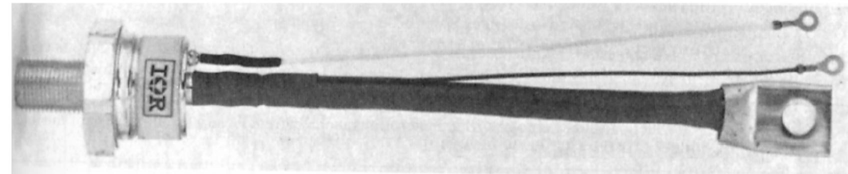
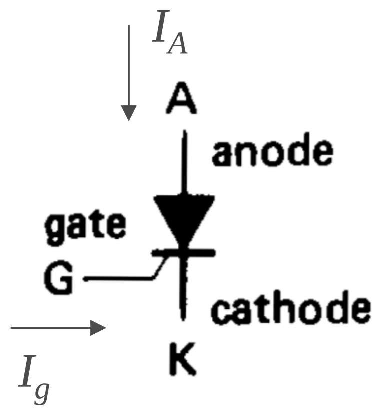
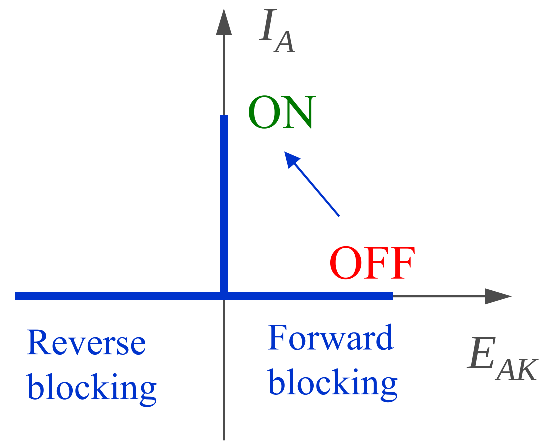
Thyristors

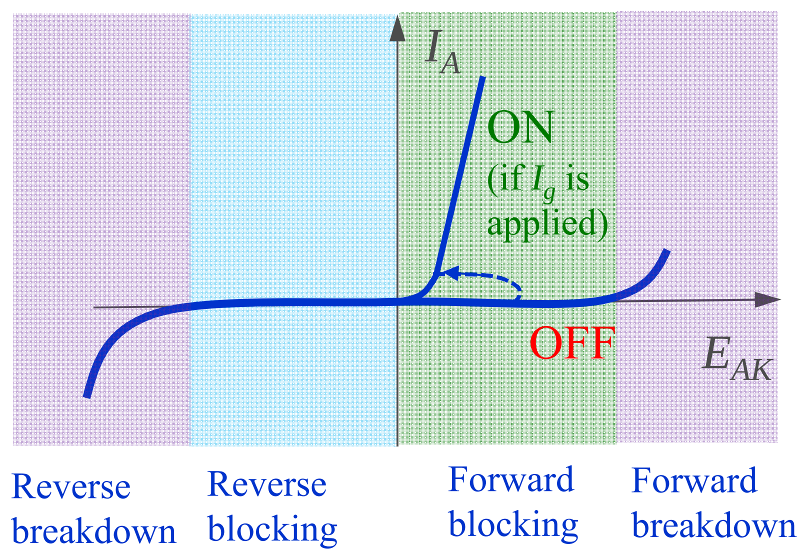


- Usually referred to semiconductor/silicon controlled rectifier (SCR)
- 3 terminals: A (anode), K (cathode) and G (gate)
- A thyristor behaves like a diode except that the instant of conduction can be controlled by "G"; that enables converting DC to AC
- Two conditions to conduct
  1. $E_{AK}>0$
  2. 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



