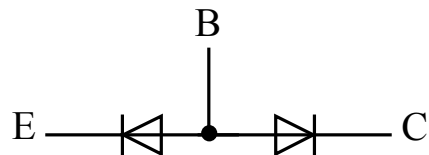
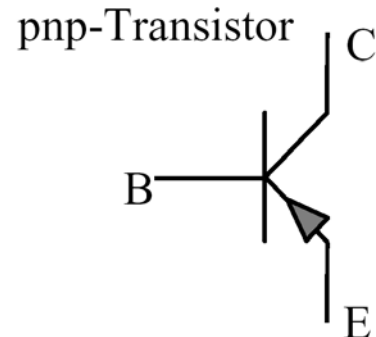
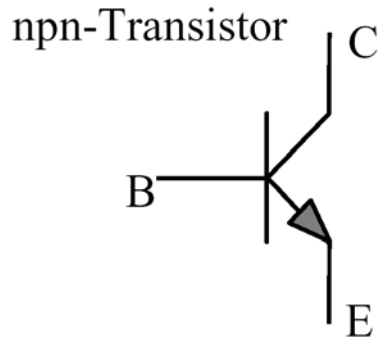
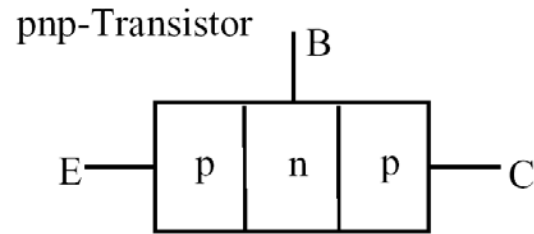
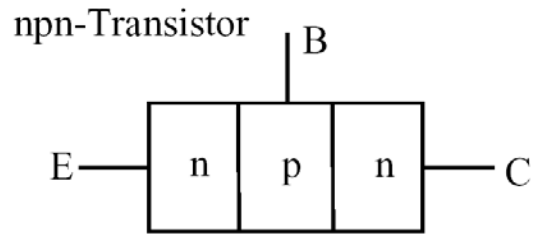


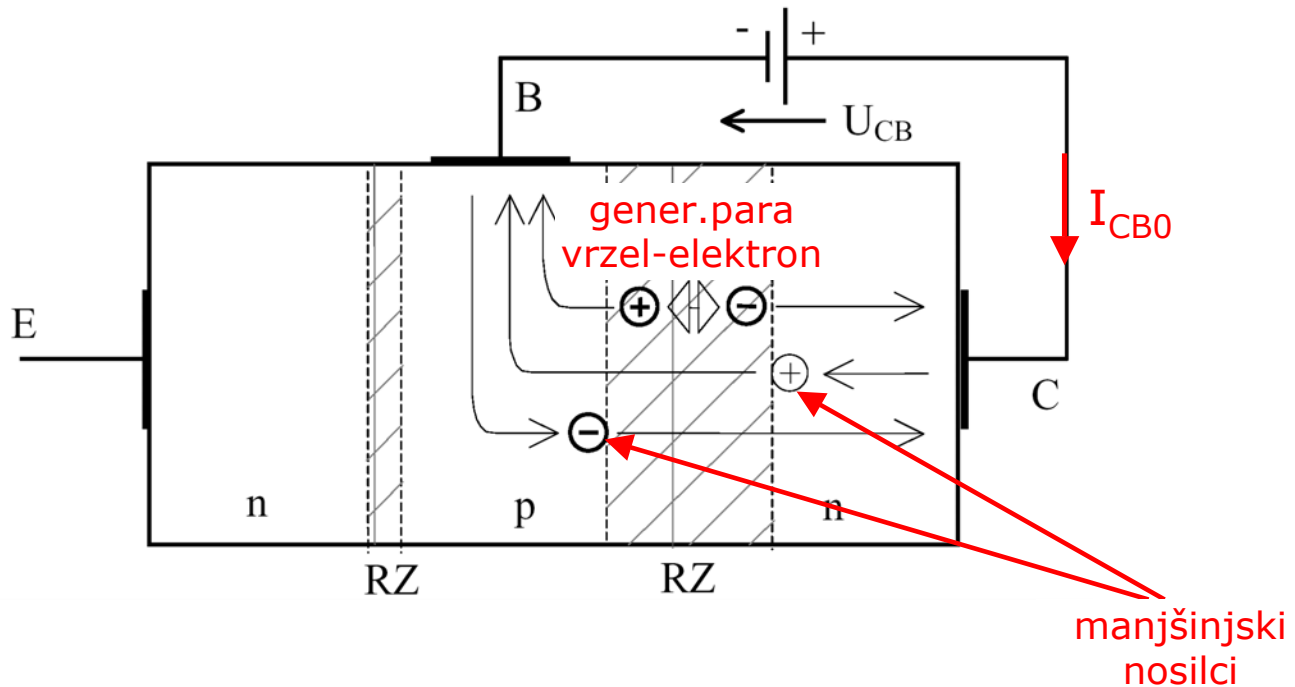
Bipolarni tranzistor

S



Bipolarni tranzistor

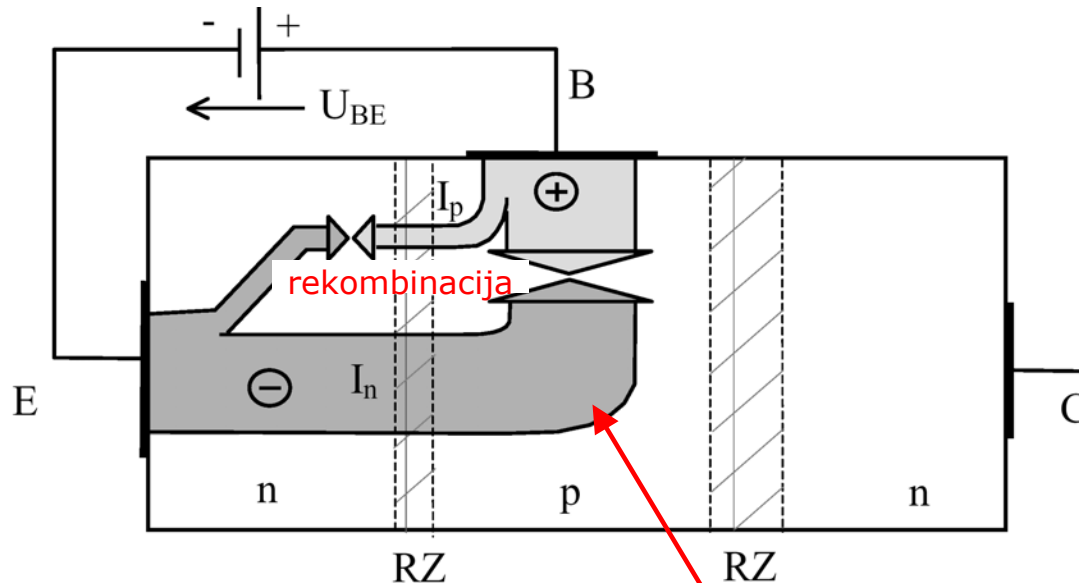
- krmiljenje tranzistorja, tranzistorski efekt-**korak 1**
 - zaporni sloj U_{CB} reverzno polariziran



- skozi reverzno polariziran zaporni sloj teče mirovni tok I_{CB0} (tok manjšinjskih nosilcev naboja!)

Bipolarni tranzistor

- krmiljenje tranzistorja, tranzistorski efekt-**korak 2**
 - zaporni sloj U_{BE} prevodno polariziran

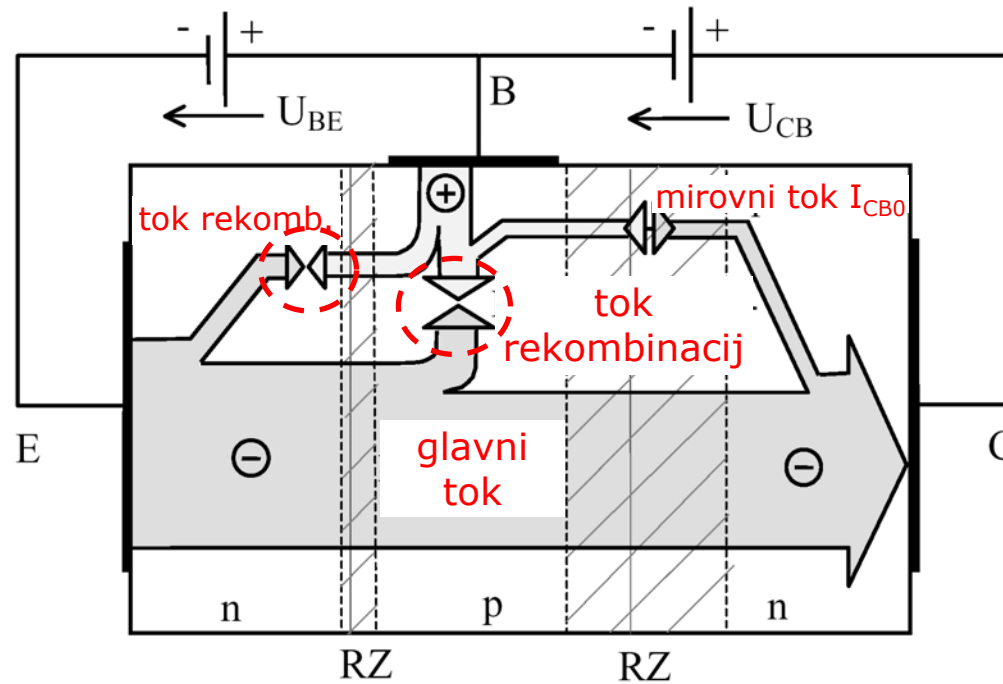


- elektroni iz E so inicirani v B (tok I_N); vrzeli iz B so inicirane v E (tok I_p)
- ker velja $n_N \gg n_p \rightarrow I_N \gg I_p$

velik "pritok" elektronov
(manjšinski naboje v področju B)

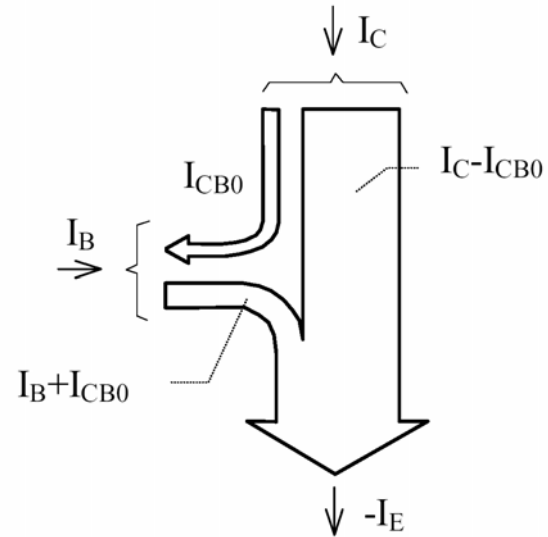
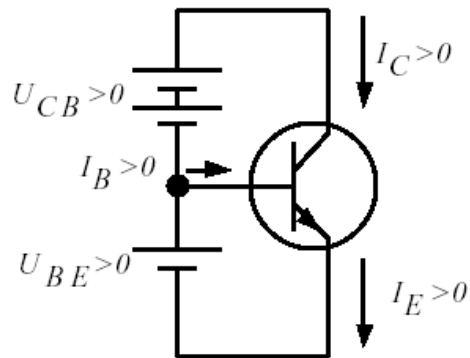
Bipolarni tranzistor

- krmiljenje tranzistorja, tranzistorski efekt-**korak 3**
 - združimo korak 1 in korak 2



Bipolarni tranzistor

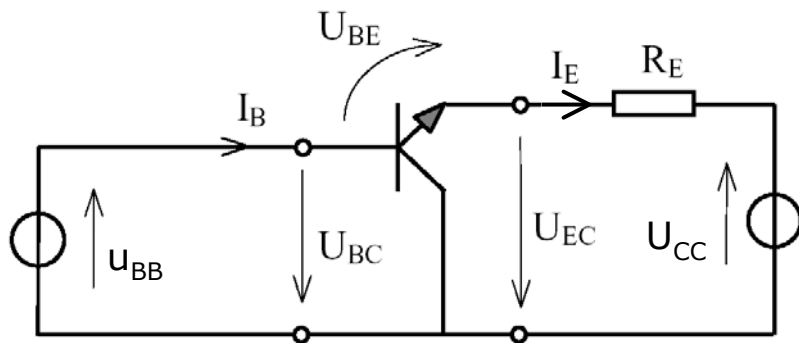
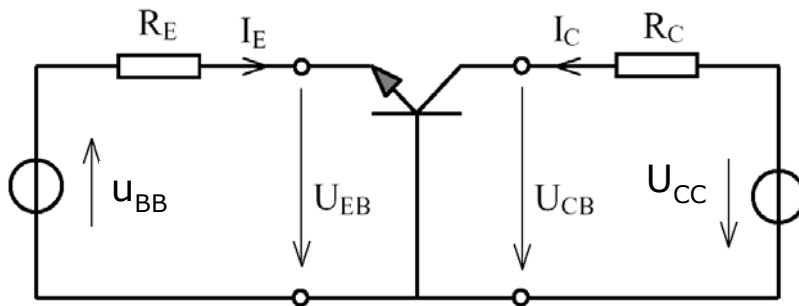
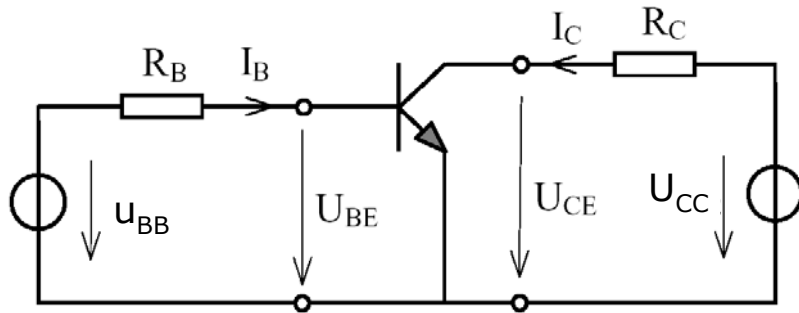
➤ simbolna predstavitev



➤ tokovno ojačenje

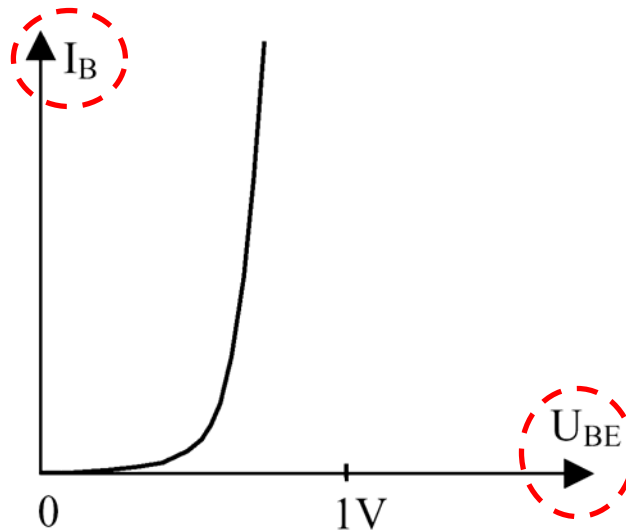
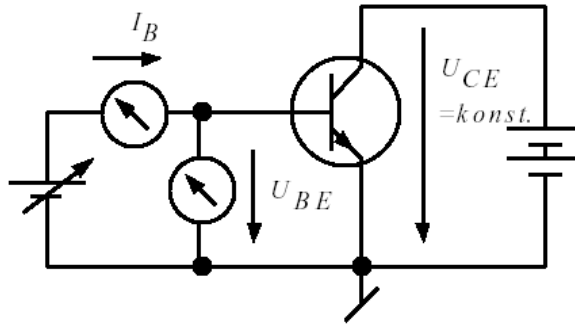
Bipolarni tranzistor

