ELEKTRONIKA 3

Zapiski avditornih vaj EL

Šolsko leto 2009 / 2010
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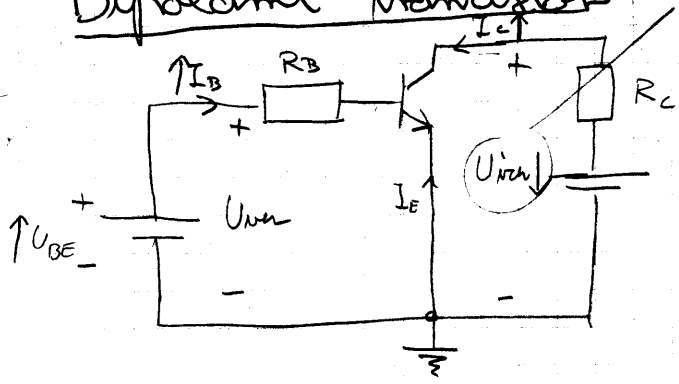
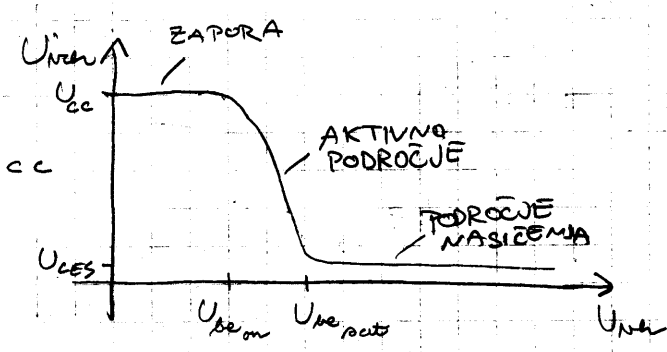
UREJANJE DOKUMENTA	
VERZIJA	01.01
DATUM	13.01.2010

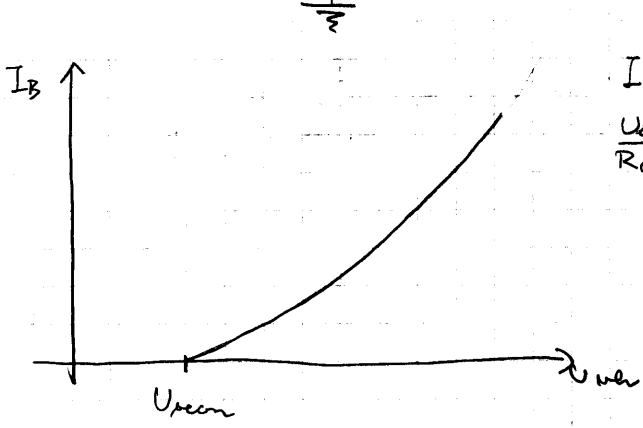
OPOMBE

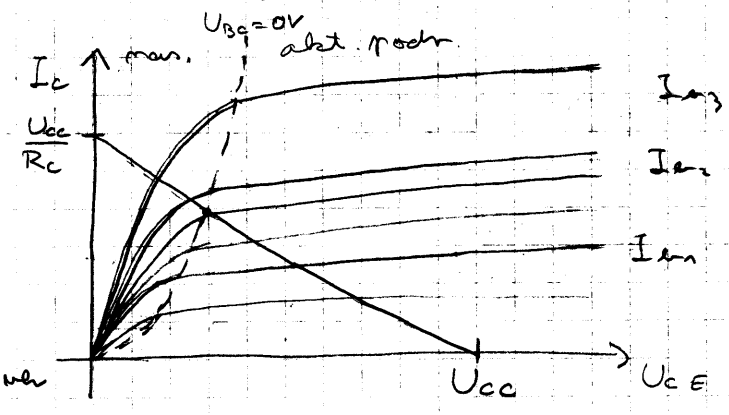
Bipolarni tranzistor



ker $U_{izh} = U_{CC} - I_C R_C$

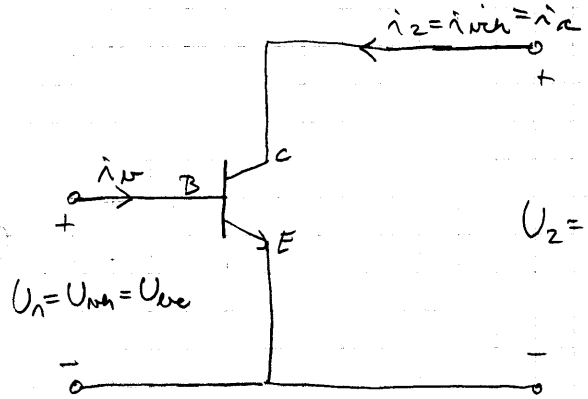


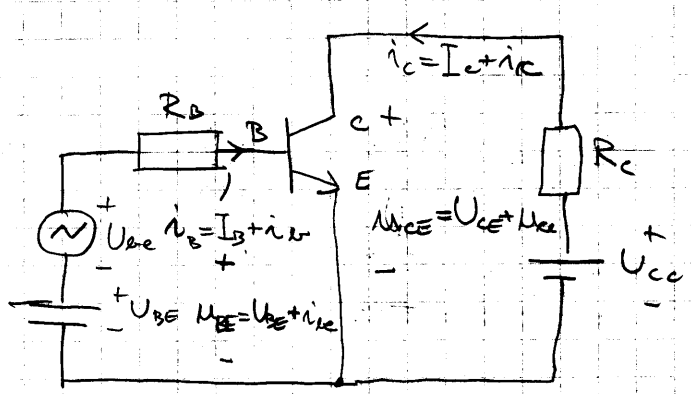


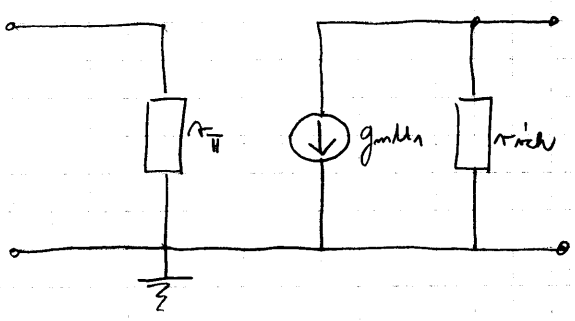


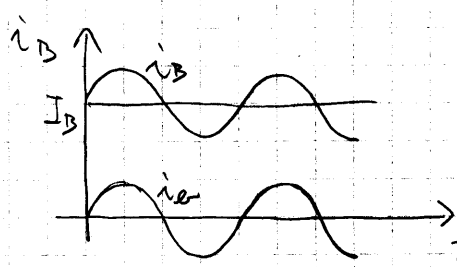
$$U_{CC} = U_{RC} + U_{CE} = I_C R_C + U_{CE}$$

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









Elementi modela:

$$g_m = \frac{di_c}{du_{be}} = \frac{I_S}{U_T} e^{\frac{u_{be}}{U_T}} \Big|_{u_{be}=U_{BE}} = \frac{I_C}{U_T} = g_m$$

$$i_c = I_S e^{\frac{u_{be}}{U_T}}$$

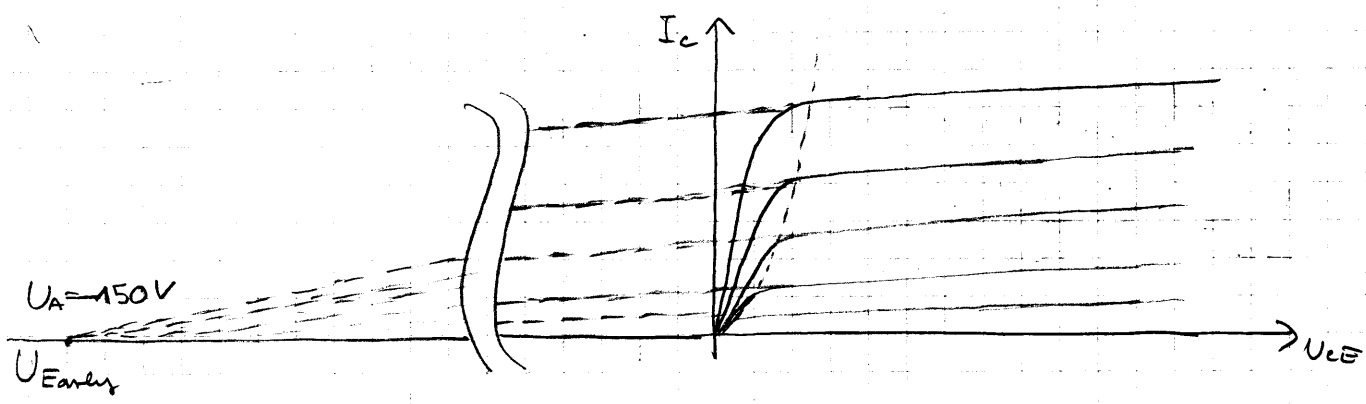
$(g_{21} = \frac{di_2}{du_1})$

$$r_\pi = \frac{du_{be}}{di_b} = \frac{du_{be}}{di_c} \cdot \beta = \frac{\beta}{g_m} = r_\pi$$

$(r_{11} = \frac{du_1}{di_1})$

$i_c = \beta i_b$

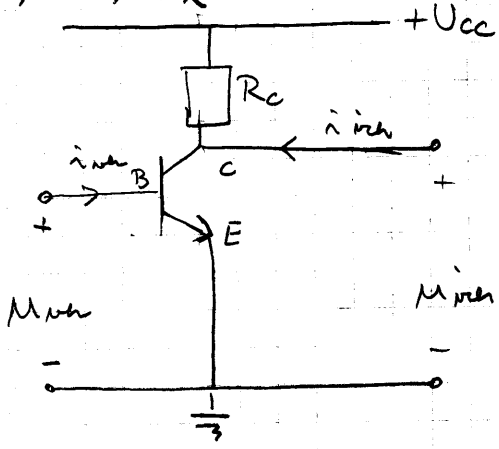
$i_b = \frac{i_c}{\beta}$



$$\frac{1}{r_{izh}} = \frac{di_2}{du_{ce}} = \frac{di_c}{du_{CE}} = \frac{I_C}{U_A}$$

$$r_{izh} = \frac{U_A}{I_C}$$

☒ Za podano vezje izračunajte r_{vh}, $r_{ izh}$, A_u in A_i

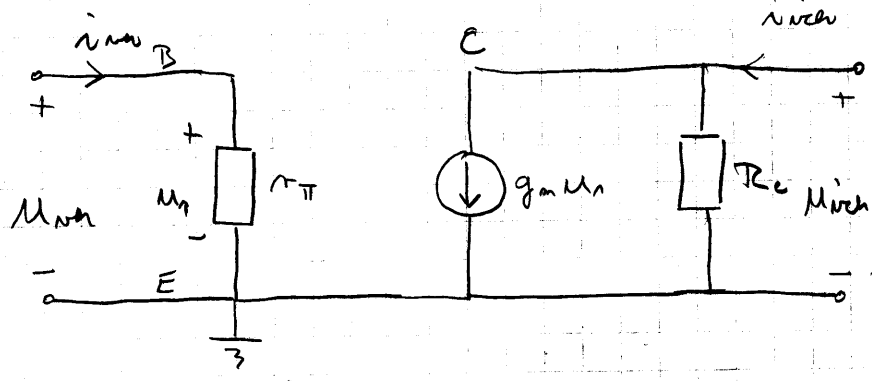


$I_c = 100\,\mu A$

$\beta = 100$

$r_{izh(T)} \to \infty \left(\frac{U_A}{I_c}\right)$

$R_c = 5\,k\Omega$



Rc priključ med C in maso, ker minamo izmenični nap,

$\frac{dU_{cc}}{dt} = 0$ - ni U_{cc}-ja

$$A_u = \frac{u_{izh}}{u_{vh}}$$

$$r_{vh} = \frac{u_{vh}}{i_{vh}} = r_\pi = \frac{\beta}{g_m} = \frac{\beta}{\frac{I_c}{U_T}} = 26\,k\Omega$$

$$r_{izh} = \frac{u_{izh}}{i_{izh}} = R_c = 5\,k\Omega$$

vhod kratko sklenemo, tok. vir odpade

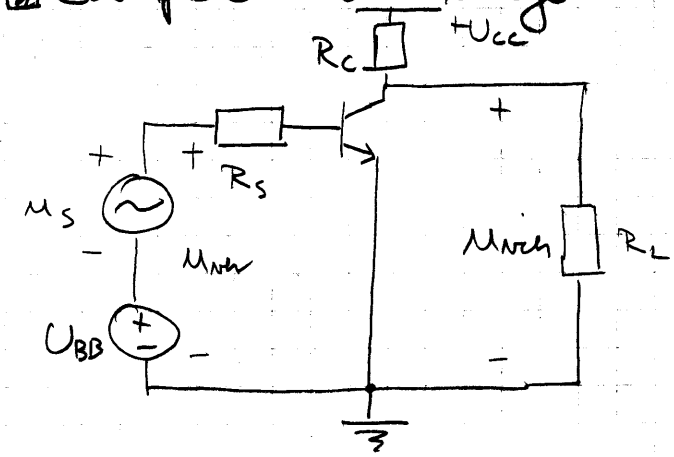
$$A_u = \frac{u_{izh}}{u_{vh}} = \frac{-g_m u_{vh} R_c}{u_{vh}} = -g_m R_c = -\frac{I_c}{U_T} R_c = -19{,}2$$

$u_{izh} = u_{Rc} = -g_m u_1 R_c$

$$A_i = \frac{i_{izh}}{i_{vh}} = \frac{i_c}{i_v} = \frac{\beta i_v}{i_v} = \beta = 100$$

$i_{izh} = g_m u_1 = g_m I_{vh} r_\pi \Rightarrow A_i = g_m r_\pi = g_m \frac{\beta}{g_m} = \beta$

Za podano vezje izračunajte A_u



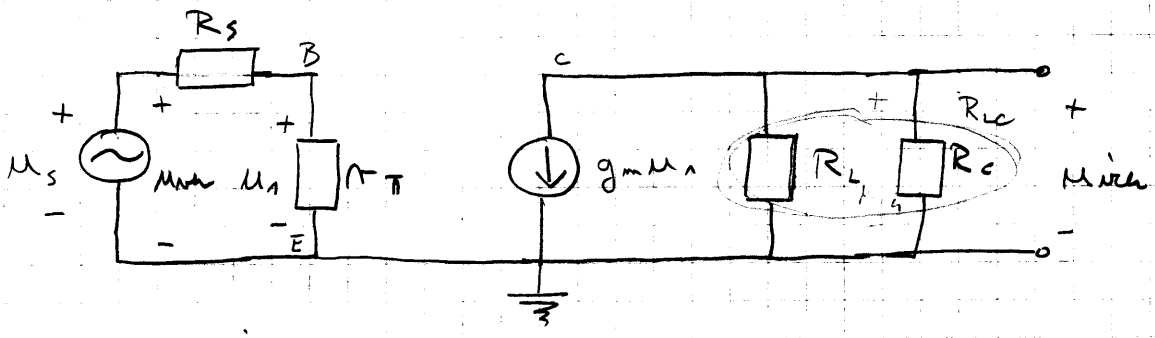
$\beta = 100$

$I_C = 100\mu A$

$R_C = 5k\Omega$

$R_S = 20k\Omega$

$R_L = 10k\Omega$



$$A_u = \frac{u_{izh}}{u_{vh}}$$

$$\frac{1}{R_{LC}} = \frac{1}{R_L} + \frac{1}{R_C} \Rightarrow R_{LC} = \frac{R_L R_C}{R_L + R_C}$$

$$u_{izh} = -g_m u_1 \frac{R_L R_C}{R_L + R_C} = -g_m \frac{r_\pi}{R_S + r_\pi} \frac{R_L R_C}{R_L + R_C} u_{vh}$$

~~$A_u = -g_m \frac{R_L R_C}{R_L + R_C}$~~

$$u_1 = \frac{r_\pi}{R_S + r_\pi} u_{vh}$$

$$A_u = \frac{u_{izh}}{u_{vh}} = -g_m \frac{r_\pi}{R_S + r_\pi} \frac{R_L R_C}{R_L + R_C} = -7{,}25$$

Izračunajte delovno točko in porabo moči na tranzistorju

Del. točka: I_C, U_{CE}

$U_{CC} = 10V$

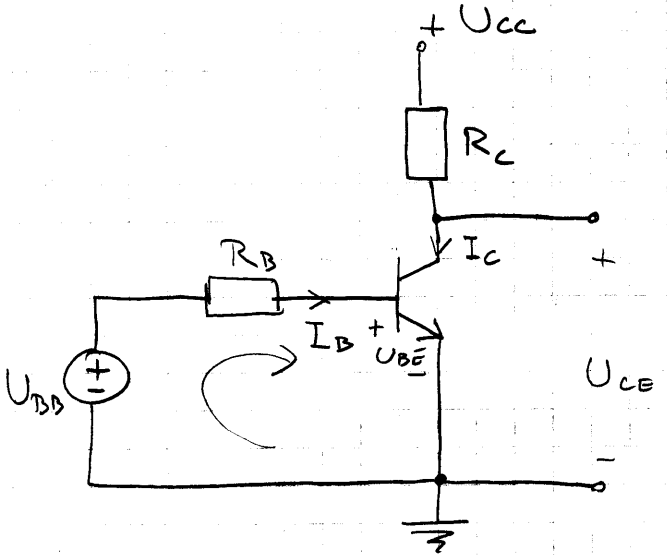
$U_{BB} = 4V$

$R_C = 2k\Omega$

$R_B = 220k\Omega$

$U_{BE} = 0{,}7V$

$\beta = 200$



$I_C = \beta I_B$

$-U_{BB} + R_B I_B + U_{BE} = 0$

$I_B = \frac{U_{BB} - U_{BE}}{R_B} = 15\mu A$

$I_C = \beta I_B = 3mA$

$U_{CE} = U_{CC} - I_C R_C = 4V$

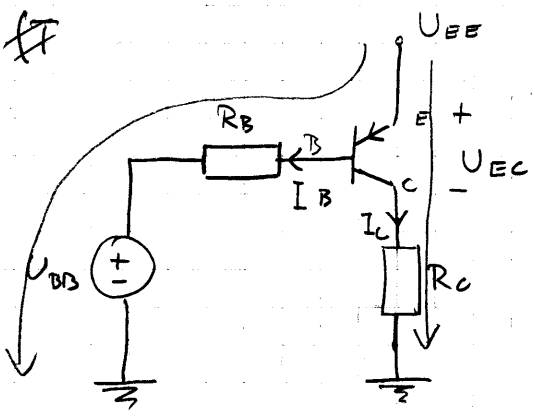
Akt. področje: $I_C = \beta I_B$

$U_{CE} \gg U_{CES}$

$P_T = I_B U_{BE} + I_C U_{CE} = 15\mu A \cdot 0{,}7V + 3mA \cdot 4V =$

$= 0{,}0105mW + 12mW = 12{,}0105mW \doteq 12mW$ $(I_C U_{CE})$

Izračunajte I_B, I_C, I_E in R_C tako, da bo $U_{EC} = \frac{1}{2} U_{EE}$



$U_{EE} = 5V$

$U_{BB} = 1,5V$

$R_B = 580k\Omega$

$U_{EB} = 0,6V$

$\beta = 100$

$U_{EC} = 2,5V \Rightarrow U_{RC} = 2,5V \; (= U_{EE} - U_{EC})$

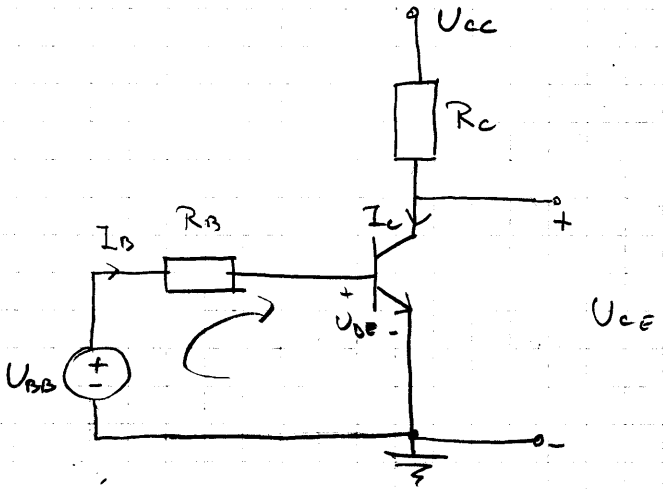
$U_{EE} = U_{BB} + R_B I_B + U_{EB} \Rightarrow I_B = \frac{U_{EE} - U_{BB} - U_{EB}}{R_B} = 5\mu A$

$I_C = \beta \cdot I_B = 0,5mA$

$I_E = I_B + I_C = 0,505\,mA$

$R_C = \frac{U_{RC}}{I_C} = 5k\Omega$

Izračunajte del. točko in moč na tranzistorju



$U_{CC} = 10V$

$U_{BB} = 8V$

$R_C = 4k\Omega$

$R_B = 220k\Omega$

$\beta = 100$

$U_{BE} = 0,7$

$U_{CES} = 0,2V$

$$-U_{BB} + R_B I_B + U_{BE} = 0$$

$$I_B = \frac{U_{BB} - U_{BE}}{R_B} = 33{,}2\,\mu A$$

Akt. podr.: $I_c = \beta I_B = 3{,}32\,mA$

$U_{CE} = U_{cc} - R_c I_c = -3{,}28\,V$ // tranzistor ni v akt. podr.