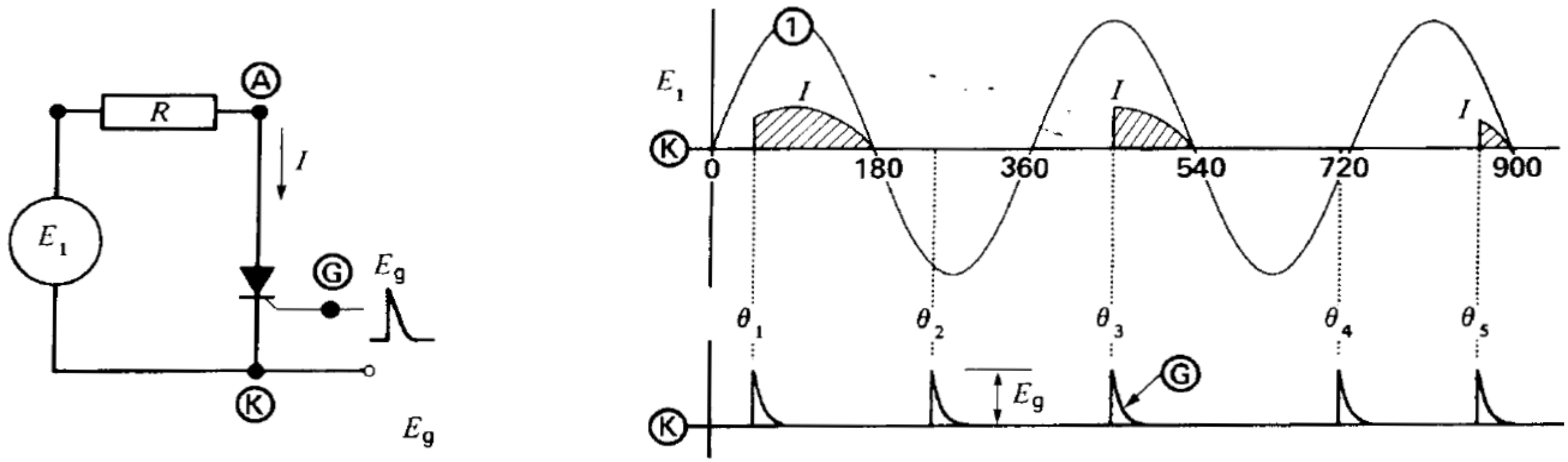


Ideal I-V characteristics



Real I-V characteristics

Principles of gate firing



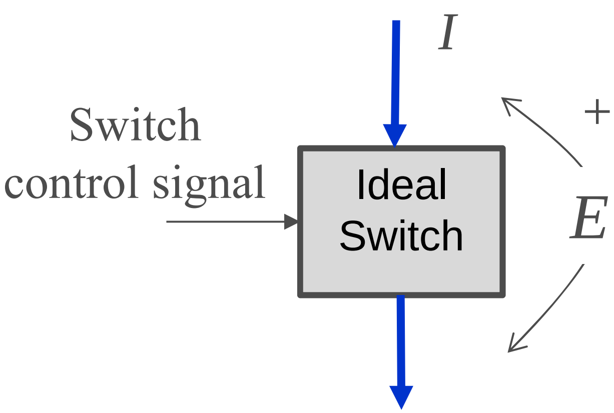
(a) (b)

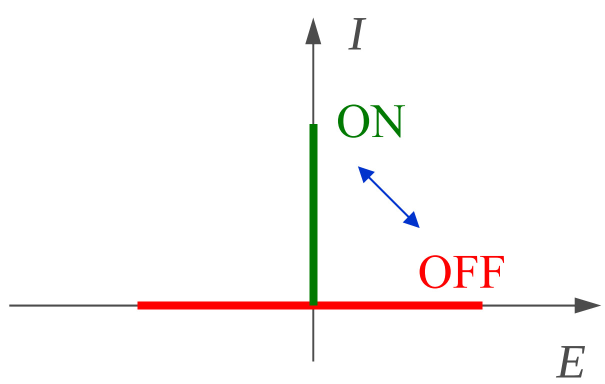
- We can control the current in an AC circuit by delaying the gate (G) pulses with respect to the start of each positive half-cycle.
  - If the pulses occur at the very beginning of each half-cycle, conduction lasts for 180º like a diode
  - If the pulses are delayed by θ, current only flows during the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

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)

