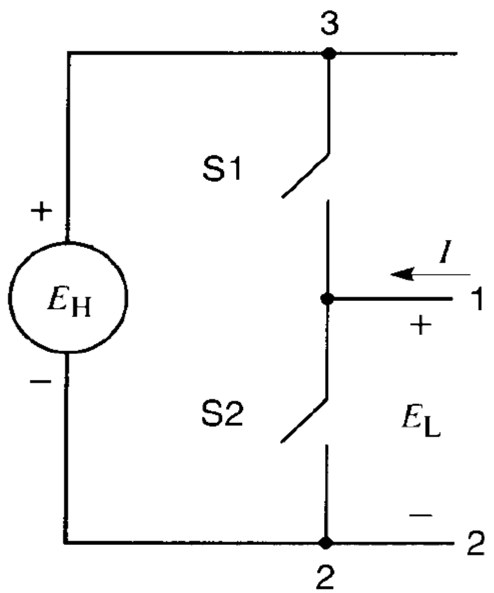
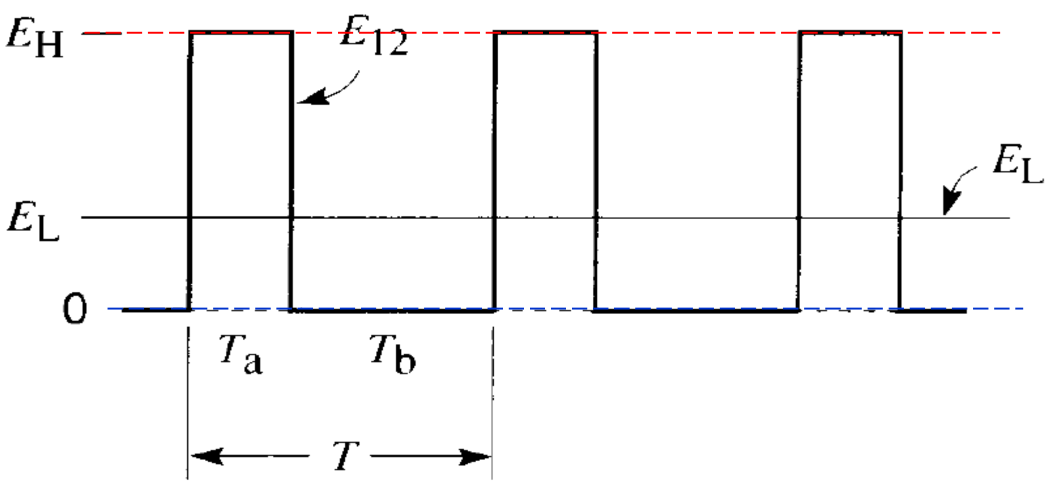


Figure 21.62
A chopper can make a fixed resistor R_o appear as a variable resistance between terminals 1-2.

- The 1-quadrant DC-to-DC converter can transform the resistance of a fixed resistor to a higher value depending on *D*.
  - It behaves like a DC transformer whose turns ratio is $1/D$
  - Unlike a transformer, which allows power to flow bi-directionally, a step-down chopper can transfer power only from the high-voltage side to the low-voltage side
- See Example 21-12

2-quadrant DC-to-DC converter





- Consider two mechanical switches S1 and S2 that open and close alternatively
  - Within the time of a cycle $T=T_a+T_b$, S1 is closed for T_a and S2 is closed for T_b
  - S1 has duty cycle $D=T_a/T$ and S2 has duty cycle $T_b/T=(1\text{-}D)$
  - Output voltage E_{12} fluctuates between E_H and 0, having the average DC output

    $E_L=DE_H$ (variable by varying D)

- **2-quadrant converter:**
  - **Specific voltage polarity**: Terminal 1 is always (+) with respect to terminal 2
  - **Bidirectional current**: current and power can flow from E_H to E_L, or vice versa since current always circulate through either S1 or S2

- Assume the load to be a battery E_o with internal resistance R
- Use inductor L as a buffer between the fluctuating E_{12} and constant E_o

  Average current $I_L=(E_L-E_o)/R$
- If average DC voltage $E_L=E_o$, then $I_L=0$ and no dc power exchange happens
- Step-down chopper (buck mode):
  - If $E_L>E_o$, power=$|E_L I_L|$ flows to E_o
- Step-up chopper (boost mode):
  - If $E_L<E_o$, power=$|E_L I_L|$ flows to E_H
- In reality, mechanical switches S1 and S2 are replaced by semi-conductor switches Q1 and Q2 each with a diode placed in antiparallel for bi-directional currents
- Q1 and Q2 cannot be closed at the same time to avoid a short-circuit across E_H; in each half cycle, they both open for a very brief **dead time** (zero current from E_H) for a safety margin
- See Example 21-13