Področje nasičenja

$I_c = \beta \cdot I_B$ //

$U_{CE} = U_{CES}$

$$I_c = -\frac{U_{CES} - U_{cc}}{R_c} = \frac{U_{cc} - U_{CES}}{R_c} = 2{,}45\,mA$$

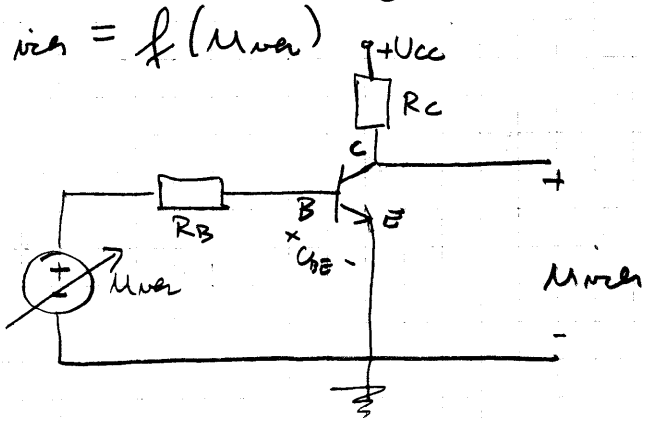
$\frac{I_c}{I_B} \doteq 74 < \beta$

nasičenje	akt. področje
$I_c < \beta I_B$	$I_c = \beta I_B$
$U_{CE} = U_{CES}$	$U_{CE} > U_{CES}$
$U_{BC} > 0$	$U_{BC} < 0$

$$P = I_B U_{BE} + I_c U_{CES} = 0{,}0332\,mA \cdot 0{,}7\,V + 2{,}45\,mA \cdot 0{,}2\,V$$
$$= 0{,}023\,mW + 0{,}49\,mW$$
$$= 0{,}513\,mW$$

4. Za podano vezje določite prenosno karakt

$U_{izh} = f(U_{vh})$



$U_{cc} = 5V$

$R_c = 5k\Omega$

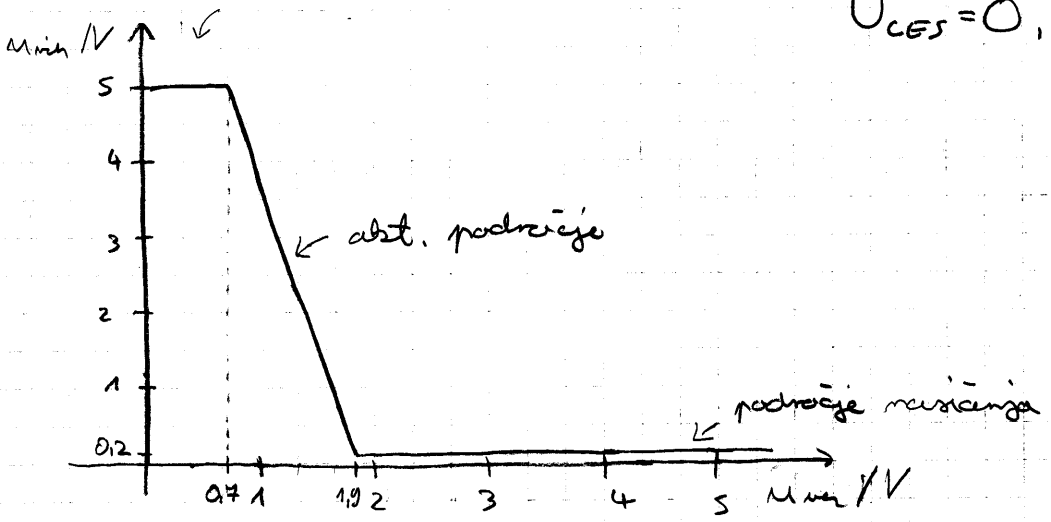
$R_B = 150k\Omega$

$U_{BE} = 0,7V$

$\beta = 120$

$U_{CES} = 0,2V$

Tranzistor zaprt, $U_{vh} < U_{BE}$



$$U_{izh} = U_{cc} - U_{Rc} = U_{cc} - I_c R_c = U_{cc} - \beta I_B R_c$$

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

$$U_{izh} = U_{cc} - \beta R_c \frac{U_{vh} - U_{BE}}{R_B}$$

$U_{vh} = 0,7 \Rightarrow \quad U_{izh} = U_{cc}$

$U_{izh} = 0,2V \Rightarrow \quad R_B U_{izh} = R_B U_{cc} - \beta R_c U_{vh} + \beta R_c U_{BE}$

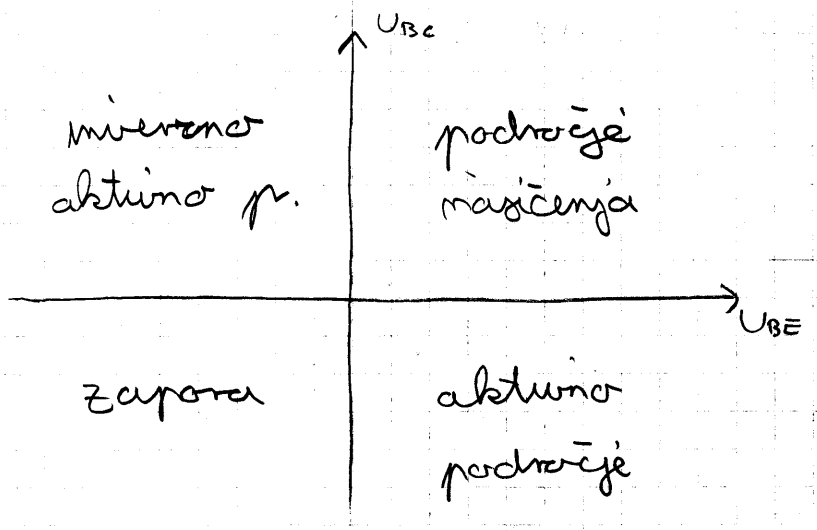
$$U_{vh} = \frac{R_B U_{izh} - R_B U_{cc} - \beta R_c U_{BE}}{-\beta R_c}$$

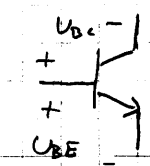
$$U_{vh} = \frac{R_B (U_{cc} - U_{izh}) + \beta R_c U_{BE}}{\beta R_c}$$

$$= \frac{R_B (U_{cc} - U_{izh})}{\beta R_c} + U_{BE}$$

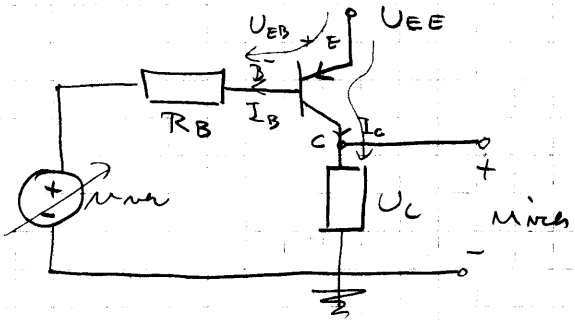
$$= \frac{150 (5 - 0,2)}{120 \cdot 5} + 0,7 = 1,9V$$

$$A_u = \frac{\text{izhod}}{\text{vhod}} = \frac{5V - 0{,}2V}{0{,}7V - 1{,}9V} = -4$$





Prenosna karakt. ras pnp



$U_{EB} = 0{,}7V$

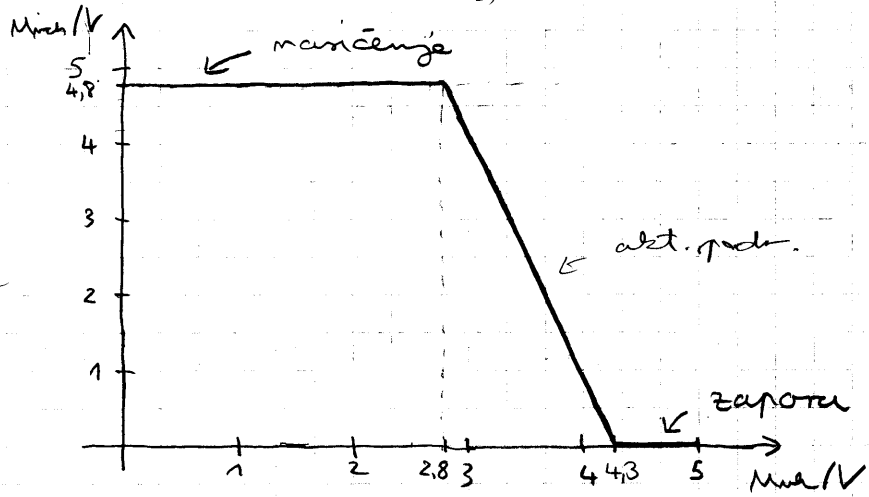
$U_{EE} = 5V$

$\beta = 80$

$U_{ECS} = 0{,}2V$

$R_C = 8k\Omega$

$R_B = 200k\Omega$



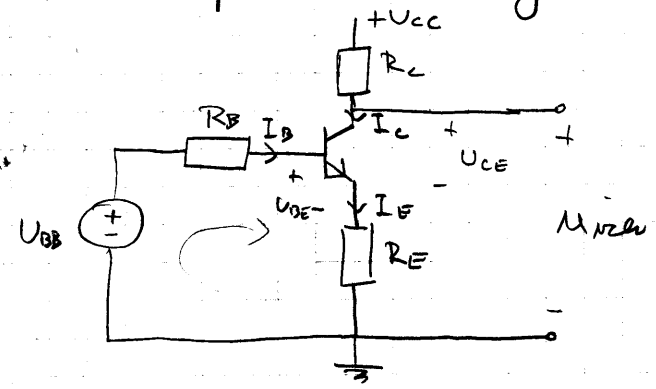
$$U_{izh} = U_{EE} - I_C R_C$$
$$= \beta I_B R_C$$
$$= \frac{R_C}{R_B}\beta(U_{EE} - U_{EB} - U_{vh})$$

$$U_{EE} = U_{EB} + U_{vh} + R_B I_B$$
$$I_B = \frac{U_{EE} - U_{EB} - U_{vh}}{R_B}$$

$$U_{vh} = -\frac{1}{\beta}\frac{R_B}{R_C}U_{izh} + U_{EE} - U_{EB} = U_{EE} - U_{EB} - \frac{1}{\beta}\frac{R_B}{R_C}U_{izh}$$

$U_{izh} = 4{,}8V \rightarrow U_{vh} = 2{,}8V$

Za podano vezje izračunajte D.T.



$U_{cc} = 12V$

$U_{BB} = 6V$

$R_c = 0{,}4k\Omega$

$R_B = 25k\Omega$

$R_E = 0{,}6k\Omega$

$U_{BE} = 0{,}7V$

$\beta = 75$

$$-U_{BB} + R_B I_B + U_{BE} + R_E I_E = 0$$

$$-U_{cc} + R_c I_c + U_{CE} + R_E I_E = 0$$

$$I_c = \beta I_B$$

$$I_E \doteq +I_c + I_B$$

$$-U_{BB} + R_B I_B + U_{BE} + R_E \beta I_B + R_E I_B = 0$$

$$-U_{cc} + R_c \beta I_B + U_{CE} + R_E \beta I_B + R_E I_B = 0$$

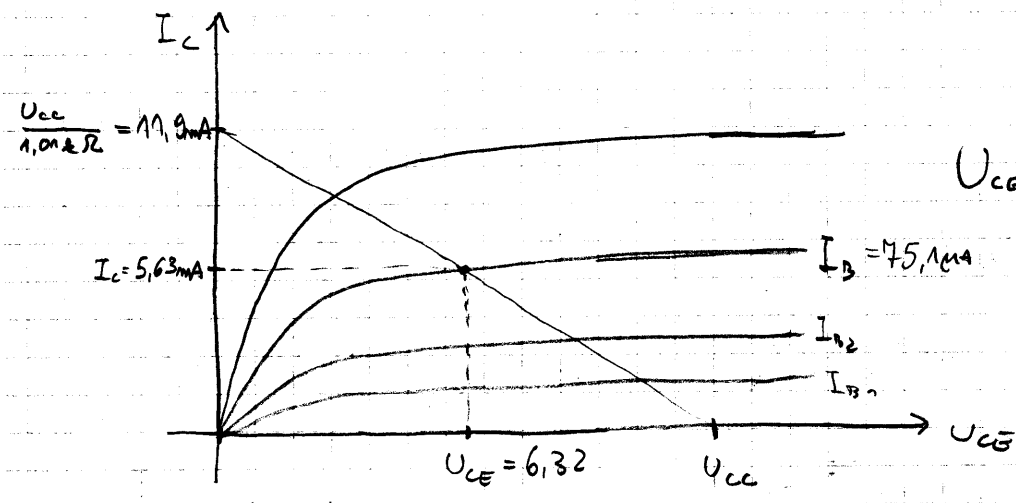
$$R_B I_B + R_E (1+\beta) I_B = U_{BB} - U_{BE}$$

$$I_B = \frac{U_{BB} - U_{BE}}{R_B + R_E(1+\beta)} = 75{,}1\mu A$$

$$I_c = \beta I_B = 5{,}63mA$$

$$U_{CE} = U_{cc} - I_B (R_c \beta + R_E(\beta + 1))$$

$$= 6{,}32V$$

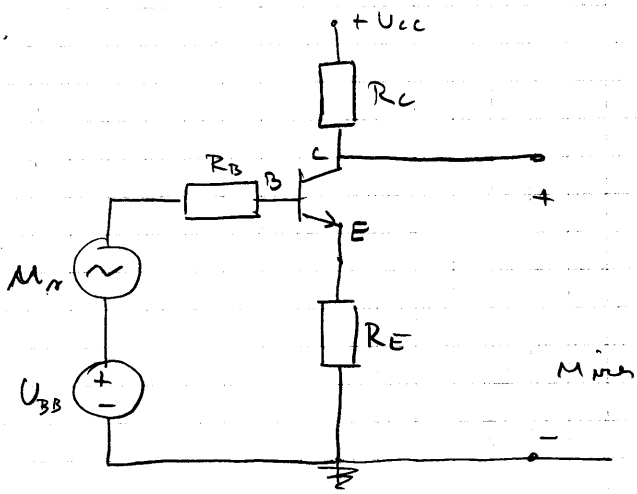


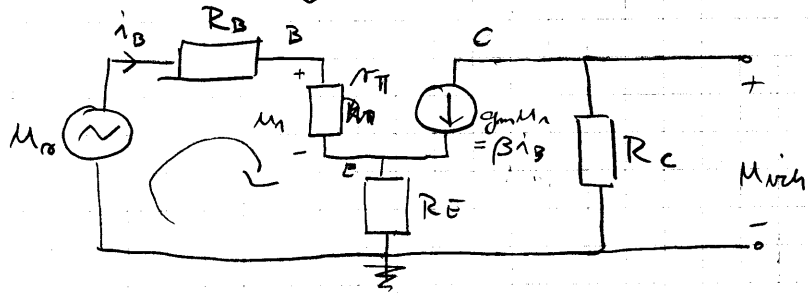
$$I_E = \frac{\beta + 1}{\beta} I_c$$

$$U_{CE} = U_{cc} - I_c R_c - \frac{\beta+1}{\beta} I_c R_E$$

$$= U_{cc} - I_c \left[R_c + \frac{\beta+1}{\beta} R_E \right]$$

$$= U_{cc} - I_c \cdot 1{,}01k\Omega$$





$$A_u = \frac{u_{izh}}{u_{vh}}$$

$$u_{izh} = U_{Rc} = -g_m u_1 R_c = -\beta i_B R_c$$

$$u_v = R_B i_B + r_\pi i_B + R_E(i_B + \beta i_B)$$
$$= i_B(R_B + r_\pi + R_E(1+\beta))$$

$$i_B = \frac{u_v}{(R_B + r_\pi + R_E(1+\beta))}$$

$$u_{izh} = -\frac{\beta R_c}{R_B + r_\pi + R_E(1+\beta)} \cdot u_v$$

$$A_u = -\frac{\beta R_c}{R_B + r_\pi + R_E(1+\beta)} = -\frac{R_c}{\frac{R_B}{\beta} + \frac{1}{g_m} + \frac{1+\beta}{\beta} R_E}$$

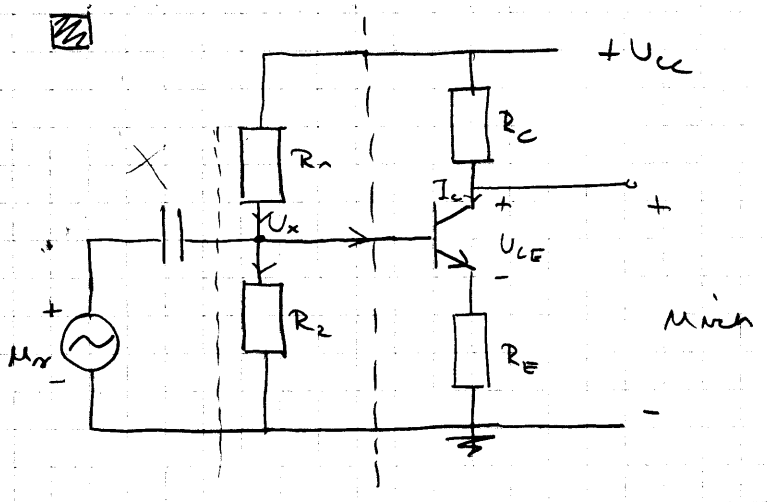
$$r_\pi = \frac{\beta}{g_m} = \frac{\beta \cdot U_T}{I_C}$$

$$\frac{r_\pi}{\beta} = \frac{1}{g_m}$$

$$g_m = \frac{I_C}{U_T} = \frac{5{,}63\,mA}{26\,mV}$$

$$\frac{1}{g_m} = \frac{26\,mV}{5{,}63\,mA}$$

$$A_u = -0{,}42$$



Izračunajte D.T.!

$R_1 = 56\,k\Omega$

$R_2 = 12{,}2\,k\Omega$

$R_C = 2\,k\Omega$

$R_E = 0{,}4\,k\Omega$

$U_{CC} = 10\,V$

$U_{BE} = 0{,}7\,V$

$\beta = 100$

$$I_{R1} = I_{R2} + I_B$$

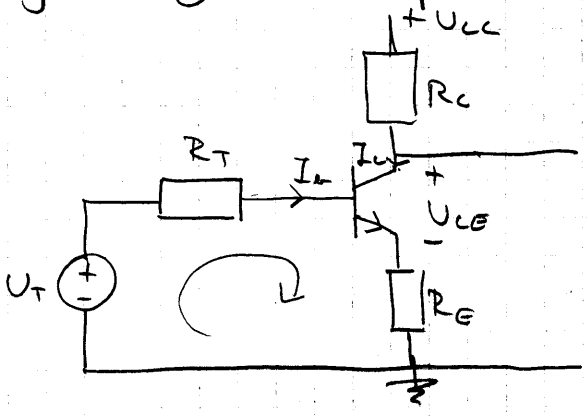
$$\frac{U_{CC} - U_x}{R_1} = \frac{U_x}{R_2} + I_B \qquad (1)$$

$$U_x = U_{RE} + U_{BE}$$

$$U_x = (1+\beta) I_B R_E + U_{BE} \qquad (2)$$

Iz (1) in (2) bi izračunali U_x in I_B.

Bolj elegantna pot: Theveninova transf.



$$U_T = \frac{R_2}{R_1 + R_2} U_{CC} = 1{,}79\,V$$

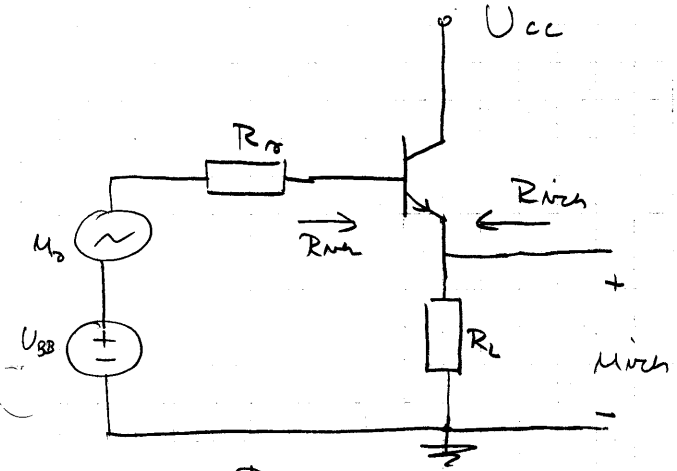
$$R_T = \frac{R_1 R_2}{R_1 + R_2} = 10\,k\Omega$$

$$U_T = R_T I_B + U_{BE} + (1+\beta) I_B R_E \Rightarrow I_B = \frac{U_T - U_{BE}}{R_T + (1+\beta) R_E} = 21{,}6\,\mu A$$

$$I_C = \beta I_B = 2{,}16\,mA$$

$$U_{CE} = U_{cc} - R_c I_c - R_E I_E =$$
$$= U_{cc} - R_c I_c - R_E (I_c + I_B) = 4{,}81\,V$$

