Electric Energy Conversion

2. Power semiconductor devices

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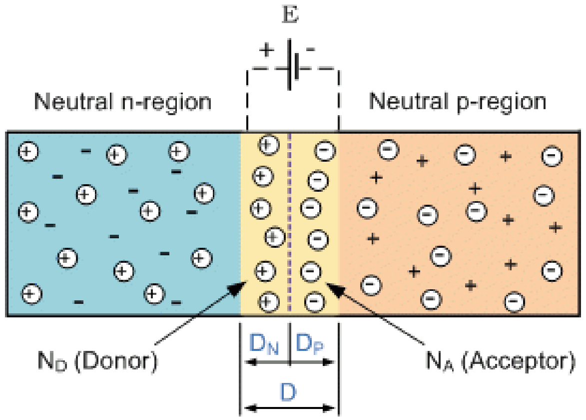
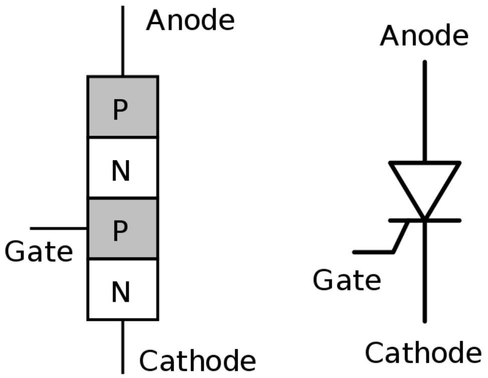
Outline

- Semiconductors
- Diode
- Thyristor
- Transistors
- Power losses

Semiconductors

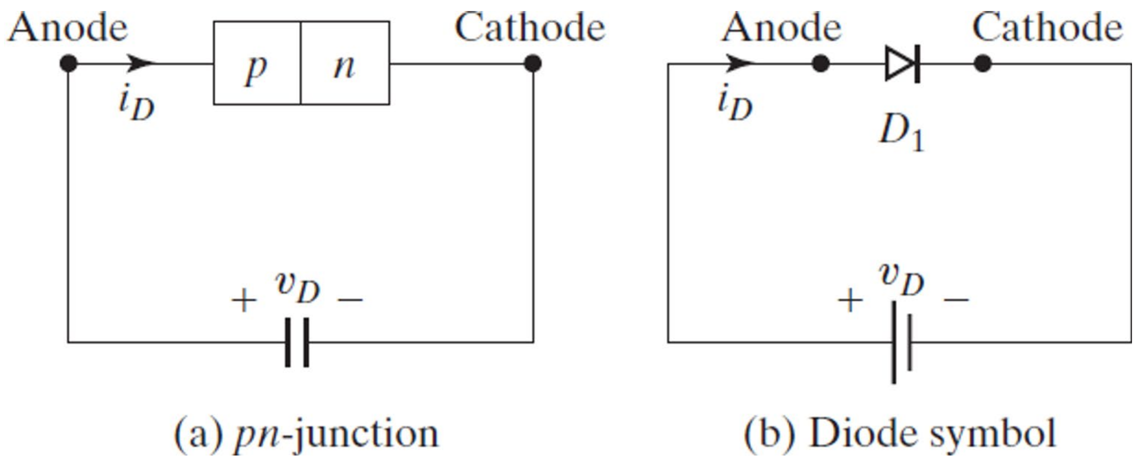
- Semiconductors can be understood as **switches** or amplifiers. They are used to control the **amount of energy transfer** in a circuit.
- They are neither conductors nor dielectrics. But when they are dopped, their conductivity increases. There are two doppings:
- **P-type:** when a tetravalent atom (such as silicon) is doped with a trivalent atom (such as aluminium, boron or gallium), there are three electrons for four covalent bonds, generating a hole through which the flow of charges takes place. Because of the positive charge of the hole, they are known by the letter P.
- **N-type:** formed by doping a tetravalent atom (such as silicon) with a pentavalent atom (such as phosphorus, antimony or arsenic). As there are five electrons and four covalent bonds, one negatively charged electron (hence the letter N) is free to move through the material, increasing the conductivity of the intrinsic semiconductor.





Diode

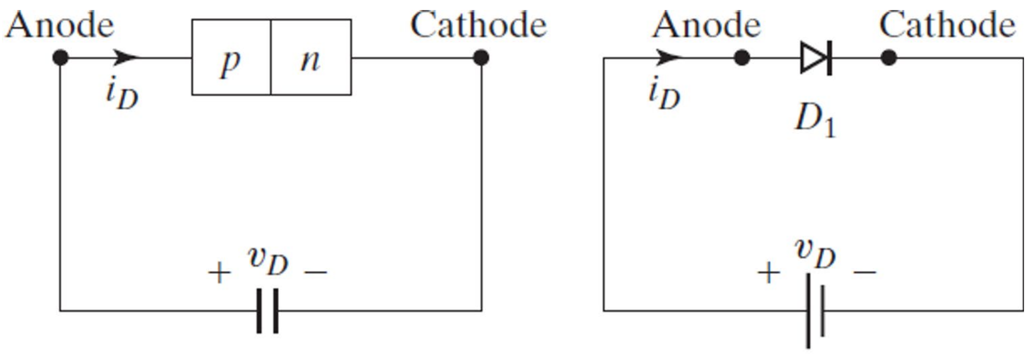
- A diode is a two-terminal pn-junction device.
- One of the simplest and most common semiconductor devices.



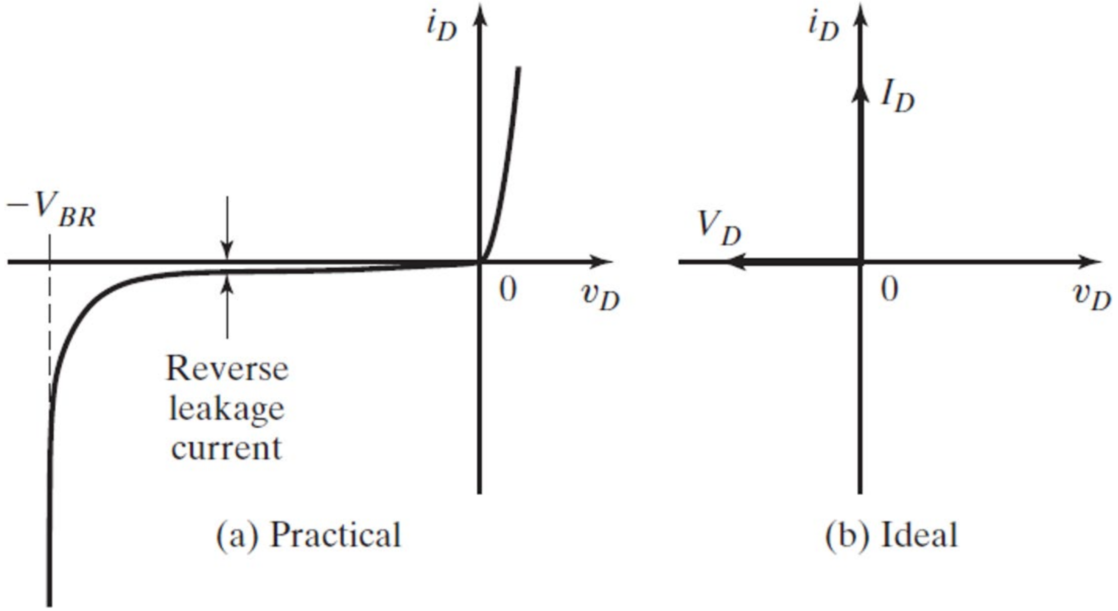
- When the anode potential is positive with respect to the cathode, the diode is said to be **forward-biased** and the diode conducts.
- When the cathode potential is positive with respect to the anode, the diode is said to be **reverse-biased** and the diode does not conduct (only a leakage current).

Diode

- The diode conduction (ON-state) and blocking (OFF-state) are defined by the voltage applied to it alone. Therefore, it is considered an **uncontrolled switch**.
- In this course, we will approximate the diode to its **ideal characteristics**, neglecting its exponential behaviour. Only the voltage drop will be considered.



(a) *pn*-junction (b) Diode symbol

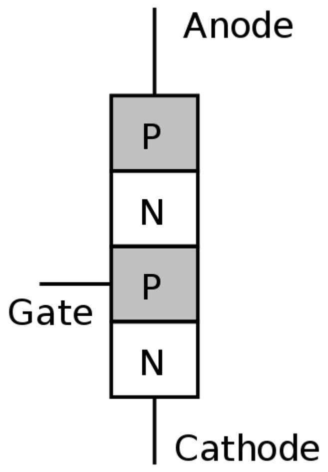


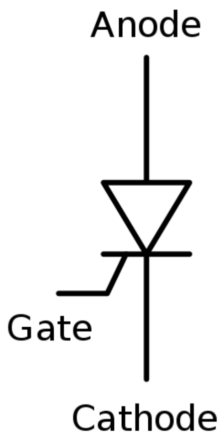
(a) Practical (b) Ideal

Source: M. Rashid. Power Electronics: Devices, Circuits and Applications. Pearson Education.

Thyristor

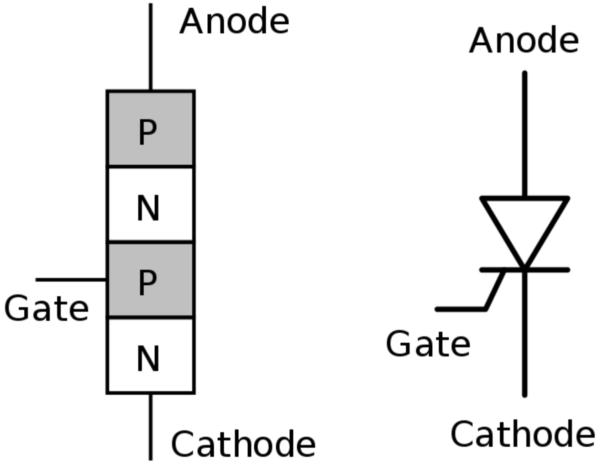
- A thyristor or silicon-controlled rectifier (SCR) is four-layer semiconductor device of PNPN structure with three pn-junctions. It has a Cathode, an Anode and a Gate.
- For the thyristor to begin to conduct, it must have a **gate current** applied **while** it has a positive anode-to-cathode voltage.
- After establishing conduction, the gate signal is no longer required to maintain anode current. It will continue to conduct as long as the anode current remains positive and above a minimum value defined by the material.