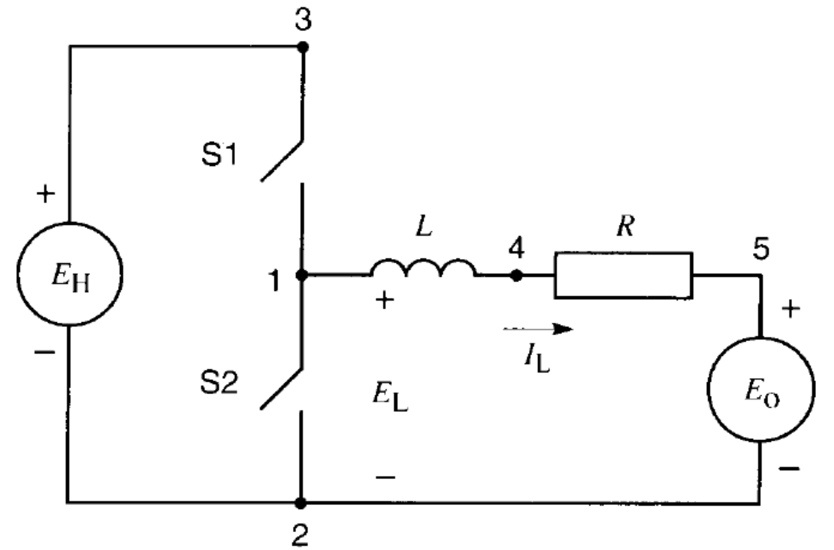


Figure 21.64
Power can flow from E_H to E_O and vice versa.

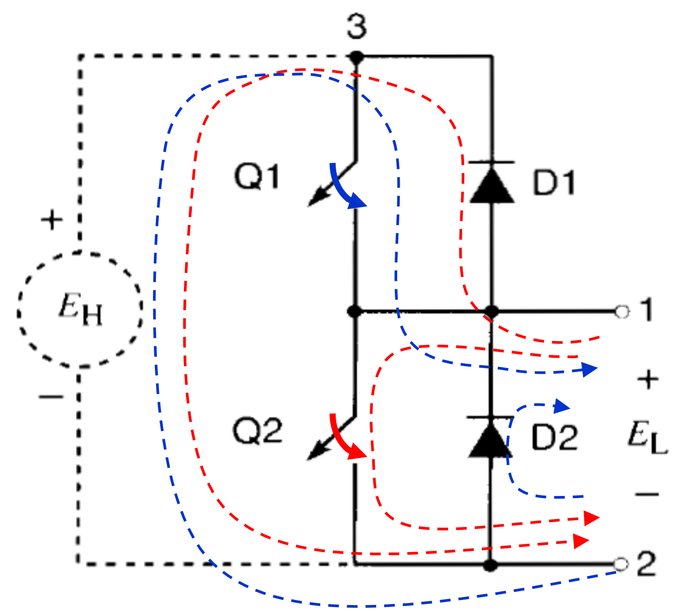
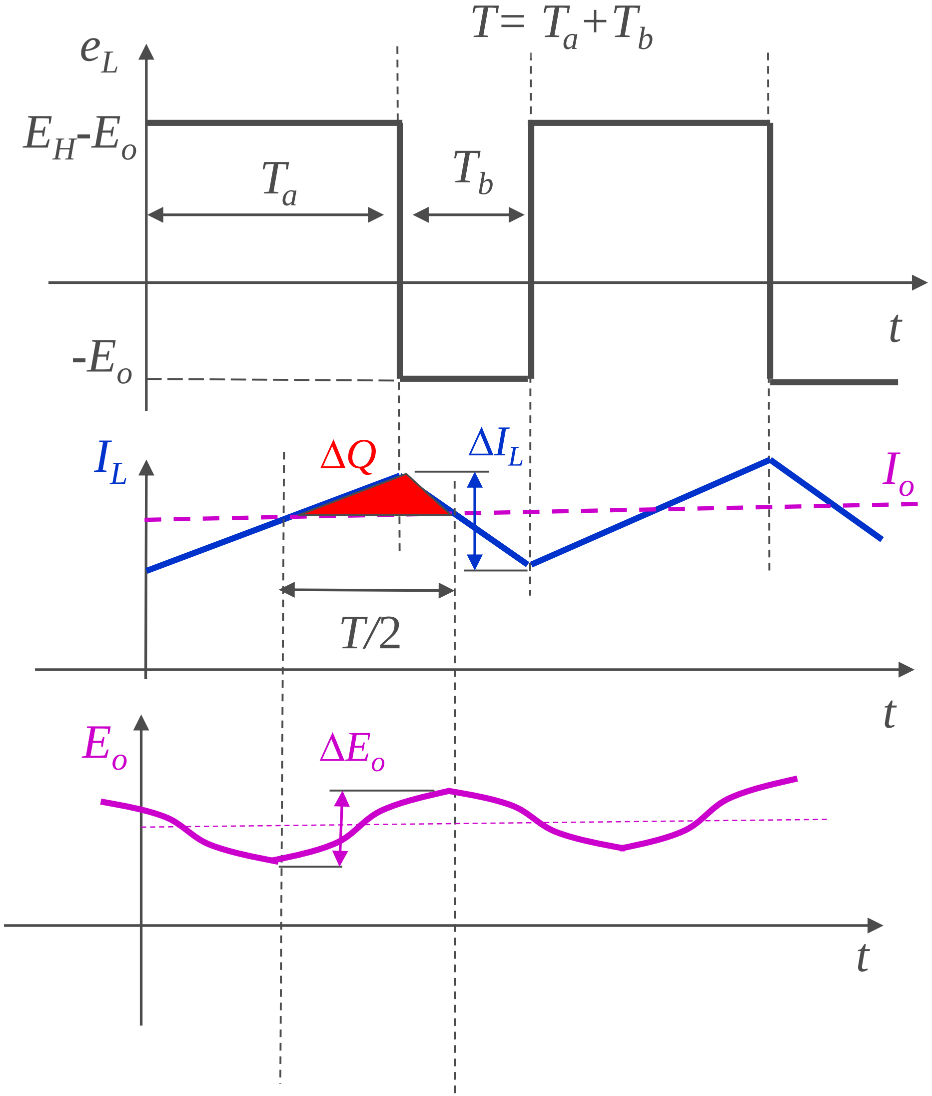