➤ osnovne vezalne sheme



Karakteristike bipolarnega tranzistorja

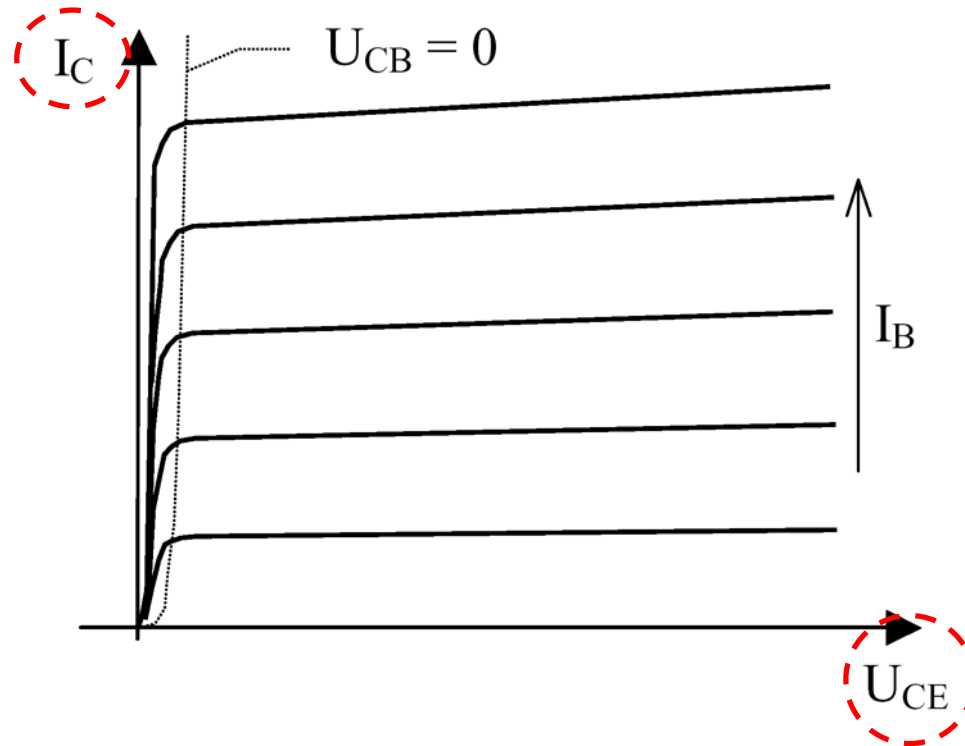
➤ vhodna



$$r_{BE} = \left. \frac{dU_{BE}}{dI_B} \right|_{U_{CE} = \text{konst}}$$

Karakteristike bipolarnega tranzistorja

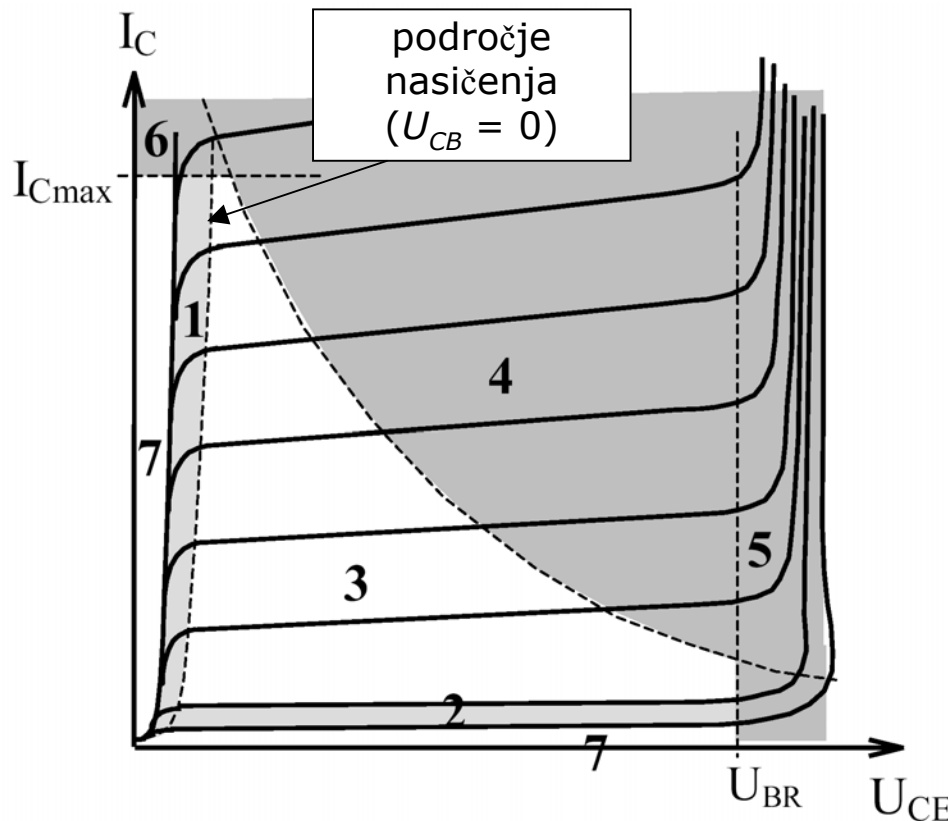
➤ izhodna



Slika: Izhodna karakteristika ($I_C = f(U_{CE})$; $I_B = \text{parameter}$) NPN tranzistorja v orientaciji s skupnim emitorjem

Karakteristike bipolarnega tranzistorja

➤ izhodna karakt., mejne vrednosti

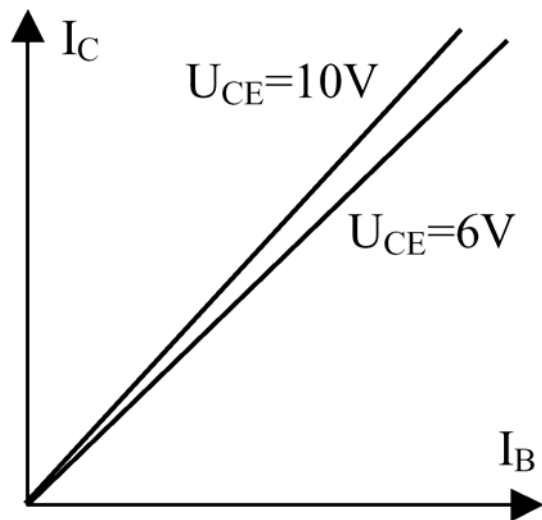


- 1) področje nasičenja
- 2) področje mirovnih tokov (zaporno področje)
- 3) aktivno področje
- 4) nedovoljeno podr. (prekoračitev dovolj.moči)
- 5) področje preboja (prekoračitev dovolj.napetosti)
- 6) prekoračitev maksimalnega toka
- 7) področje karakteristik, ki ga ni možno doseči

Slika: Mejne vrednosti in delovno področje bipolarnega tranzistorja

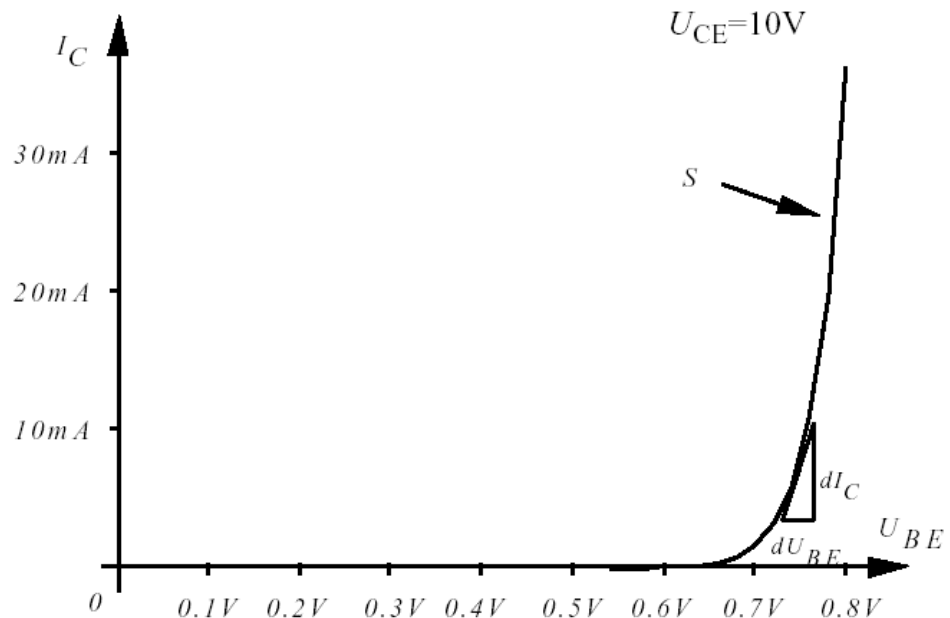
Karakteristike bipolarnega tranzistorja

➤ krmilna karakterisitka



$$\beta = \left. \frac{dI_C}{dI_B} \right|_{U_{CE}=\text{konst}}$$

Slika: Krmilna karakteristika $I_C = f(I_B)$

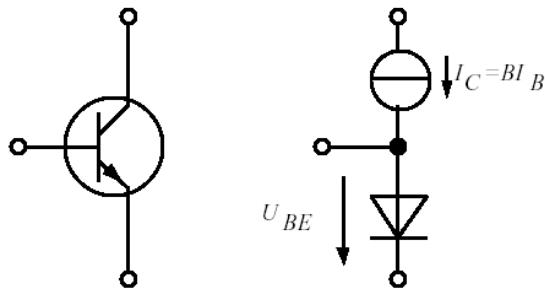


$$S = \left. \frac{dI_C}{dU_{BE}} \right|_{U_{CE}=\text{konst}}$$

Slika: Krmilna karakteristika $I_C = f(U_{BE})$

Modeli bipolarnega tranzistorja

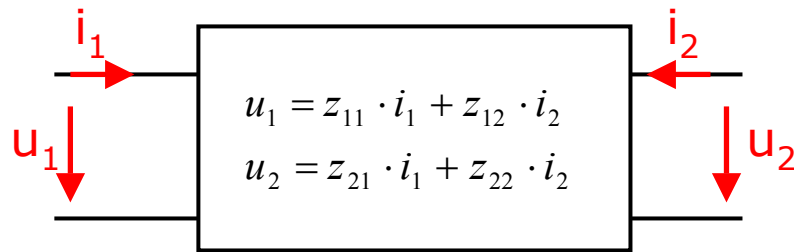
➤ cilj modela: poenostaviti opis, analizo vezja



Slika: Ebers-Moll-ov model NPN tranzistorja

Modeli bipolarnega tranzistorja

➤ cilj modela: poenostaviti opis, analizo vezja



$$u_1 = a_{11} \cdot u_2 - a_{12} \cdot i_2$$

$$i_1 = a_{21} \cdot u_2 - a_{22} \cdot i_2$$

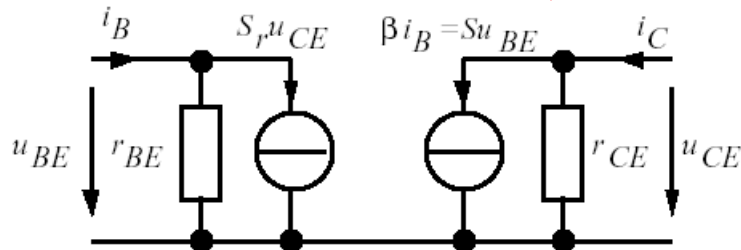
$$u_1 = h_{11} \cdot i_1 + h_{12} \cdot u_2$$

$$i_2 = h_{21} \cdot i_1 + h_{22} \cdot u_2$$

$$i_1 = y_{11} \cdot u_1 + y_{12} \cdot u_2$$

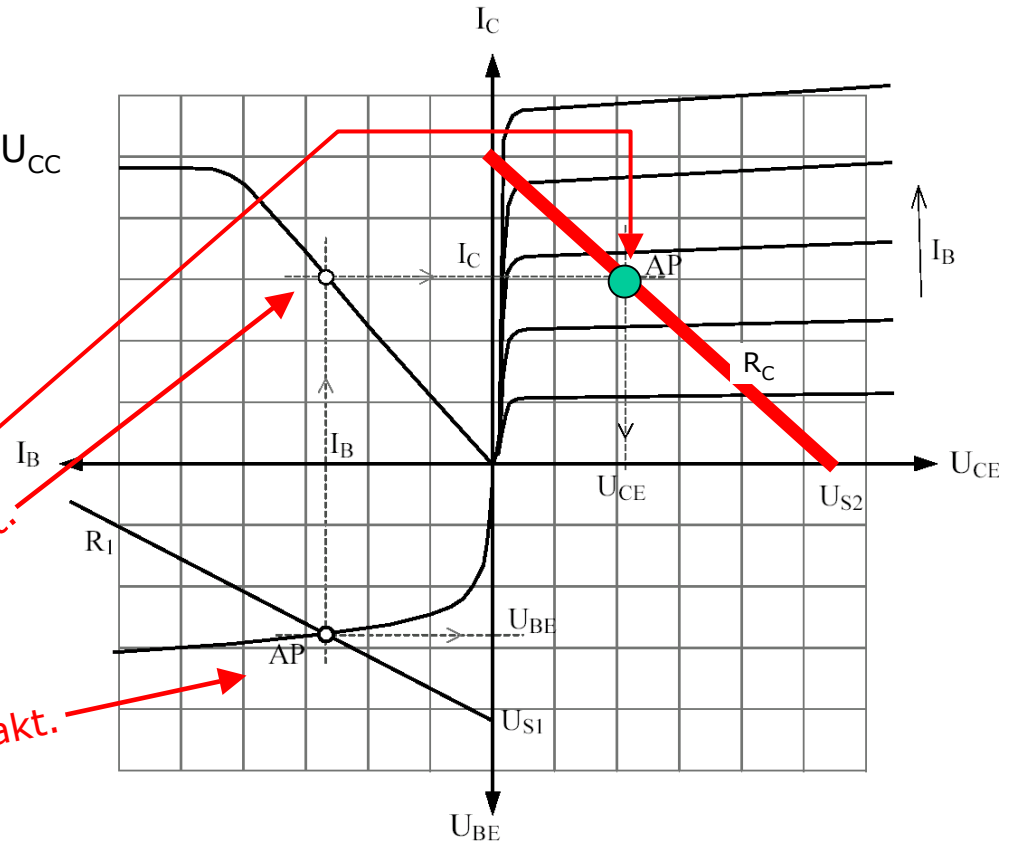
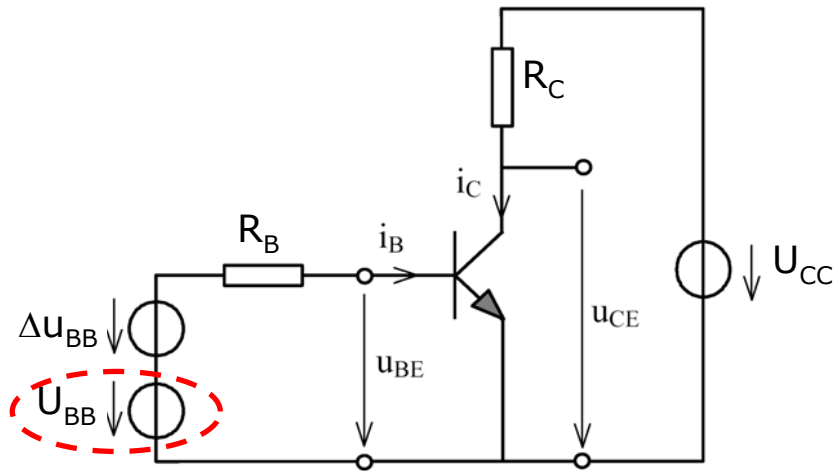
$$i_2 = y_{21} \cdot u_1 + y_{22} \cdot u_2$$

orientacija s skupnim E



Tranzistor kot ojačevalnik

➤ cilj: ojačati majhno spremembo Δu_{BB} oz. Δu_{BE}



definira "lego"
mirovne
delovne točke ...