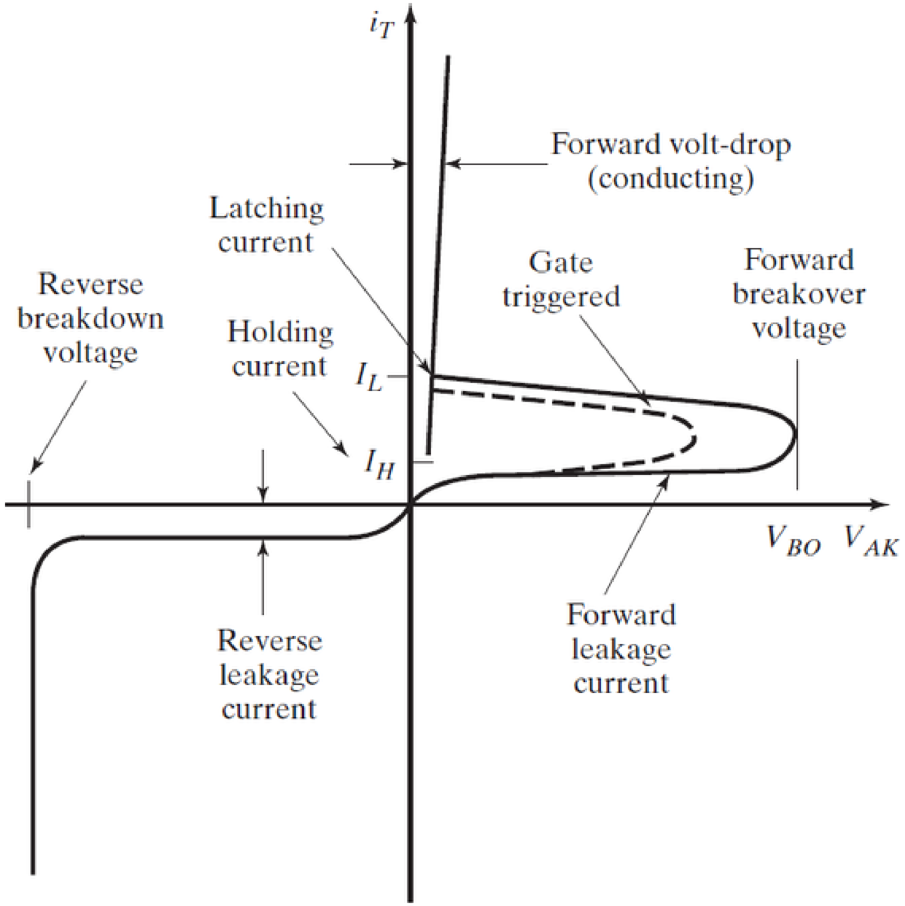




Thyristor

- The thyristor conduction (ON-state) depends on both the forward voltage and the gate signal, while its blocking (OFF-state) depends on the voltage alone. Therefore, it is considered a **partially-controlled switch**.





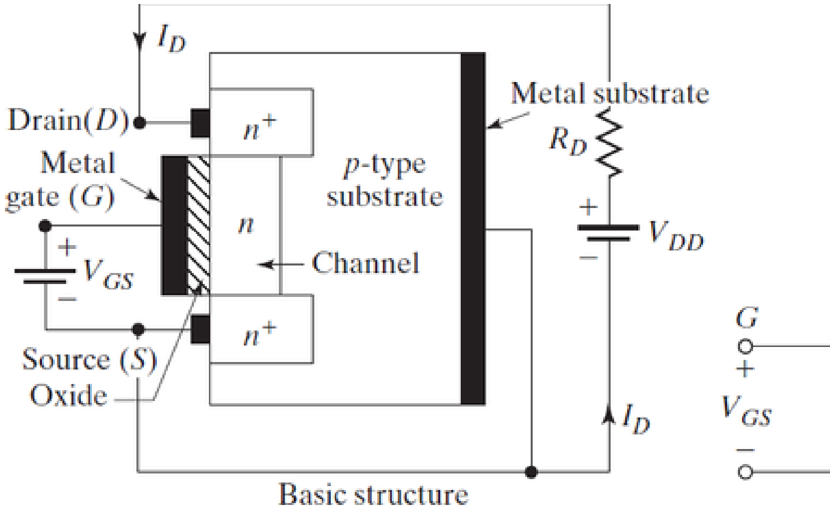
(b) v–i Characteristics

Transistor

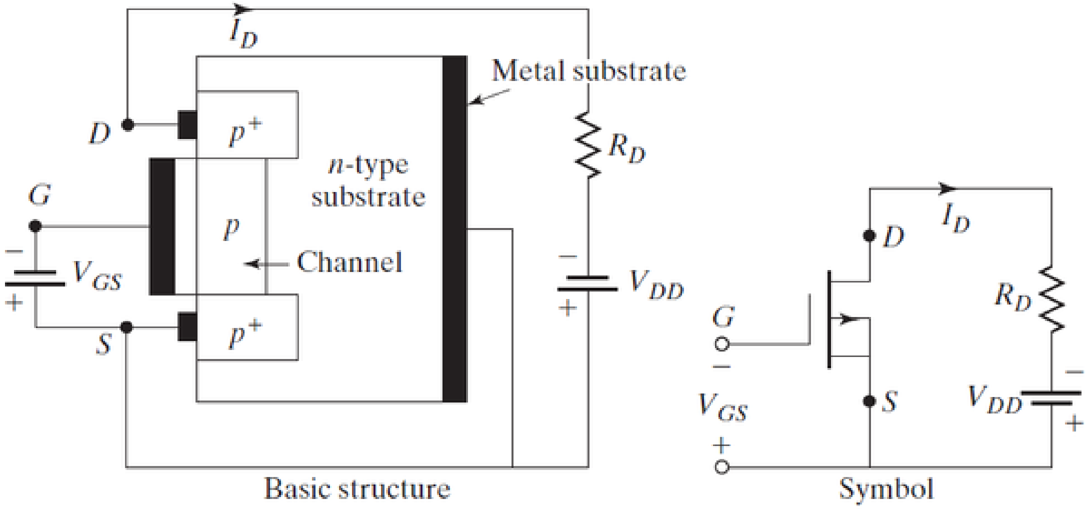
- Transistors are **fully controllable**. They conduct or block depending on the signal applied to its gate or base. As the current flow depends on the gate or base voltage, they can also be operated as amplifiers.
- There are many types of transistors, such as BJT, MOSFET and IGBT.
- The switching speed of modern transistors is much higher than that of thyristors and they are extensively employed in DC/DC and DC/AC converters.

Transistor

MOSFETs

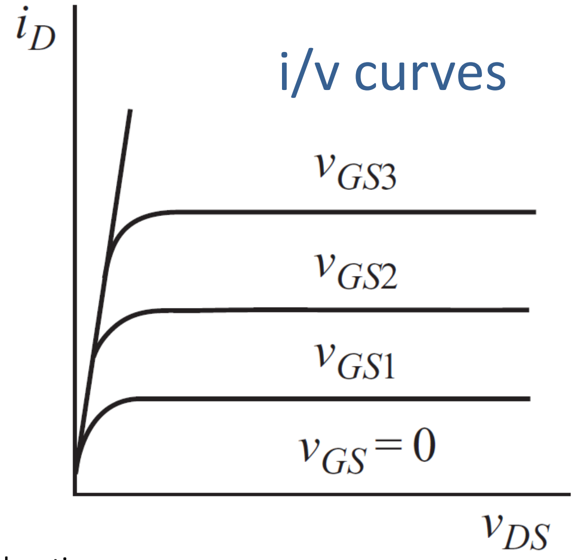


(a) n-Channel depletion-type MOSFET



(b) p-Channel depletion-type MOSFET

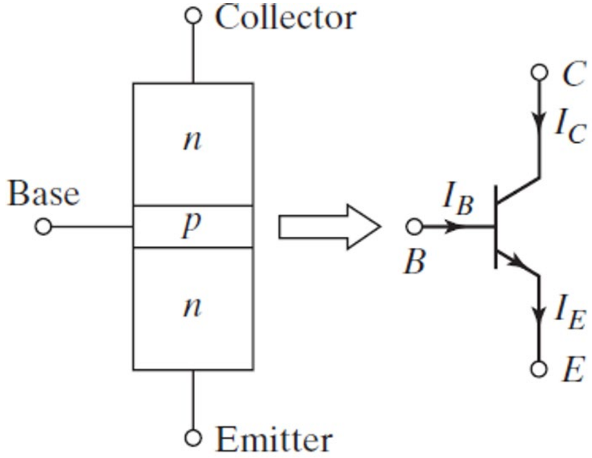
i/v curves



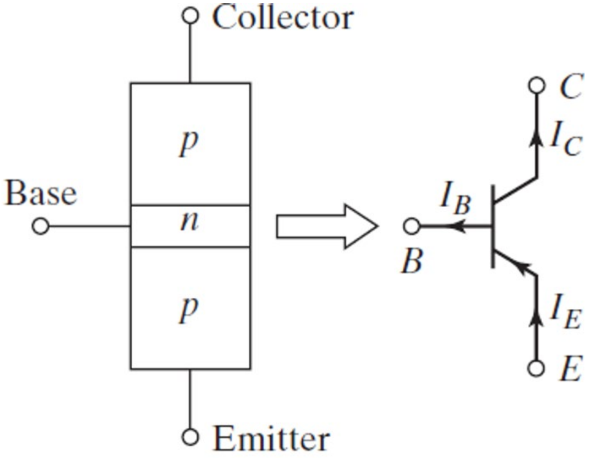
Source: M. Rashid. Power Electronics: Devices, Circuits and Applications. Pearson Education.