Figure 21.69
Two-quadrant electronic converter.

Output voltage ripple filter

- A LC low-pass filter is applied to create almost flat DC output voltage E_o
- Ripples only appear in I_L, not I_o.



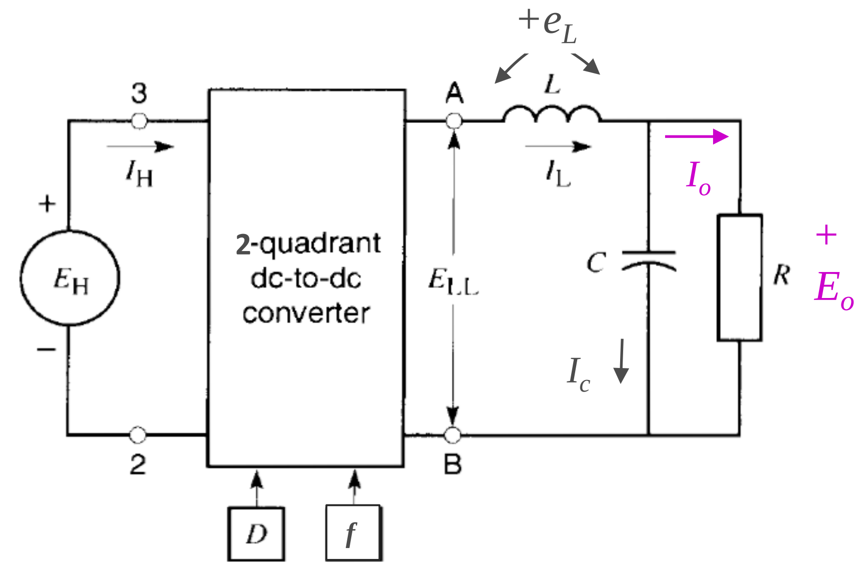


Figure 21.73
Four-quadrant dc-to-dc converter feeding a passive dc load *R*.

$$f_{LC} = \frac{1}{2\pi\sqrt{LC}} \ll f = \frac{1}{T}$$

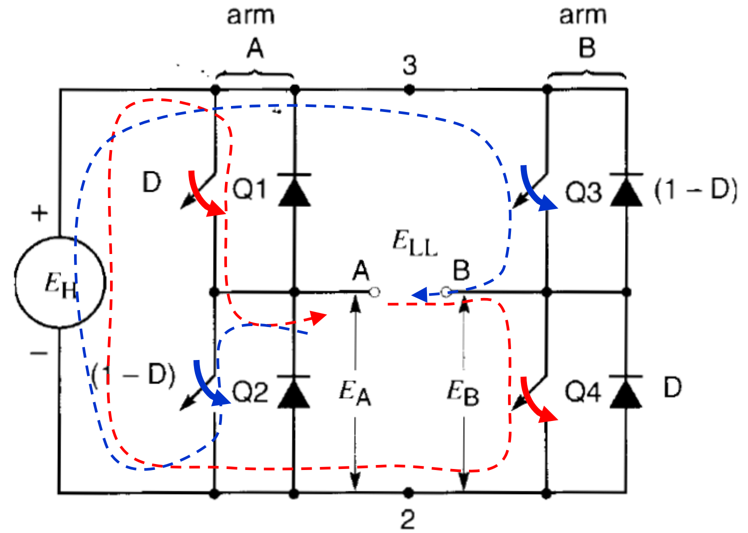
$$\Delta I_L = \frac{E_o}{L} T_b = \frac{E_o}{L}(1-D)T$$

$$\Delta Q = \int I_c dt = \frac{1}{2}\frac{\Delta I_L}{2}\frac{T}{2} = \frac{\Delta I_L T}{8} = \frac{E_o}{8L}(1-D)T^2$$

$$\frac{\Delta E_o}{E_o} = \frac{\Delta Q}{CE_o} = \frac{(1-D)T^2}{8LC} = \frac{\pi^2(1-D)}{2}\left(\frac{f_{LC}}{f}\right)^2 \approx 0$$