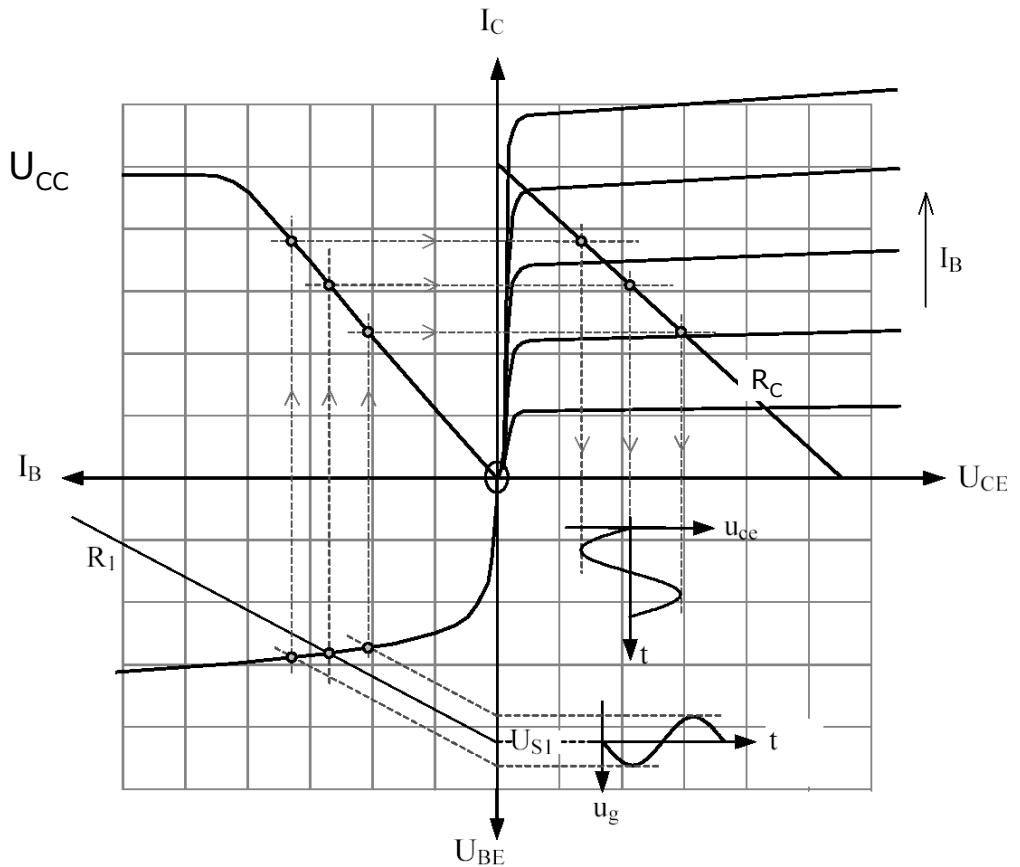
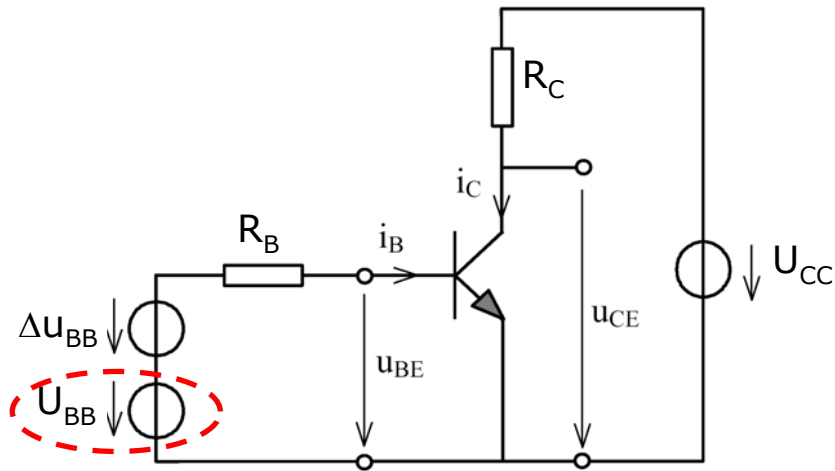
v izhodni karakt.

v krmilni karakt.

v vhodni karakt.

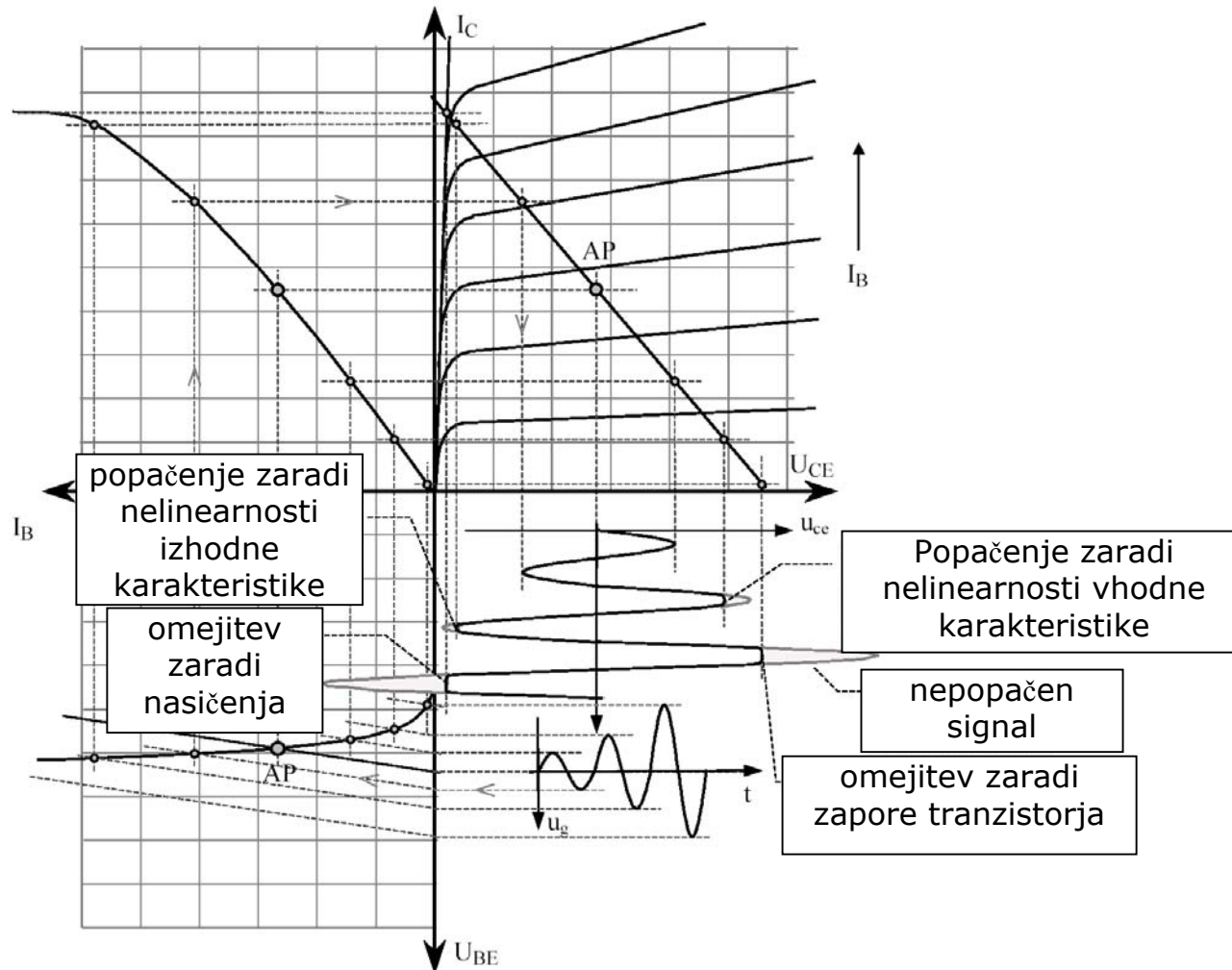
Tranzistor kot ojačevalnik

➤ cilj: ojačati majhno spremembo Δu_{BB} oz. Δu_{BE}



Tranzistor kot ojačevalnik

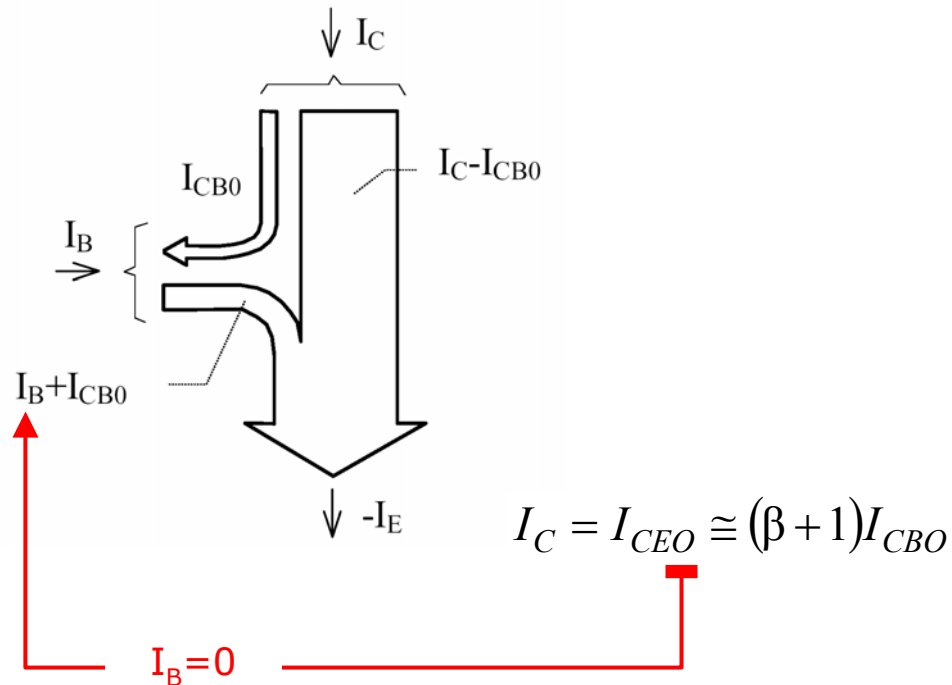
➤ popačenje:



(Ne)stabilnost mirovne delovne točke

➤ vzrok: temperaturna odvisnost tranzistorskih lastnosti

❖ mirovni tok tranzistorja

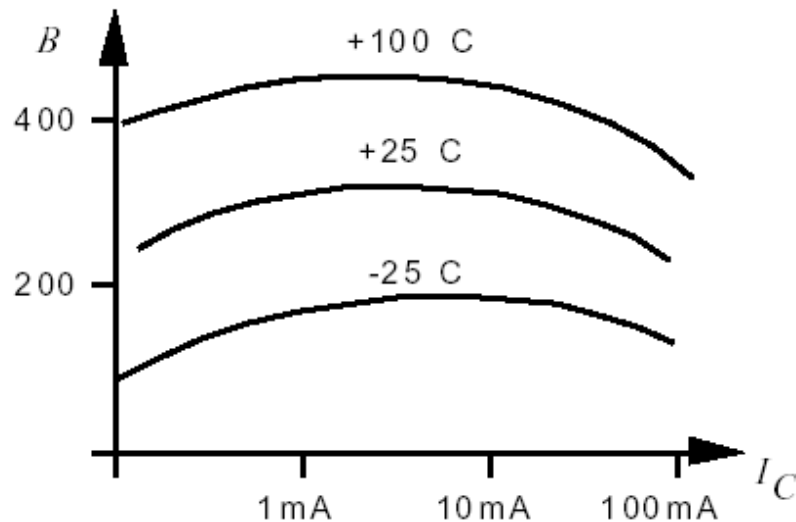


$$I_C \cong \beta I_B + \underline{(\beta + 1)I_{CBO}}$$

(Ne)stabilnost mirovne delovne točke

➤ vzrok: temperaturna odvisnost tranzistorskih lastnosti

❖ tokovno ojačenje B

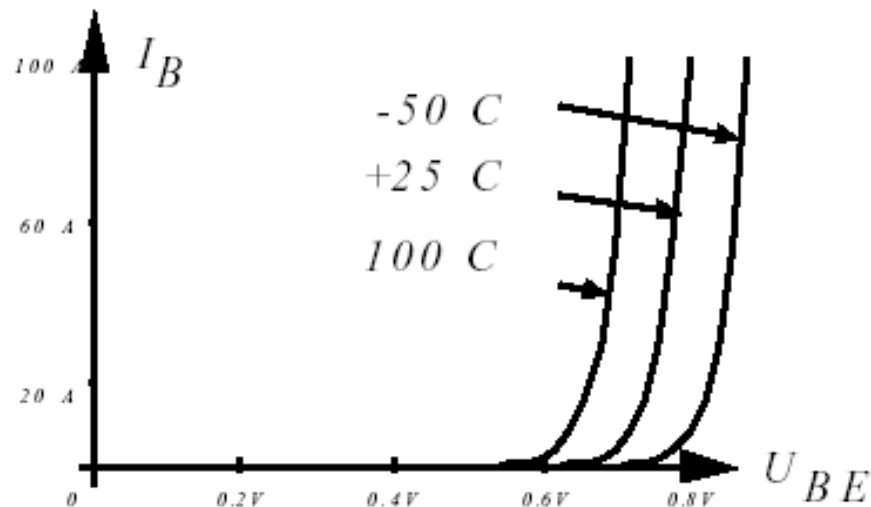


Slika: Temperaturna odvisnost tokovnega ojačenja

(Ne)stabilnost mirovne delovne točke

➤ vzrok: temperaturna odvisnost tranzistorskih lastnosti

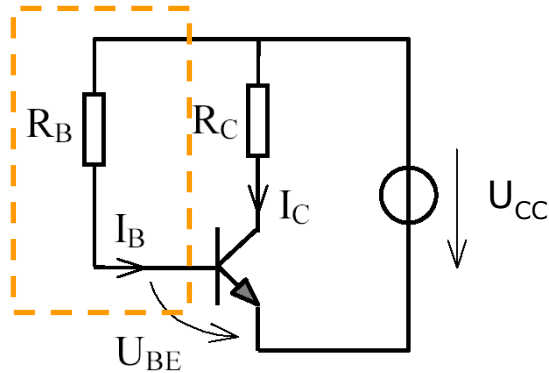
❖ napetost kolena U_{BE}



❖ dodatni vzroki: spremembe napajalne napetosti, upornosti vezja

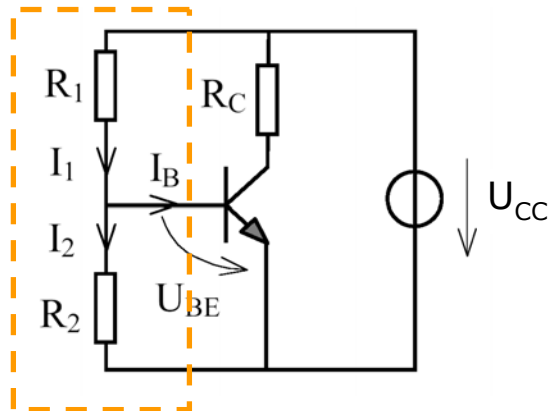
Stabilizacija mirovne delovne točke

➤ začetna postavitev mirovne delovne točke



$$R_B = \frac{U_S - U_{BE}}{I_B}$$

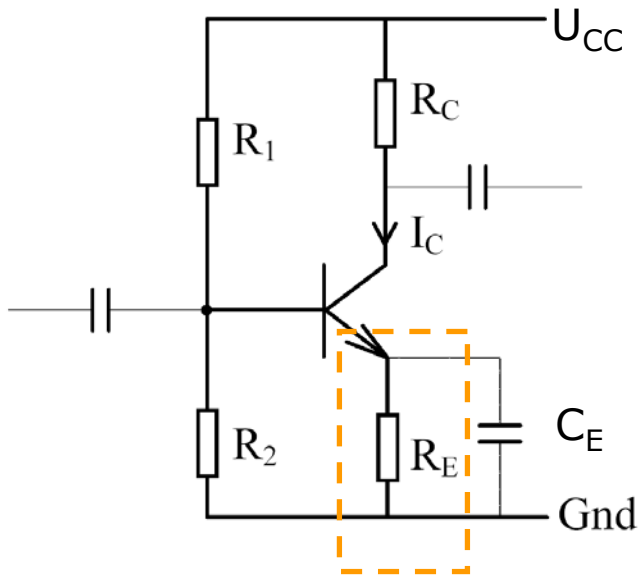
$$I_C \approx I_B \cdot B = \frac{U_S - U_{BE}}{R_B} \cdot B$$



$$U_{BE} = U_S \cdot \frac{R_2}{R_1 + R_2} - I_B \cdot \frac{R_1 \cdot R_2}{R_1 + R_2}$$