Za podano verje izračunajte R_{vh}, R_{vis} in A_M

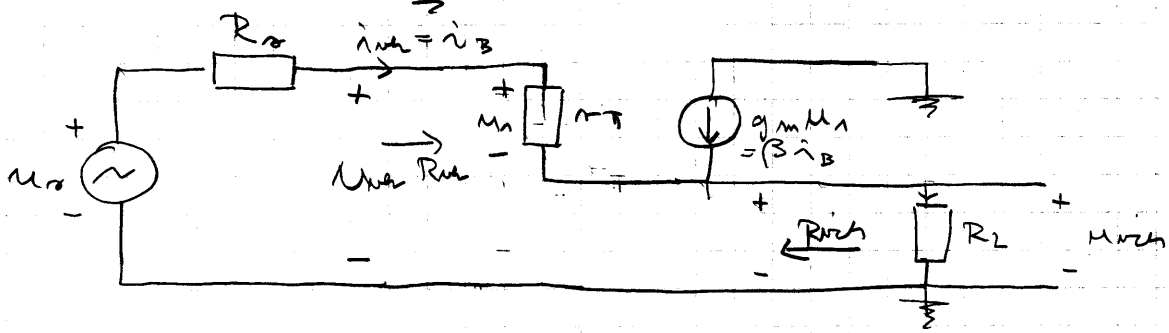


$\beta = 100$

$I_c = 100\,\mu A \Rightarrow r_\pi = 26\,k\Omega$

$R_s = 1\,k\Omega$

$R_L = 1\,k\Omega$



$$A_M = \frac{u_{vis}}{u_s}$$

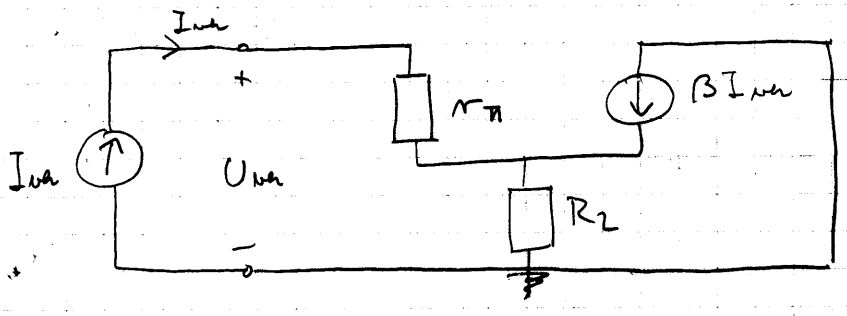
$$i_B + g_m u_1 = i_{R_L}$$

$$\frac{u_s - u_{vis}}{R_s + r_\pi} + \beta \frac{u_s - u_{vis}}{R_s + r_\pi} = \frac{u_{vis}}{R_L}$$

$$\frac{u_s (1+\beta)}{R_s + r_\pi} = \frac{u_{vis}(1+\beta)}{R_s + r_\pi} + \frac{u_{vis}}{R_L} = \frac{u_{vis}[(1+\beta)R_L + R_s + r_\pi]}{(R_s + r_\pi) R_L}$$

$$u_s = \underbrace{\frac{(1+\beta)R_L + R_s + r_\pi}{(1+\beta) R_L}}_{1/A_M} u_{vis}$$

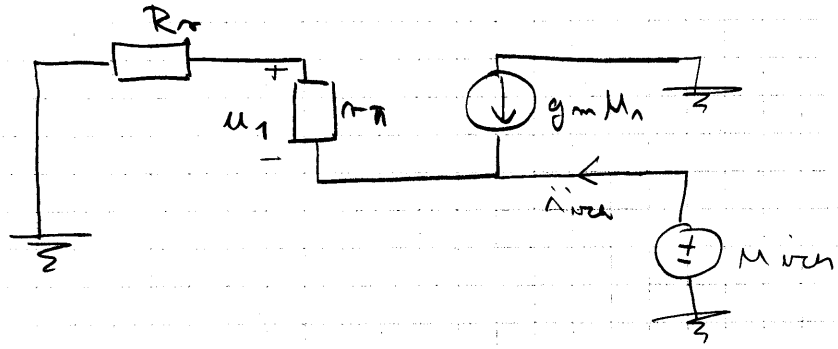
$$A_M = \frac{1}{1 + \frac{R_s + r_\pi}{(1+\beta) R_L}} = 0{,}79$$



$$R_{vh} = \frac{U_{vh}}{I_{vh}}$$

$$U_{vh} = U_{r_\pi} + U_{R_L} = r_\pi I_{vh} + R_L(I_{vh} + \beta I_{vh})$$

$$R_{vh} = r_\pi + R_L(1+\beta) = 127\,k\Omega$$ ~~izbola~~



R_{ivh} gledamo pri kratkostklenjenem izhodu vhodu

$$R_{ivh} = \frac{u_{ivh}}{i_{ivh}}$$

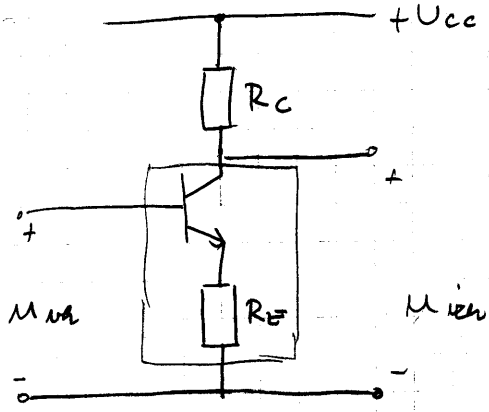
$$u_1 = -\frac{r_\pi}{r_\pi + R_s} u_{ivh}$$

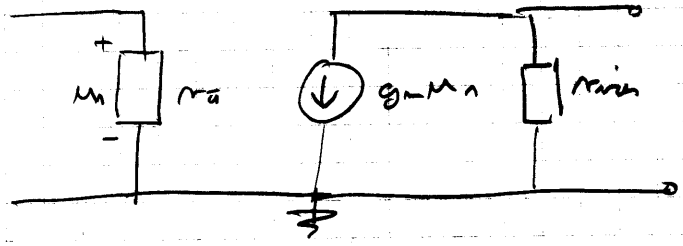
$$i_{ivh} = -g_m u_1 + \frac{u_{ivh}}{r_\pi + R_s} = \left(g_m \frac{r_\pi}{r_\pi + R_s} + \frac{1}{r_\pi + R_s}\right) u_{ivh} =$$

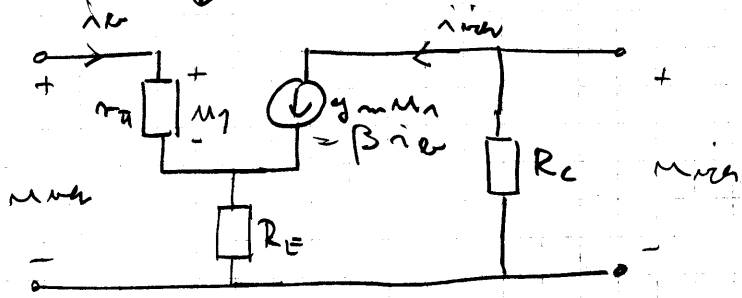
$$= \frac{g_m r_\pi + 1}{r_\pi + R_s} u_{ivh} = \frac{\beta + 1}{r_\pi + R_s} u_{ivh}$$

$$R_{ivh} = \frac{r_\pi + R_s}{\beta + 1}$$ - nizka izhodna upornost

$$= 270\,\Omega$$







$$u_{vh} = u_{rπ} + u_{RE}$$
$$= i_v r_π + (1+\beta) i_v R_E$$
$$= i_v (r_π + (1+\beta) R_E)$$

$$r_{vh} = \frac{u_{vh}}{i_{vh}} = r_π + (1+\beta) R_E = r_π \left(1 + \frac{\beta}{r_π} R_E\right) = r_π (1 + g_m R_E)$$

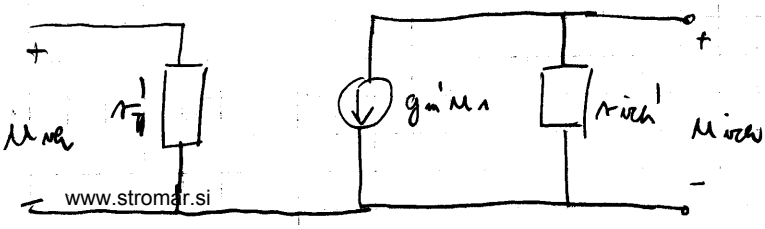
i_v

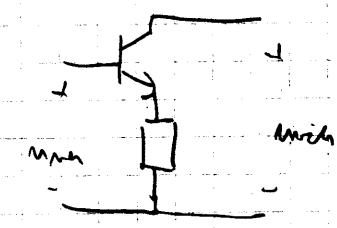
$$u_{vh} = u_{rπ} + u_{RE}$$
$$= i_v r_π + (i_v + i_c) R_E$$
$$= \frac{i_c}{\beta} r_π + \left(\frac{1}{\beta} + 1\right) i_c R_E$$
$$= i_c \left[\frac{1}{\beta} r_π + \left(\frac{1}{\beta} + 1\right) R_E\right]$$

$g_m \Rightarrow \quad \frac{r_π}{\beta} = \frac{1}{g_m}$

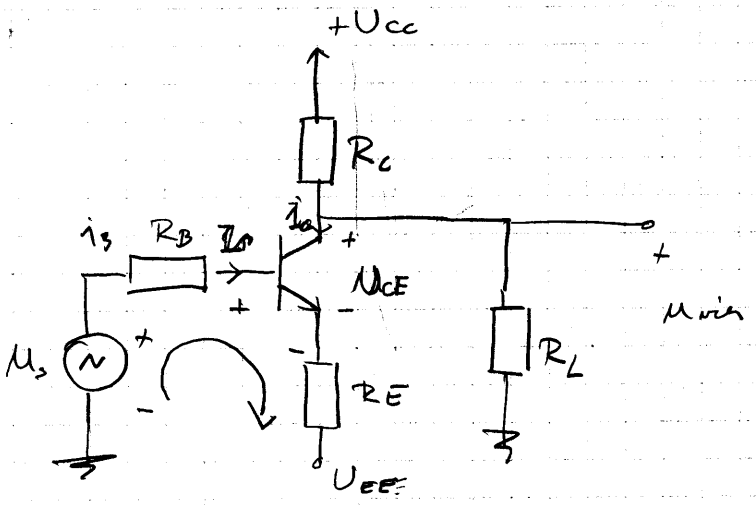
$$g_m' = \frac{i_c}{u_{vh}} = \frac{1}{\frac{1}{g_m} + R_E\left(1 + \frac{1}{\beta}\right)} = \frac{g_m}{1 + g_m R_E}$$

$$r_{izh}' = r_{izh} (1 + g_m R_E)$$





4. Izračunajte delovno točko in delovno premico za podano vezje



$U_{CC} = 12V$

$U_{EE} = -5V$

$R_C = R_L = R_E = 5k\Omega$

$R_B = 10k\Omega$

$U_{BE} = 0{,}7V$

$\beta = 100$

$$I_B R_B + U_{BE} + R_E I_E + U_{EE} = 0$$

$$I_B R_B + U_{BE} + R_E I_B(\beta+1) + U_{EE} = 0$$

$$I_B = \frac{-U_{BE} - U_{EE}}{R_B + R_E(\beta+1)} = 8{,}35\mu A$$

$$I_C = \beta I_B = \underline{0{,}835mA}$$

$$I_C = I_{RC} - I_{RL}$$

$$I_C = \frac{U_{RC}}{R_C} - \frac{U_{RL}}{R_L}$$

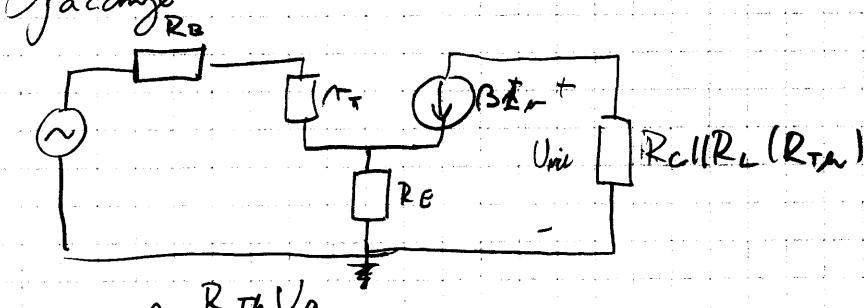
$$I_C = \frac{U_{CC} - U_{vis}}{R_C} - \frac{U_{vis}}{R_L}$$

$$U_{vis} = 3{,}91V$$

$$U_{CE} = U_{vis} - U_{RE} - U_{EE}$$

$$U_{CE} = U_{vis} - I_E R_E - U_{EE} = \underline{4{,}7V}$$ ✓ ust. obm.

Ojačanje



$$u_{vis} = -\beta \frac{R_{Th} u_n}{R_B + r_T + (1+\beta)R_E}$$

$$A_M = -\frac{\beta R_{Th}}{R_B + r_T + (1+\beta)R_E}$$

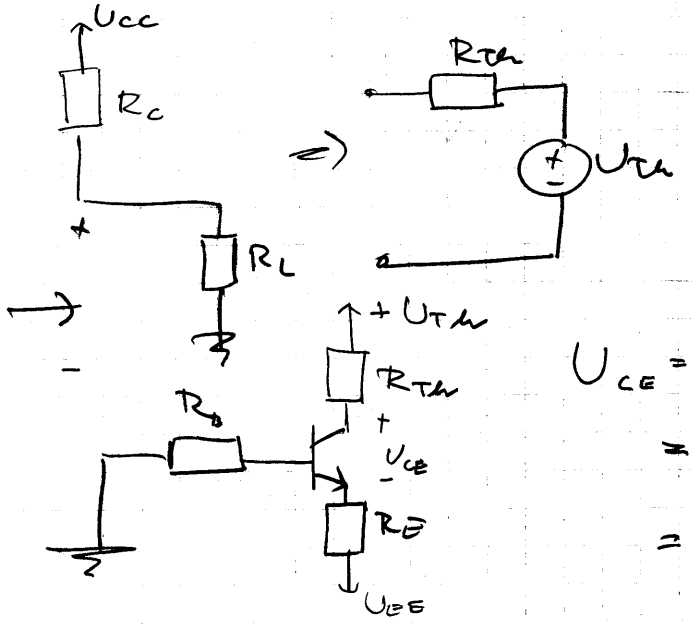
$$U_{vis} = -\beta I_b R_{Th}$$

$$U_n = U_{RB} + U_{rT} + U_{RE}$$

$$= I_B R_B + I_B r_T + (1+\beta) R_E I_B$$

$$I_B = \frac{U_n}{R_B + r_T + (1+\beta)R_E}$$

Delovna premica:



$R_{Th} = R_C \| R_L = 2{,}5\,k\Omega$

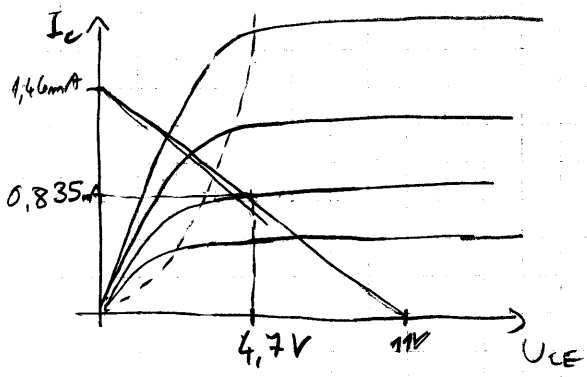
$U_{Th} = \frac{R_L}{R_C + R_L} \cdot U_{CC} = 6\,V$

$U_{CE} = U_{Th} - U_{EE} - U_{R_{Th}} - R_E$

$= U_{Th} - U_{EE} - I_C R_{Th} - I_E R_E$

$= 6V - (5V) - I_c \cdot 2{,}5\,k\Omega - \frac{101}{100} I_c 5\,k\Omega$

$U_{CE} = 11V - I_c \cdot 7{,}5\,k\Omega$



☑ Izračunajte R_B in R_C za dane zahteve!

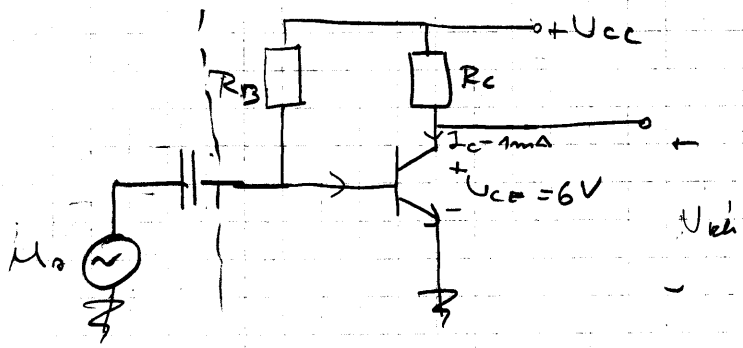
$I_c = 1\,mA$

$U_{CE} = 6V$

$U_{BE} = 0{,}7V$

$U_{CC} = 12V$

$\beta = 100$



$U_{CC} = R_C I_C + U_{CE} \Rightarrow R_C = \frac{U_{CC} - U_{CE}}{I_C} = 6\,k\Omega$

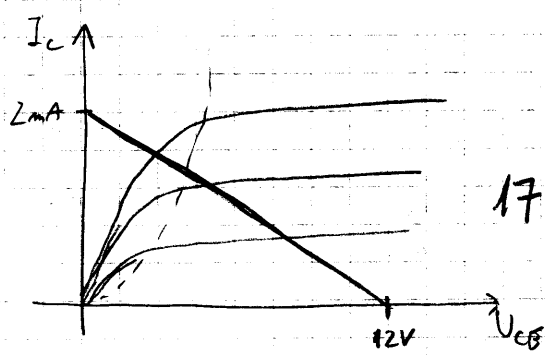
$I_B = \frac{I_C}{\beta} = \frac{1mA}{100} = 10\,\mu A$

$R_B = \frac{U_{CC} - U_{BE}}{I_B} = 1{,}13\,M\Omega$

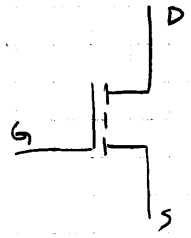
$\beta = 50 \Rightarrow I_c = 1mA, U_{CE} = 6V$

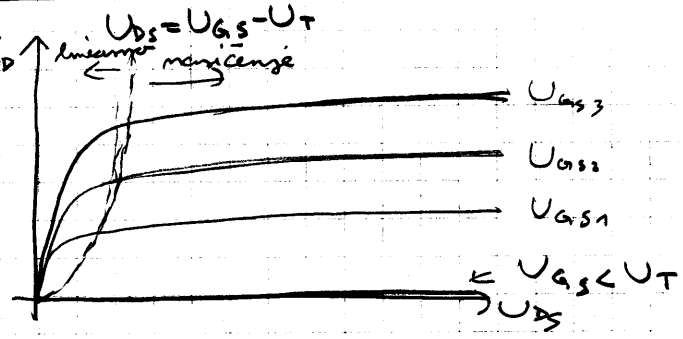
$\beta = 100 \Rightarrow I_c = 0{,}5mA, U_{CE} = 9V$

$\beta = 150 \Rightarrow I_c = 1{,}5mA, U_{CE} = 3V$



Unipolarni tranzistor





$U_T > 0$

ind. kanal

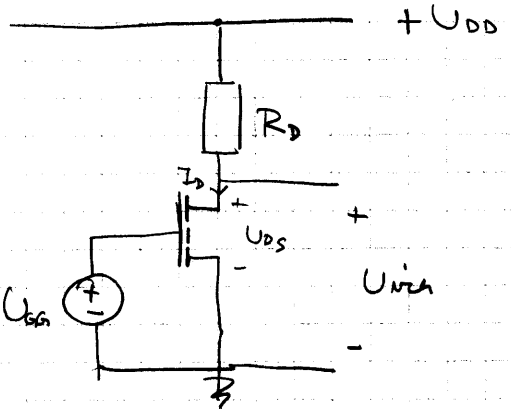
$$I_{Dn} = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (U_{GS} - U_T)^2 (1 + \lambda U_{DS}) \quad \ldots \text{nasičenje}$$

Ker kanalt ... nasičenja nima ravne

$$= \frac{k_n}{2} (U_{GS} - U_T)^2 (1 + \lambda U_{DS}) \quad \ldots \quad k_n = \mu_n C_{ox} \frac{W}{L}$$

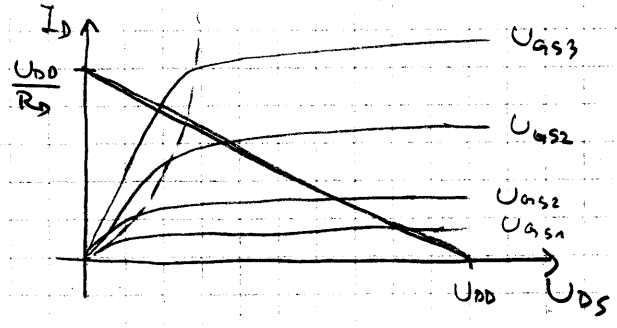
$$k_n (U_{GS} - U_T)^2 (1 + \lambda U_{DS}) \quad \ldots \quad k_n = \frac{\mu_n C_{ox}}{2} \frac{W}{L}$$

$$I_{Dn} = \frac{\mu_n C_{ox}}{2} \frac{W}{L} \left[2 \cdot (U_{GS} - U_T) U_{DS} - U_{DS}^2 \right] \quad \ldots \text{lin. področje}$$



$$U_{DS} = U_{DD} - I_D R_D$$

$$I_D = \frac{U_{DD} - U_{DS}}{R_D}$$



Zapora $U_{GS} < U_T$, $I_D = 0$

Področje nasičenja $U_{GS} > U_T$

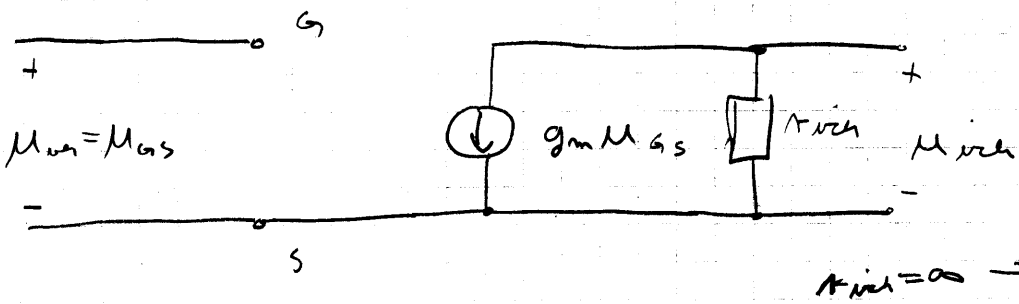
$U_{DS} > U_{GS} - U_T$

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (U_{GS} - U_T)^2 (1 + \lambda U_{DS})$$

Lin. podr. $U_{GS} > U_T$

$U_{DS} < U_{GS} - U_T$

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} \left[2 (U_{GS} - U_T) U_{DS} - U_{DS}^2 \right]$$



$r_{vih} = \infty$ → karakt. nedotrvne ($\lambda = 0$)