4-quadrant DC-to-DC converter

- It consists of two identical 2-quadrant converters having the same switching frequency, e.g. 100kHz
- **Switching rules:**
  - Q1 and Q2 on arm A open and close alternately
  - Q3 and Q4 on arm B open and close alternately
  - Q1 and Q4 open and close simultaneously (duty cycle D)
  - Q2 and Q3 open and close simultaneously (duty cycle 1-D)
- **4-quadrant:**
  - E_{LL} changes between $-E_H$ and $+E_H$
  - The DC current flow of the load between A and B is bidirectional



$$E_{A2}=DE_H \qquad E_{B2}=(1\text{-}D)E_H$$

$$E_{LL}=E_{A2}\text{-}E_{B2}=(2D\text{-}1)E_H$$

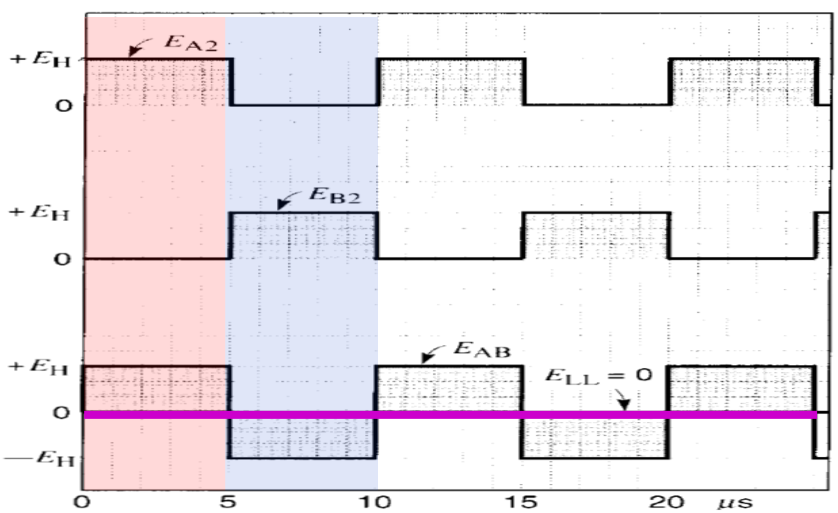


Figure 21.71
Voltage output when $D = 0.5$. The average voltage is zero.