Stabilizacija mirovne delovne točke

➤ ... s pomočjo tokovne povratne vezi

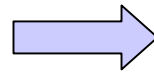


$$R_E \cong \frac{U_{R_E}}{I_C}$$

$$R_C = \frac{U_{CC} - U_{CE} - U_{R_E}}{I_C}$$

$$R_1 = \frac{U_{CC} - U_{BE} - U_{R_E}}{I_{R_2} + I_B}$$

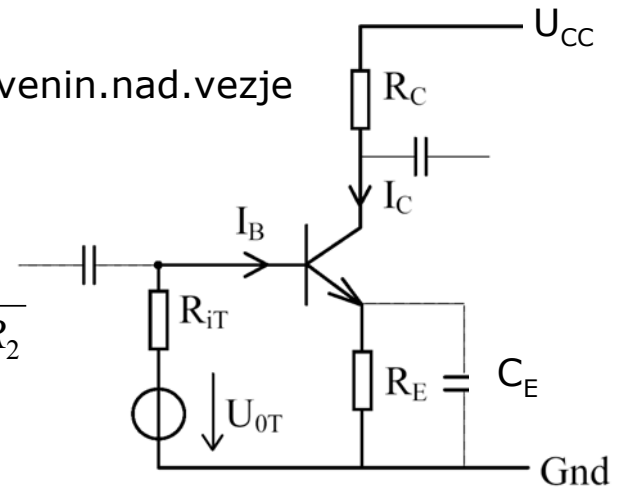
$$R_2 = \frac{U_{BE} + U_{R_E}}{I_{R_2}}$$



Thevenin.nad.vezje

$$U_{0T} = U_{CC} \frac{R_2}{R_1 + R_2}$$

$$R_{iT} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$



$$I_C = B \cdot I_B + (B + 1)I_{CB0}$$

$$U_{0T} - I_B \cdot R_{iT} - U_{BE} - (I_B + I_C) \cdot R_E = 0$$

$$I_C = \frac{(U_{0T} - U_{BE}) \cdot B + (B + 1) \cdot (R_{iT} + R_E) \cdot I_{CB0}}{R_{iT} + (B + 1) \cdot R_E}$$

$$B + 1 \cong B$$

$$I_C \cong \frac{U_{0T} - U_{BE} + (R_{iT} + R_E) \cdot I_{CB0} \cdot B}{R_{iT} + B \cdot R_E}$$

Stabilizacija mirovne delovne točke

➤ Faktor stabilnosti

$$I_C \cong \frac{U_{0T} - U_{BE} + (R_{iT} + R_E) \cdot I_{CB0} \cdot B}{R_{iT} + B \cdot R_E}$$

$$\begin{aligned} \Delta I_C &= f(\Delta U_{BE}, \Delta I_{CB0}, \Delta B, \Delta U_{CC}, \Delta R_x) = \\ &= \frac{\delta I_C}{\delta U_{BE}} \cdot \Delta U_{BE} + \frac{\delta I_C}{\delta I_{CB0}} \cdot \Delta I_{CB0} + \frac{\delta I_C}{\delta B} \cdot \Delta B + \frac{\delta I_C}{\delta U_{CC}} \cdot \Delta U_{CC} + \frac{\delta I_C}{\delta R_x} \cdot \Delta R_x \end{aligned}$$

$$\Delta I_C = f(\Delta I_{CB0}) \approx \frac{\delta I_C}{\delta I_{CB0}} \cdot \Delta I_{CB0}$$

$$\Delta I_C \cong \frac{(R_{iT} + R_E) \cdot B}{R_{iT} + B \cdot R_E} \cdot \Delta I_{CB0}$$

Če predpostavimo $R_{iT} \ll B \cdot R_E$, dobimo

$$S_{\Delta I_{CB0}} = \frac{\Delta I_C}{\Delta I_{CB0}} \cong \frac{(R_{iT} + R_E)}{R_E}$$

Stabilizacija mirovne delovne točke

➤ ... s pomočjo napetostne povratne vezi

$$R_B = \frac{U_{CE} - U_{BE}}{I_B} \quad R_C = \frac{U_{CC} - U_{CE}}{I_C + I_B}$$

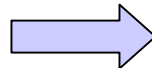
$$I_C = B \cdot I_B + (B + 1)I_{CBO}$$

$$U_{CE} - U_{BE} - I_B R_B = 0$$

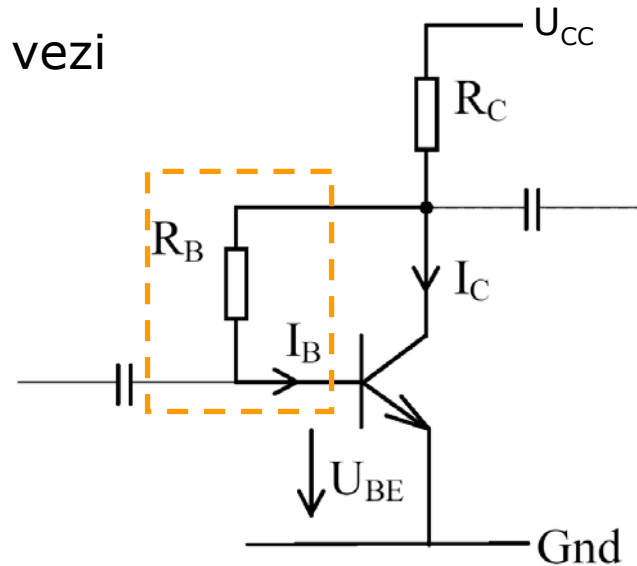
$$U_{CC} - U_{CE} - (I_C + I_B)R_C = 0$$

$$I_C = \frac{(U_{CC} - U_{BE}) \cdot B + (B + 1) \cdot (R_B + R_C) \cdot I_{CBO}}{R_B + (B + 1) \cdot R_C}$$

$$B + 1 \cong B$$



$$I_C \cong \frac{U_{CC} - \underline{U_{BE}} + (R_B + R_C) \cdot \underline{I_{CBO}}}{R_B + \underline{B} \cdot R_C} \underline{B}$$



Stabilizacija mirovne delovne točke

➤ Faktor stabilnosti

$$\Delta I_C = f(\Delta I_{CB0}) \approx \frac{\delta I_C}{\delta I_{CB0}} \cdot \Delta I_{CB0}$$

$$\Delta I_C \cong \frac{(R_B + R_C) \cdot B}{R_B + B \cdot R_C} \cdot \Delta I_{CB0}$$

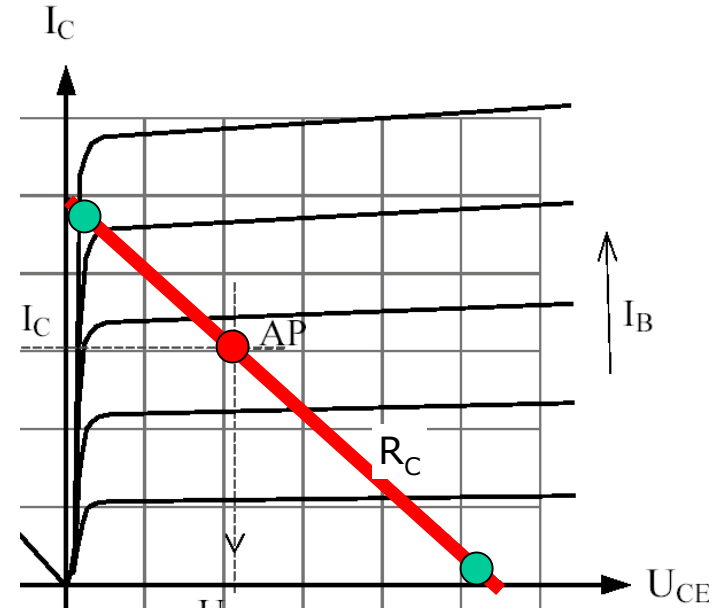
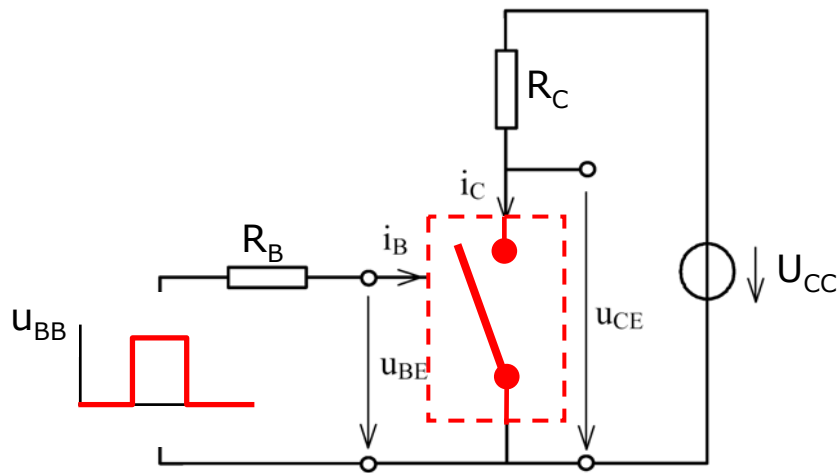
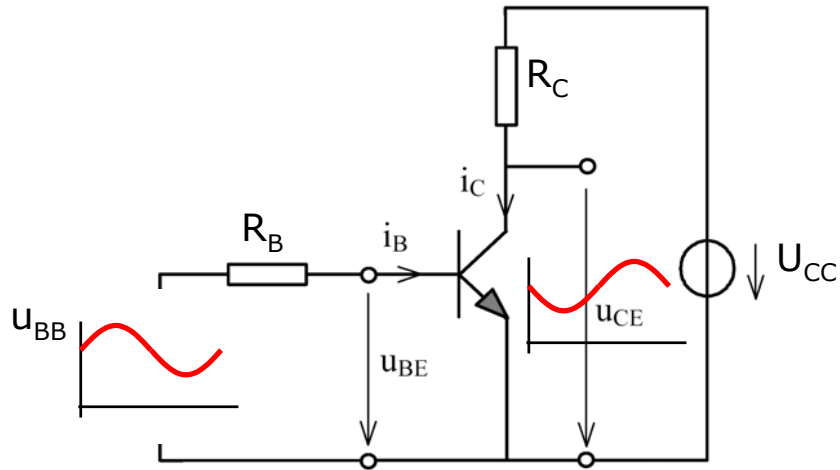
Če predpostavimo $R_B \ll B \cdot R_C$, dobimo

$$I_C \cong \frac{U_{CC} - U_{BE} + (R_B + R_C) \cdot I_{CB0} \cdot B}{R_B + B \cdot R_C}$$

$$S_{\Delta I_{CB0}} = \frac{\Delta I_C}{\Delta I_{CB0}} \cong \frac{(R_B + R_C)}{R_C}$$

Tranzistor kot stikalo

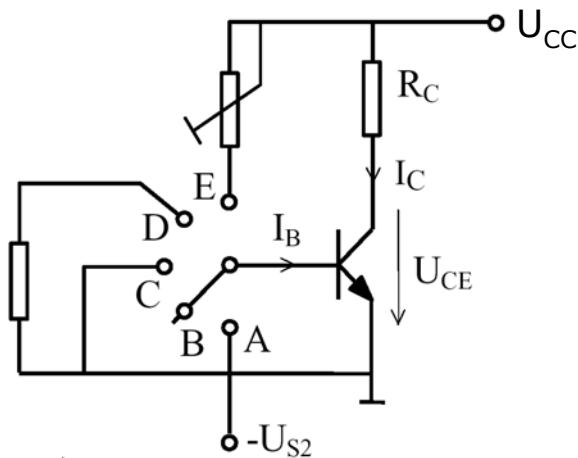
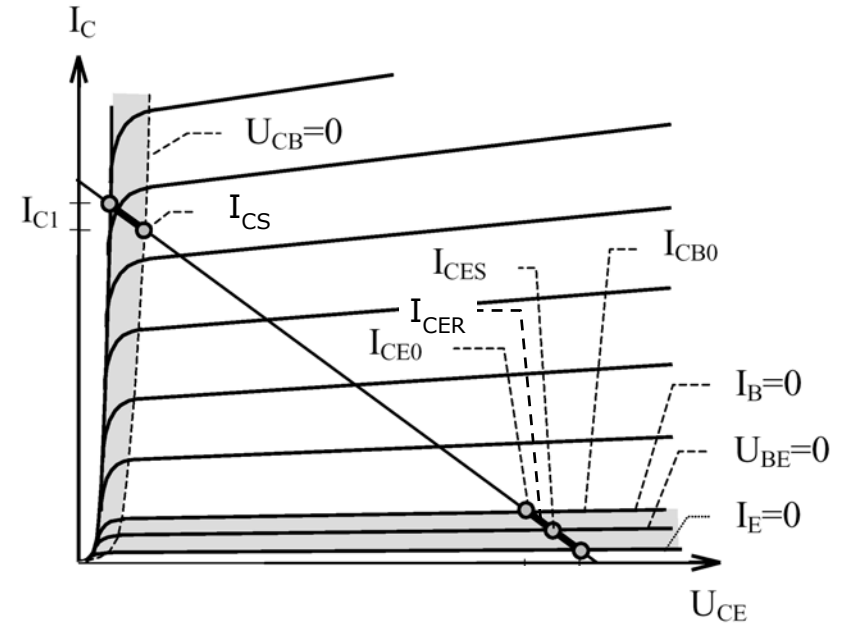
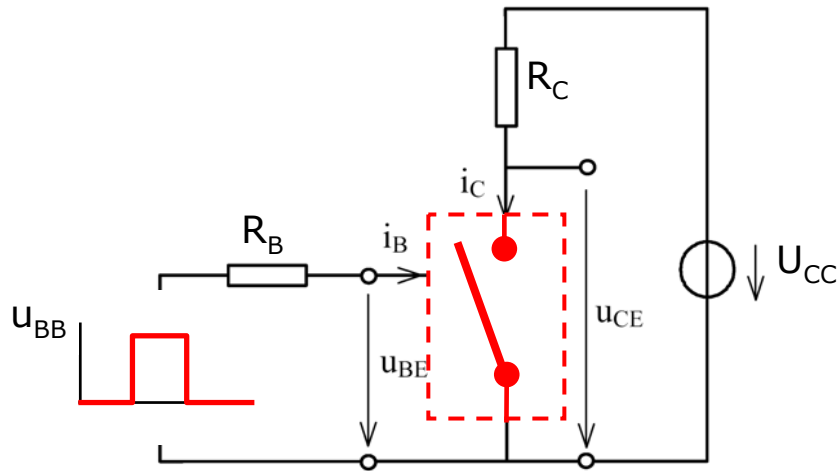
➤ cilj: vklop/izklop bremena



"lega" mirovne delovne točke ...