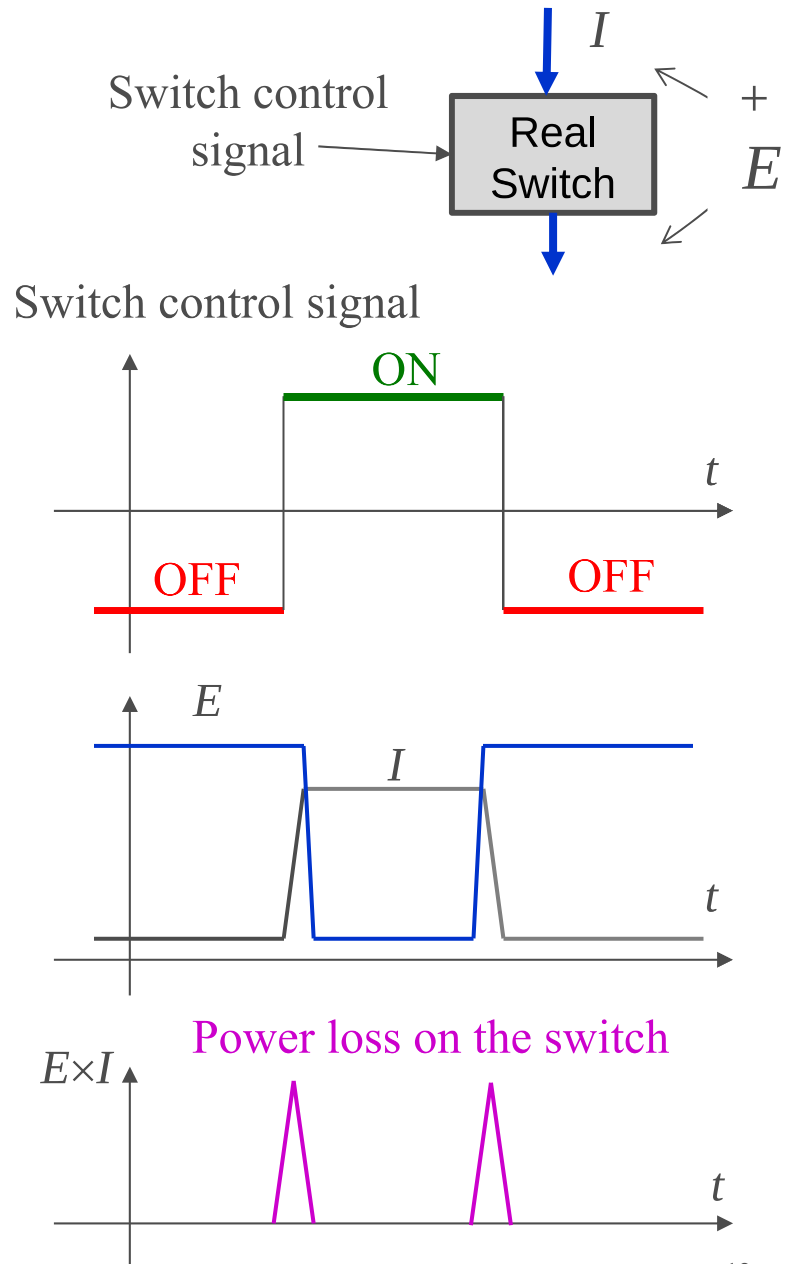
- **Ideal switch**
  - Vanishingly small power required from the control signal to trigger the switch
  - Switch between ON and OFF instantaneously when triggered by the control signal
  - When OFF, block arbitrarily large forward and reverse voltages with zero current flow
  - When ON, conduct arbitrarily 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
  - Have OFF-state leakage current
  - Have 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*|)



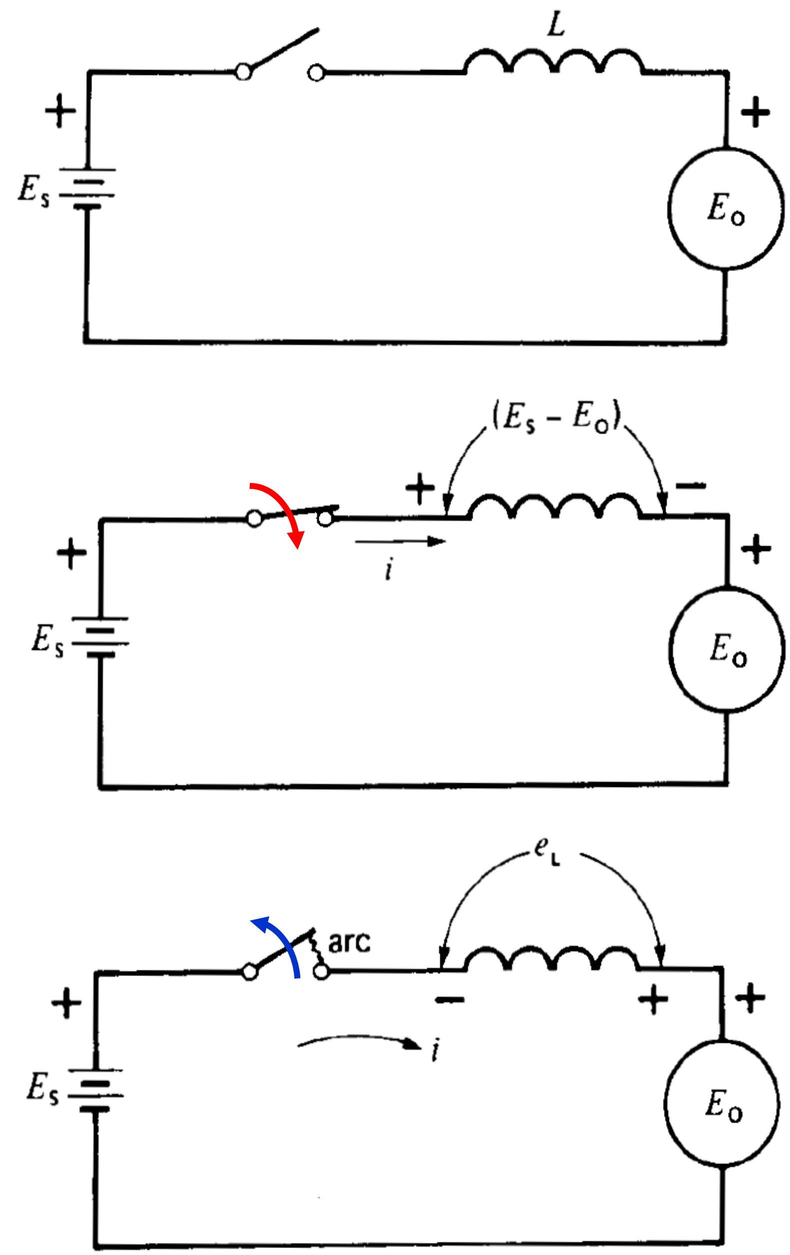
Step-down DC-to-DC converter (buck chopper)