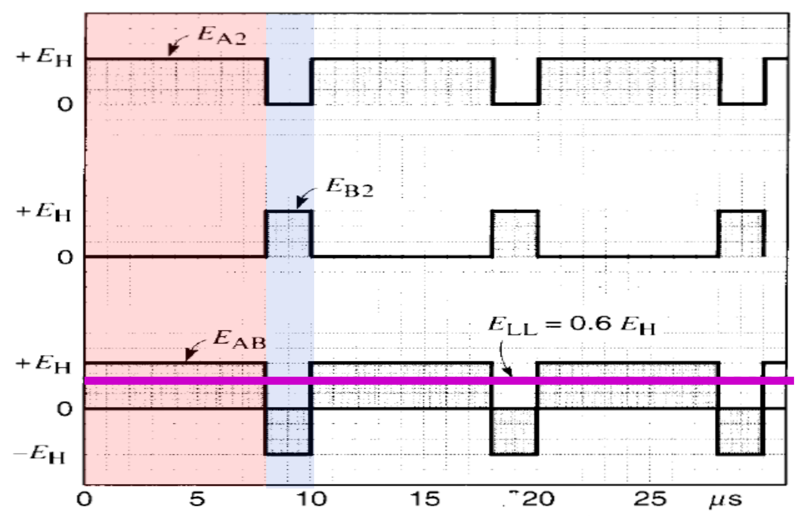
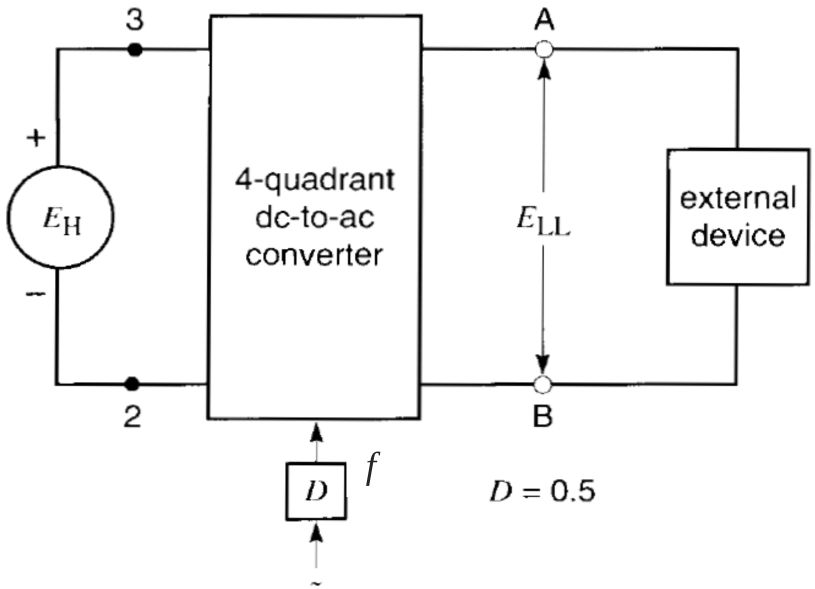
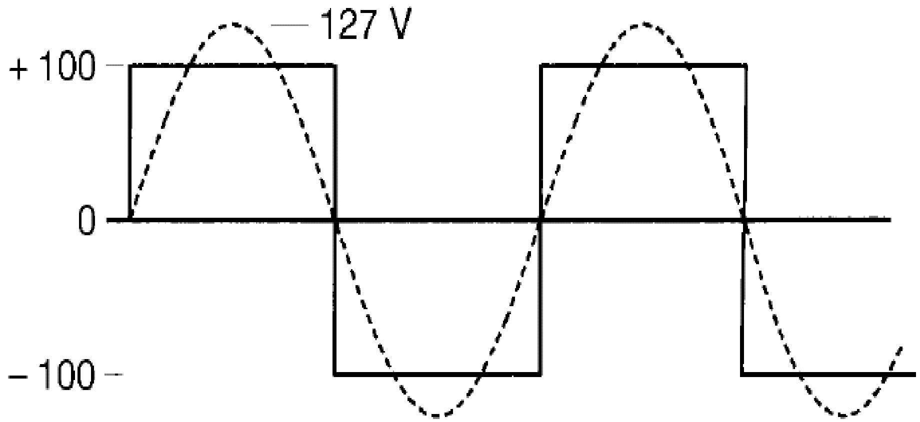


Figure 21.72
Voltage output when $D = 0.8$. The average voltage E_{LL} is 0.6 E_H.

DC-to-AC rectangular wave converter



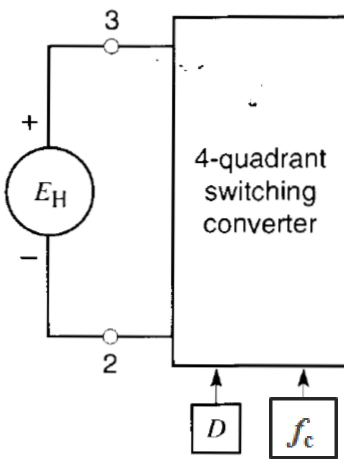
$$E_{LL} = \frac{400}{\pi}\left[\sin(2\pi ft) + \frac{1}{3}\sin(6\pi ft) + \frac{1}{5}\sin(10\pi ft) + \ldots\right]$$



- The 4-quadrant converter with D=0.5 is able to transform a DC voltage E_H into a rectangular AC voltage $\pm E_H$, which contains a fundamental sinusoidal component having an amplitude of $1.27E_H$ and an effective value of $1.27E_H/\sqrt{2}=0.90E_H$
- It is bidirectional (DC-to-AC and AC-to-DC) and frequency-variable
- The output has a fixed amplitude and large 3rd, 5th and 7th harmonics.

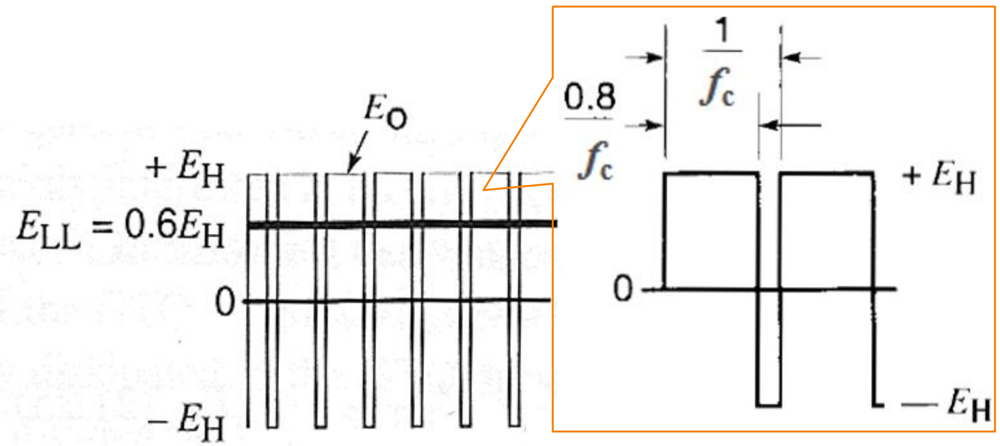
PWM (pulse width modulation)