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (U_{GS} - U_T)^2 (1 + \lambda U_{DS})$$

$$g_m = \frac{\partial I_D}{\partial U_{GS}} = 2 \frac{\mu_n C_{ox}}{2} \frac{W}{L} (U_{GS} - U_T) \Big|_{u_{GS} = U_{GS}}$$

$$\boxed{g_m = \mu_n C_{ox} \frac{W}{L} (U_{GS} - U_T)}$$

$$r_{vih} = \frac{\partial U_{DS}}{\partial I_D}$$

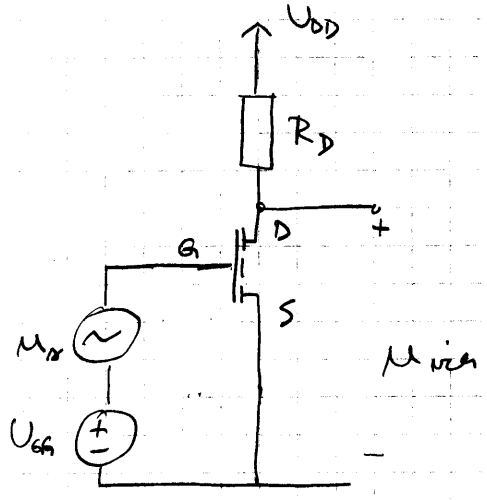
$$\frac{1}{r_{vih}} = \frac{\partial I_D}{\partial U_{DS}} = \lambda \cdot \underbrace{\frac{\mu_n C_{ox}}{2} \frac{W}{L} (U_{GS} - U_T)^2}_{\approx I_D}$$

$$\boxed{r_{vih} = \frac{1}{\lambda I_D}}$$

Izračunajte DT in A_u za podano vezje

D.T. (I_D, U_{DS})

$A_u = \frac{u_{vih}}{u_g}$



$U_{DD} = 5V$

$R_D = 5k\Omega$

$\frac{\mu_n C_{ox}}{2} = 20 \frac{\mu A}{V^2}$

$W = 10\mu m$

$L = 1\mu m$

$U_{GG} = 2V$

$U_T = 0,8V$

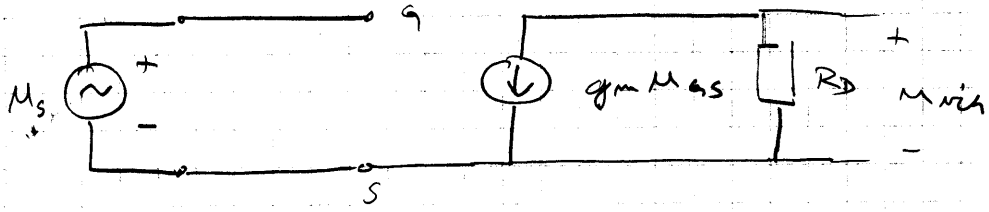
$\lambda = 0$

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (U_{GS} - U_T)^2 = 20 \frac{\mu A}{V^2} \cdot \frac{10}{1} (2V - 0,8V)^2 = 0,288 mA$$

$$U_{DS} = U_{DD} - I_D R_D = 5V - 0,288 mA \cdot 5k\Omega = 3,56V > \underbrace{2 - 0,8V}_{U_{GS} - U_T} \checkmark$$

– nasičenje

$$g_m = \mu_n C_{ox} \frac{W}{L}(U_{GS} - U_T) = 40 \frac{\mu A}{V^2} \cdot \frac{10}{1}(2V - 0{,}8V) = 480 \mu S$$



$$u_{izh} = -g_m u_{GS} R_D$$

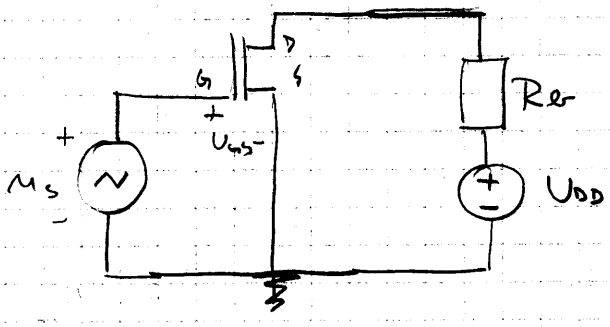
$$A_u = -g_m R_D = -480 \frac{mA}{V} \cdot 5 k\Omega = -2{,}4$$

$U_{GG} = 2V \rightarrow 2{,}5V$:

	$U_{GG} = 2V$	$U_{GG} = 2{,}5V$
I_D	0,288 mA	0,578 mA
U_{DS}	3,65 V	2,11 V
g_m	480 μA/V	680 μA/V
A_u	−2,4	−3,4

☒ Za podano vezje izračunajte DT, A_u in porabo moči

D.T. (I_D, U_{DS}), $A_u = \frac{u_{izh}}{u_s}$, ~~poba~~ poraba moči (tranzistor, breme, baterija)



$\frac{\mu_n C_{ox}}{2} \frac{W}{L} = 0{,}2 \frac{mA}{V^2} = k$

$U_T = -2V$ (vgrajeni kanal)

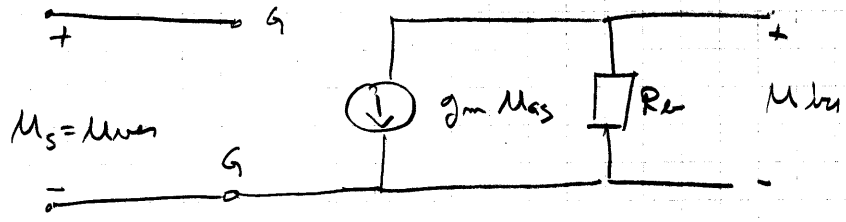
$R_B = 20 k\Omega$

$u_s = U_{GS} \cos \omega t = 1V \cos \omega t$

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L}(U_{GS} - U_T)^2$$

$$= 0{,}2 \frac{mA}{V^2} \cdot (0V - (-2V))^2 = 0{,}8 mA$$

$U_{DS} = U_{DD} - I_D R_D = 40V - 0{,}8\,mA \cdot 20k\Omega = 24V > U_{GS} - U_T$



$$u_{iz} = -g_m u_{gs} R_D$$

$$A_u = -g_m R_D$$

$$g_m = \mu_n C_{ox} \frac{W}{L}(U_{GS} - U_T) = 0{,}4 \frac{mA}{V^2}(0V - (-2V)) = 0{,}8 \frac{mA}{V}$$

$$A_u = -0{,}8 \frac{mA}{V} \cdot 20k\Omega = -16$$

Brez nadomestne vezave za majhne signale:

$$u_s = 1V \cdot \cos\omega t$$

$$i_D = k(U_{GS} + u_{gs} - U_T)^2$$

$$= k(\underbrace{U_{GS}}_{0V} + 1V\cos\omega t - U_T)^2$$

$$= k \cdot (U_{GS} - U_T + 1V\cos\omega t)^2$$

$$= k(U_{GS} - U_T)^2 + 2k(U_{GS} - U_T) \cdot 1V\cos\omega t + k \cdot 1V^2 \cos^2\omega t$$

$$\cos^2\omega t = \frac{1 + \cos 2\omega t}{2}$$

$$i_D = k(U_{GS} - U_T)^2 + 2k(U_{GS} - U_T)1V\cos\omega t + k \cdot 1V^2 \frac{1 + \cos 2\omega t}{2}$$

$$= 0{,}2 \frac{mA}{V^2} \cdot 4V^2 + 2 \cdot 0{,}2 \frac{mA}{V^2}(2V) \cdot 1V\cos\omega t + 0{,}2 \frac{mA}{V^2} \cdot \frac{1}{2} \cdot 1V^2 +$$

$$+ 0{,}2 \frac{mA}{V^2} \cdot \frac{1}{2} \cos 2\omega t \cdot 1V^2$$

$$= 0{,}9\,mA + 0{,}8\,mA \cdot \cos\omega t + 0{,}1\,mA \cos 2\omega t$$

$$u_{DS} = U_{DD} - R_L \cdot i_D$$
$$= 40V - 20k\Omega\,(0{,}9mA + 0{,}8mA\cos\omega t + 0{,}1mA\cos 2\omega t)$$
$$= 22V - 16V\cos\omega t - 2V\cos 2\omega t$$

$$A_u = \frac{u_{izh}}{u_{vh}} = \frac{-16V\cos\omega t}{1V\cos\omega t} = \underline{\underline{-16}}$$

~~Poglacer~~ Popačenje zaradi 2. harmonske:

$$D_{2,1} = \frac{U_2}{U_1} = \frac{2}{16} = \frac{1}{8} = 12{,}5\%$$

EL v, 16.10.

$$p_T(t) = i_D(t)\,u_{DS}(t) = k\cdot(U_{GS} - U_T + u_{gs})^2 \cdot$$
$$\cdot \underbrace{(U_{DD} - R_L k (U_{GS} - U_T + u_{gs})^2)}_{u_{DS} = U_{DD} - R_L i_D}$$

$$p_T(t) = k U_{DD}(U_{GS} - U_T + u_{gs})^2 - k^2 R_L (U_{GS} - U_T + u_{gs})^4$$
$$= 0{,}2\cdot 40\cdot(2+\cos\omega t)^2 - 0{,}2^2\cdot 20(2+\cos\omega t)^4$$

1 2 1
1 3 3 1
1 4 6 4 1

$$= 8\cdot(4 + 4\cos\omega t + \cos^2\omega t) - 0{,}8(16 + 32\cos\omega t +$$
$$+ 24\cos^2\omega t + 8\cos^3\omega t + \cos^4\omega t)$$
$$= 19{,}2 + 6{,}4\cos\omega t - 11{,}2\cos^2\omega t - 6{,}4\cos^3\omega t - 0{,}8\cos^4\omega t$$

$$\overline{p_T} = \frac{1}{T}\int_0^T p_T(t)\,dt =$$
$$= \frac{1}{T}\left(19{,}2\int_0^T dt + 6{,}4\int_0^T \cos\omega t\,dt - 11{,}2\int_0^T \cos^2\omega t - 6{,}4\int_0^T \cos^3\omega t\,dt - 0{,}8\int_0^T \cos^4\omega t\,dt\right)$$

$$\int_0^T \cos\omega t\,dt = 0 \quad \int_0^T \cos^3\omega t\,dt = 0 \quad \int_0^T \cos^2\omega t\,dt = \frac{T}{2} \quad \int_0^T \cos^4\omega t\,dt = \frac{3T}{8}$$

$$\overline{p_T} = \frac{1}{T}\left(19{,}2T - 11{,}2\frac{T}{2} - 0{,}8\,\frac{3T}{8}\right) = 13{,}3\,mW$$

mirovna moč: $P_T = I_D \cdot U_{DS} = 0{,}8mA\cdot 24V = 19{,}2\,mW$

$$p_{DD}(t) = i_D U_{DD} = U_{DD} \cdot k (U_{GS} - U_T + u_{gs})^2$$
$$= 40 \cdot 0{,}2 (2 + \cos\omega t)^2$$
$$= 32 + 32\cos\omega t + 8\cos^2\omega t$$

$$\overline{p_{DD}} = \frac{1}{T}\int_0^T p_{DD}(t)\,dt = \frac{1}{T}\left(32T + 8\frac{T}{2}\right) = 36\ mW$$

$$P_{DD} = I_D U_{DD} = 0{,}8\ mA \cdot 40\ V = 32\ mW$$

$$p_{R_b}(t) = R_b \cdot i_D^2(t) = R_b k^2 (U_{GS} - U_T + u_{gs})^4$$
$$= 20 \cdot 0{,}2^2 (2 + \cos\omega t)^4 =$$

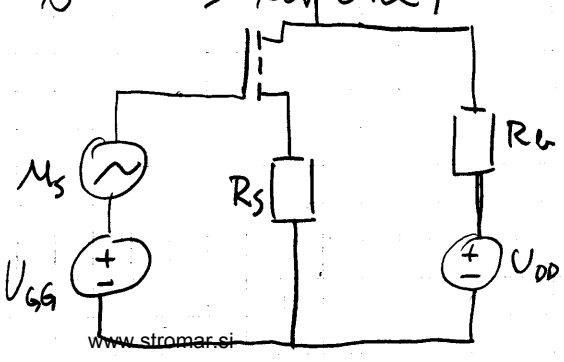
$$= 0{,}8(16 + 32\cos\omega t + 24\cos^2\omega t + 8\cos^3\omega t + \cos^4\omega t)$$
$$= 12{,}8 + 256\cos\omega t + 19{,}2\cos^2\omega t + 6{,}4\cos^3\omega t + 0{,}8\cos^4\omega t$$

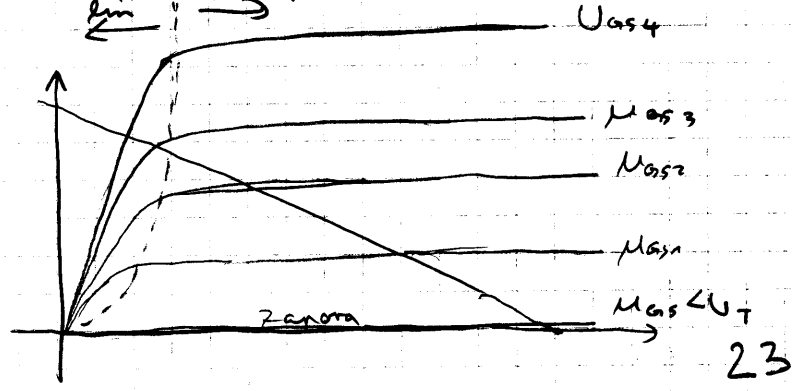
$$\overline{p_{R_b}} = \frac{1}{T}\int_0^T p_{R_b}(t)\,dt = 22{,}7\ mW$$

$$P_{R_b} = R_b \cdot I_D^2 = 20 \cdot 0{,}8^2 = 12{,}8\ mW$$

MOČ	MIROVNA		DELOVNA	
	mW	%	mW	%
TRANZISTOR	19,2	60	13,3	37
UPOR	12,8	40	22,7	63
BATERIJA	32	100	36	100

☒ Izračunajte D.T. (I_D, U_{DS}), $A_u = \frac{u_{izh}}{u_s}$ in maks. amplitudo $|U_s|_{max}$ (prevč $u_+ \rightarrow$ lin. področ., prevč $u_- \rightarrow$ zapora)





$U_T = 2V$

$U_{GG} = 5V$

$R_S = 1k\Omega$

$R_D = 15k\Omega$

$k = \frac{\mu_n C_{ox}}{2} \frac{W}{L} = 0{,}25 \frac{mA}{V^2}$

$U_{DD} = 30V$

D.T., A_M, $|U_S|_{max}$

$I_D = k(U_{GS} - U_T)^2$

$U_{GS} = U_{GG} - U_{RS} = U_{GG} - I_D R_S$

$U_{GS} = U_{GG} - R_S k (U_{GS} - U_T)^2$

$U_{GS} = U_{GG} - R_S k (U_{GS}^2 - 2U_{GS}U_T + U_T^2)$

$U_{GS} = U_{GG} - R_S k U_{GS}^2 + 2R_S k U_{GS} U_T - R_S k U_T^2$

$R_S k U_{GS}^2 + U_{GS}(1 - 2R_S k U_T) + R_S k U_T^2 - U_{GG} = 0$

$U_{GS\,1,2} = \frac{-(1 - 2R_S k U_T) \pm \sqrt{(1-2R_S k U_T)^2 - 4R_S k (R_S k U_T^2 - U_{GG})}}{2R_S k}$

$= \pm 4V$ (ni $-4V$ v rešitvi)

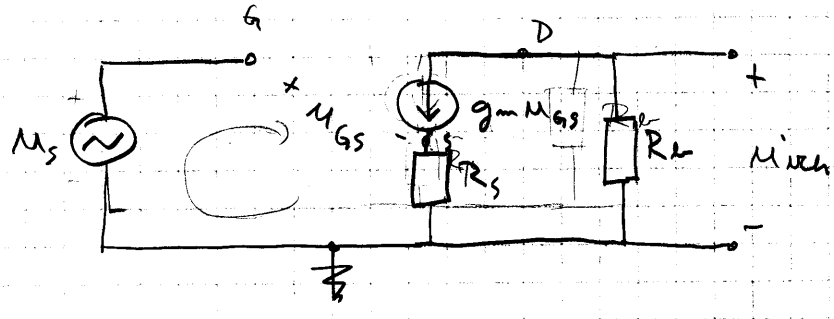
$U_{GS} = 4V$

$I_D = k(U_{GS} - U_T)^2 = 0{,}25(4-2)^2_{mV} = \underline{\underline{1mA}}$

$U_{DS} = U_{DD} - R_D I_D - R_S I_D = \underline{\underline{14V}}$

$14V > 4V - 2V = 2V$ ✓ mejenje

$g_m = 2k(U_{GS} - U_T)\Big|_{U_{GS} = U_{GS}} = 2 \cdot 0{,}25 \frac{mA}{V^2}(4V - 2V) = 1mS$



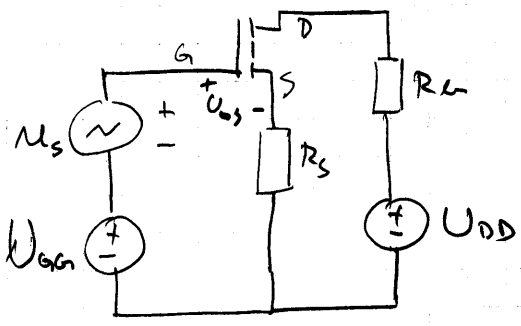
$A_M = \frac{U_{izh}}{U_S}$

$U_{izh} = -R_D g_m U_{GS}$

$U_{GS} + U_{RS} = U_S \Rightarrow U_{GS} + g_m U_{GS} R_S = U_S \Rightarrow U_{GS} = \frac{U_S}{1 + g_m R_S}$

$U_{izh} = -R_D g_m U_{GS} = -\frac{R_D g_m}{1 + g_m R_S} U_S$

$$A_m = -\frac{R_d g_m}{1 + R_s g_m} = -7{,}5$$

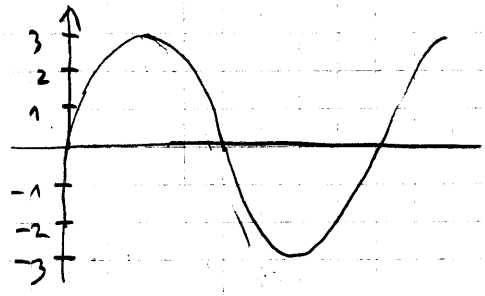


$U_{GG} = 5V$
$U_T = 2V$

Ko se tranzistor zapre:

$U_{GS} = U_T$, $I_D = 0 \Rightarrow U_{RS} = 0$

$u_{GS} = U_{GG} + u_s$
$2V = 5V + u_s \Rightarrow u_s = -3V$



$u_{s\,max} = 3V$

Ko gre tranz. v linearno območje

$U_{DS} = U_{GS} - U_T$
$U_{DS} = U_{DD} - I_D(R_d + R_s) = U_{GS} - U_T$
$U_{DD} - k(U_{GS} - U_T)^2(R_d + R_s) = U_{GS} - U_T$
$30 - 0{,}25\,(U_{GS} - 2)^2(15+1) = U_{GS} - 2$
$32 - (0{,}25 U_{GS}^2 - U_{GS} + 1)\cdot 16 = U_{GS}$
$-4U_{GS}^2 + 15U_{GS} + 16 = 0$

$$U_{GS\,1,2} = \frac{-15 \pm \sqrt{15^2 + 4\cdot 4\cdot 16}}{-8} = \begin{cases} -0{,}866V \;//\; U_{GS} > U_T \\ +4{,}616V \;\checkmark \end{cases}$$

$U_{GS} = 4{,}616V$

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(U_{GS} - U_T)^2 = 1{,}711\,mA$$

$U_{RS} = I_D \cdot R_s = 1{,}711\,mA \cdot 1k\Omega = 1{,}711V$

$$-U_{GG} - u_s + U_{GS} + U_{RS} = 0$$

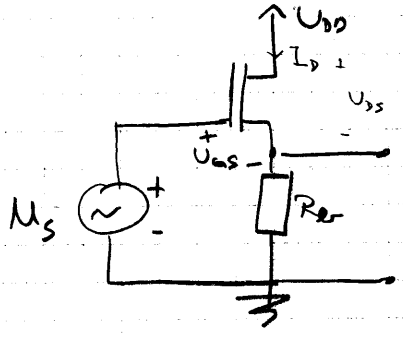
$$u_s = U_{GS} + U_{RS} - U_{GG} = 1{,}327\,V$$

$$\underline{u_s = -3\,V}$$

$$|u_s|_{MAX} = 1{,}327\,V$$

ELN, 23.11.