- Voltage step-up/step-down in AC systems can easily be done with a transformer, but in DC systems, a DC-to-DC switching converter is required using a different approach
- 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 the switch closes, energy is transferred from E_S to E_o during time of closure T_1

$$E_S - E_o = L\frac{di}{dt} \quad \Rightarrow \quad i = \frac{E_S - E_o}{L}t$$

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

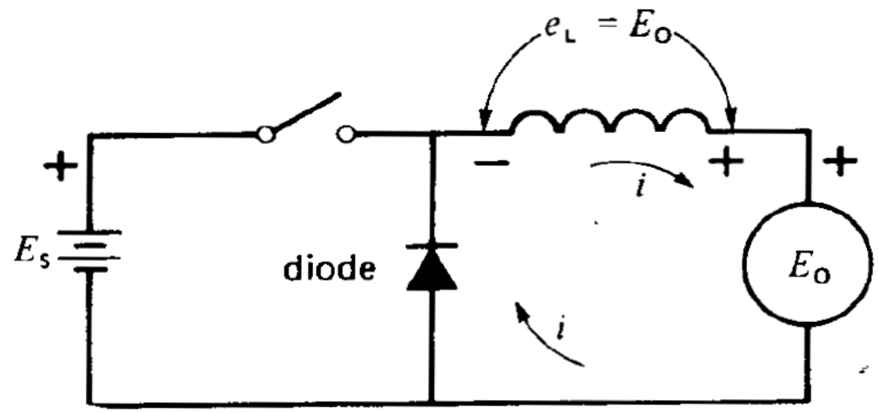
  - When the switch opens, magnetic energy W stored in the inductor is dissipated in the arc across the switch, so efficiency of power transfer is poor



Basic 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

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

$$I_a=\frac{E_S-E_o}{L}T_1$$

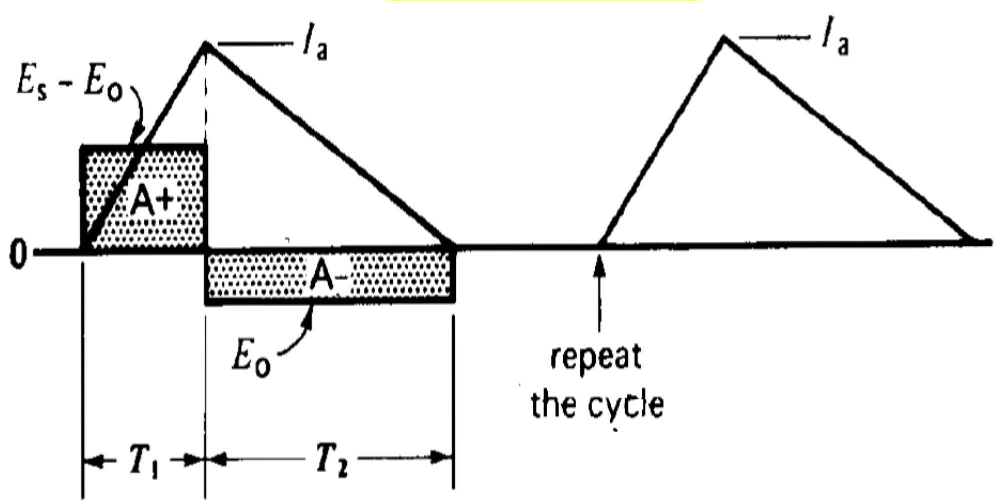
(from previous the slide)

$$\Rightarrow \quad E_oT_2=(E_S-E_o)T_1$$

A+ = A-

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

- 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

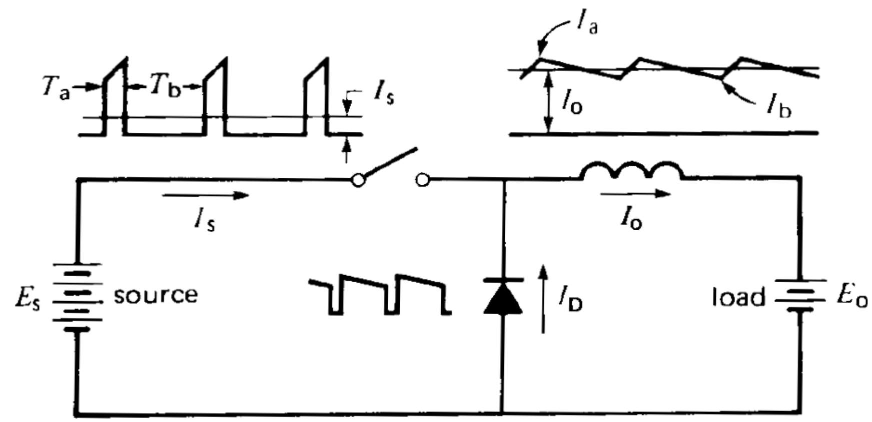


Figure 21.60a
Currents in a chopper circuit.