- 4-quadrant DC-to-DC converter using a carrier frequency f_c and different values of D

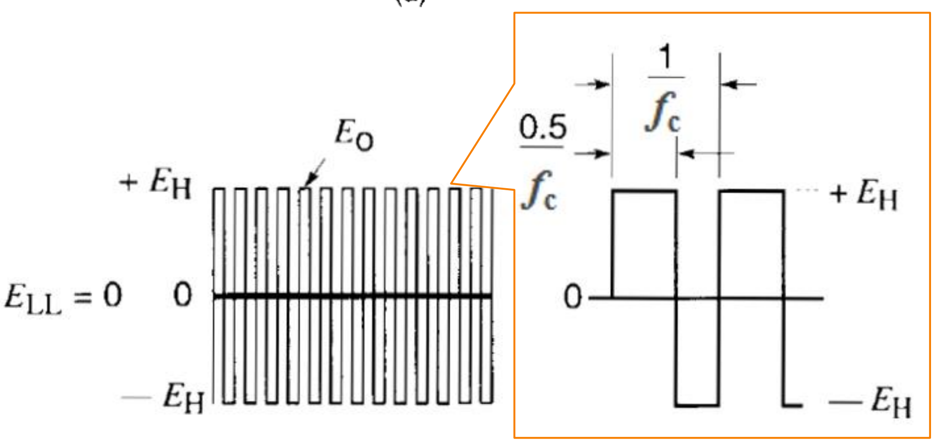


$$E_{LL} = (2D\text{-}1)E_H$$

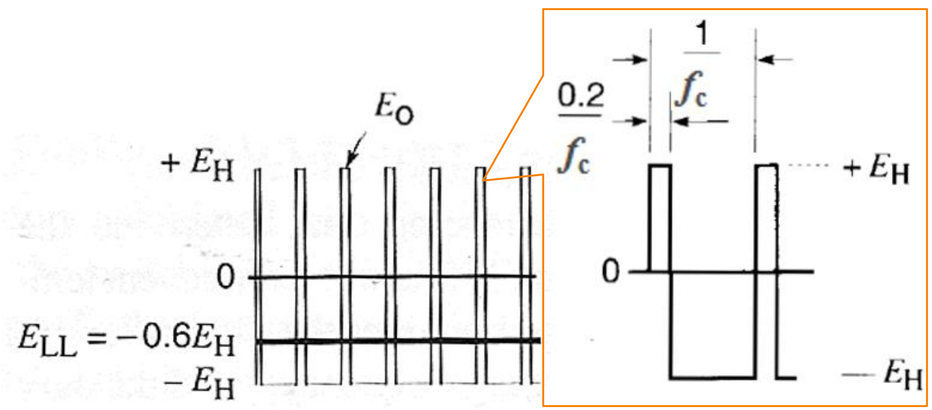
(a)