☒ Za podano verjo izr. D.T., Am in $|U_s|_{MAX}$



$U_{DD} = 5\,V$

$\frac{\mu_n C_{ox}}{2}\frac{W}{L} = 0{,}5\,\frac{mA}{V^2}$

$U_T = -1\,V$

$\underline{R_B = 10\,k\Omega}$

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(U_{GS} - U_T)^2$$

$$-U_{GS} = U_{RB} = I_D \cdot R_B$$

$$U_{GS} = -0{,}5\,\frac{mA}{V^2}(U_{GS} - (-1V))^2 \cdot 10\,k\Omega$$

$$U_{GS} = -5\,\frac{A}{V^2}(U_{GS} + 1V)^2\,\frac{V}{A}$$

$$U_{GS} = -5(U_{GS}^2 + 2U_{GS} + 1)$$

$$5U_{GS}^2 + 11U_{GS} + 5 = 0$$

$$U_{GS\,1,2} = \frac{-11 \pm \sqrt{121 - 4\cdot 5\cdot 5}}{2{,}5} = \begin{cases} -0{,}6417\,V \checkmark \\ -1{,}5858\,V \end{cases}$$

$$U_{GS} = -0{,}6417\,V$$

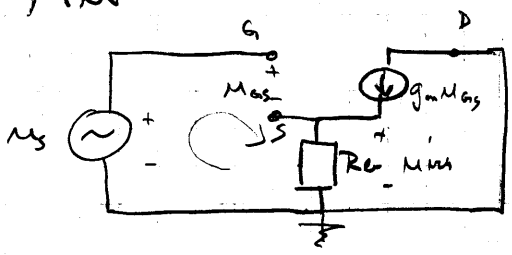
$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(U_{GS} - U_T)^2 = 64{,}17\,\mu A$$

$$U_{DS} = U_{DD} - I_D R_B = U_{DD} - U_{RB} = U_{DD} + U_{GS} = 4{,}358\,V$$

$U_{DS} \geq U_{GS} - U_T$

$4{,}358\,V \geq -0{,}6417\,V - (-1\,V)$ ✓

A_M:



$$A_M = \frac{u_{izh}}{u_S}$$

$$u_{izh} = u_{R_D} = g_m u_{GS} R_D$$

$$-u_S + u_{GS} + u_{R_D} = 0$$

$$-u_S + u_{GS} + g_m u_{GS} R_D = 0$$

$$u_{GS} = \frac{u_S}{1 + g_m R_D}$$

$$u_{izh} = \frac{g_m R_D}{1 + g_m R_D} u_S$$

$$A_M = \frac{g_m R_D}{1 + g_m R_D}$$

$$g_m = 2\frac{\mu_n C_{ox}}{2}\frac{W}{L}(u_{GS} - U_T)\Big|_{u_{GS}=U_{GS}} = 1\frac{mA}{V^2}(-0{,}6417V + 1V)$$

$$= 0{,}358mS$$

$$A_M = 0{,}78$$

$|u_S|_{max}$:

Tranzistor se zapre: $U_{GS} \leq U_T$

$$I_D = 0 \rightarrow U_{GS} = U_S$$

$$U_S = U_T = -1V = \underline{u_S}$$

Lin področje: $U_{DS} = U_{GS} - U_T$

$$U_{DS} = U_{DD} - U_{R_D} = U_{DD} - k(U_{GS} - U_T)^2 R_D$$

$$U_{DD} - k(U_{GS} - U_T)^2 R_D = U_{GS} - U_T$$

$U_{GS} - U_T = X$

$U_{DD} - R_D \quad 10k\Omega \; 0{,}5\frac{mA}{V^2} X^2 + X - 5V = 0$

$5X^2 + X - 5 = 0$

$X_{1,2} = \frac{-1 \pm \sqrt{1+4 \cdot 5 \cdot 5}}{2 \cdot 5} = \begin{cases} 0{,}905V \checkmark & U_{GS} > U_T \rightarrow X > 0 \\ -1{,}1V \not\checkmark \end{cases}$

$U_{GS} - U_T = 0{,}905V$

$U_{GS} = -0{,}095V$

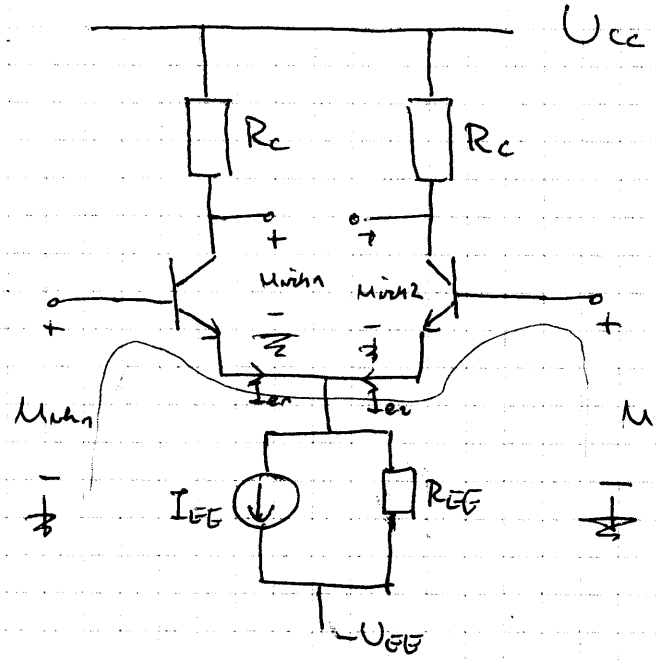
$U_{RD} = R_D \cdot I_D = R_D \frac{\mu_n C_{ox}}{2} \frac{W}{L} (U_{GS} - U_T)^2 = 4{,}095V$

$U_S = U_{GS} + U_{RD} = 4V = U_S$

$|U_S|_{max} = 1V$

Dvostopenjske vezave

Emitorsko sklopljen par



$U_{in1} - U_{BE1} + U_{BE2} - U_{in2} = 0$

$U_{BE1} - U_{BE2} = U_{in1} - U_{in2}$

$I_C = I_S e^{\frac{U_{BE}}{U_T}}$

$\frac{I_C}{I_S} = e^{\frac{U_{BE}}{U_T}}$

$\ln \frac{I_C}{I_S} = \frac{U_{BE}}{U_T}$

$U_{BE} = U_T \ln \frac{I_C}{I_S}$

$U_{BE1} = U_T \ln \frac{I_{C1}}{I_{S1}}$

$U_{BE2} = U_T \ln \frac{I_{C2}}{I_{S2}}$

Pri $I_{S1} = I_{S2}$

$$\frac{I_{c1}}{I_{c2}} = e^{\frac{U_{BE1} - U_{BE2}}{U_T}} = e^{\frac{U_{vh1} - U_{vh2}}{U_T}} = \frac{I_{c1}}{I_{c2}}$$

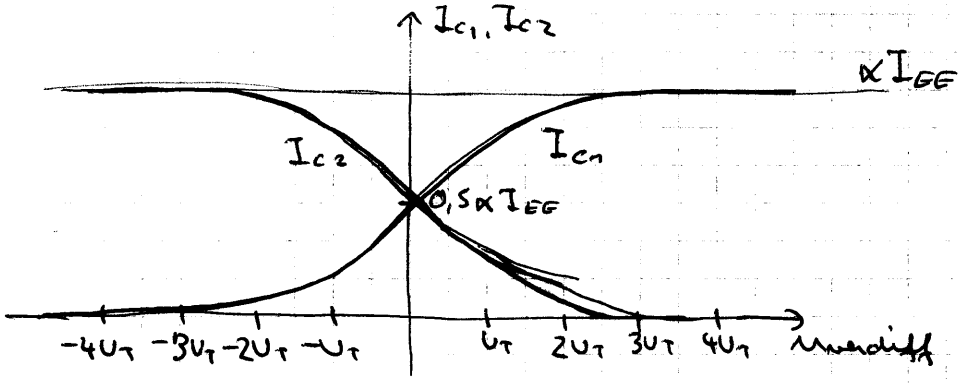
zanemarimo tok skozi R_{EE}

$$I_{e1} + I_{e2} = I_{EE} = \frac{1}{\alpha}(I_{c1} + I_{c2})$$

$$I_{c1} = \frac{\alpha \cdot I_{EE}}{1 + e^{-\frac{U_{vhdiff}}{U_T}}}$$

$U_{vh1} - U_{vh2} = U_{vhdiff}$

$$I_{c2} = \frac{\alpha I_{EE}}{1 + e^{\frac{U_{vhdiff}}{U_T}}}$$

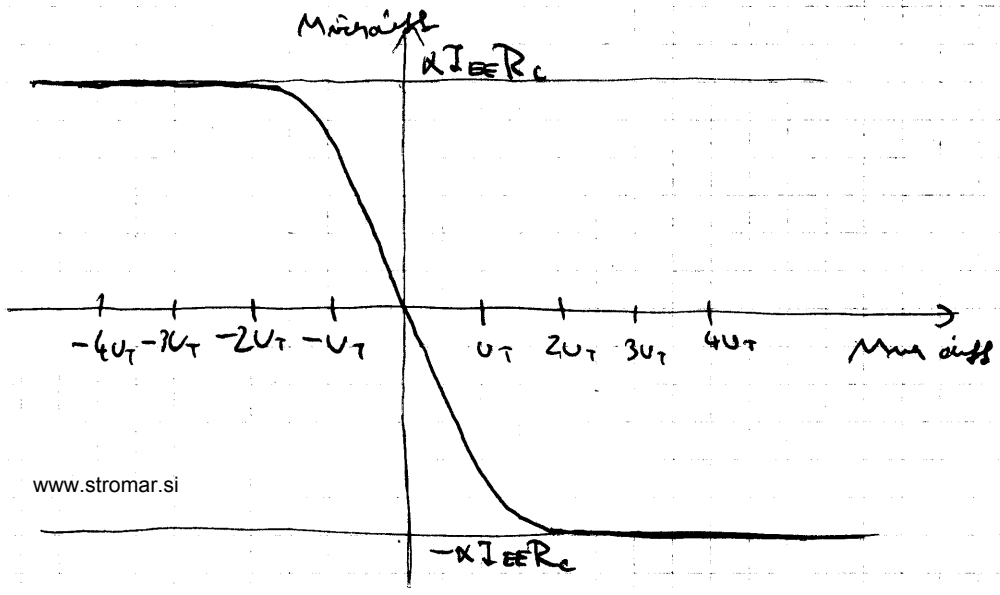


$$U_{vh1} = U_{CC} - I_{c1} R_C$$

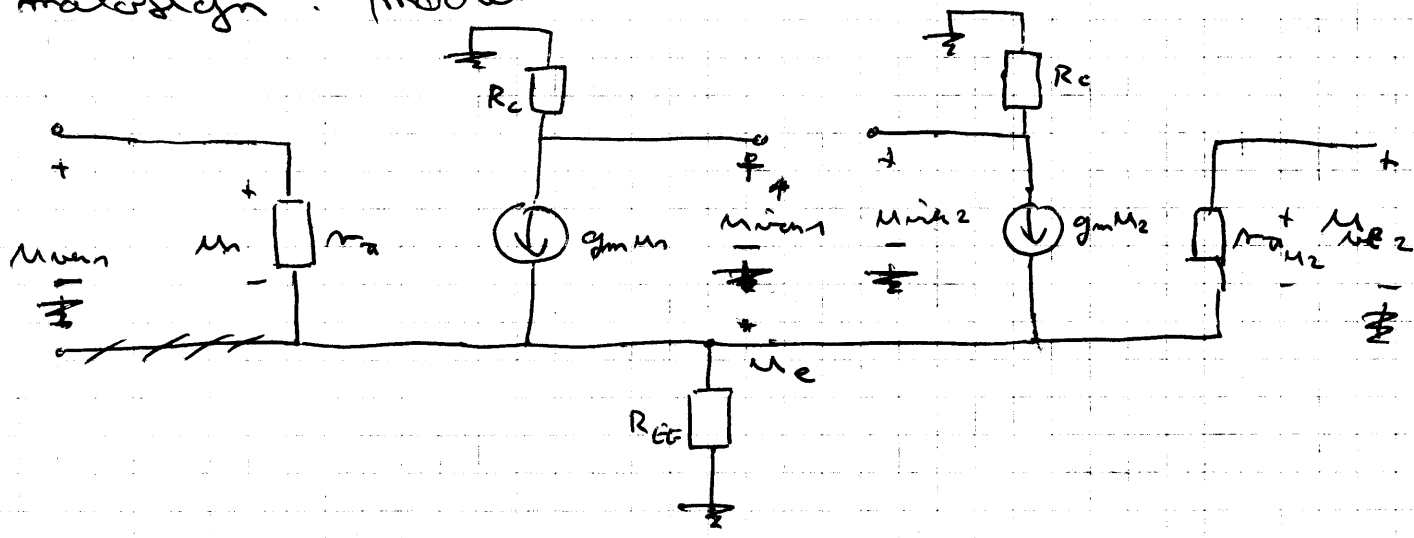
$$U_{vh2} = U_{CC} - I_{c2} R_C$$

$$U_{vhdiff} = U_{vh1} - U_{vh2} = \alpha I_{EE} R_C \tanh\left(-\frac{U_{vhdiff}}{2U_T}\right)$$

$$\tanh x = \frac{e^x - e^{-x}}{e^x + e^{-x}} = \frac{e^{2x} - 1}{e^{2x} + 1} = \frac{2}{e^{-2x} + 1} - 1$$



malosignalni model:



$$\frac{U_{ver1}-U_e}{r_\pi}+g_m(U_{ver1}-U_e)+g_m(U_{ver2}-U_e)+\frac{U_{ver2}-U_e}{2R_\pi\,/\,r_\pi}=\frac{U_e}{R_{EE}}$$

$$U_e=\frac{\frac{U_{ver1}+U_{ver2}}{2}}{2+\frac{1}{g_mR_{EE}\left(1+\frac{1}{\beta}\right)}}$$

$$U_{vich1}=-g_mU_1R_c=-g_mR_c(U_{ver1}-U_e)$$

$$U_{vich2}=-g_mU_2R_c=-g_mR_c(U_{ver2}-U_e)$$

⋮ prepustimo matematikom

inženirski način:

$$U_{vhdij}=U_{vich1}-U_{vich2}$$

$$U_{vhskup}=\frac{U_{vich1}+U_{vich2}}{2}$$

$$U_{ver1}=\frac{U_{vhdij}}{2}+U_{vhsk}$$

$$U_{ver2}=-\frac{U_{vhdij}}{2}+U_{vhsk}$$

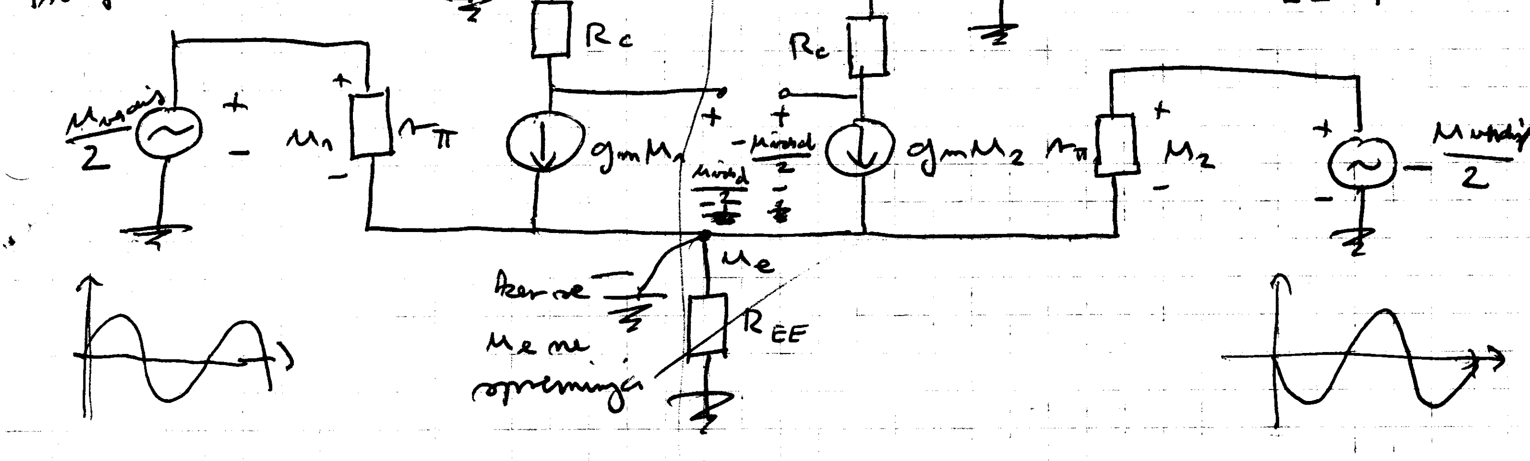
$$U_{vichdij}=U_{vich1}-U_{vich2}$$

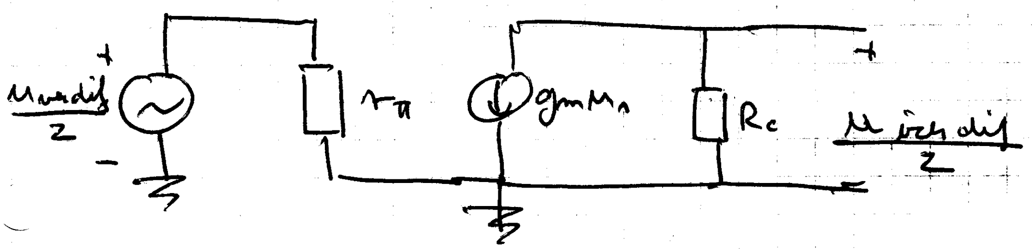
$$U_{vichsk}=\frac{U_{vich1}+U_{vich2}}{2}$$

$$\Rightarrow\quad U_{vich1}=\frac{U_{vichdij}}{2}+U_{vichsk}$$

$$U_{vich2}=-\frac{U_{vichdij}}{2}+U_{vichsk}$$

Protifazno krmiljenje:



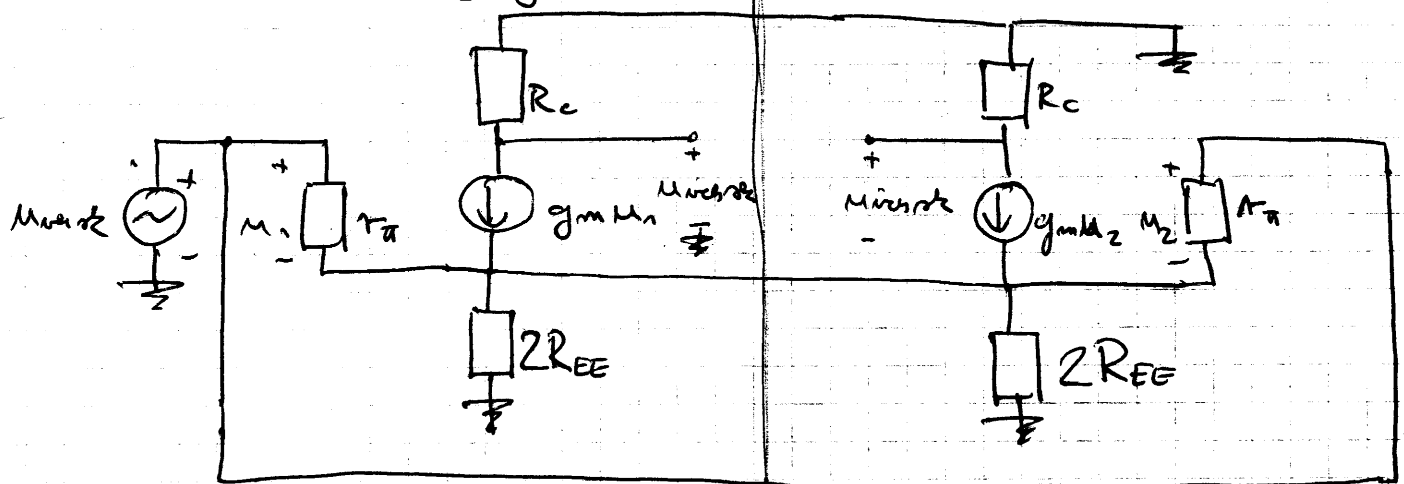


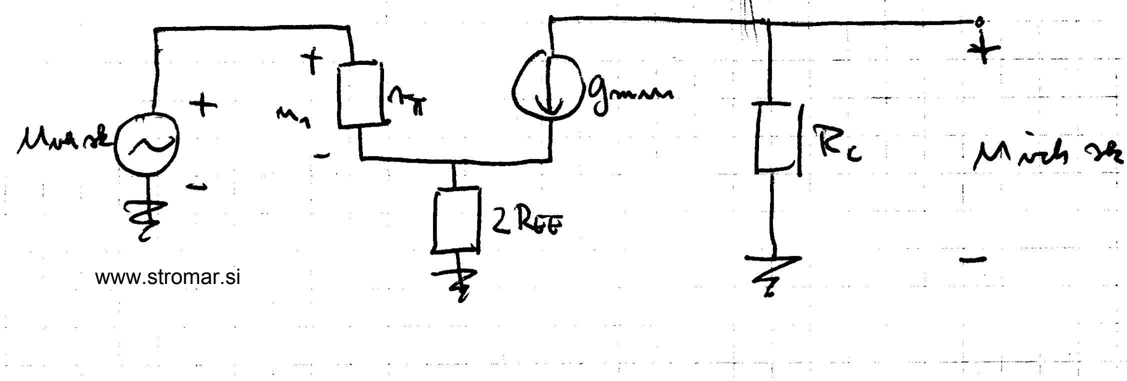
$$\frac{u_{izh\,dif}}{2} = -g_m u_1 R_c = -g_m R_c \frac{u_{vh\,dif}}{2}$$

$$A_{dm} = -g_m R_c = \frac{u_{izh\,dif}}{u_{vh\,dif}}$$

differential mode

Sofazno krmiljenje:





$$u_{ulaz\,sk} - \lambda_b r_\pi - (\beta+1) i_b 2R_{EE} = 0$$

$$\lambda_b = \frac{u_{ulaz\,sk}}{r_\pi + 2R_{EE}(\beta+1)}$$

$$u_{izl\,sk} = -\beta i_b R_c = -\frac{\beta R_c}{r_\pi + 2R_{EE}(\beta+1)}\, u_{ulaz\,sk}$$

$$A_{cm} = \frac{u_{izl\,sk}}{u_{ulaz\,sk}} = -\frac{\beta R_c}{r_\pi + 2R_{EE}(\beta+1)} = -\frac{g_m R_c}{1+2g_m R_{EE}(1+\frac{1}{\beta})}$$

common mode

$$g_m = \frac{\beta}{r_\pi}$$

$$A_{cm} = -\frac{g_m R_c}{1+2g_m R_{EE}(1+\frac{1}{\beta})}$$

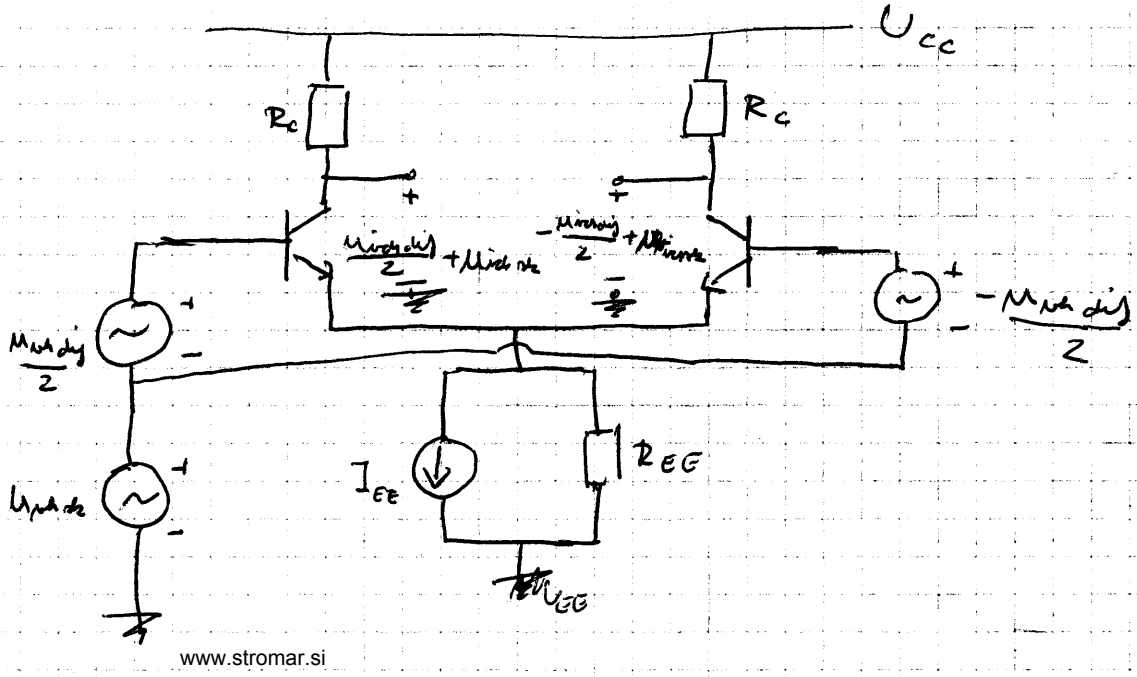
$$CMRR = \left|\frac{A_{dm}}{A_{cm}}\right| = \frac{g_m R_c}{\frac{g_m R_c}{1+2g_m R_{EE}(1+\frac{1}{\beta})}}$$