Transistor

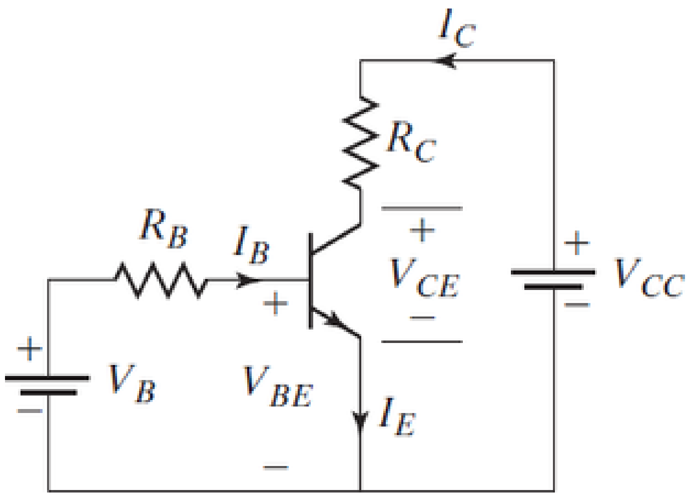
BJTs



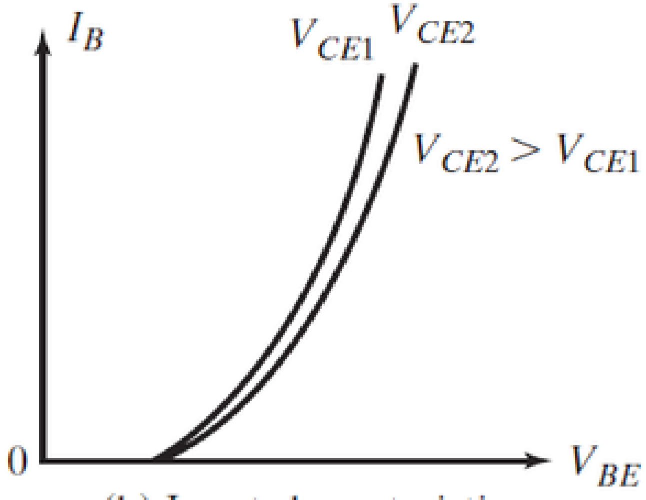
(a) *NPN*-transistor



(b) *PNP*-transistor



(a) Circuit diagram

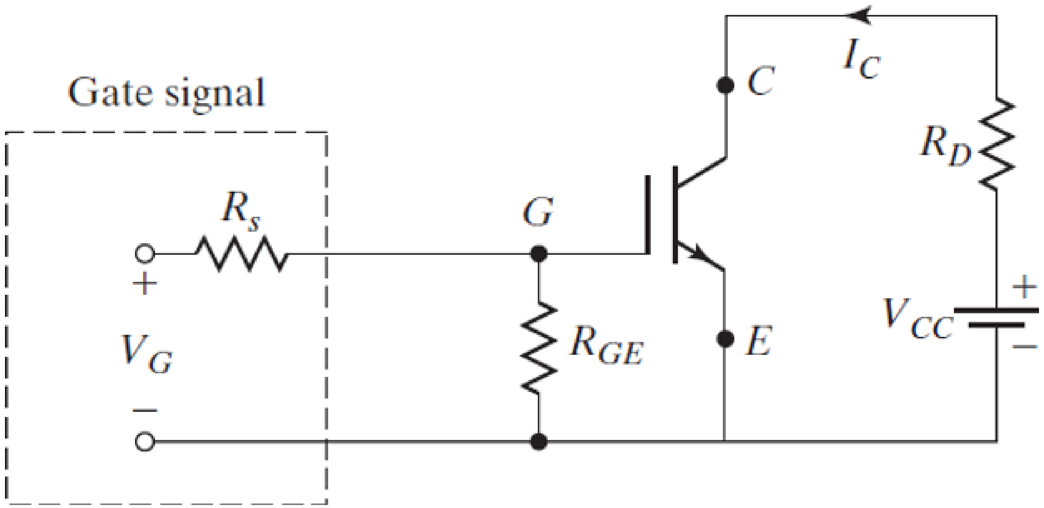


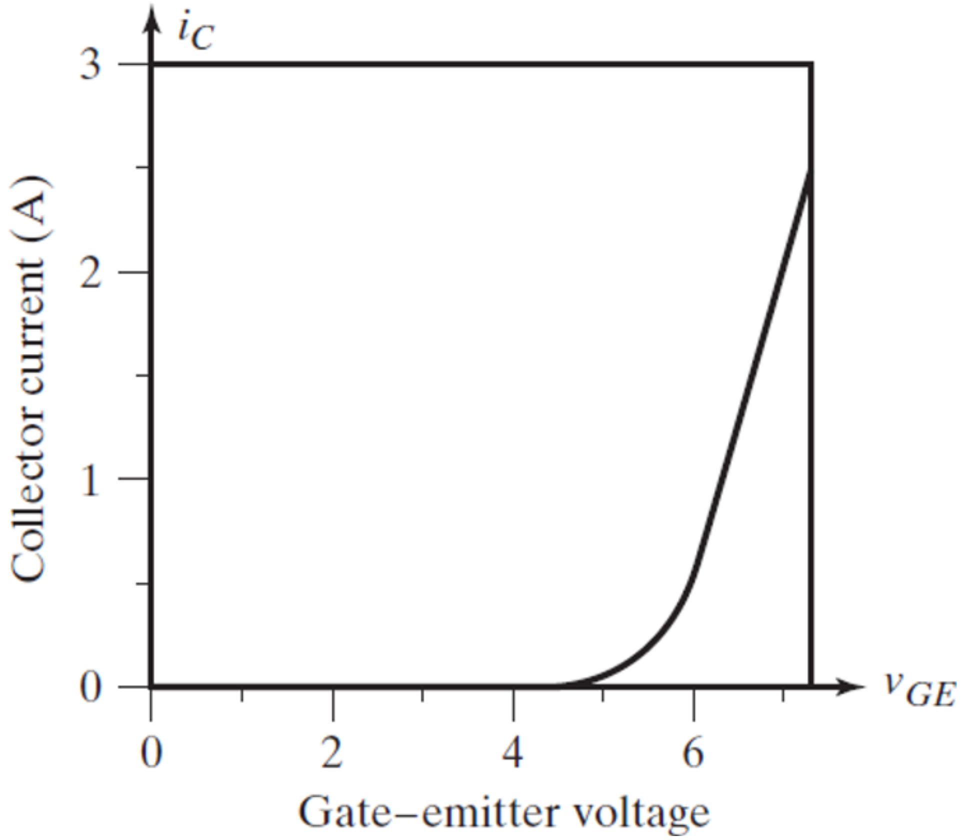
(b) Input characteristics

Source: M. Rashid. Power Electronics: Devices, Circuits and Applications. Pearson Education.