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

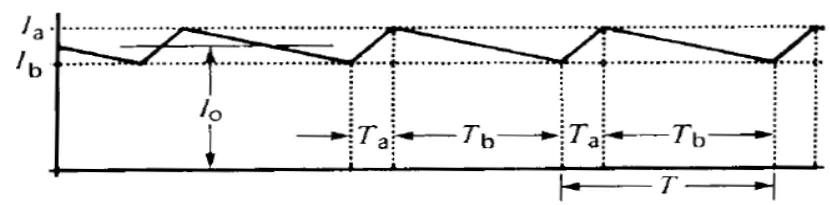


Figure 21.60b
Current in the load.

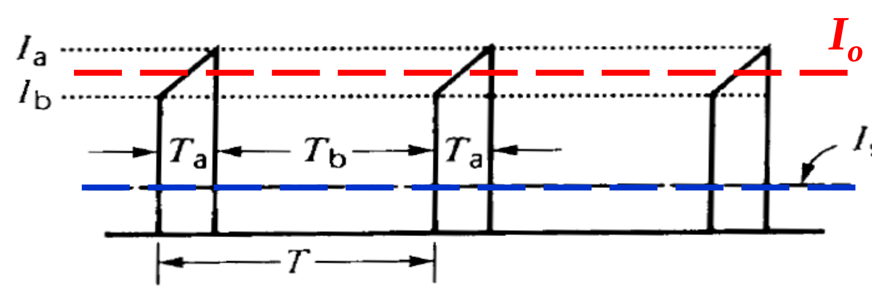


Figure 21.60c
Current pulses provided by the source.

Impedance transformation

Duty cycle $D<1$

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

$R_o = E_o/I_o$

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

$= R_o/D^2$

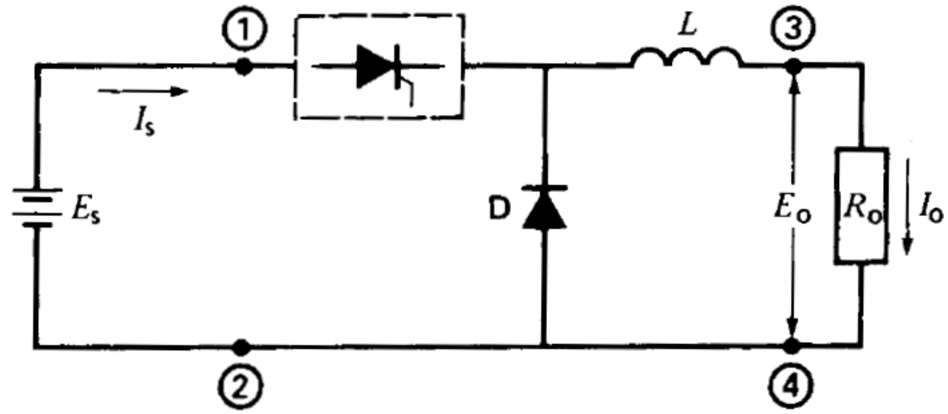
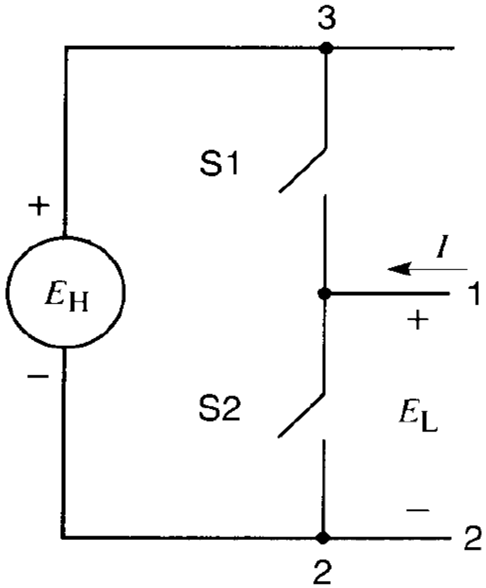
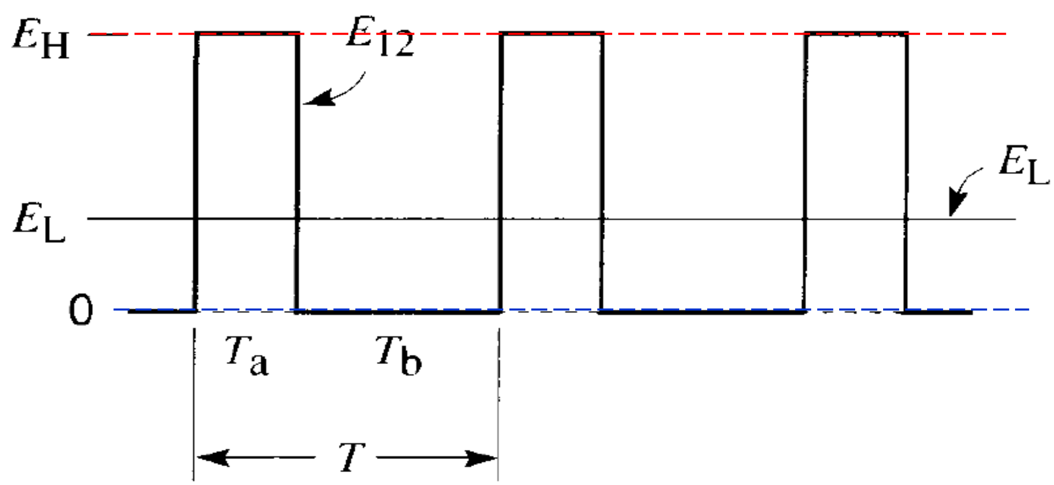