COMMON MODE REJECTION RATIO – regulacijski faktor

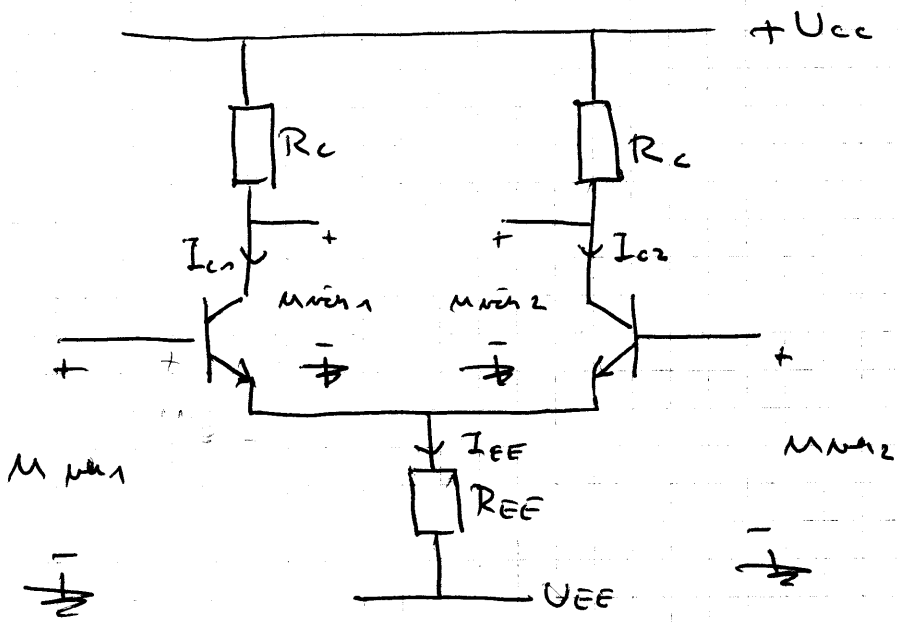
$$CMRR = 1+2g_m R_{EE}\left(1+\frac{1}{\beta}\right)$$

$$u_{ulaz1} = \frac{u_{ulaz\,dif}}{2} + u_{ulaz\,sk}$$

$$u_{ulaz2} = -\frac{u_{ulaz\,dif}}{2} + u_{ulaz\,sk}$$



☒ Za podano vezje izračunajte rejekcijski faktor



$U_{CC} = 15V$

$U_{EE} = -15V$

$R_C = R_{EE} = 10k\Omega$

$\beta \to \infty \; (I_B \to 0)$

$U_{BE} = 0{,}7V$

$$CMRR = 1 + 2 g_m R_{EE}$$

$$g_m = \frac{I_c}{U_T}$$

$$I_{EE} = I_{c1} + I_{c2} - 2I_c \Rightarrow I_c = \frac{I_{EE}}{2}$$

$$I_{EE} = \frac{U_E - U_{EE}}{R_{EE}} = \frac{-U_{BE} - U_{EE}}{R_{EE}} = 1{,}43\ mA$$

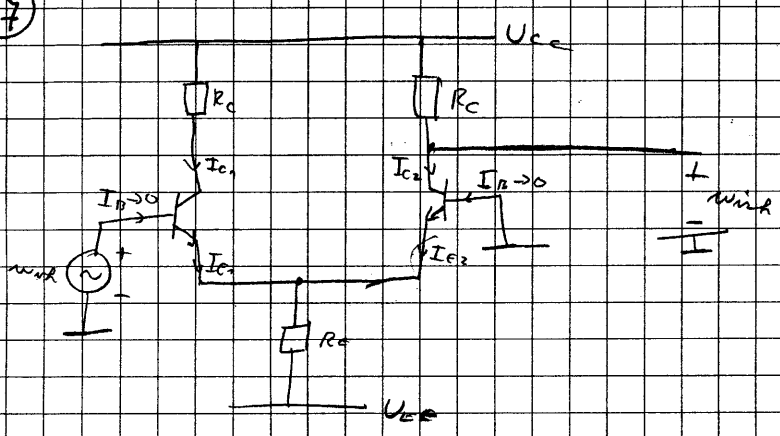
$$CMRR = 1 + 2\frac{I_c}{U_T} R_{EE} = 1 + 2\frac{I_{EE}}{2}\frac{1}{U_T} R_{EE} = 1 + I_{EE}\cdot\frac{1}{U_T} R_E$$

$$= 551$$

$$CMRR_{dB} = 20 \log CMRR = 54{,}8\ dB$$

če β sprejema ∞. $\Rightarrow$ $I_C = I_E \frac{1+\beta}{\beta} = \frac{I_E}{\alpha}$

(7)



$U_{CC} = 15\,V$

$U_{EE} = -15\,V$

$R_C = 10{,}8\,\Omega$

$R_E = 15{,}3\,\Omega$

$U_{BE} = 0{,}7\,V$

$\beta \to \infty$

$A_m = \frac{u_{ink}}{u_{mk}}$

$$I_{E_0} + I_{E_C} = I_{R_E} = \frac{U_{RE}}{R_E} = \frac{-U_{BE} - U_{EE}}{R_E} = \frac{-0{,}7\,V - (-15)\,V}{15{,}3\,\Omega} = 1\,mA$$

$$I_{E_1} = I_{E_2} = 0{,}5\,mA = I_{C_1} = I_{C_2} = I_C$$

$$A_{dm} = -g_m R_C = -\frac{I_C}{U_T} \cdot R_C = -\frac{0{,}5\,mA}{26\,mV} \cdot 10{,}8\,\Omega = -19{,}3$$

$$A_{cm} = -\frac{g_m R_C}{1 + 2g_m R_E\left(1 + \frac{1}{\beta}\right)} = -\frac{g_m R_C}{1 + 2g_m R_E} = -0{,}35$$

$$u_{ink} = u_{ink_2} = -\frac{u_{inkdif}}{2} + u_{ink\,sk}$$

$$u_{ink} = -\frac{1}{2} A_{dm} u_{inkdif} + A_{cm} \frac{u_{ink\,sk}}{2}$$

$$u_{ink} = -\frac{1}{2} A_{dm} u_{mk} + A_{cm} \frac{u_{mk}}{2}$$

$$u_{inkdif} = u_{ink_1} - u_{ink_2} = u_{mk}$$

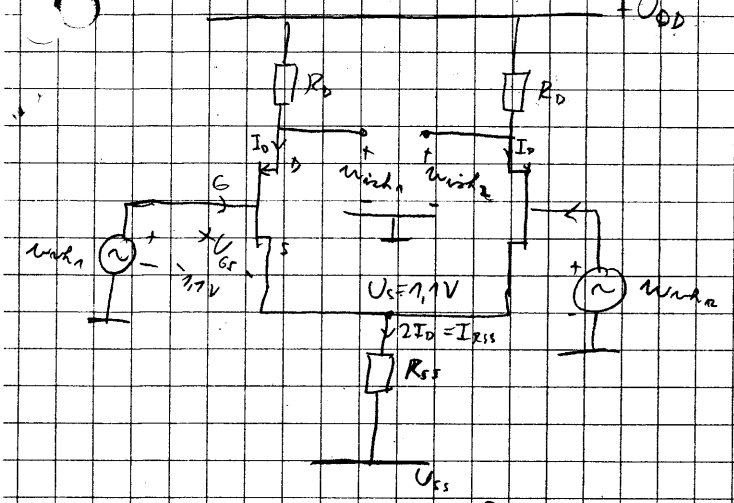
$$u_{ink\,sk} = \frac{u_{mk}}{2}$$

$$A_m = \frac{u_{ink}}{u_{mk}} = -\frac{1}{2} A_{dm} + \frac{1}{2} A_{cm} = 9{,}9$$

[redacted] 35

(str. 34 ne obstaja)

(8) Sklopljeni par JFET tranzistorjev



$U_{DD} = 15V$

$U_{SS} = -15V$

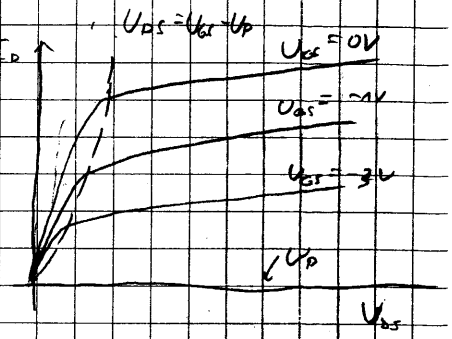
$R_D = 10k\Omega$

$R_{SS} = 20k\Omega$

$U_P = -2V$

$I_{DSS} = 2mA$

CMMR = ?



$$I_D = I_{DSS}\left(1 - \frac{U_{GS}}{U_P}\right)^2$$

$$g_m = \frac{\partial I_D}{\partial U_{GS}} = -2 I_{DSS}\left(\frac{1}{U_P}\right)\cdot\left(1 - \frac{U_{GS}}{U_P}\right)_{U_{GS}=U_{GS\,DT}} = -\frac{2 I_{DSS}}{U_P}\left(1 - \frac{U_{GS}}{U_P}\right)\Big|_{D.T.}$$

Izračunajmo D.T.:

$$0 = U_{GS} + U_{RSS} + U_{SS}$$

$$-U_{GS} = 2 I_D R_{SS} + U_{SS}$$

$$I_D = I_{DSS}\left(1 - \frac{U_{GS}}{U_P}\right)^2$$

$$\sqrt{\frac{I_D}{I_{DSS}}} = 1 - \frac{U_{GS}}{U_P} \Rightarrow U_{GS} = U_P\left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

$$-U_P\left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right) = 2 I_D R_{SS} + U_{SS}$$

$$1 - \sqrt{\frac{I_D}{I_{DSS}}} = -\frac{2 I_D R_{SS} + U_{SS}}{U_P}$$

$$1 + \frac{2 I_D R_{SS} + U_{SS}}{U_P} = \sqrt{\frac{I_D}{I_{DSS}}}$$

$$1 + \frac{2(2 I_D R_{SS} + U_{SS})}{U_P} + \left(\frac{2 I_D R_{SS} + U_{SS}}{U_P}\right)^2 = \frac{I_D}{I_{DSS}}$$

↑ kvadratna enačba → $I_D = 0{,}5\,mA$ (neg. ničl. ravnot. odpade)

$$U_{GS} = U_P\left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

$$U_{GS} = -2V\left(1 - \sqrt{\frac{0{,}5\,mA}{2\,mA}}\right) = -1{,}1V$$

$$I_{R_{SS}} = \frac{U_S - U_{SS}}{R_{SS}} = \frac{1{,}1V - (-15V)}{20k\Omega} = 0{,}805\,mA$$

$$g_m = -\frac{2 I_{DSS}}{U_P}\left(1 - \frac{U_{GS}}{U_T}\right)\Big|_{U_{GS}=-1{,}1V} = 0{,}89\,mS$$

$$A_{dm} = -g_m R_D = -8{,}9$$

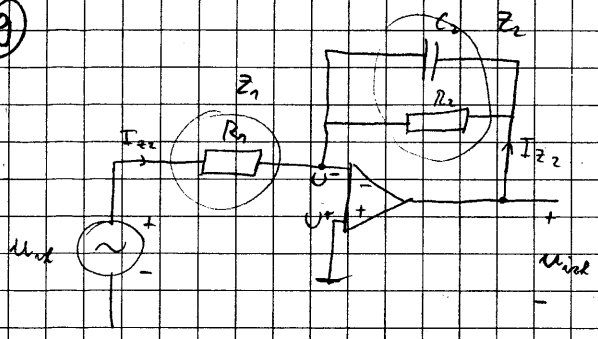
$$A_{cm} = -\frac{g_m R_D}{1 + 2 g_m R_{SS}\left(1 + \frac{1}{\beta}\right)} = -0{,}28$$

(ker $I_B = 0$)

$$CMRR = \left|\frac{A_{dm}}{A_{cm}}\right| = \frac{8{,}9}{0{,}28} = 31$$

$$CMRR_{dB} = 31{,}38\,dB$$

(9)



$$I_{Z1} = \frac{u_{ul} - U^-}{Z_1} = \frac{u_{ul}}{Z_1}$$

$$I_{Z2} = \frac{u_{izh} - U^-}{Z_2} = \frac{u_{izh}}{Z_2}$$

$$I_{Z1} = -I_{Z2} \Rightarrow \frac{u_{ul}}{Z_1} = -\frac{u_{izh}}{Z_2}$$

$$A_u = -\frac{Z_2}{Z_1}$$

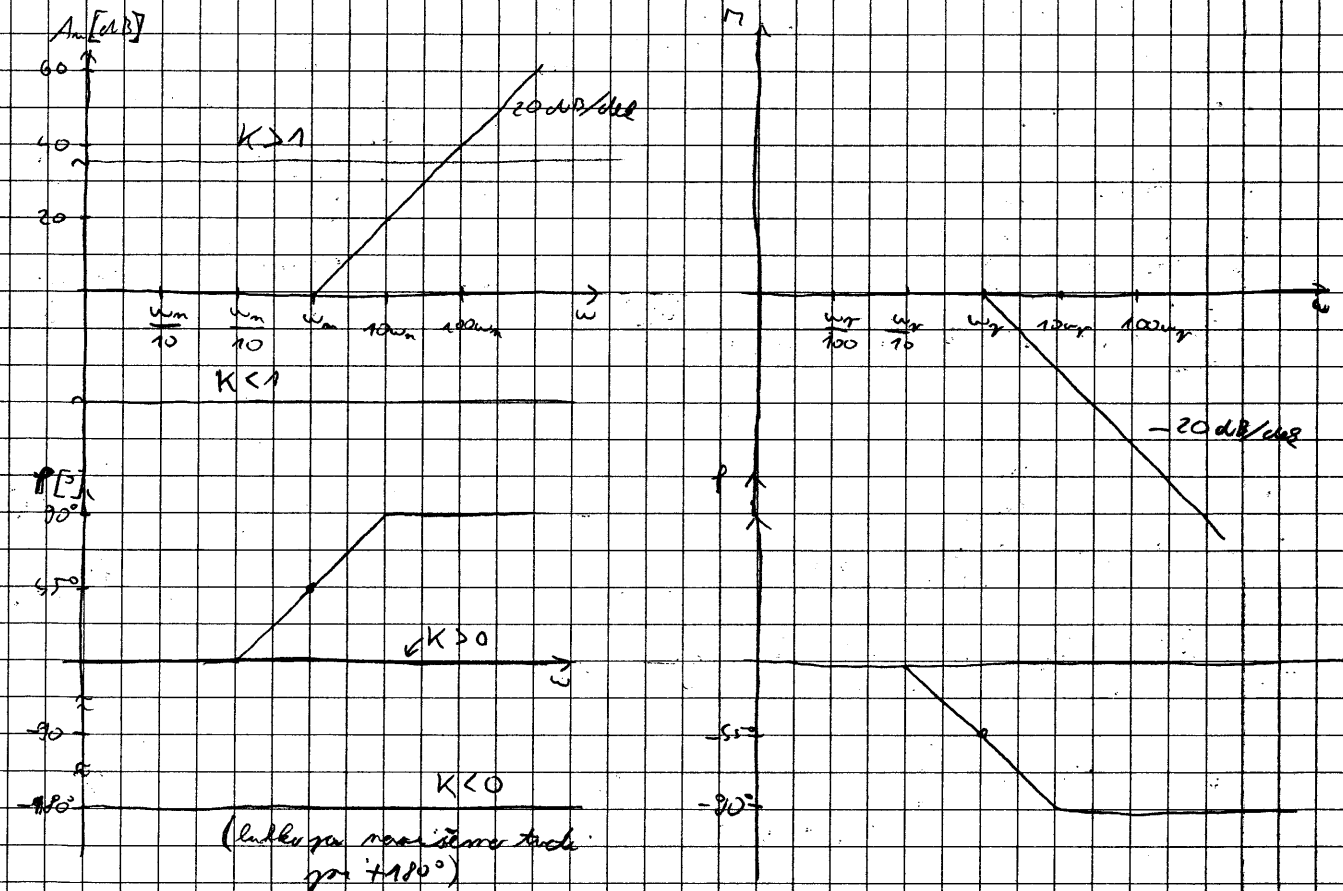
(~~uporabimo~~ uporabimo še predpostavk: $A \to \infty \Rightarrow u_{ul}^- - u_{ul}^+ \to 0$, $I_{ul}^- = I_{ul}^+ = 0$, $u_{ul}^- = u_{ul}^+$, $u_{izh} = A(u^+ - u^-)$, $\infty \cdot 0$)

$$Z_2 = \frac{1}{Y_2} = \left(\frac{1}{R_2} + j\omega C_2\right)^{-1} = \left(\frac{1 + j\omega R_2 C_2}{R_2}\right)^{-1}$$

$$A_u = -\frac{Z_2}{Z_1} = \frac{R_2}{(1 + j\omega R_2 C_2) R_1} = -\frac{R_2}{R_1} \frac{1}{1 + j\omega R_2 C_2}$$

Bodejev diagram:

$$A(j\omega) = K \frac{\left(1 + \frac{j\omega}{\omega_{n1}}\right)\left(1 + \frac{j\omega}{\omega_{n2}}\right) \cdots \left(1 + \frac{j\omega}{\omega_N}\right)}{\left(1 + \frac{j\omega}{\omega_{p1}}\right)\left(1 + \frac{j\omega}{\omega_{p2}}\right) \cdots \left(1 + \frac{j\omega}{\omega_P}\right)}$$



če $\left(1 + \frac{j\omega}{\omega}\right)^m \Rightarrow m$ - stopnja

Kako določimo potrebno območje za risanje BD?