Tranzistor kot stikalo

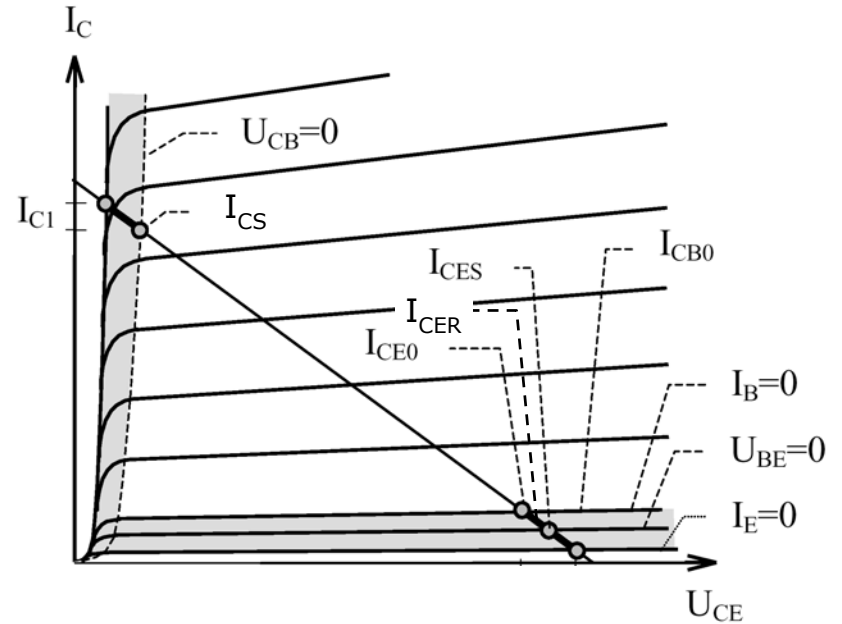
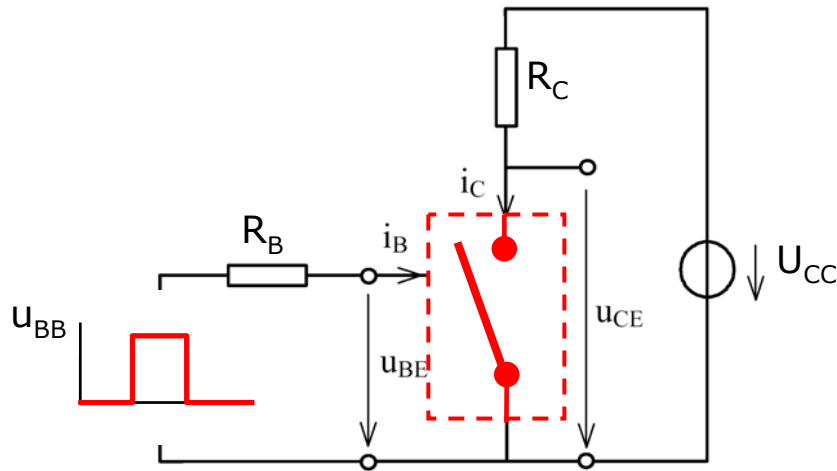
➤ načini izkrmiljenja stikala v zapornem področju



- A: zapora z neg. krmilno napetostjo
- B: zapora z $I_B=0$
- C: zapora z $U_{BE}=0$
- D: zapora z R vezanim med B in GND
- E: prevajanje tranzistorja (nasičenje)

Tranzistor kot stikalo

➤ jakost izkrmiljenja stikala v področju nasičenja



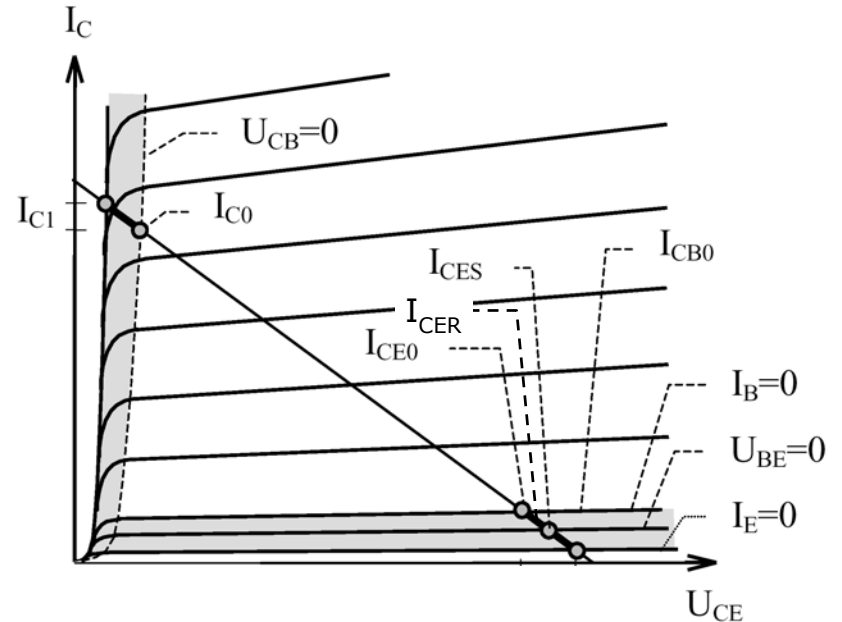
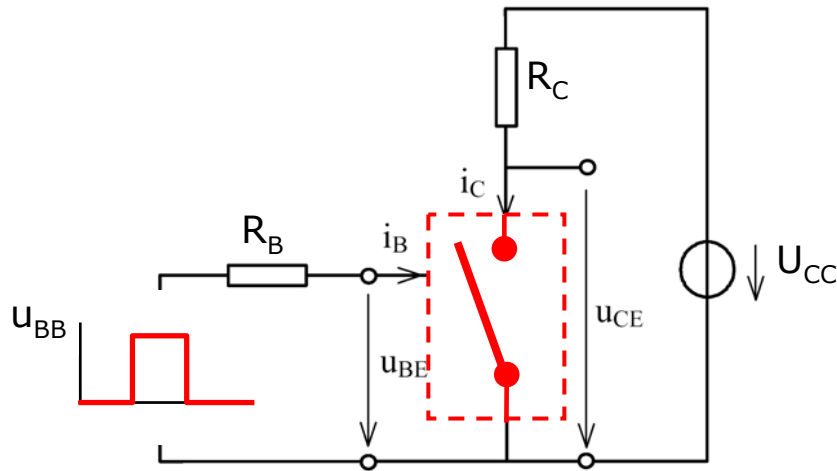
$$I_B = \frac{U_{BB} - U_{BE}}{R_B}$$

$$U_{CE} = U_{CC} - R_C I_C = U_{CC} - \frac{\beta \cdot R_C}{R_B} (U_{BB} - U_{BE})$$

$$U_{CB} = U_{CE} - U_{BE} = 0 \quad \Rightarrow \quad I_{CS} = \frac{U_{CC} - U_{CE}}{R_C} = \frac{U_{CC} - U_{BE}}{R_C} \quad \Rightarrow \quad \text{pri} \quad I_{BS} = \frac{I_{CS}}{\beta}$$

Tranzistor kot stikalo

➤ jakost izkrmiljenja stikala v področju nasičenja



$$U_{CB} = U_{CE} - U_{BE} = 0 \quad \Rightarrow \quad I_{CS} = \frac{U_{CC} - U_{CE}}{R_C} = \frac{U_{CC} - U_{BE}}{R_C} \quad \Rightarrow \quad \text{pri} \quad I_{BS} = \frac{I_{CS}}{\beta}$$

➤ dejanski bazni tok I_B je vedno večji od izračunane vrednosti I_{BS}

$$\gamma = \frac{I_B}{I_{BS}} \quad \dots \text{faktor prekrmljenja}$$

➤ tranzistor se nahaja v globokem nasičenju; $U_{BE} > U_{CE}$

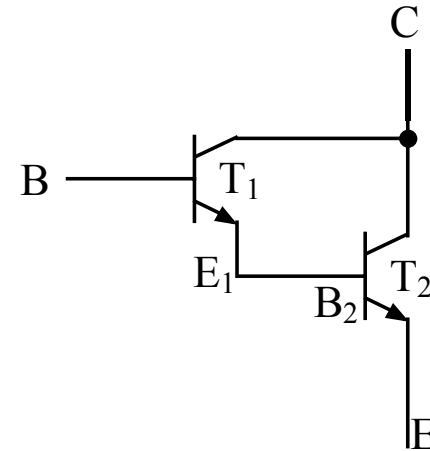
Tranzistor kot stikalo

- bazno prekrmiljenje povzroči povečanje krmilnih izgub

$$I_{C2} = \beta_2 \cdot I_{B2} = \beta_2 \cdot I_{E1} = \beta_2 \cdot (I_{C1} + I_{B1})$$

$$\beta = \frac{I_{C1} + I_{C2}}{I_{B1}} = \frac{I_{C1} + \beta_2 (I_{C1} + I_{B1})}{I_{B1}}$$

$$\beta = \beta_1 + \beta_1 \beta_2 + 1 \approx \beta_1 \beta_2$$

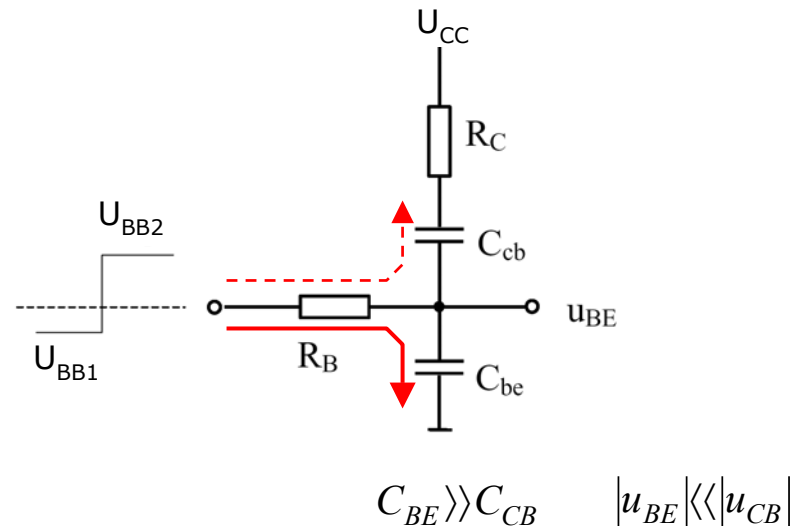
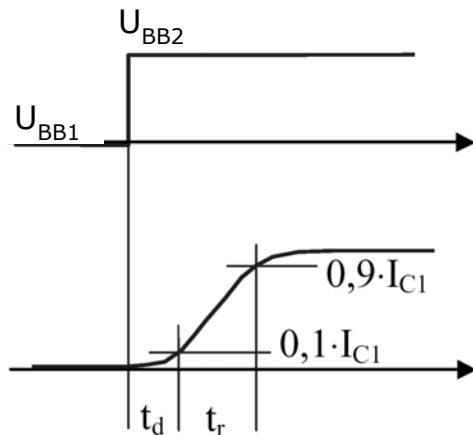


Slika: Darlington vezava tranzistorjev

Dinamične (preklopne) lastnosti tranzistorja

- vzrok: vpliv medelektrodne kapacitivnosti ter nakopičen naboj manjšinjskih nosilcev

❖ vklop tranzistorja

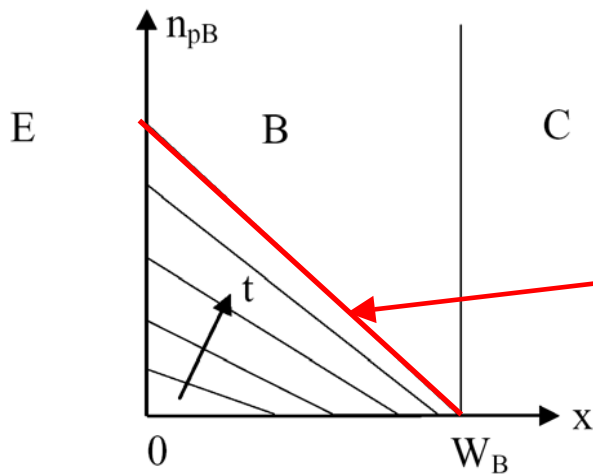
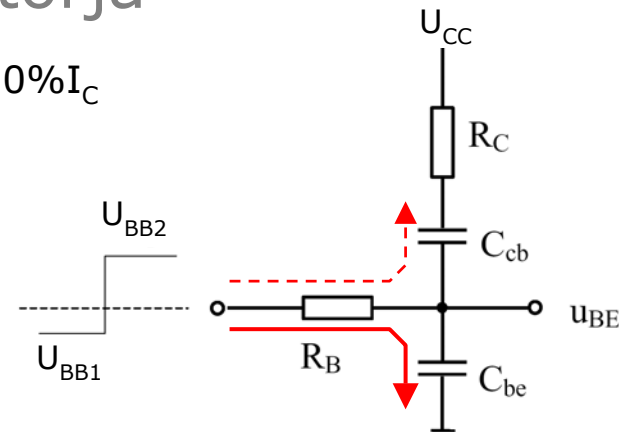
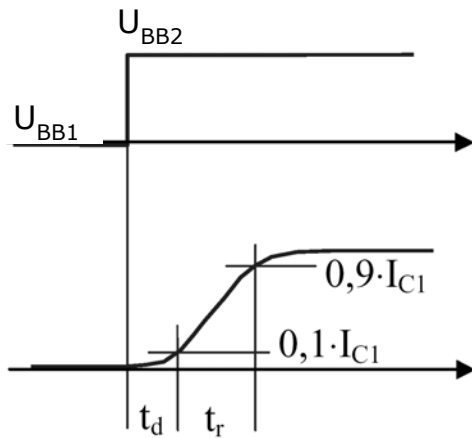


-čas zakasnitve od t_0 do porasta napetosti u_{BE} do vrednosti 0

$$t_{d1} = R_B C_{BE} \cdot \ln \frac{U_{BB2} - U_{BB1}}{U_{BB2}}$$

Vklop tranzistorja

-čas zakasnitve od t_{d1} do porasta kolekt.toka do $10\%I_C$



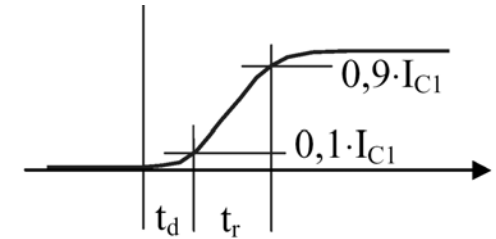
Slika: Prostorska razporeditev manjšinjskih nosilcev naboja preko preseka baze v odvisnosti od časa t med časom zakasnitve

razporeditev naboja, ko začne tranzistor prevajati ($\approx t_d$)

$$t_{d2} = (\tau_B + R_C C_{CB}) \cdot B \cdot \ln \frac{\gamma}{\gamma - 0,1}$$

Vklop tranzistorja

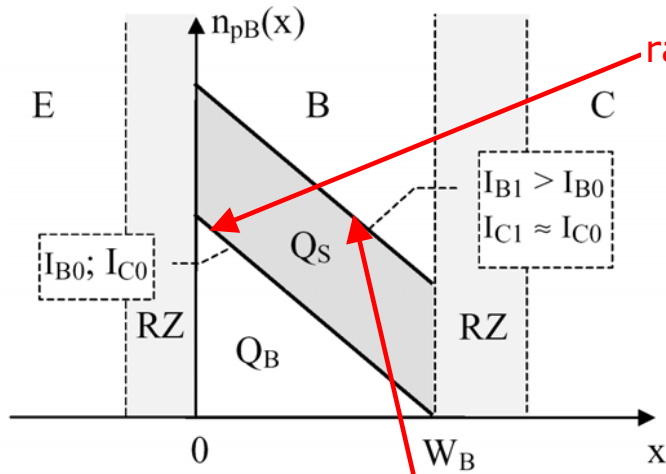
-čas porasta t_r ; časovni interval od $10\%I_C$ do $90\%I_C$