Transistor

IGBTs

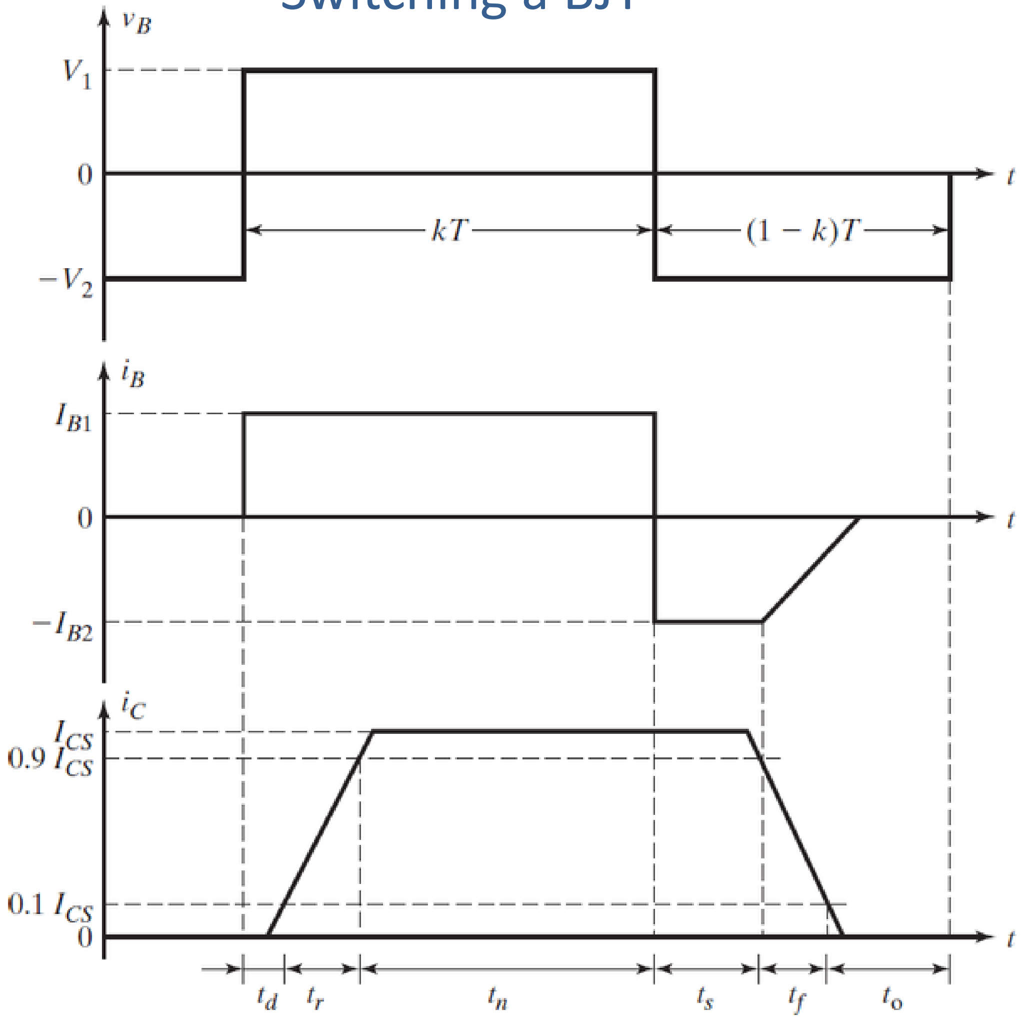




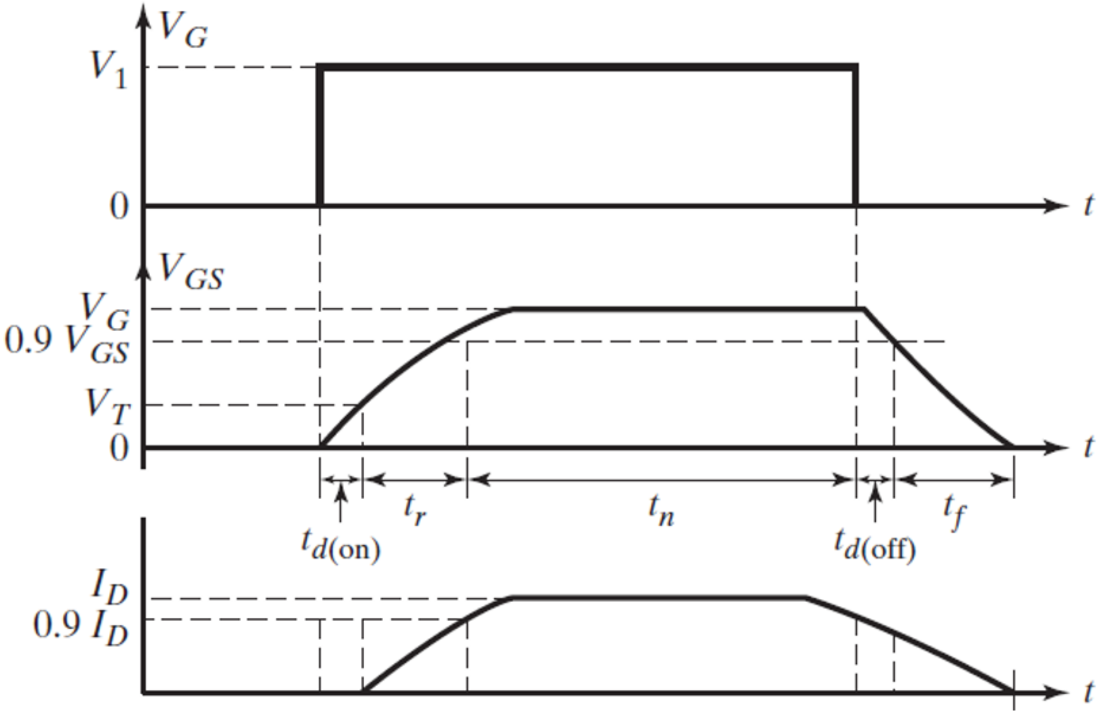
Source: M. Rashid. Power Electronics: Devices, Circuits and Applications. Pearson Education.

Transistor

Switching a BJT



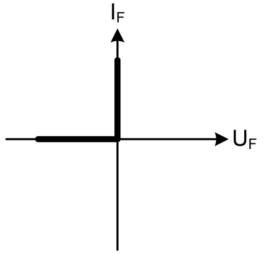
Switching a MOSFET



Source: M. Rashid. Power Electronics: Devices, Circuits and Applications. Pearson Education.

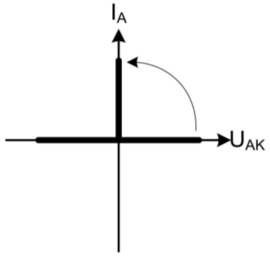
Summary

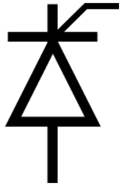
Diode



Uncontrolled. Conducts in one direction

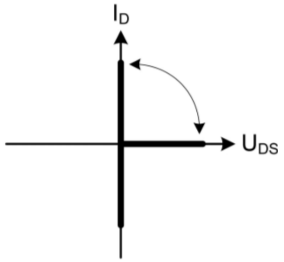
Thyristor

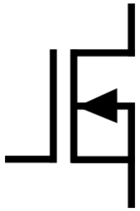




Partially controlled. OFF-to-ON controlled, but ON-to-OFF by lack of voltage. Conducts in one direction.

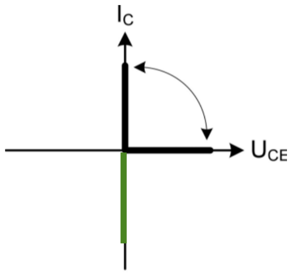
Transistor (MOSFET)

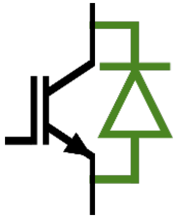




Totally controlled, both OFF-to-ON and ON-to-OFF. Conducts in both directions. Lower ampacity. Used in high-frequency applications.

Transistor (IGBT)





Totally controlled, both OFF-to-ON and ON-to-OFF. Conducts in one direction. Higher ampacity. Used in high-power applications. A diode is added in antiparallel to allow conduction also in the opposite direction.

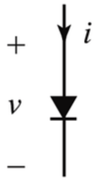
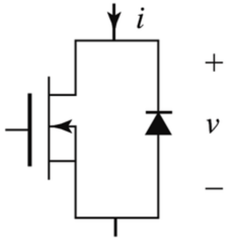
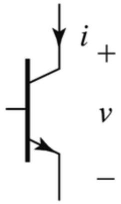
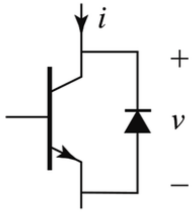
Source: image from https://www.electronics-tutorials.ws/diode/diode_2.html

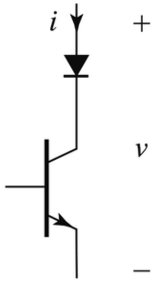
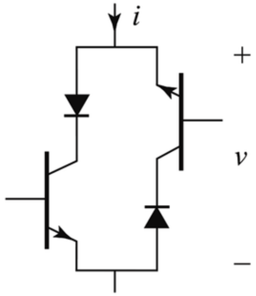
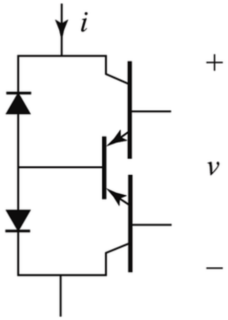
Comparison of power transistors

Switch Type	Base/Gate Control Variable	Control Characteristic	Switching Frequency	On-State Voltage Drop	Max. Voltage Rating V_s	Max. Current Rating I_s	Advantages	Limitations
MOSFET	Voltage	Continuous	Very high	High	1 kV $S_s = V_s I_s$ $= 0.1$ MVA	150 A $S_s = V_s I_s$ $= 0.1$ MVA	Higher switching speed Low switching loss Simple gate-drive circuit Little gate power Negative temperature coefficient on drain current and facilitates parallel operation	High on-state drop, as high as 10 V Lower off-state voltage capability Unipolar voltage device
BJT	Current	Continuous	Medium 20 kHz	Low	1.5 kV $S_s = V_s I_s$ $= 1.5$ MVA	1 kA $S_s = V_s I_s$ $= 1.5$ MVA	Simple switch Low on-state drop Higher off-state voltage capability High switching loss	Current controlled device and requires a higher base current to turn-on and sustain on-state current Base drive power loss Charge recovery time and slower switching speed Secondary breakdown region High switching losses Unipolar voltage device
IGBT	Voltage	Continuous	High	Medium	3.5 kV $S_s = V_s I_s$ $= 1.5$ MVA	2 kA $S_s = V_s I_s$ $= 1.5$ MVA	Low on-state voltage Little gate power	Lower off-state voltage capability Unipolar voltage device

Note: The voltage and current ratings are expected to increase as the technology develops.

Comparison of power transistors

Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Diode		x	x		
MOSFET	x		x	x	
BJT/IGBT	x		x		
BJT/IGBT with an antiparallel diode	x		x	x	

Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
BJT/IGBT with a series diode	x	x	x		
Two BJTs/ IGBTs with two series diodes	x	x	x	x	
Two BJTs/ IGBTs with two antiparal-lel diodes	x	x	x	x	