Figure 21.62
A chopper can make a fixed resistor R_o appear as a variable resistance between terminals 1-2.

- 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 *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

Basic 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

$$E_L=DE_H \qquad \text{(variable by varying } D\text{)}$$

- **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

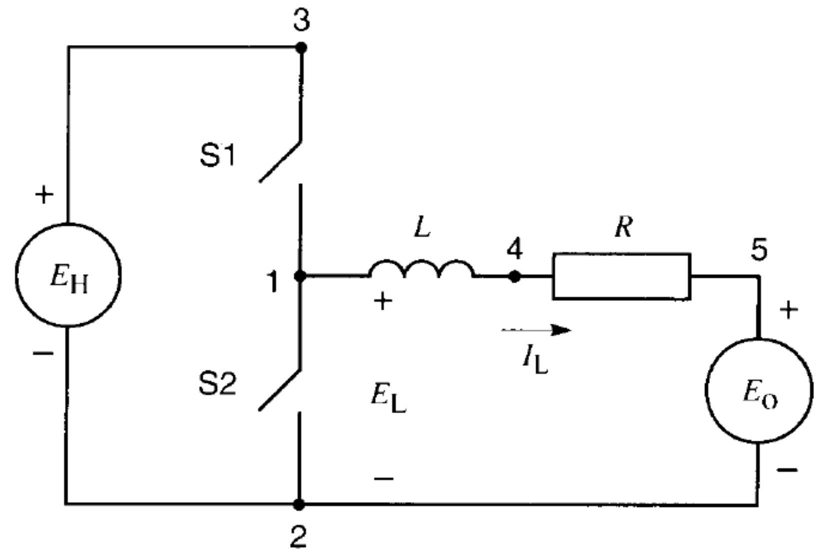


Figure 21.64
Power can flow from E_H to E_O and vice versa.