-napetost u_{CB} se začne zmanjševati,

razporeditev naboja na meji nasičenja $u_{CB}=0$

-ko je $u_{CB}=0$, "izgine" pospeševalna napetost na spoju CB,



- z nadaljnjim zmanjševanjem u_{CB} (**prekrmiljenje**) se v bazi na strani K se pojavi presežek manjš.naboja,

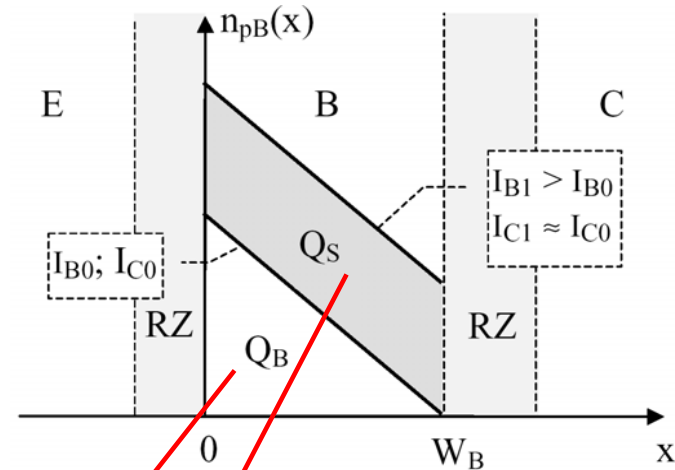
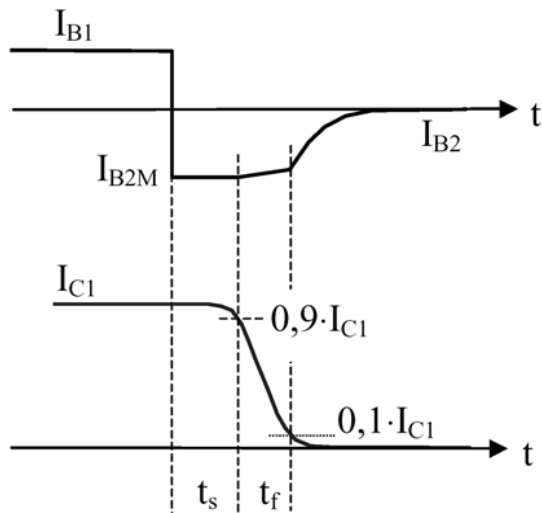
razporeditev naboja, ko se tranzistor nahaja v prevodnem stanju

$$t_r \cong \tau_B \cdot B \cdot \ln \frac{\gamma - 0,1}{\gamma - 0,9}$$

$$t_{ON} = t_d + t_r$$

Dinamične (preklopne) lastnosti tranzistorja

❖ izklop tranzistorja

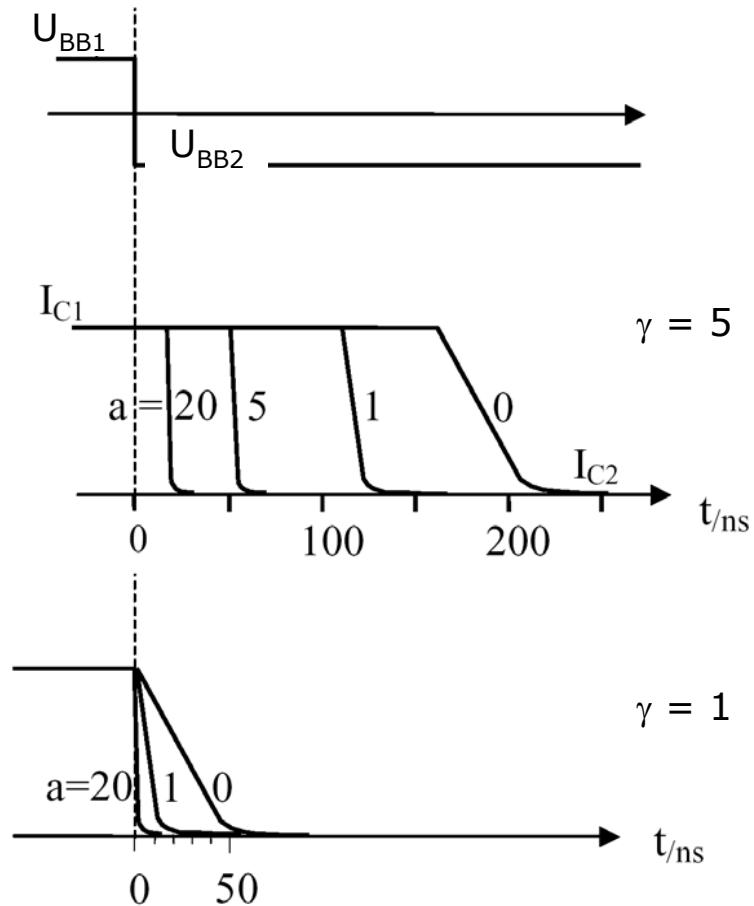


-čas sprostitve t_s $t_s = \tau_S \cdot \ln \frac{a + \gamma}{a + 0,1} + \tau_E \cdot \ln \frac{a + 0,1}{a + 0,9}$

-čas upada t_f $t_f = \tau_E \cdot \ln \frac{a + 0,9}{a + 0,1}$

$a = \frac{-I_{B2M}}{I_{B0}}$...faktor negativnega izkrmiljenja

Izklop tranzistorja

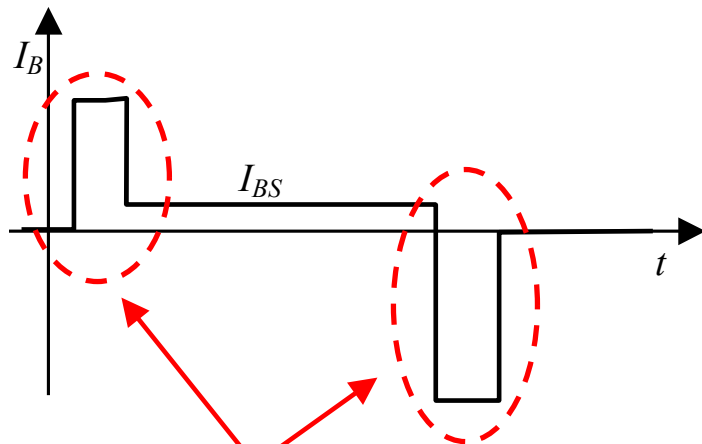


Orientacijski prikaz odvisnosti
preklopnih časov od faktorja baznega
prekrmljenja γ in faktorja baznega
negativnega izkrmiljenja a

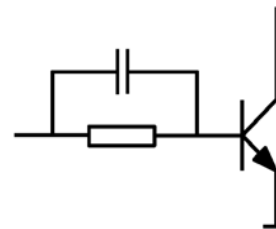
bazno prekrmljenje

Bazno prekrmiljenje...sklepna misel

bazno prekrmiljenje

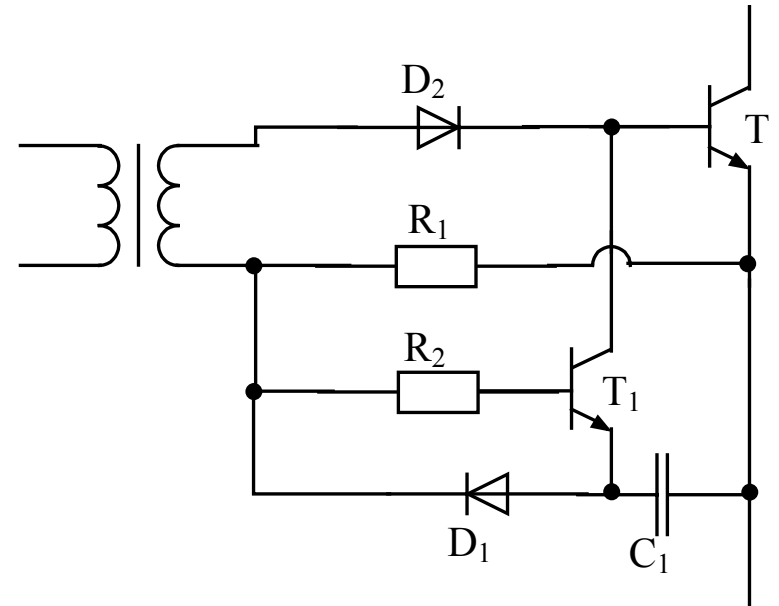
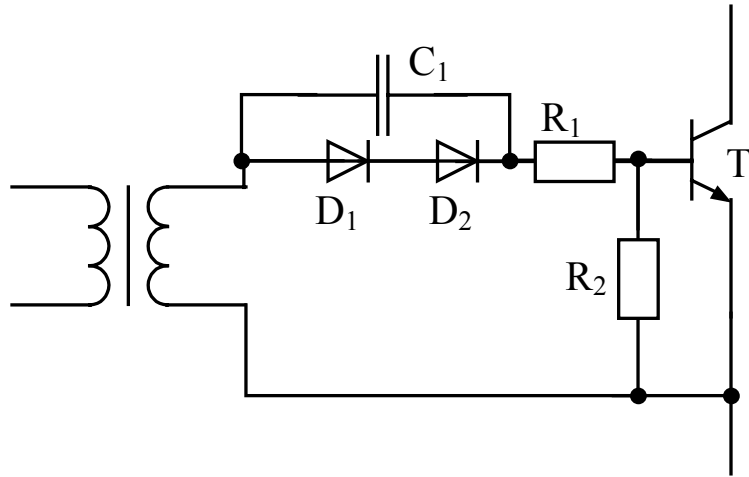


dinamično prekrmiljenje



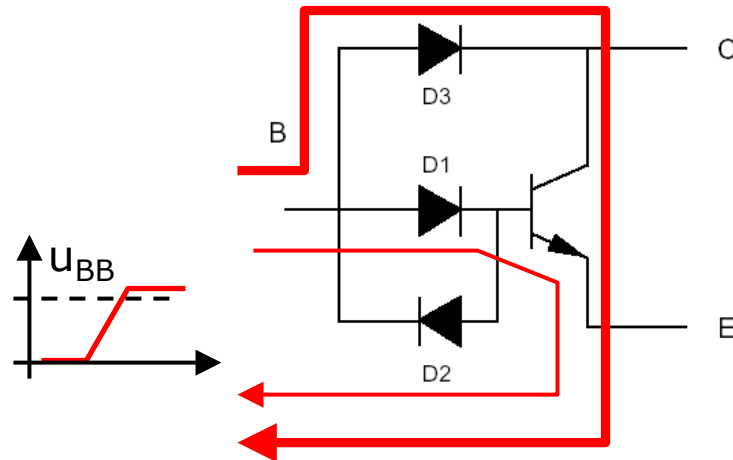
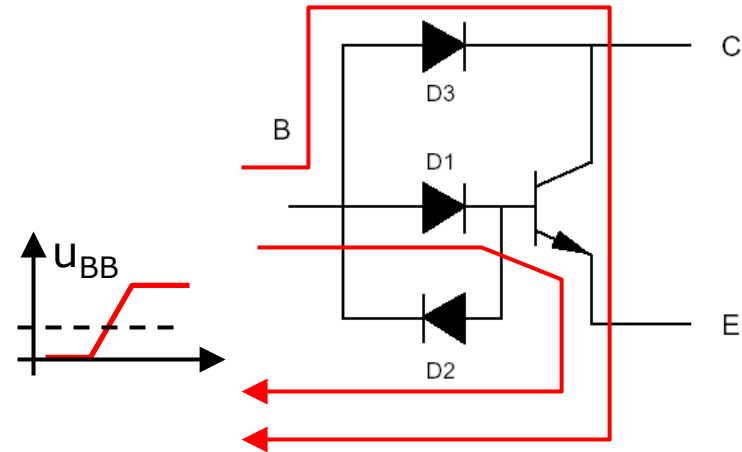
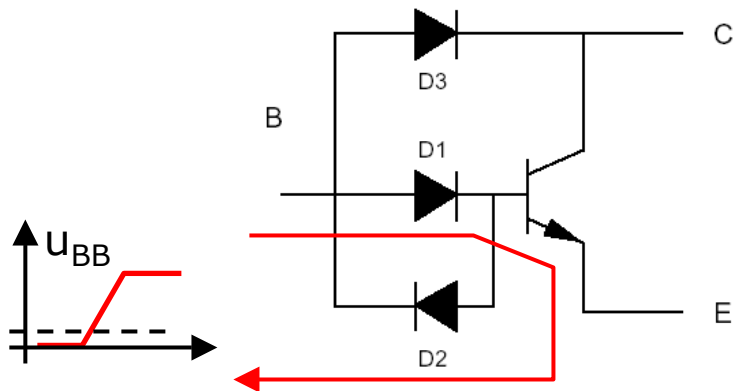
- cilj: pospešiti vklop/izklop
- zmanjšati t_d in t_s

...dinamično prekrmljenje

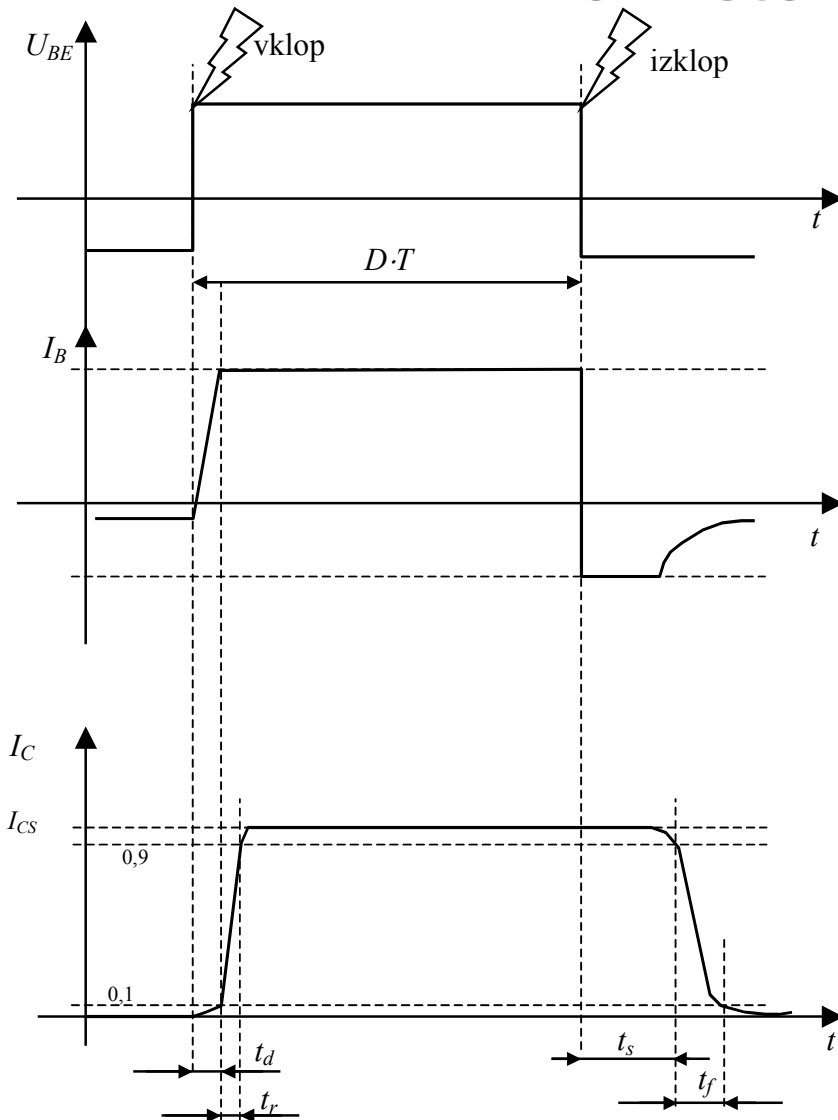


...dinamično prekrmiljenje

➤ desaturacijsko vezje (angl. Baker clamp)