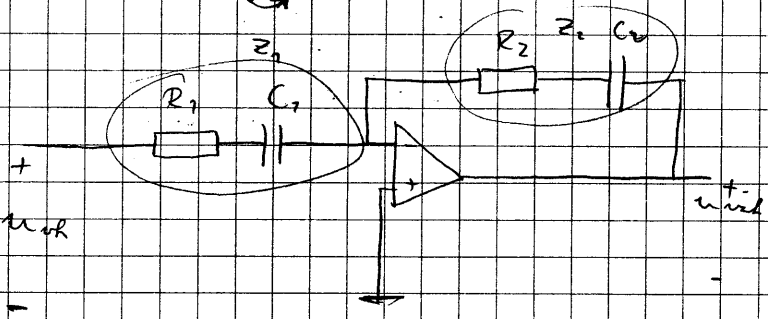
Primer:

$$A_m = \frac{1 + R_2 + j\omega C_2}{R + \frac{1}{j\omega C_1}} = \frac{(1+R_2)\left(1 + \frac{j\omega C_2}{1+R_2}\right) \cdot j\omega C_1}{j\omega R C_1 + 1} =$$

$$= \frac{(1+R_2)\, j\omega C_1 \left(1 + \frac{j\omega}{\frac{1+R_2}{C_2}}\right)}{1 + j\omega \frac{1}{RC_1}} = \frac{\overbrace{C(1+R_2)}^{K} \left(j\omega\right)\left(1 + \frac{j\omega}{\frac{1+R_2}{C}}\right)}{\left(1 + \frac{j\omega}{RC_1}\right)}$$

- naklon 20 dB/dek,
- prelomna kotna frekvenca 10^3
- faza 90°

(10)



$R_1 = 1\,k\Omega$

$R_2 = 10\,k\Omega$

$C_1 = 1\,mF$

$C_2 = 100\,mF$

$A_m = ?$

$$A_m = -\frac{Z_2}{Z_1} = -\frac{R_2 + \frac{1}{j\omega C_2}}{R_1 + \frac{1}{j\omega C_1}} = \frac{\frac{j\omega C_2 R_2 + 1}{j\omega C_2}}{\frac{j\omega C_1 R_1 + 1}{j\omega C_1}} =$$

$$Z_2 = R_2 + \frac{1}{j\omega C_2}$$

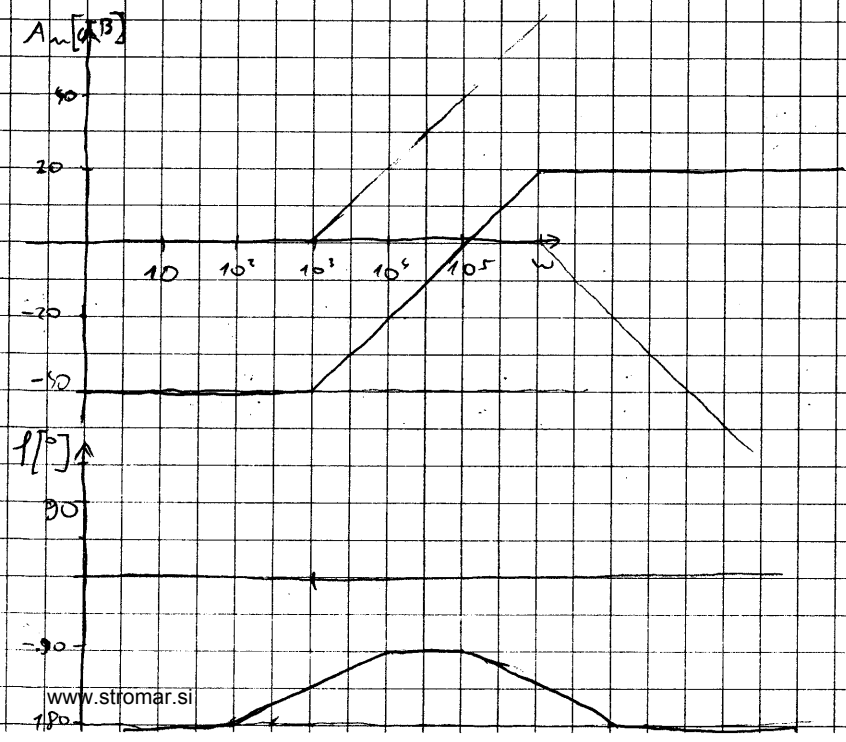
$$Z_1 = R_1 + \frac{1}{j\omega C_1} = -\frac{1 + j\omega R_2 C_2}{1 + j\omega R_1 C_1} \cdot \frac{j\omega C_1}{j\omega C_2} = -\frac{C_1}{C_2} \frac{1 + \frac{j\omega}{\frac{1}{R_2 C_2}}}{1 + \frac{j\omega}{\frac{1}{R_1 C_1}}} =$$

$$-\frac{C_1}{C_2} = -\frac{1\,mF}{100\,mF} = -0{,}01 \qquad = -10^{-2} \cdot \frac{1 + \frac{j\omega}{10^3}}{1 + \frac{j\omega}{10^6}}$$

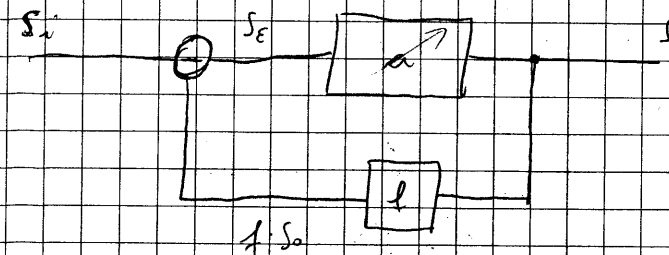
$$\omega_{n1} = \frac{1}{R_2 C_2} = \frac{1}{10^{-2} \cdot 10 \cdot 10^3} = 10^3$$

$$\omega_{p1} = \frac{1}{R_1 C_1} = \frac{1}{10^{-3} \cdot 10^3} = 10^6$$

$$A_{mVF} = -\frac{R_2}{R_1} = -\frac{10\,k\Omega}{1\,k\Omega} = -10$$



11) Povratna zveza (negativna)



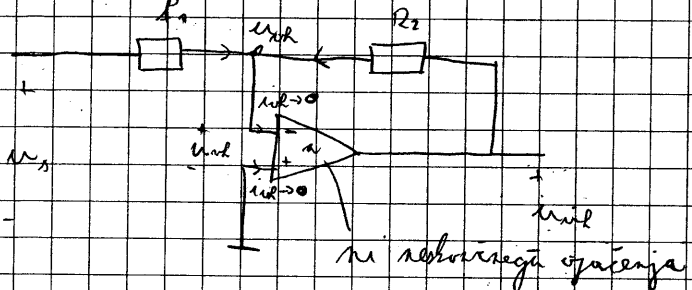
$$S_\varepsilon = S_i - f S_o$$

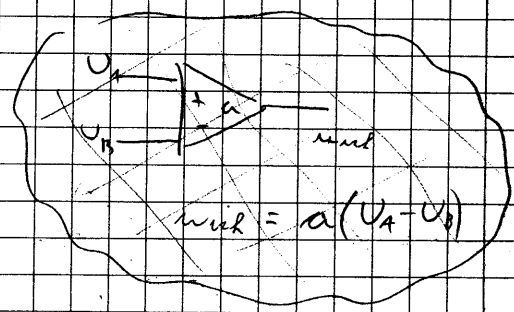
$$S_o = a S_\varepsilon = a(S_i - f S_o)$$

$$S_o(1 + a f S_o) = a S_i$$

$$\frac{S_o}{S_i} = \frac{a}{1 + af} \Big|_{af \gg 1} = \frac{1}{f}$$

11)





$$\frac{u_s - u_{vk}}{R_1} + \frac{u_{ik} - u_{vk}}{R_2} = 0$$

$$\frac{u_s}{R_1} + \frac{u_{ik}}{R_2} = u_{vk}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$u_{ik} = a U_{vk} \Rightarrow u_{vk} = -\frac{u_{ik}}{a}$$

$$A_u = \frac{u_{ik}}{u_s}$$

$$\frac{u_s}{R_1} + \frac{u_{vk}}{R_2} = -\frac{u_{ik}}{a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\frac{u_s}{R_1} = \frac{u_{ik}}{a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) - \frac{u_{ik}}{R_2}$$

$$\frac{u_{ik}}{u_s} = -\frac{R_2}{R_1}\,\frac{1}{1 + \frac{1}{a}\left(1 + \frac{R_2}{R_1}\right)} = -\frac{R_2}{R_1}\Big|_{a \gg 1}$$

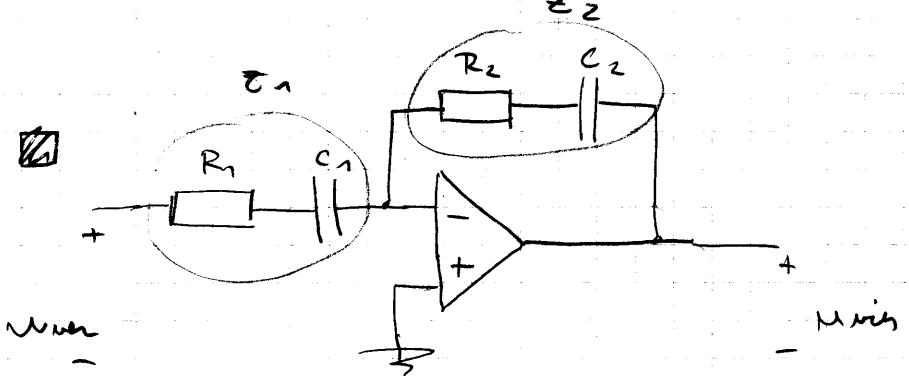
2 primera: $a = 10^3$, $a = 10^5$

$R_1 = 1\,k\Omega$

$R_2 = 10\,k\Omega$

1) $a = 10^3$: $A_u = -\frac{10}{1}\cdot\frac{1}{1 + \frac{1}{10^3}(1+10)} = -10\,\frac{1}{1 + \frac{11}{10^3}} = \underline{\underline{-9{,}90}}$

2) $a = 10^5$: $A_u = -\frac{10}{1}\cdot\frac{1}{1 + \frac{1}{10^5}(1+10)} = \underline{\underline{-9{,}998}}$



$R_1 = 1k\Omega$

$R_2 = 10k\Omega$

$C_1 = 1mF$

$C_2 = 100mF$

$A_u = \frac{u_{izh}}{u_{vh}} = ?$

$$A_u = -\frac{Z_2}{Z_1} = -\frac{R_2 + \frac{1}{j\omega C_2}}{R_1 + \frac{1}{j\omega C_1}} = -\frac{\frac{j\omega C_2 R_2 + 1}{j\omega C_2}}{\frac{j\omega C_1 R_1 + 1}{j\omega C_1}} =$$

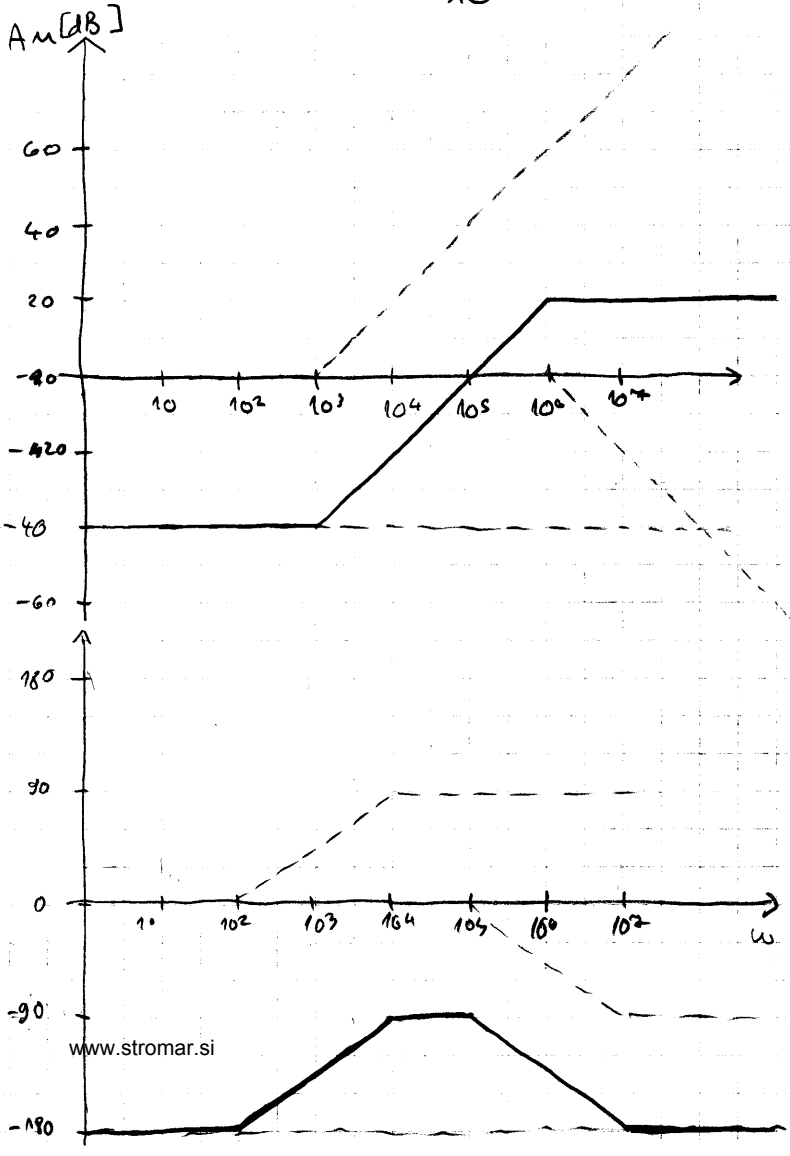
$$= -\frac{1 + j\omega C_2 R_2}{1 + j\omega R_1 C_1} \frac{j\omega C_1}{j\omega C_2} = -\frac{C_1}{C_2} \frac{1 + j\omega \frac{1}{R_2 C_2}}{1 + \frac{j\omega}{\frac{1}{R_1 C_1}}}$$

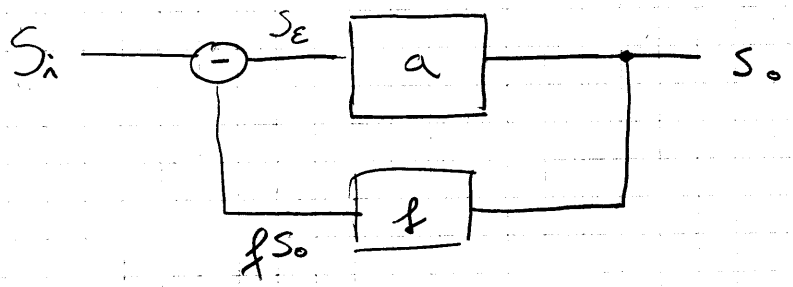
$$-\frac{C_1}{C_2} = -\frac{1mF}{-100mF} = -0{,}01$$

$$\omega_{m1} = \frac{1}{R_2 C_2} = \frac{1}{10 \cdot 10^3 \cdot 10^{-4}} = 10^3$$

$$\omega_{m2} = \frac{1}{R_1 C_1} = \frac{1}{10^3 \cdot 10^{-9}} = 10^6$$

$$A_u = -10^{-2} \frac{1 + \frac{j\omega}{10^3}}{1 + \frac{j\omega}{10^6}}$$



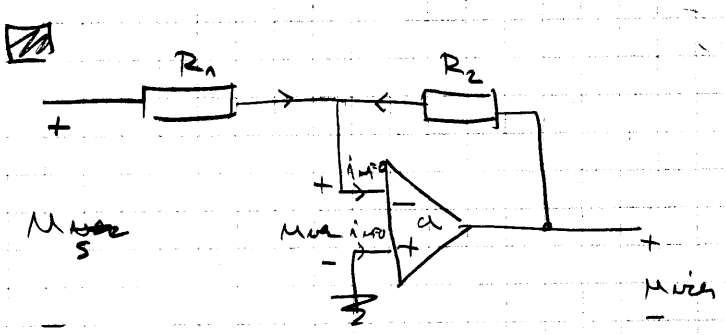


$$S_\varepsilon = S_i - f S_o$$

$$S_o = a \cdot S_\varepsilon$$
$$= a(S_i - f S_o)$$

$$S_o(1 + af) = a S_i$$

$$\frac{S_o}{S_i} = \frac{a}{1+af} \approx \frac{a}{af} = \frac{1}{f}$$



$$u_{vich} = -a\, u_{ver}$$
$$u_{ver} = -\frac{u_{vich}}{a}$$

$$\frac{u_s - u_{ver}}{R_1} + \frac{u_{vich} - u_{ver}}{R_2} = 0$$

$$\frac{u_s}{R_1} + \frac{u_{vich}}{R_2} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right) u_{ver}$$

$$\frac{u_s}{R_1} + \frac{u_{vich}}{R_2} = -\frac{u_{vich}}{a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\frac{u_s}{R_1} = -\frac{u_{vich}}{a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) - \frac{u_{vich}}{R_2}$$

$$\frac{u_{vich}}{u_s} = -\frac{R_2}{R_1}\,\frac{1}{1 + \frac{1}{a}\left(1 + \frac{R_2}{R_1}\right)} = -\frac{R_2}{R_1}\Bigg|_{a \gg 1}$$

$a = 10^4, 10^5$

$R_1 = 1\,k\Omega$

$R_2 = 10\,k\Omega$

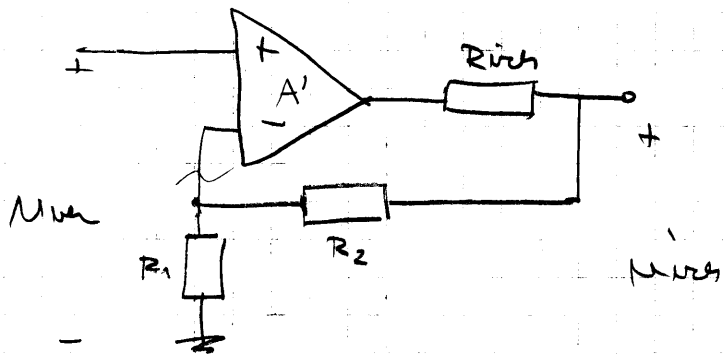
1) $a = 10^4$:

$$A_u = -\frac{10k}{1k}\,\frac{1}{1+\frac{1}{10^4}\left(1+\frac{10k}{1k}\right)} = -9{,}989$$

2) $a = 10^5$:

$$A_u = -\frac{10}{1}\cdot\frac{1}{1+\frac{1}{10^5}(1+10)} = -9{,}998$$

Za podano vezje določite frekv. potek ojačanja



$$A' = \frac{A_0}{1+j\frac{\omega}{\omega_0}}$$

$A_0 = 10^5$

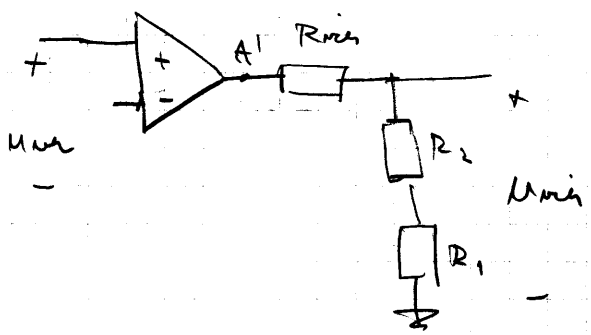
$\omega_0 = 20\pi\ s^{-1}$

$R_{vh} = 50\,\Omega$

$R_1 = 10\,\Omega$

$R_2 = 100\,\Omega$

$$A_u = \frac{U_{vh}}{U_{vh}} = \frac{a}{1+fa}$$



$$U_{vh} = A' U_{vh}\,\frac{R_1+R_2}{R_1+R_2+R_{vh}}$$

$$a = A'\,\frac{R_1+R_2}{R_1+R_2+R_{vh}}$$

$$f = \frac{R_1}{R_1+R_2} \qquad \left(U_- = \frac{R_1}{R_1+R_2}\,U_{vh}\right)$$

$$a = \frac{A_0}{1+j\frac{\omega}{\omega_0}}\,\frac{R_1+R_2}{R_1+R_2+R_{vh}} = 10^5\,\frac{1}{1+j\frac{\omega}{20\pi}}\cdot\frac{110}{160} = \frac{11}{16}\cdot 10^5\,\frac{1}{1+j\frac{\omega}{20\pi}}$$

$$f = \frac{10}{110} = \frac{1}{11}$$

$$A_M = \frac{\frac{11}{16}\cdot 10^5 \frac{1}{1+\frac{j\omega}{20\pi}}}{1+\frac{1}{11}\cdot\frac{11}{16}10^5\frac{1}{1+\frac{j\omega}{20\pi}}} =$$

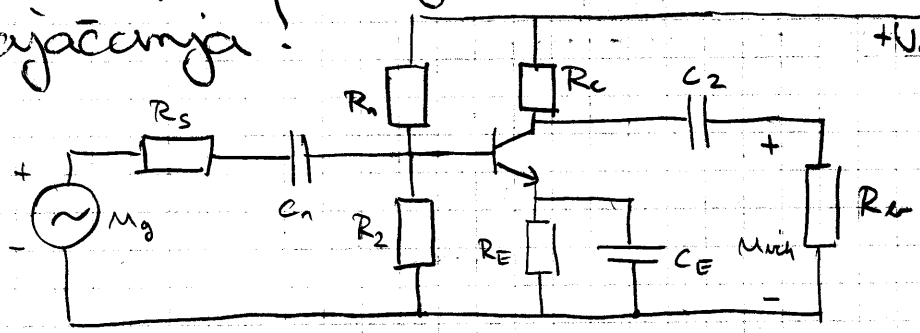
$$= \frac{11\cdot 10^5}{16\left(1+\frac{j\omega}{20\pi}\right)\left[1+\frac{10^5}{16}\frac{1}{1+\frac{j\omega}{20\pi}}\right]} =$$

$$= \frac{\frac{11}{16}\,10^5}{\left(1+\frac{j\omega}{20\pi}\right)\frac{1+\frac{j\omega}{20\pi}+\frac{10^5}{16}}{1+\frac{j\omega}{20\pi}}} =$$

$$= \frac{11}{16}\cdot 10^5 \frac{1}{6251+\frac{j\omega}{20\pi}} = \frac{11}{16}\,\frac{10^5}{6251}\,\frac{1}{1+\frac{j\omega}{20\pi\,6251}}$$

4.1.

Za podani ojač. določite frekv. potek ojačenja!