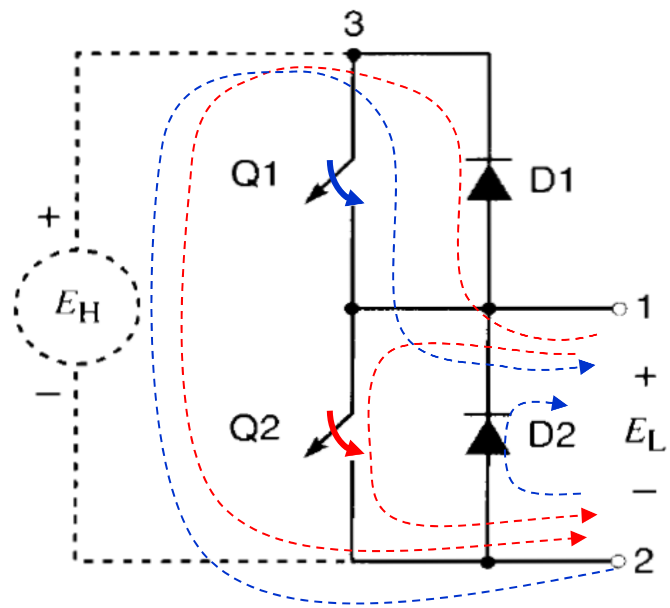
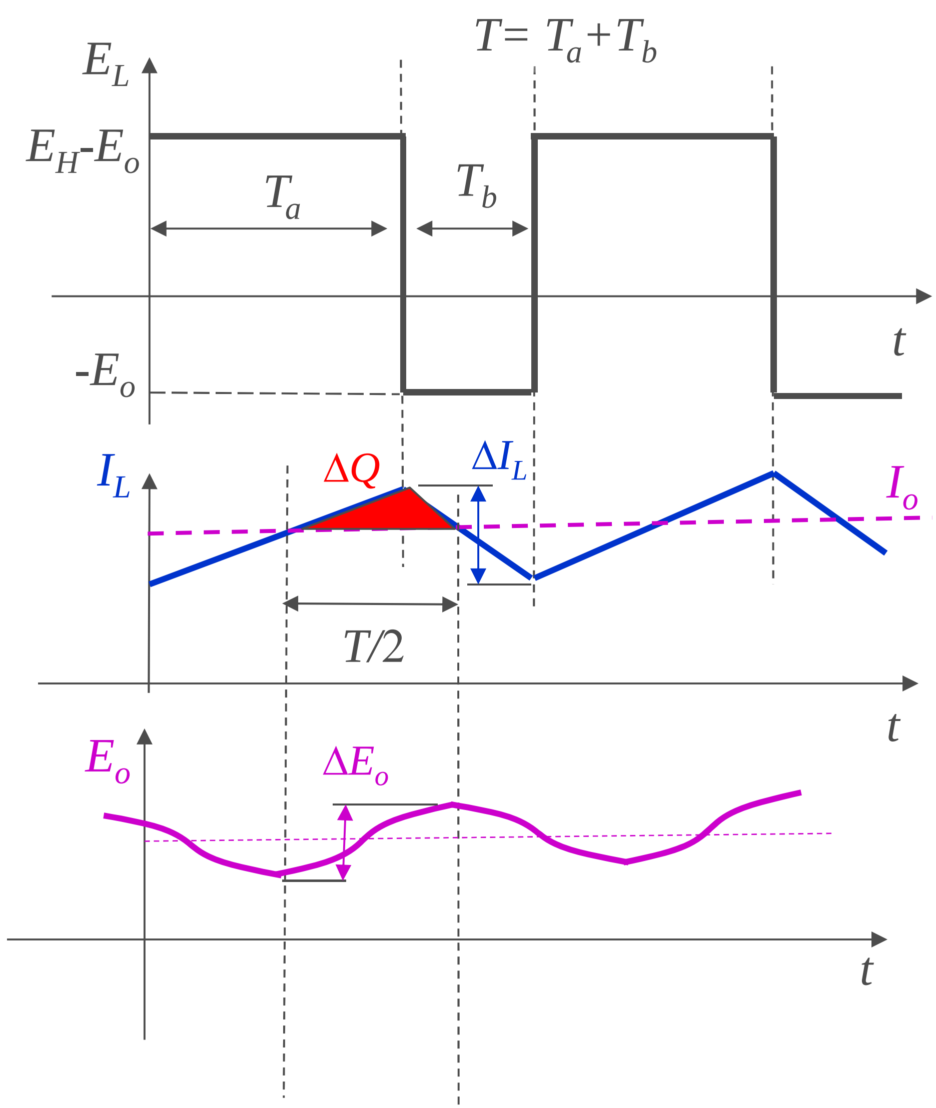


Figure 21.69
Two-quadrant electronic converter.

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.



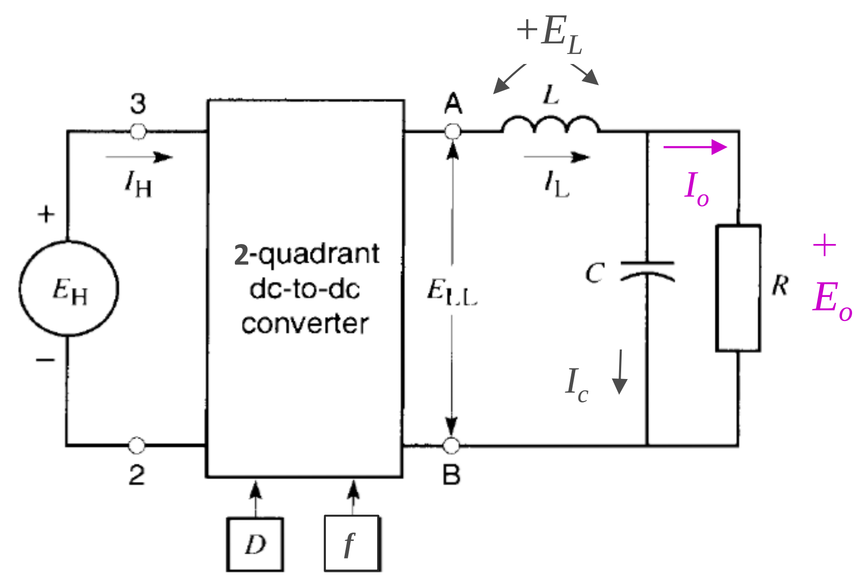


Figure 21.73
Four-quadrant dc-to-dc converter feeding a passive dc load *R*.