Tranzistor kot stikalo



Podatki:

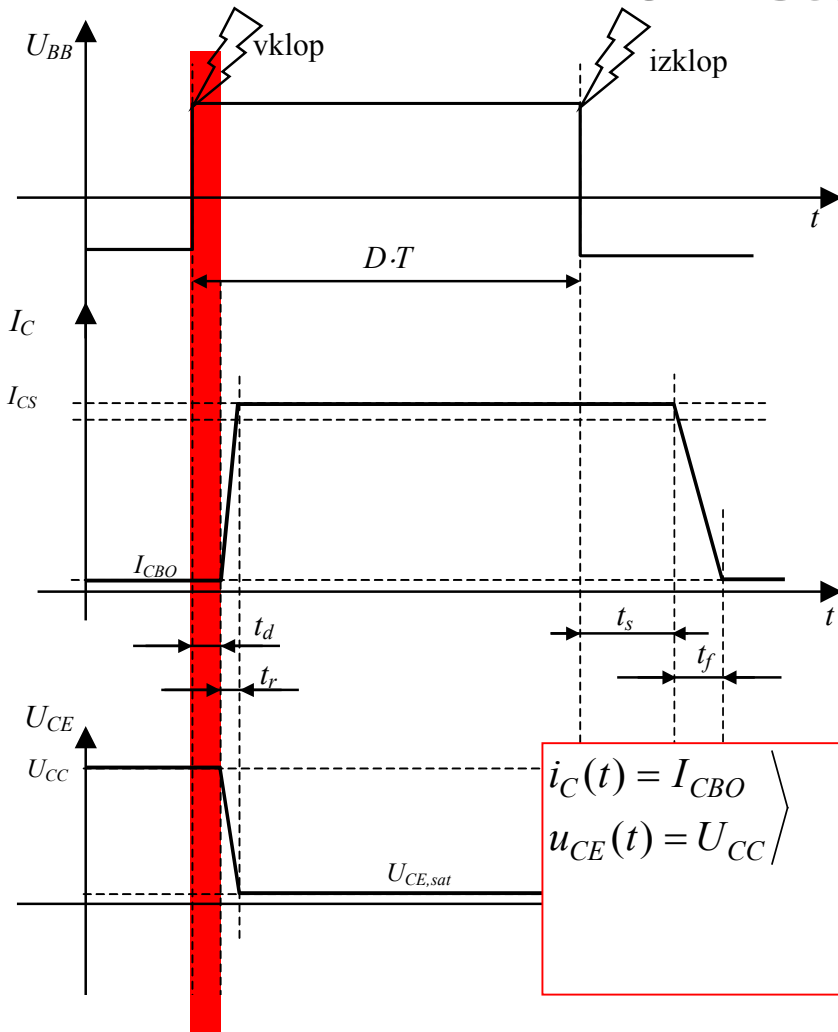
$$U_{CC} = 250\text{V} \quad I_{CS} = 100\text{A} \quad I_B = 8\text{A}$$

$$U_{CE,sat} = 2\text{V} \quad I_{CBO} = 3\text{mA}$$

$$t_r = 1\mu\text{s} \quad t_f = 3\mu\text{s} \quad t_d = 0,5\mu\text{s}$$

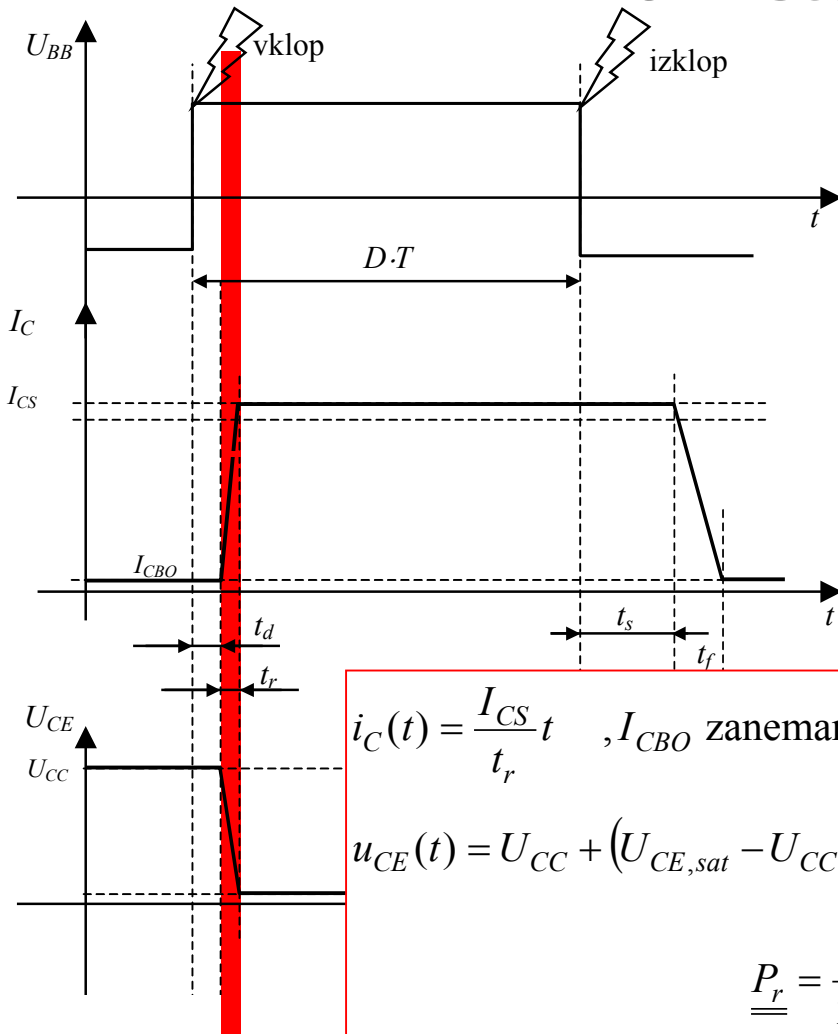
$$f_s = 10\text{kHz} \quad D = 50\% \quad t_s = 5\mu\text{s}$$

Tranzistor kot stikalo



$$\begin{aligned}
 & \left. \begin{aligned} i_C(t) &= I_{CBO} \\ u_{CE}(t) &= U_{CC} \end{aligned} \right\} \\
 & p_d(t) = I_{CBO} \cdot U_{CC} = 0,75 \text{ W} \\
 & \underline{\underline{P_d}} = \frac{1}{T} \int_0^{t_d} p_d(t) dt = I_{CBO} \cdot U_{CC} \cdot t_d \cdot f_s = \underline{\underline{3,75 \text{ mW}}}
 \end{aligned}$$

Tranzistor kot stikalo



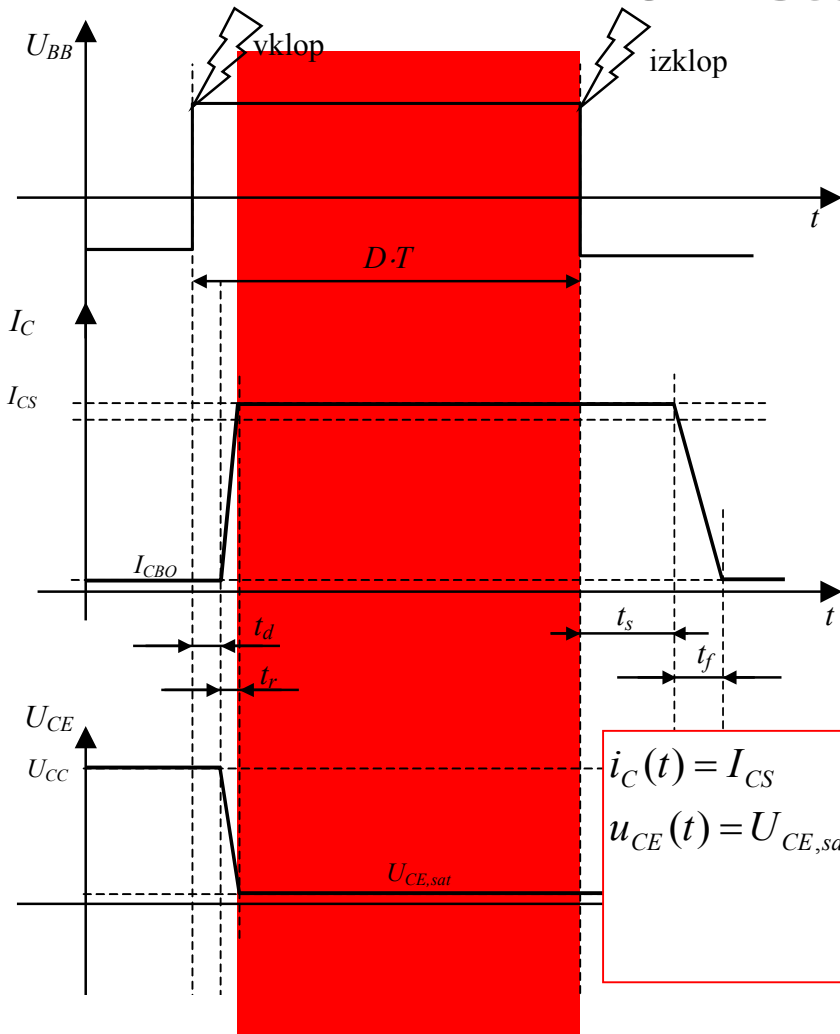
$$i_C(t) = \frac{I_{CS}}{t_r} t, \quad I_{CBO} \text{ zanemarimo}$$

$$u_{CE}(t) = U_{CC} + (U_{CE,sat} - U_{CC}) \frac{t}{t_r}$$

$$p_r(t) = \frac{I_{CS}}{t_r} t \cdot \left[U_{CC} + (U_{CE,sat} - U_{CC}) \frac{t}{t_r} \right]$$

$$\underline{\underline{P_r}} = \frac{1}{T} \int_0^{t_r} p_r(t) dt = I_{CS} \cdot t_r \cdot f_s \left[\frac{U_{CC}}{2} + \frac{U_{CE,sat} - U_{CC}}{3} \right] = \underline{\underline{42,33 \text{ W}}}$$

Tranzistor kot stikalo

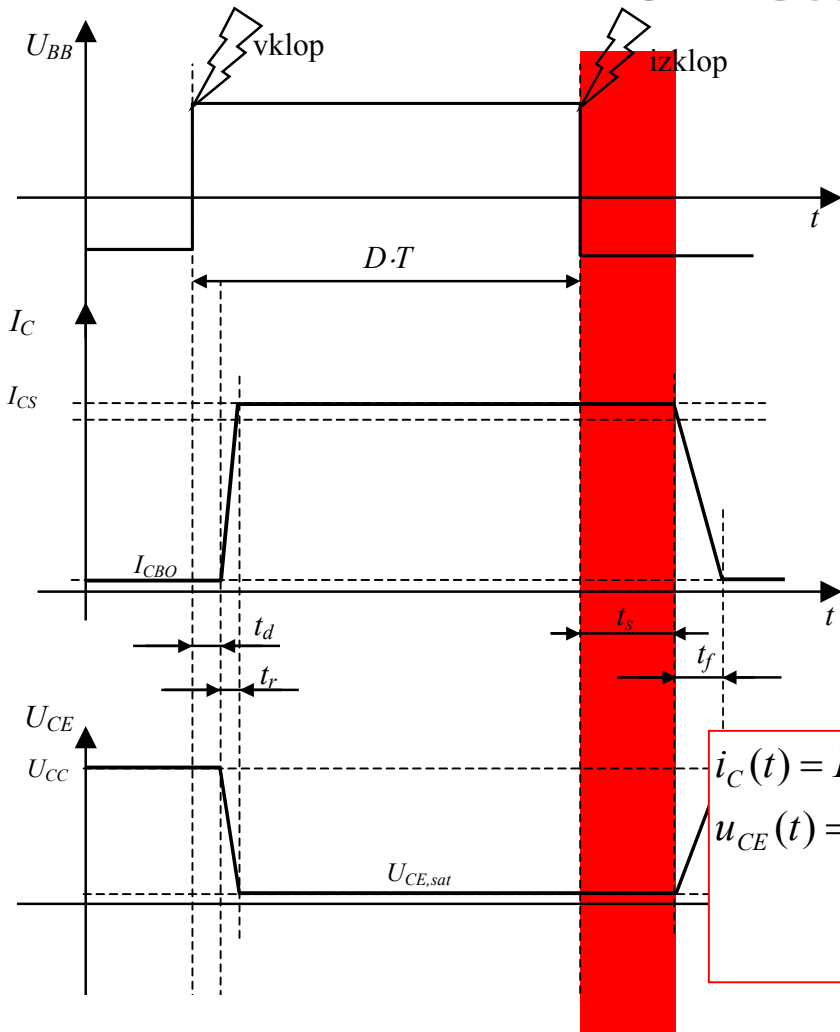


$$\left. \begin{aligned} i_C(t) &= I_{CS} \\ u_{CE}(t) &= U_{CE,sat} \end{aligned} \right\}$$

$$p_N(t) = I_{CS} \cdot U_{CE,sat} = 0,2 \text{ W}$$

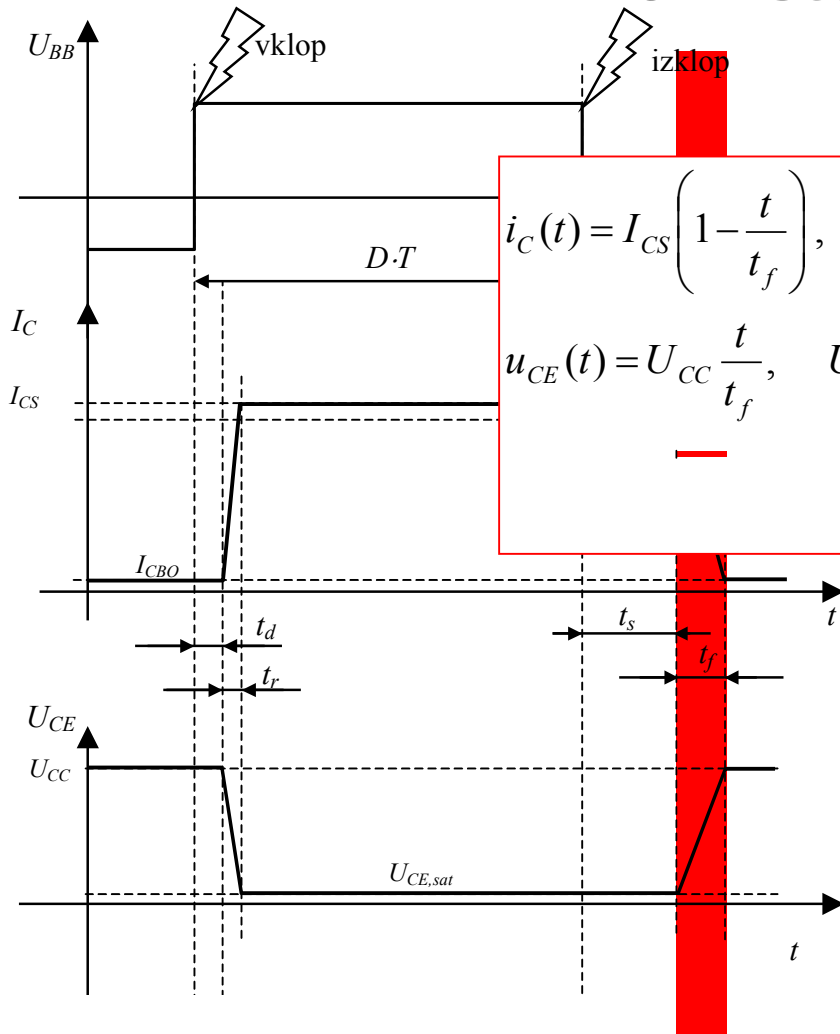
$$\underline{\underline{P_N}} = \frac{1}{T} \int_0^{t_N} p_N(t) dt = I_{CS} \cdot U_{CE,sat} \cdot t_N \cdot f_s = \underline{\underline{\quad \text{W}}}$$