(b) $D = 0.8$ $E_{LL} = +0.6\ E_H$



(c) $D = 0.5$ $E_{LL} = 0$



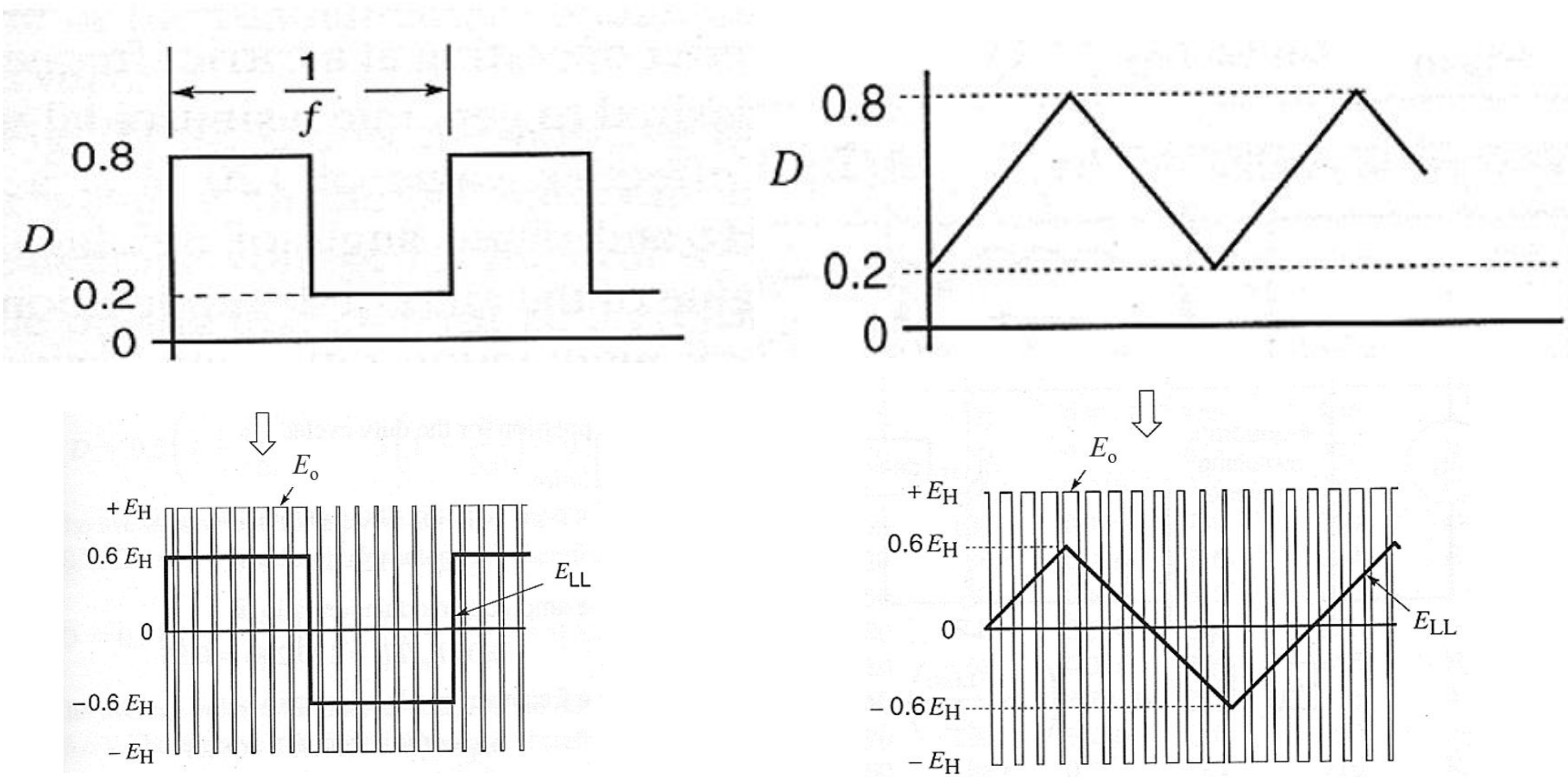
(d) $D = 0.2$ $E_{LL} = -0.6\ E_H$

- To obtain $E_{LL}(t)$= a periodical waveform g(t),

$$D(t) = \frac{g(t)}{2E_H} + \frac{1}{2}$$

DC-to-AC non-sine wave converters with PWM

- With D varying periodically between 0.8 and 0.2 at a frequency $f < 0.1 f_c$
- Although f_c is fixed, the ON/OFF pulse widths change continually with D.
- That is why this type of switching is called Pulse Width Modulation (PMW)



DC-to-AC sine wave converter with PMW

- To obtain $E_{LL}(t)=E_m\sin(2\pi ft+\theta)$

$$D(t)=\frac{E_m}{2E_H}\sin(2\pi ft+\theta)+\frac{1}{2}$$

Amplitude modulation ratio $m=E_m/E_H$

Frequency modulation ratio $m_f=f_c/f=T/T_c$

- Create a 83.33Hz sine voltage wave with peak value E_m=100V using a DC-to-AC converter with E_H=200V and f_c=1000Hz:

T=1/83.33=0.012s=12000μs

T_c=1/1000=1000μs

$m_f=T/T_c$=12, so each T_c covers 360/12=30°

Calculate D for $\phi(t)=2\pi ft+\theta$=0°, 30°, 60°, …, which correspond to $E_{LL}=100\sin\phi$ (V)

In each carrier period T_c, Q1&Q4 are ON for first DT_c =1000D(μs) and then Q2&Q3 are ON for the remaining $(1-D)T_c$ = 1000(1-D) (μs)