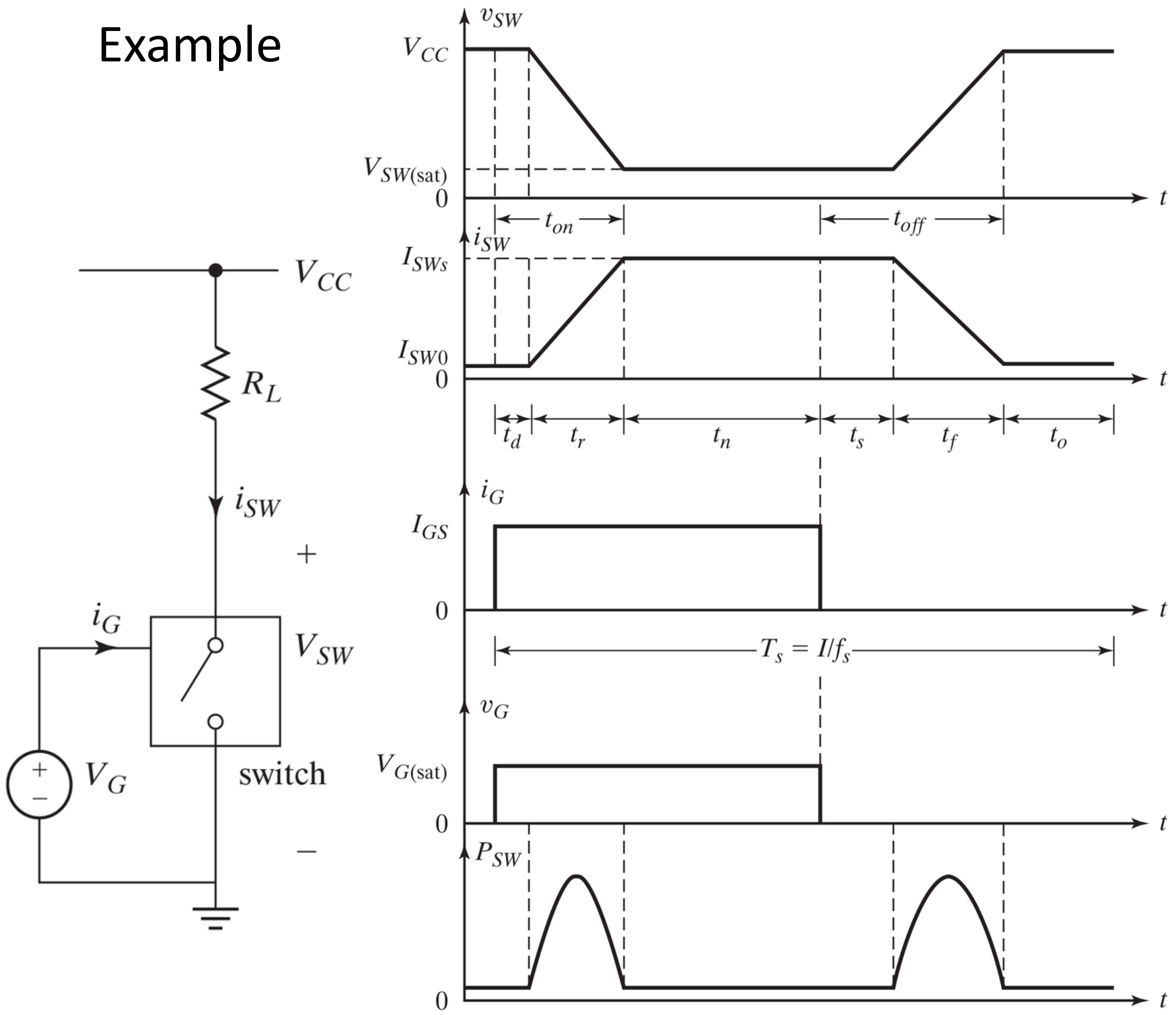
Source: M. Rashid. Power Electronics: Devices, Circuits and Applications. Pearson Education.

Outline

- Semiconductors
- Diode
- Thyristor
- Transistors
- Power losses

Power losses

Example



The average dissipated power (P_D) can be calculated as:

$$P_D = P_{ON} + P_{SW} + P_G$$

ON-state power

switching power

gate power

$$P_{ON} = \frac{1}{T_s}\int_0^{t_n} p\,dt$$

$$P_{SW} = f_s\left(\int_0^{t_d} p\,dt + \int_0^{t_r} p\,dt + \int_0^{t_s} p\,dt + \int_0^{t_f} p\,dt\right)$$

Where f_s is the switching frequency, t_d, t_r , t_s and t_f are the delay time, rise time, storage time and fall time, respectively

Example - Power losses

- Calculate the conduction and switching losses of the following transistor. Consider the ON and OFF delays equal to zero ($t_d = 0$ μs, $t_s = 0$ μs).

$V_{CC} = 250$ V

$V_{BE(sat)} = 3$ V

$I_B = 8$ A

$V_{CE(sat)} = 2$ V

$I_{CS} = 100$ A

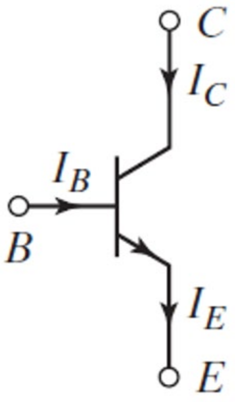
$I_{CEO} = 3$ mA (leakage current)

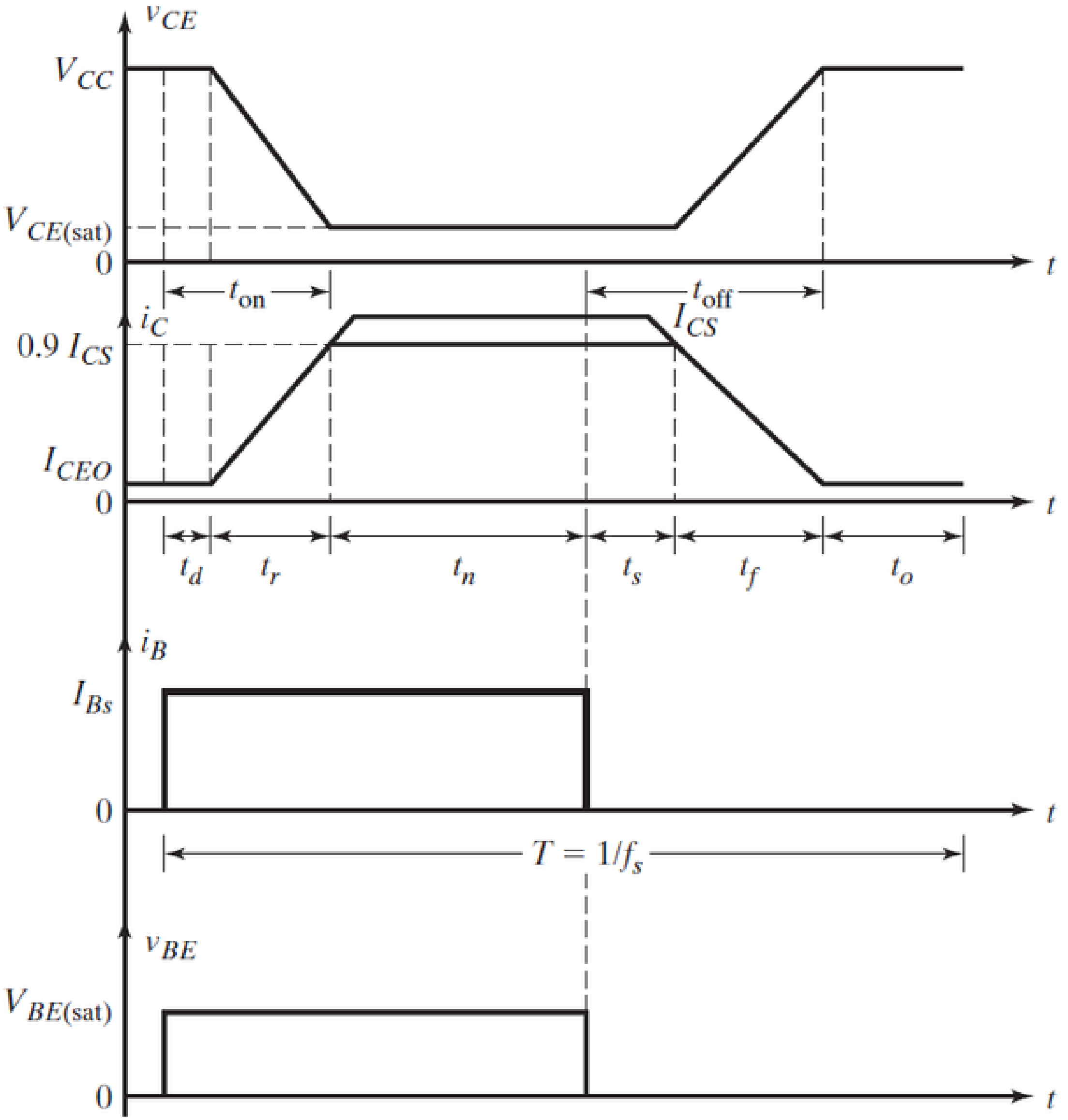
$t_r = 1$ μs

$t_f = 3$ μs

$f_s = 10$ kHz

$k = 50\%$ (duty cycle)