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

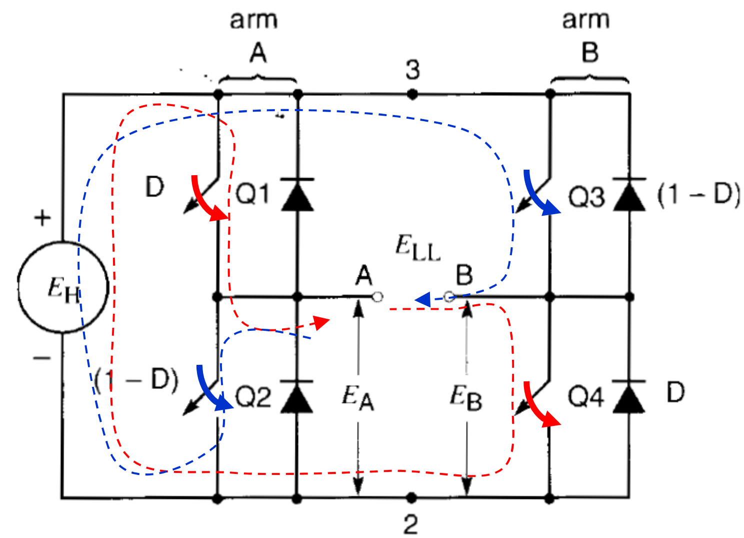
$$\Delta I_L = \frac{E_o}{L} T_b = \frac{E_o}{L}(1-D)T$$

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

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

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



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

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

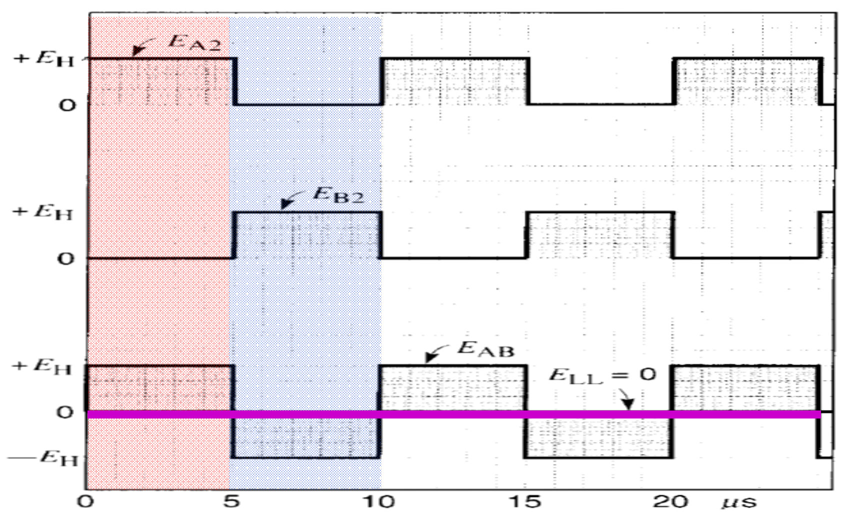


Figure 21.71
Voltage output when $D = 0.5$. The average voltage is zero.

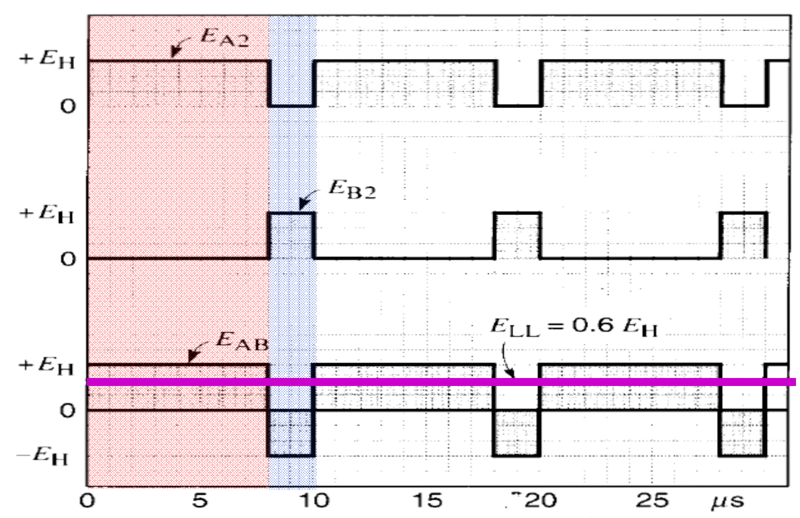


Figure 21.72
Voltage output when $D = 0.8$. The average voltage E_{LL} is $0.6\ E_H$.