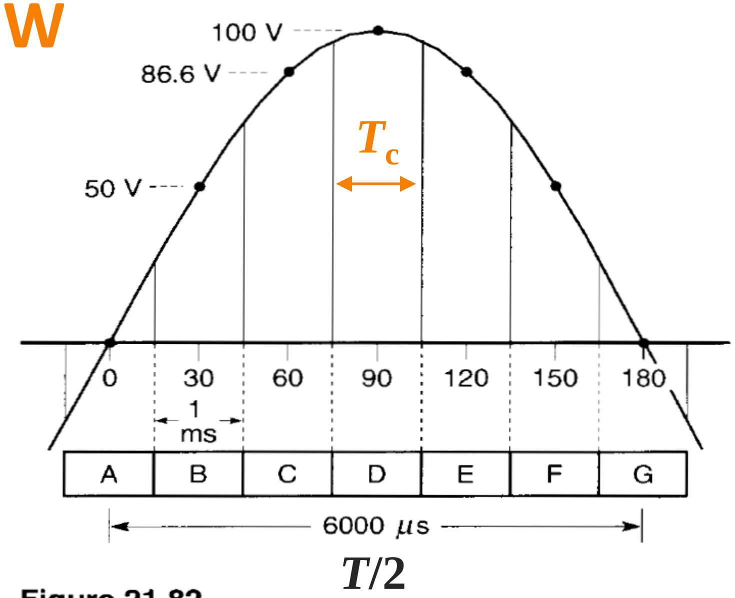


Figure 21.82
Positive half-cycle of the fundamental 83.33 Hz voltage comprises six carrier periods of 1 ms each.

TABLE 21E GENERATING A SINE WAVE

angle [deg]	E_{LL} [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

DC-to-AC sine wave converter with Bipolar/Unipolar PWM

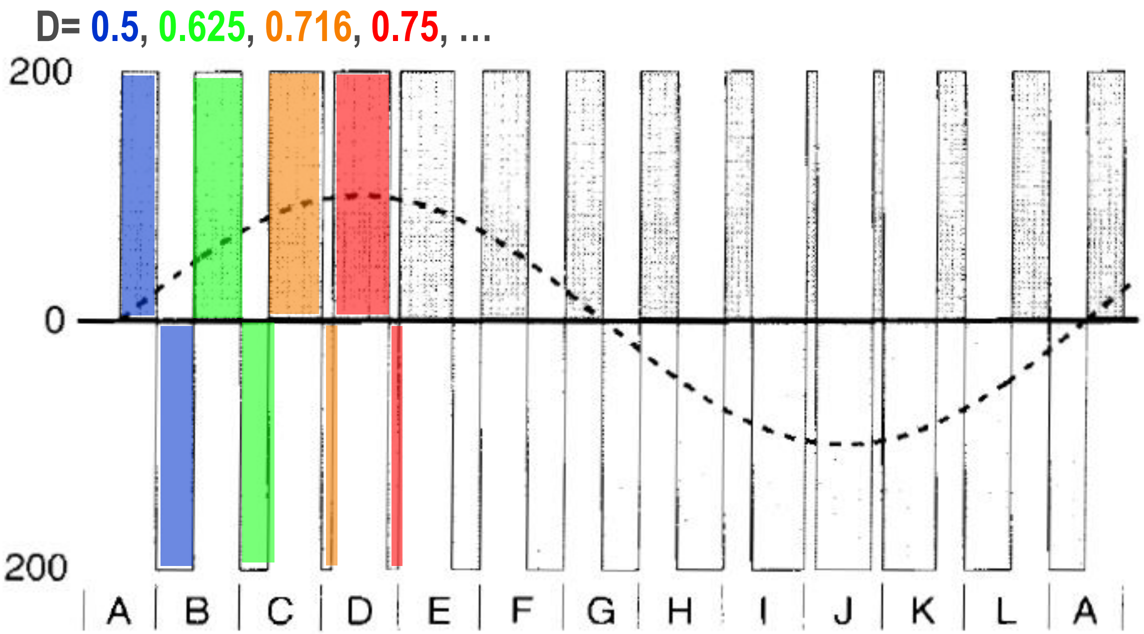


Figure 21.83
Alternative (+) and (−) pulses contain the sinusoidal component.

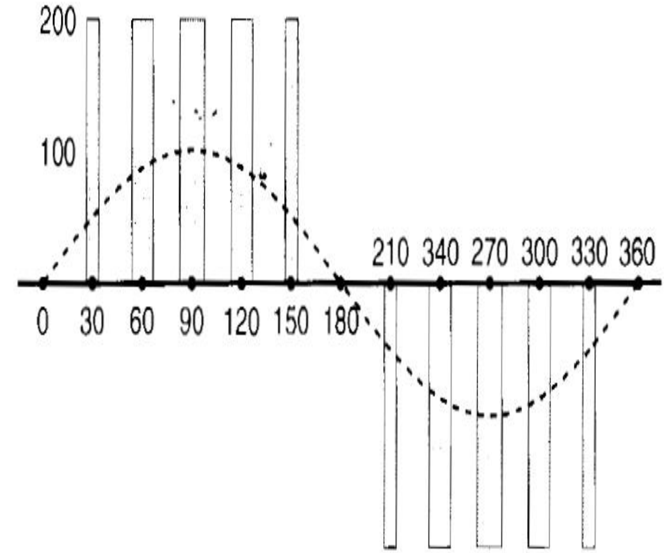


Figure 21.84
Sequential (+) and (−) pulses contain the sinusoidal components.

- Once the carrier frequency is filtered out, the resulting voltage will be sinusoidal
- A higher carrier frequency would yield a better sinusoidal waveform but would increase the power losses of the electronic switches, e.g. IGBTs