- During rise time

$$i_c(t) = \frac{I_{CS}}{t_r} t$$

$$v_{CE}(t) = V_{CC} + \frac{t}{t_r}\left(V_{CE(sat)} - V_{CC}\right)$$

- During fall time

$$i_c(t) = I_{CS}\left(1 - \frac{t}{t_f}\right)$$

$$v_{CE}(t) = \frac{V_{CC}}{t_f} t$$

Example - Power losses

a) Calculate each period

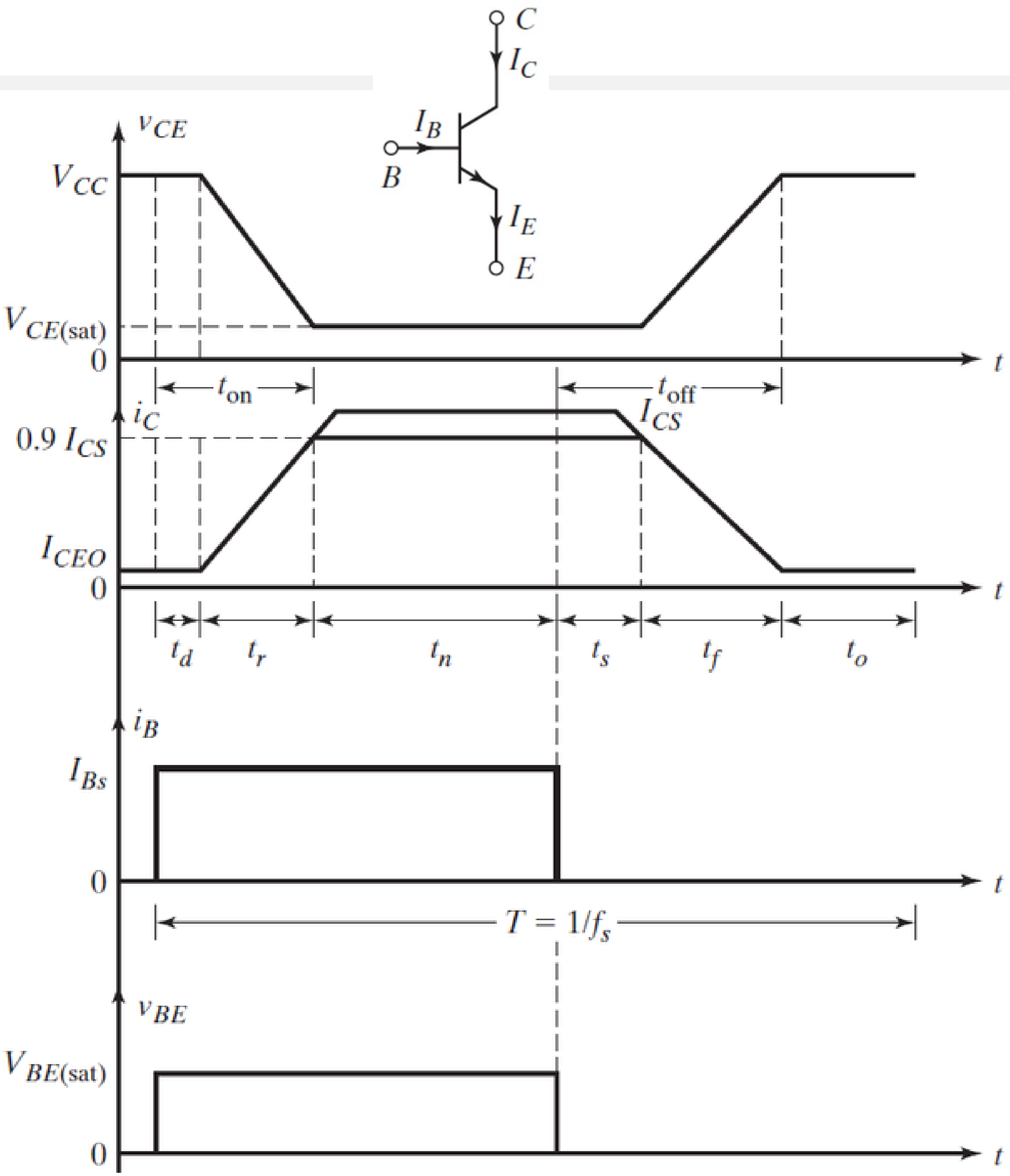
- If the switching frequency is 10 kHz, the period T is

$$T = \frac{1}{f_s} = 100\ \mu s$$

- As the duty is 50 %, ON and OFF periods are the same length and equal to $kT = 50\ \mu s$

$$t_n = 50 - 1 = 49\ \mu s$$

$$t_o = 50 - 3 = 47\ \mu s$$



Example - Power losses

b) Losses during the turn-on period (rise time)

$$i_c(t) = \frac{I_{CS}}{t_r} t \qquad v_{CE}(t) = V_{CC} + \frac{t}{t_r}\left(V_{CE(sat)} - V_{CC}\right)$$

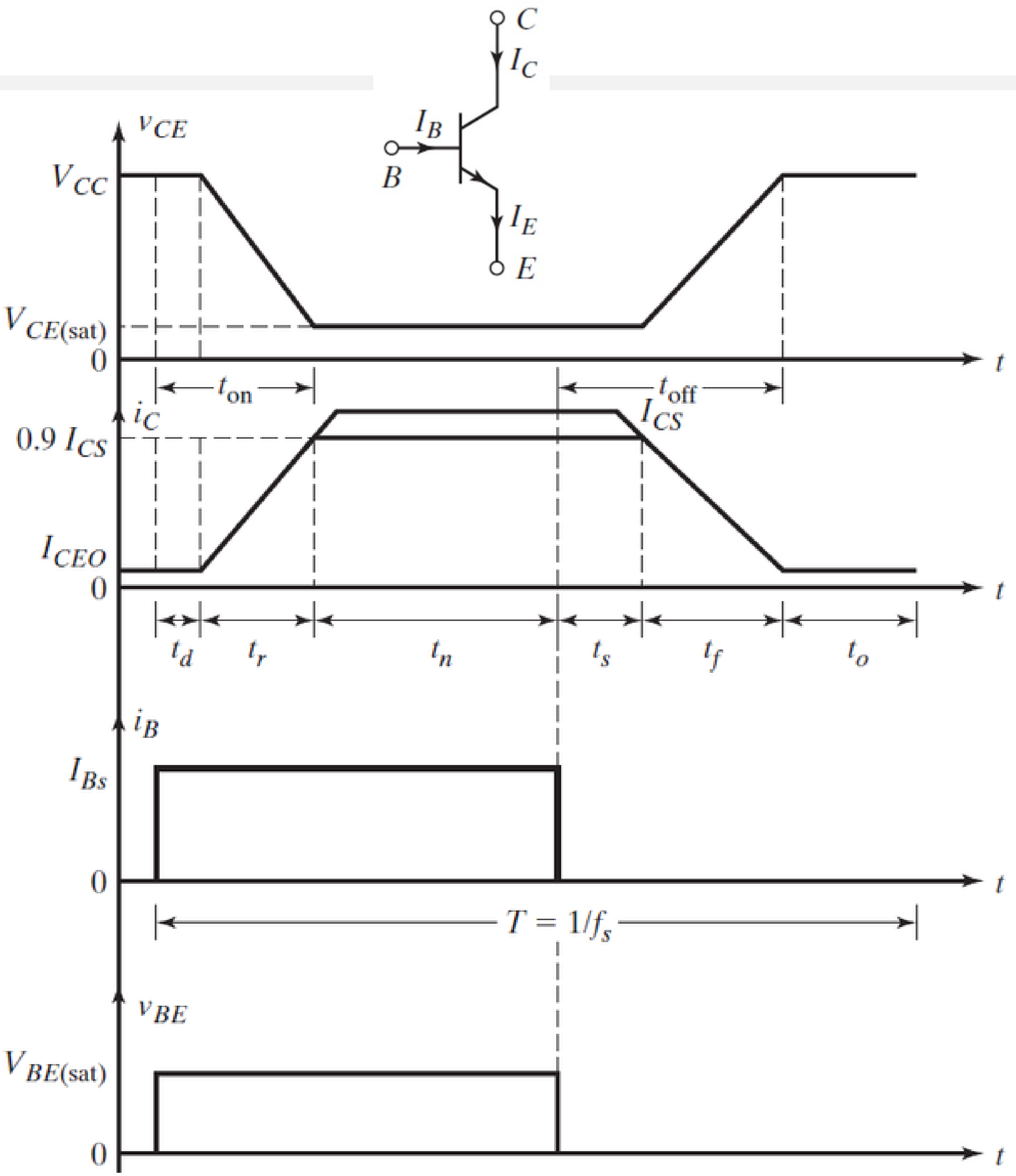
- The instantaneous power is:

$$p_r(t) = i_c v_{CE} = I_{CS}\frac{t}{t_r}\left(V_{CC} + \left(V_{CE(sat)} - V_{CC}\right)\frac{t}{t_r}\right)$$

- The average power is:

$$P_r = \frac{1}{T}\int_0^{t_r} p_r\, dt = I_{CS}\frac{t_r}{T}\left(\frac{V_{CC}}{2} + \frac{V_{CE(sat)} - V_{CC}}{3}\right)$$

$$= 100\frac{10^{-6}}{10^{-4}}\left(\frac{250}{2} + \frac{2-250}{3}\right) = \boxed{42.33 \text{ W}}$$



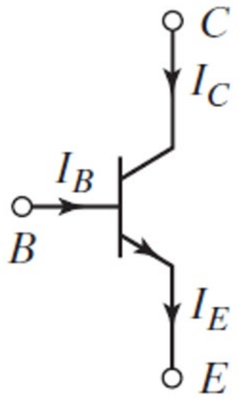
Example - Power losses

c) Losses during the turn-off period (fall time)

$$i_c(t) = I_{CS}\left(1 - \frac{t}{t_f}\right) \qquad v_{CE}(t) = \frac{V_{CC}}{t_f}t$$

- The instantaneous power is:

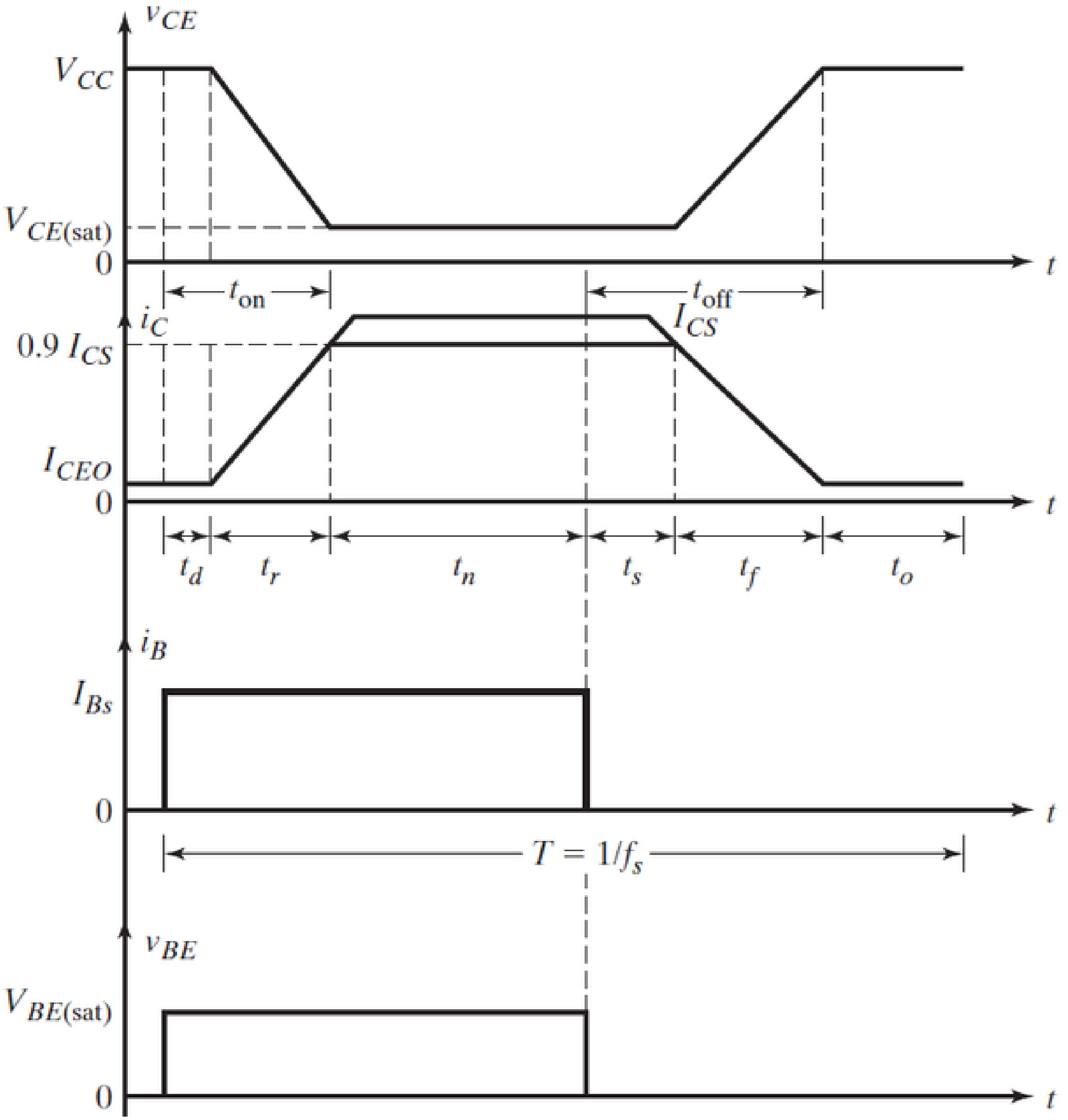
$$p_f(t) = i_c v_{CE} = V_{CC} I_{CS} \frac{t}{t_f}\left(1 - \frac{t}{t_f}\right)$$



- The average power is:

$$P_f = \frac{1}{T}\int_0^{t_f} p_f \, dt = V_{CC} I_{CS} \frac{t_f}{6T}$$

$$= \frac{250 \times 100 \times 3 \times 10^{-6}}{6 \times 100 \times 10^{-6}} = \boxed{125 \text{ W}}$$



Example - Power losses

d) Losses during the conduction period

$$i_c(t) = I_{CS} \qquad v_{CE}(t) = V_{CE(sat)}$$

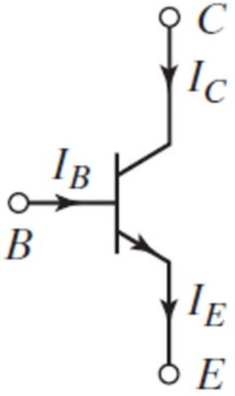
- The instantaneous power is:

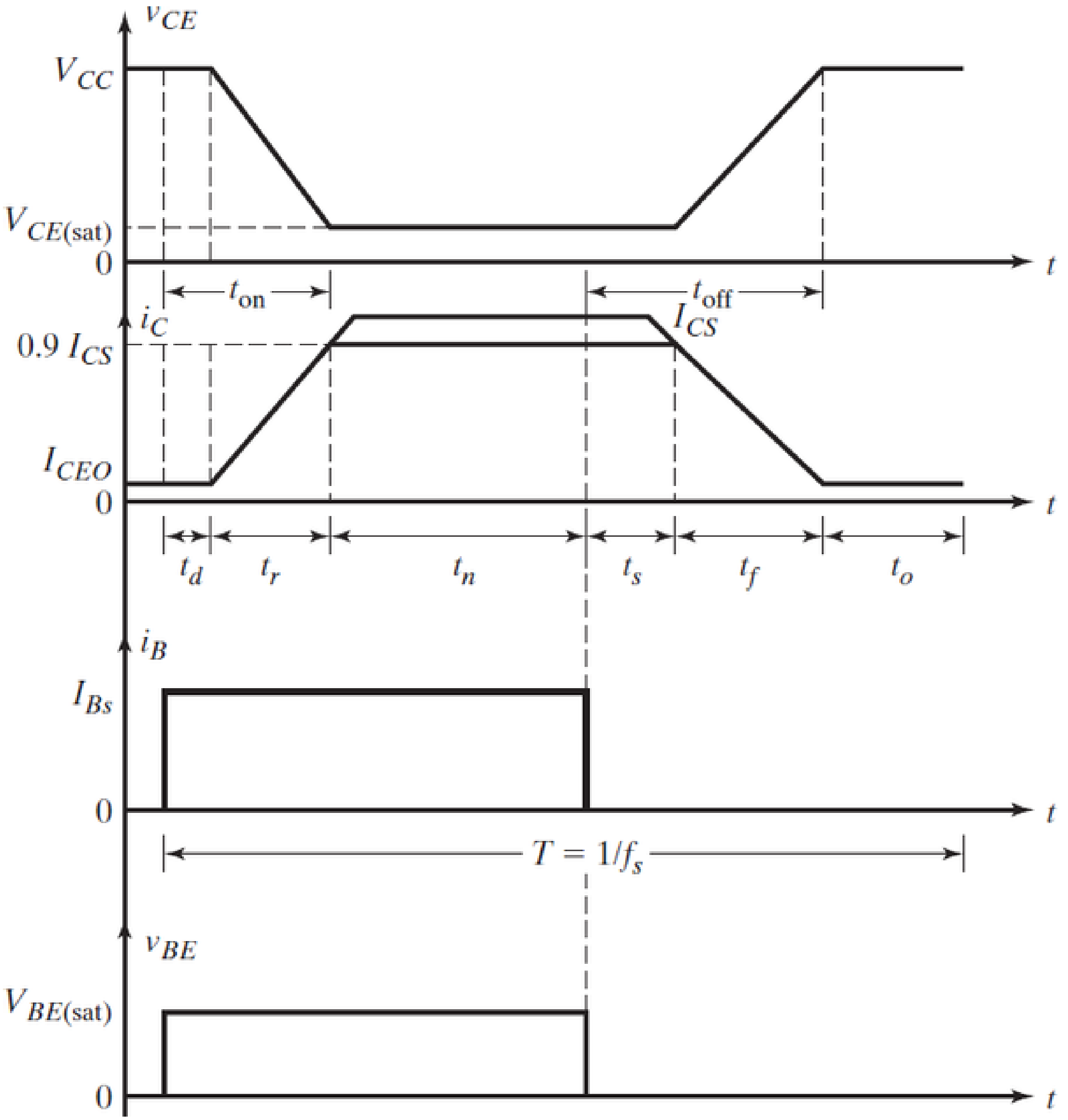
$$p_c(t) = i_c v_{CE} = V_{CE(sat)} I_{CS}$$

- The average power is:

$$P_c = \frac{1}{T}\int_0^{t_n} p_c\,dt = V_{CE(sat)} I_{CS} \frac{t_n}{T}$$

$$= \frac{2 \times 100 \times 49 \times 10^{-6}}{100 \times 10^{-6}} = \boxed{98\ \mathrm{W}}$$





Example - Power losses

e) Losses during the OFF-period

$$i_c(t) = I_{CEO} \quad v_{CE}(t) = V_{CC}$$

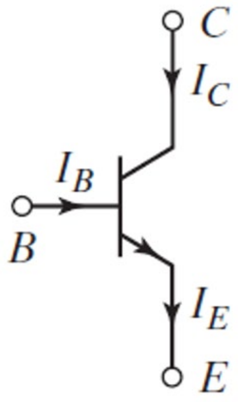
- The instantaneous power is:

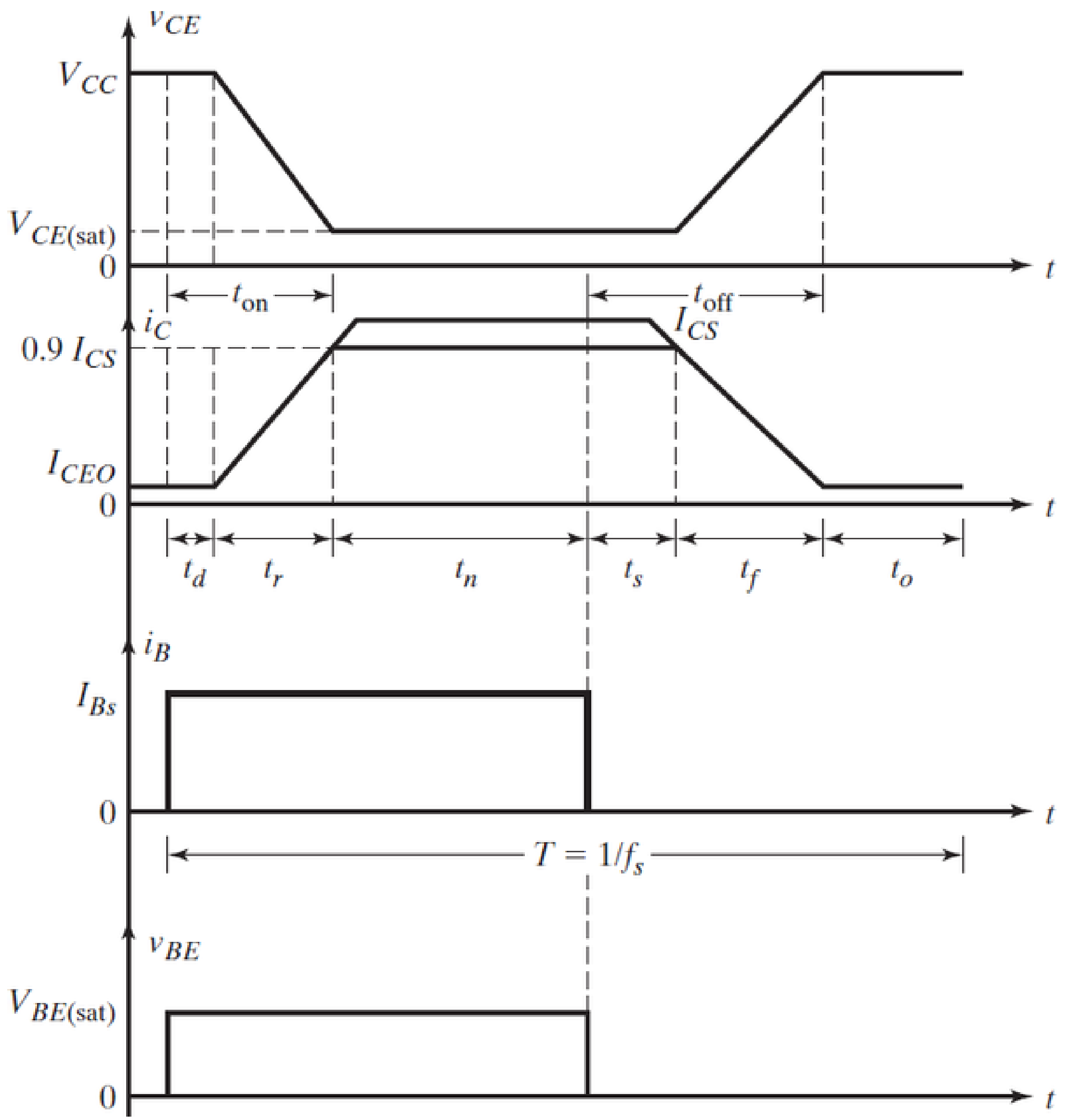
$$p_o(t) = i_c v_{CE} = V_{CC} I_{CEO}$$

- The average power is:

$$P_O = \frac{1}{T}\int_0^{t_o} p_o\, dt = V_{CC} I_{CEO} \frac{t_o}{T}$$

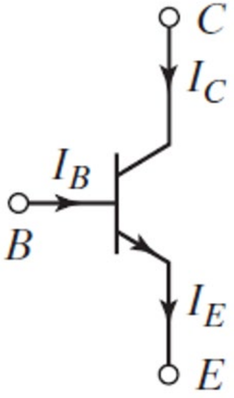
$$= \frac{250 \times 3 \times 10^{-3} \times 47 \times 10^{-6}}{100 \times 10^{-6}} = \boxed{0.3525\ \text{W}}$$





Example - Power losses

f) Total power losses

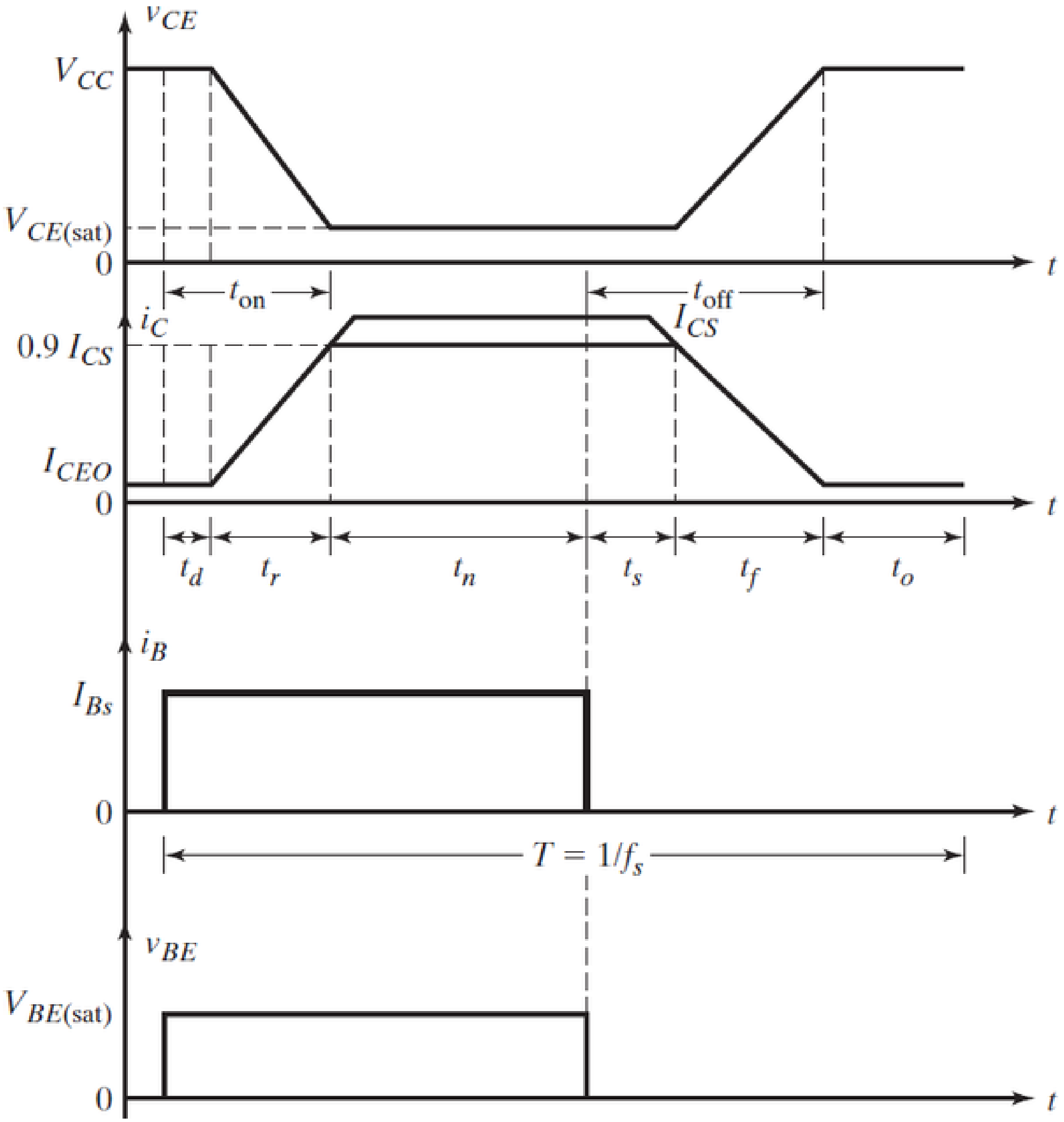


- The total power losses are:

$$P_T = P_r + P_C + P_f + P_O$$
$$= 42.33 + 98 + 125 + 0.3525$$
$$= \boxed{265.6825\ \mathrm{W}}$$

- What can we do to reduce the power losses?

A: Decrease the switching frequency but generate more harmonics



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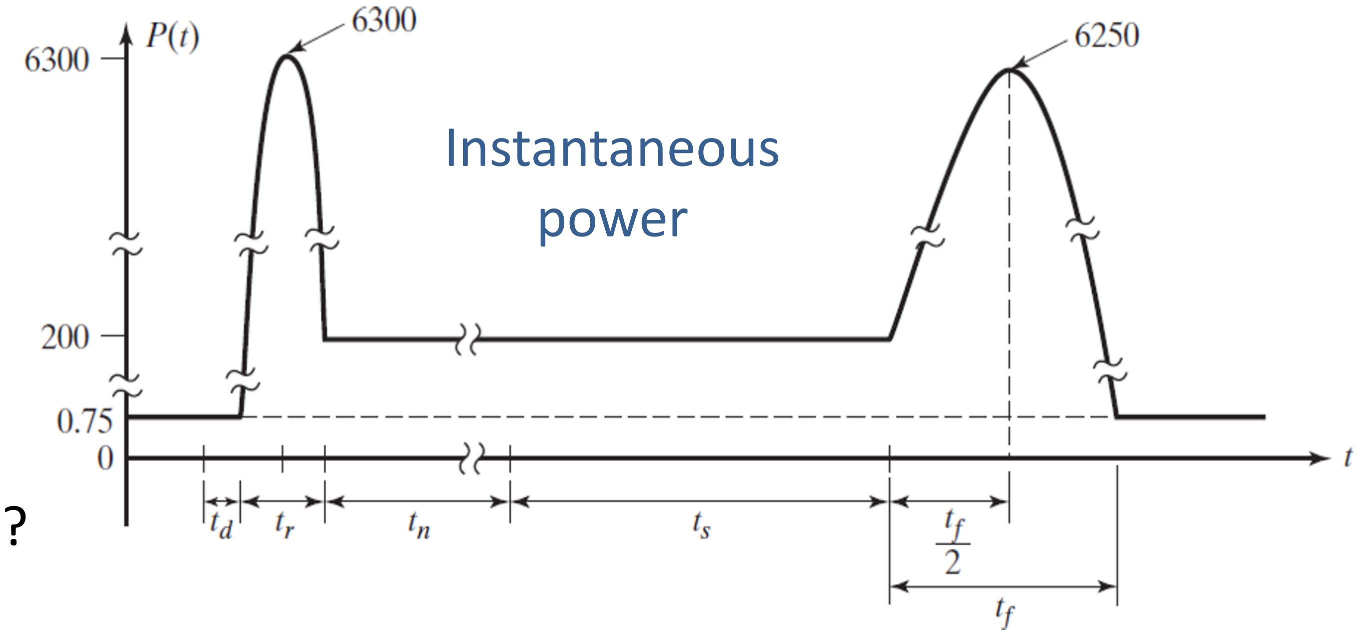

The device must be capable to dissipate also the instantaneous power loss

Electric Energy Conversion

2. Power semiconductor devices

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