Tranzistor kot stikalo



$$\begin{aligned}
 & \left. \begin{aligned} i_C(t) &= I_{CS} \\ u_{CE}(t) &= U_{CE,sat} \end{aligned} \right\} & p_s(t) &= I_{CS} \cdot U_{CE,sat} = \quad \text{W} \\
 & & \underline{\underline{P_s}} &= \frac{1}{T} \int_0^{t_s} p_s(t) dt = I_{CS} \cdot U_{CE,sat} \cdot t_s \cdot f_s = \underline{\underline{10 \text{ W}}}
 \end{aligned}$$

Tranzistor kot stikalo



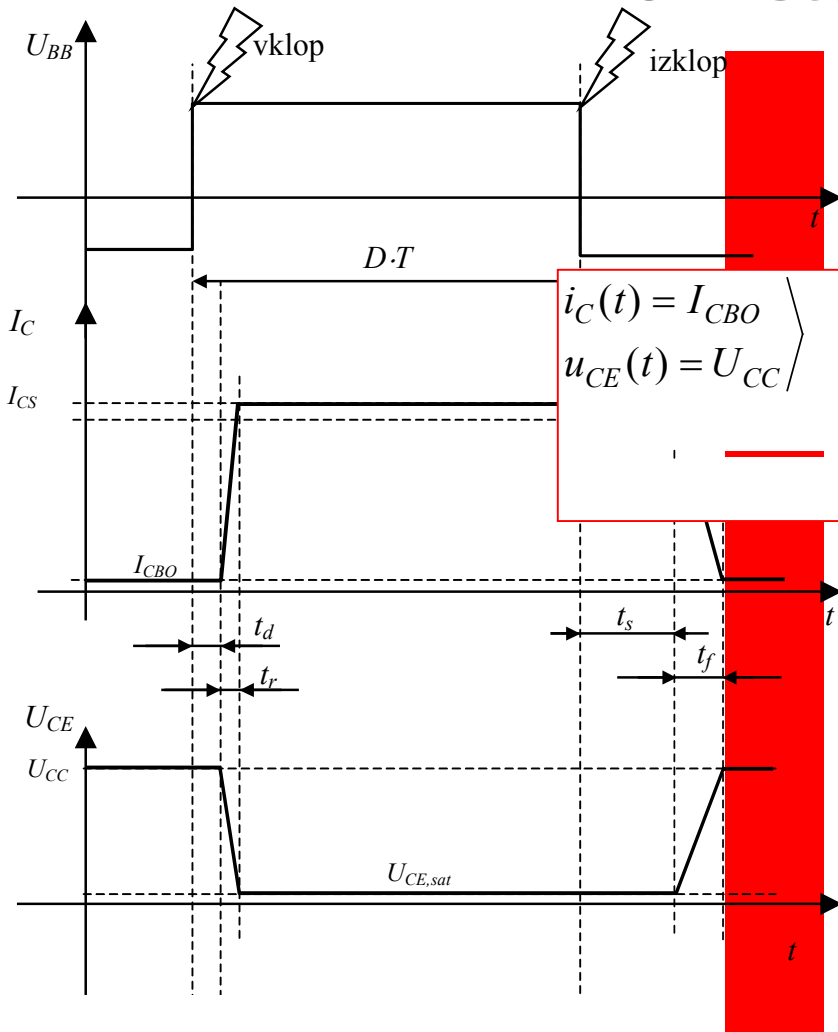
$$i_C(t) = I_{CS} \left(1 - \frac{t}{t_f} \right), \quad I_{CEO} \text{ zanemarimo}$$

$$u_{CE}(t) = U_{CC} \frac{t}{t_f}, \quad U_{CE,sat} \text{ zanemarimo}$$

$$p_f(t) = U_{CC} \frac{t}{t_f} \cdot I_{CS} \left(1 - \frac{t}{t_f} \right)$$

$$\underline{\underline{P_f}} = \frac{1}{T} \int_0^{t_f} p_f(t) dt = \frac{U_{CC} I_{CS} \cdot t_f \cdot f_s}{6} = \underline{\underline{125 \text{ W}}}$$

Tranzistor kot stikalo



$$i_C(t) = I_{CBO}$$

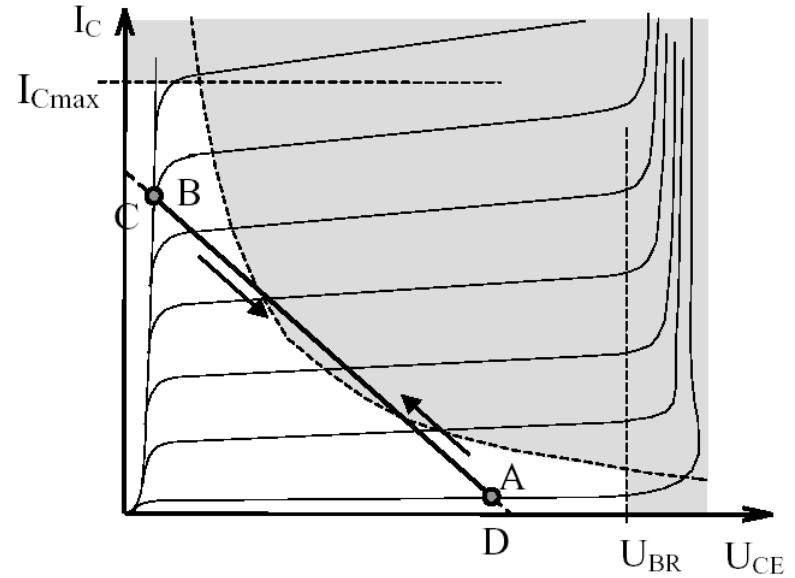
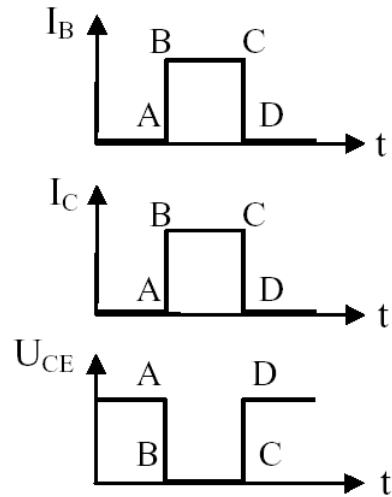
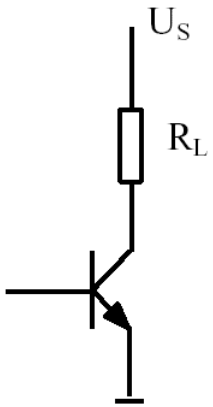
$$u_{CE}(t) = U_{CC}$$

$$p_O(t) = I_{CBO} \cdot U_{CC} = 0,75 \text{ W}$$

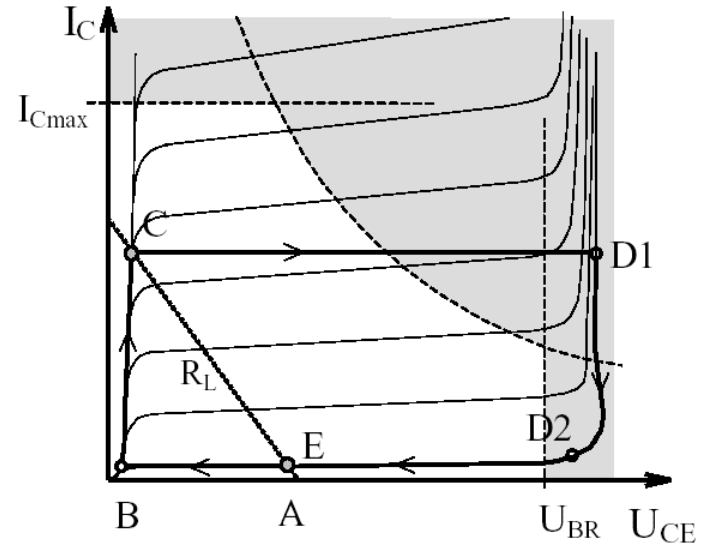
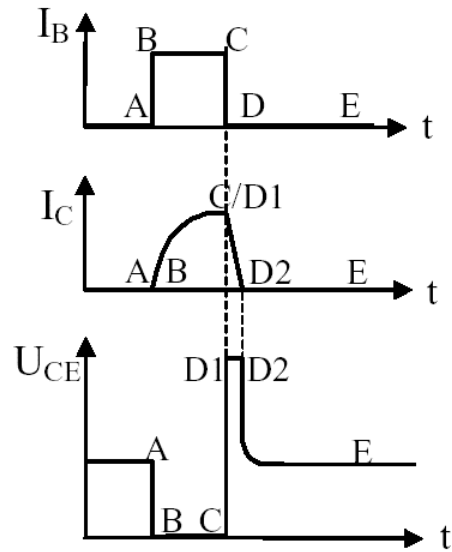
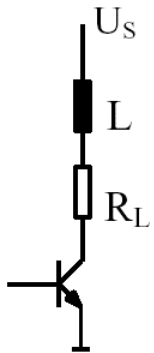
$$\underline{\underline{P_O}} = \frac{1}{T} \int_0^{t_o} p_O(t) dt = I_{CBO} \cdot U_{CC} \cdot t_o \cdot f_s = \underline{\underline{315 \text{ mW}}}$$

$$\underline{\underline{P_T = P_d + P_r + P_N + P_s + P_f + P_O = 274,65 \text{ W}}}$$

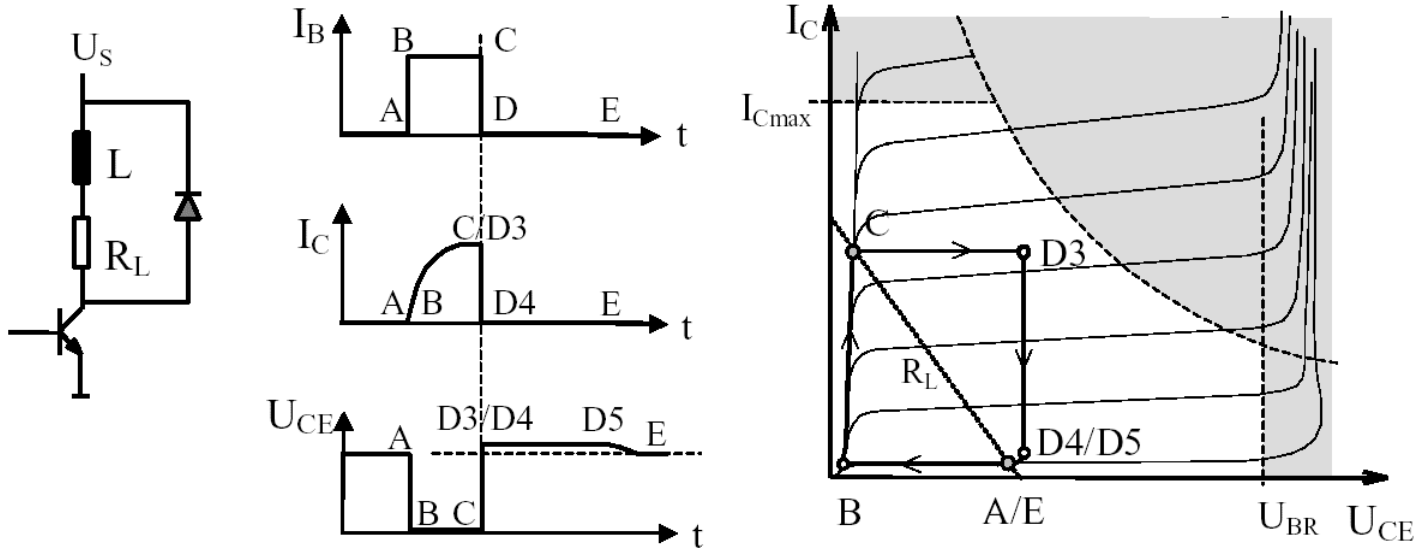
Tranzistor kot stikalo



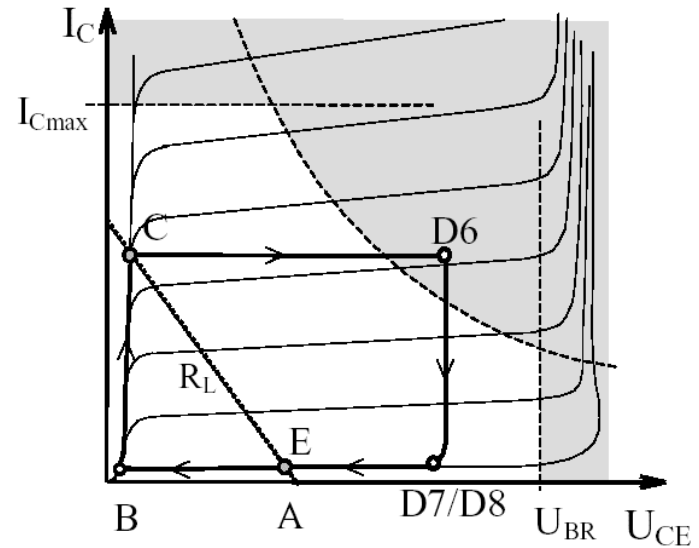
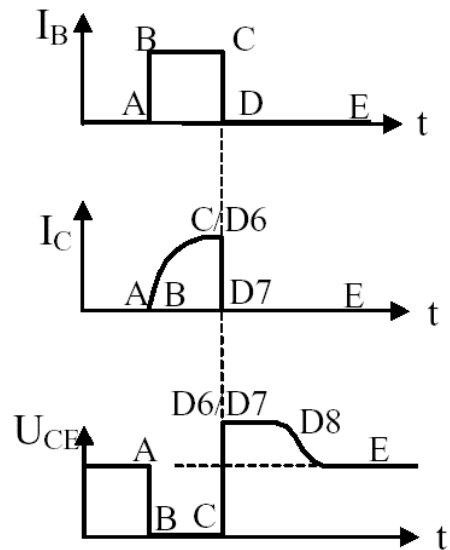
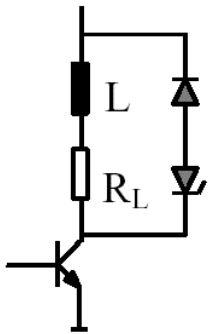
Tranzistor kot stikalo



Tranzistor kot stikalo



Tranzistor kot stikalo



Tranzistor kot stikalo