$R_s = 1k\Omega$

$R_1 = 50k\Omega$

$R_2 = 25k\Omega$

$R_E = 5k\Omega$

$R_C = 5k\Omega$

$R_v = 2k\Omega$

$U_{cc} = 12V$

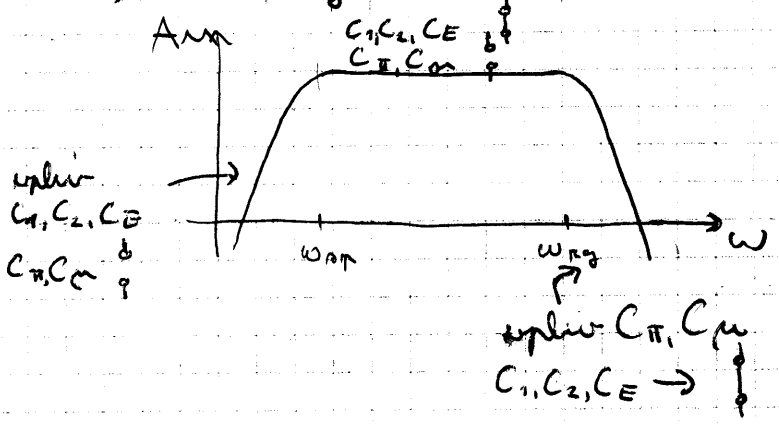
$\beta = 100$

$r_{bb'} = 50\Omega, C_\pi = 18nF, C_\mu = 4$

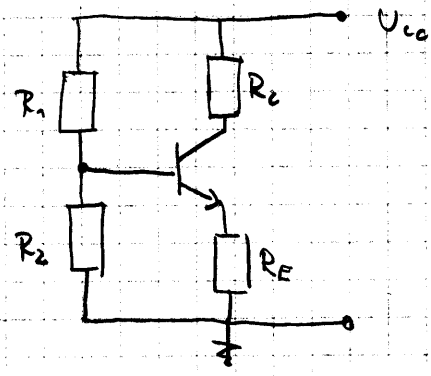
$C_1 = 3\mu F, C_2 = 8\mu F$

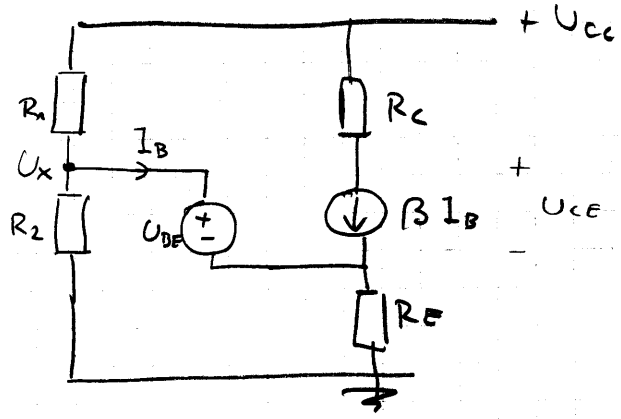
$C_E = 50\mu F$

$$A_M = \frac{M_{vih}}{M_g}$$



D.T.: I_C, U_{CE}





$$\frac{U_{cc}-U_x}{R_1} = \frac{U_x}{R_2} + I_B$$

$$U_x = U_{RE} + U_{BE}$$
$$= (1+\beta) I_B R_E + U_{BE}$$

$$\frac{U_{cc}}{R_1} = U_x\left(\frac{1}{R_1}+\frac{1}{R_2}\right) + I_B$$

$$\frac{U_{cc}}{R_1} = U_x \frac{R_1+R_2}{R_1 R_2} + I_B$$

$$\frac{U_{cc}}{R_1} = \frac{U_x}{R_1 \| R_2} + I_B$$

$$\frac{U_{cc}}{R_1} = \frac{(1+\beta)R_E I_B + U_{BE}}{R_1 \| R_2} + I_B$$

$$\frac{U_{cc}}{R_1} = I_B\left[\frac{(1+\beta)R_E}{R_1 \| R_2} + 1\right] + \frac{U_{BE}}{R_1 \| R_2}$$

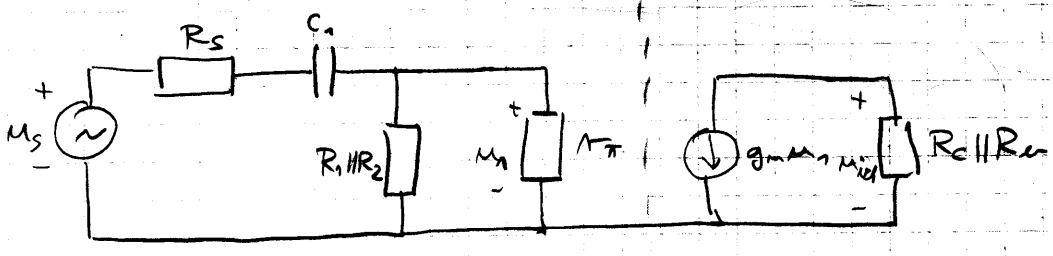
$$I_B = \frac{\frac{U_{cc}}{R_1} - \frac{U_{BE}}{R_1 \| R_2}}{\frac{(1+\beta)R_E}{R_1 \| R_2} + 1} \quad ; \quad I_C = \beta I_B = 0{,}633\,mA$$

$$g_m = \frac{I_C}{U_T} = 25{,}3\,mS \quad , \quad r_\pi = \frac{\beta}{g_m} = 3{,}95\,k\Omega$$

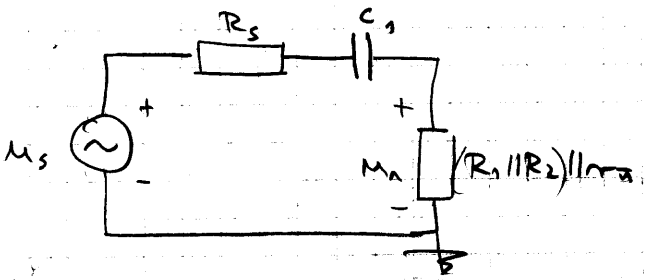
$$U_{CE} \doteq U_{cc} - I_C(R_C + R_E) = 12 - 0{,}633\,mA \cdot 10\,k\Omega = 5{,}67\,V$$ ✓ okt

Sp. frekv. meja:

1) vpliv C_1:



Dovolj, da dokažemo $u_1 = f(u_s)$, v u_{izh} je prenikava itak neodvisna od frekv.



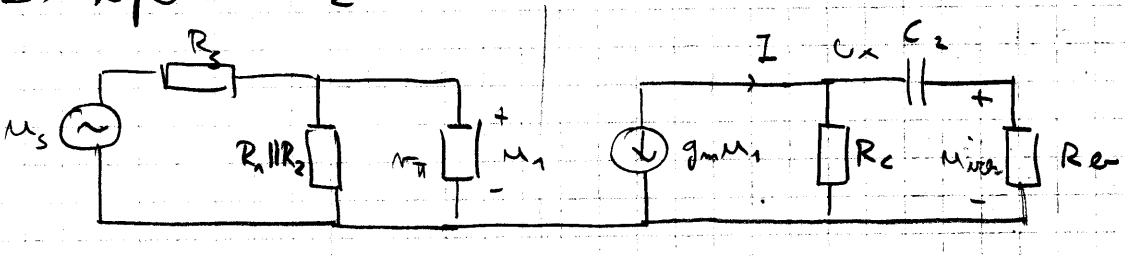
$$u_1 = \frac{(R_1 \| R_2) \| r_\pi}{R_s + (R_1 \| R_2) \| r_\pi + \frac{1}{j\omega C_1}} \cdot u_s =$$

$$H(j\omega) = \frac{(R_1 \| R_2) \| r_\pi \, j\omega C_1}{1 + \left[(R_1 \| R_2) \| r_\pi + R_s\right] j\omega C_1}$$

$$K = (R_1 \| R_2) \| r_\pi \cdot C_1$$

$$\omega_{n C_1} = \frac{1}{\left[(R_1 \| R_2) \| r_\pi + R_s\right] C_1} = \underline{795 \; s^{-1}}$$

2) vpliv C_2



Spet nas lahko zanima le $u_{vich} = f(u_1)$ - zanima ta frekv. odvisen

$$I = -g_m u_1 = \frac{U_x}{R_c} + \frac{U_x}{R_w + \frac{1}{j\omega C_2}} = U_x \left(\frac{1}{R_c} + \frac{j\omega C_2}{1 + j\omega C_2 R_w} \right) =$$

$$= U_x \frac{1 + j\omega C_2 R_w + j\omega C_2 R_c}{R_c (1 + j\omega C_2 R_w)} = U_x \frac{1 + j\omega C_2 (R_w + R_c)}{R_c (1 + j\omega C_2 R_w)}$$

$$U_x = I \frac{R_c (1 + j\omega C_2 R_w)}{1 + j\omega C_2 (R_w + R_c)}$$

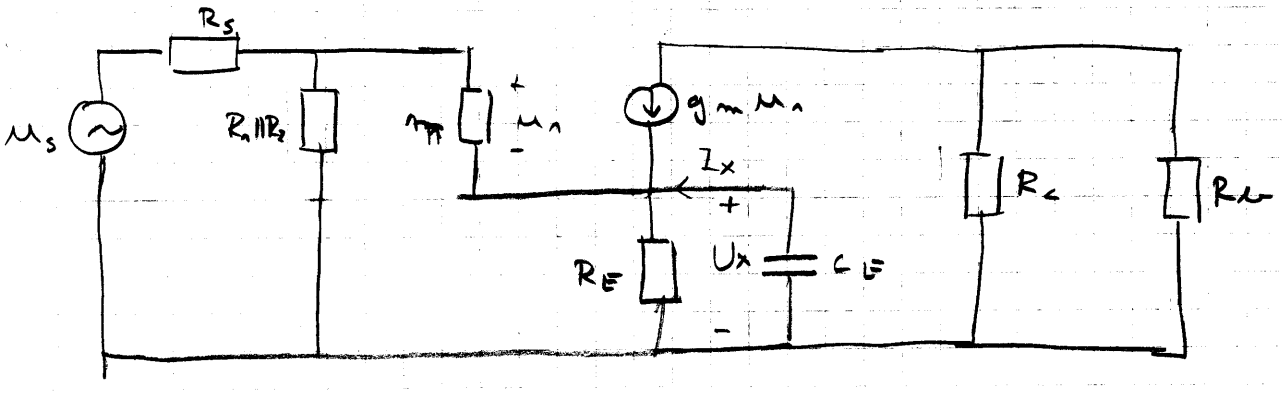
$$u_{vich} = \frac{R_w}{R_w + \frac{1}{j\omega C_2}} U_x = \frac{R_w j\omega C_2}{(1 + R_w j\omega C_2)} \frac{(1 + j\omega C_2 R_w) R_c}{1 + j\omega C_2 (R_w + R_c)} \cdot I$$

$$u_{vich} = -g_m \frac{j\omega C_2 R_w R_c}{1 + j\omega C_2 (R_w + R_c)} u_1$$

$$K = -g_m C_2 R_w R_c$$

$$\omega_{n C_2} = \frac{1}{C_2 (R_w + R_c)} = \underline{17{,}86 \; s^{-1}}$$

3) vpliv C_E ∑



$R_{EKV} = \frac{U_x}{I_x}$ – iz pr. primerov vidimo, da $\omega_p = \frac{1}{C \cdot R_{EKV}}$

u_s mimo upoštevali, ker mejnica

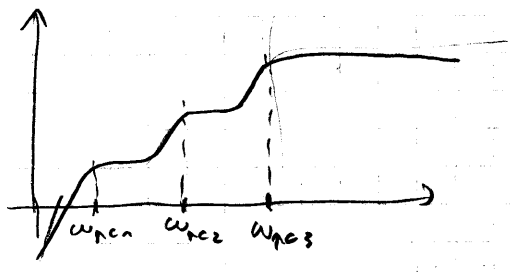
$$I_x = \frac{U_x}{R_E} + \frac{U_x}{r_\pi + (R_1 \| R_2) \| R_S} + \frac{g_m r_\pi}{r_\pi + (R_1 \| R_2) \| R_S} U_x$$

$$= U_x \left[\frac{1}{R_E} + \frac{1 + g_m r_\pi}{r_\pi + (R_1 \| R_2) \| R_S} \right]$$

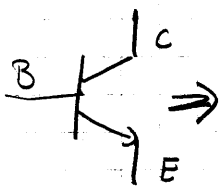
$$\frac{U_x}{I_x} = R_{EKV} = \frac{1}{\frac{1}{R_E} + \frac{1 + g_m r_\pi}{r_\pi + (R_1 \| R_2) \| R_S}} = 48\,\Omega$$

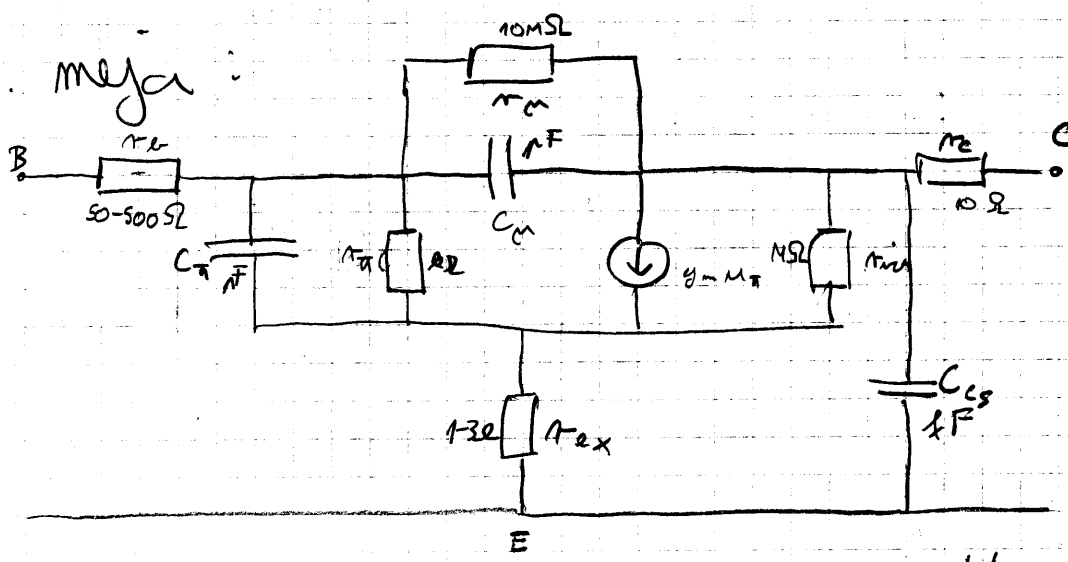
$$\omega_{pC3} = \frac{1}{C_E \cdot R_{EKV}} = 416\,s^{-1}$$

Sp. frekv. meja dodaca ω_{pC3}

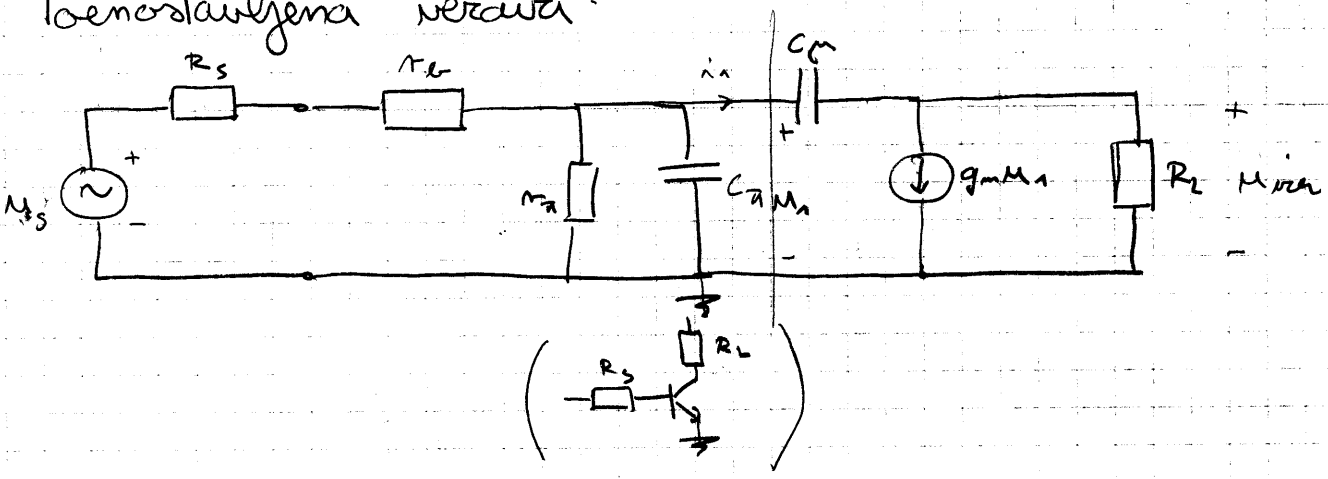


Zg. frekv. meja:





Poenostavljena vezava:



$$i_1 = (U_1 - U_{izh})\, j\omega C_\mu$$

zanemarimo

$$g_m U_1 + U_{izh} \cdot \frac{1}{R_L} + (U_{izh} - U_1)\, j\omega C_\mu = 0$$

$$g_m U_1 = -\frac{U_{izh}}{R_L}$$

$$U_{izh} = -g_m R_L U_1$$

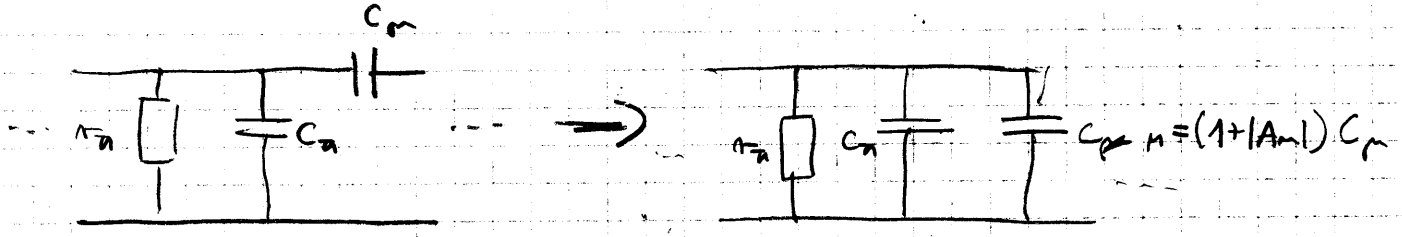
$$i_1 = (U_1 - U_{izh})\, j\omega C_\mu = (U_1 - (-g_m R_L U_1))\, j\omega C_\mu$$

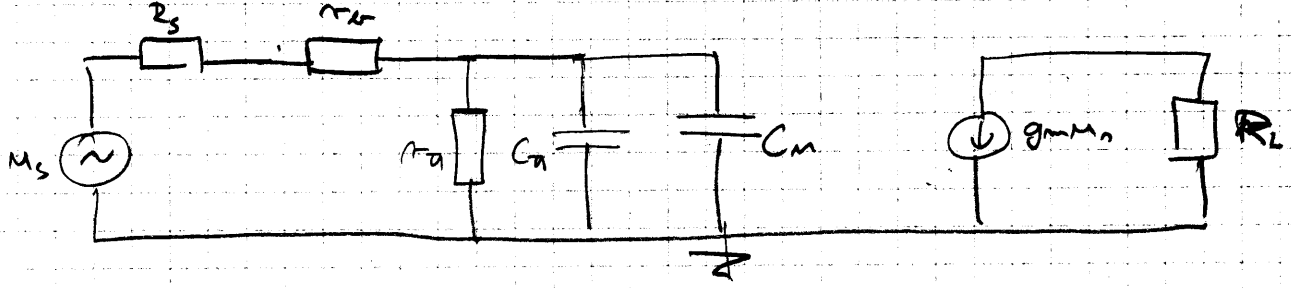
$$i_1 = U_1 (1 + g_m R_L)\, j\omega C_\mu$$

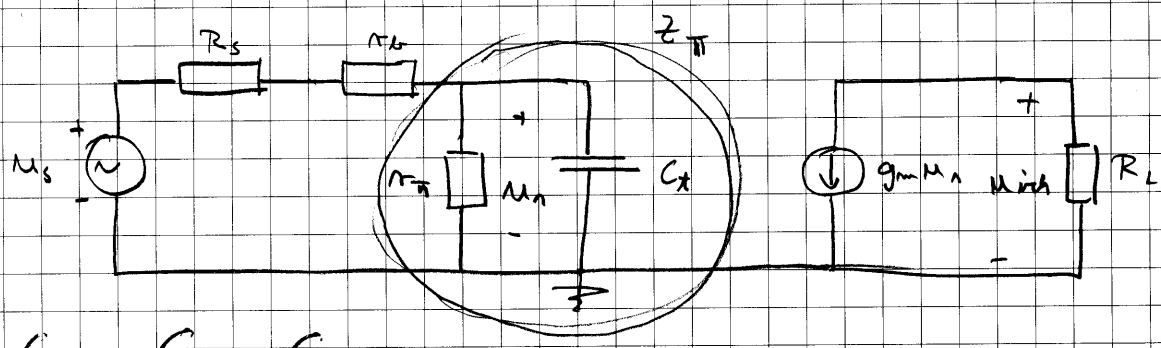
$$\frac{i_2}{U_1} = (1 + g_m R_L)\, j\omega C_\mu = C_M\, j\omega C_\mu$$

$$\downarrow$$

$$|A_M|$$







$$C_t = C_\pi + C_m$$

$$A_u = \frac{u_{izh}}{u_s}$$

$$Y_\pi = \frac{1}{r_\pi} + j\omega C_t = \frac{1 + j\omega C_t r_\pi}{r_\pi}$$

$$Z_\pi = \frac{r_\pi}{1 + j\omega C_t r_\pi}$$

$$u_{izh} = -g_m u_\pi R_L$$

$$u_\pi = \frac{Z_\pi}{Z_\pi + R_s + r_b} u_s$$

$$u_{izh} = -g_m R_L \frac{Z_\pi}{Z_\pi + R_s + r_b} u_s$$

$$A_u = -g_m R_L \frac{Z_\pi}{Z_\pi + R_s + r_b}$$

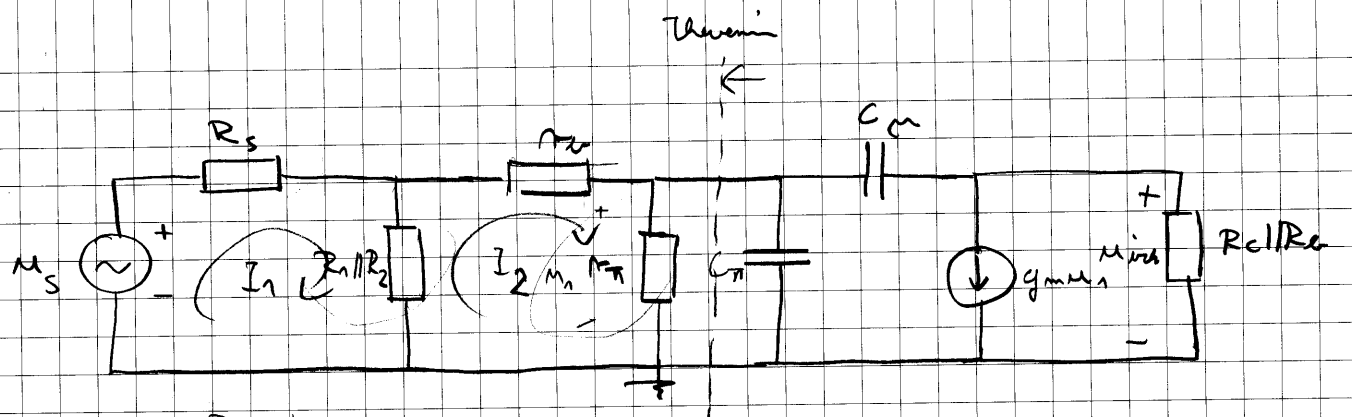
$$A_u = -g_m R_L \frac{\frac{r_\pi}{1 + j\omega C_t r_\pi}}{\frac{r_\pi}{1 + j\omega C_t r_\pi} + R_s + r_b} =$$

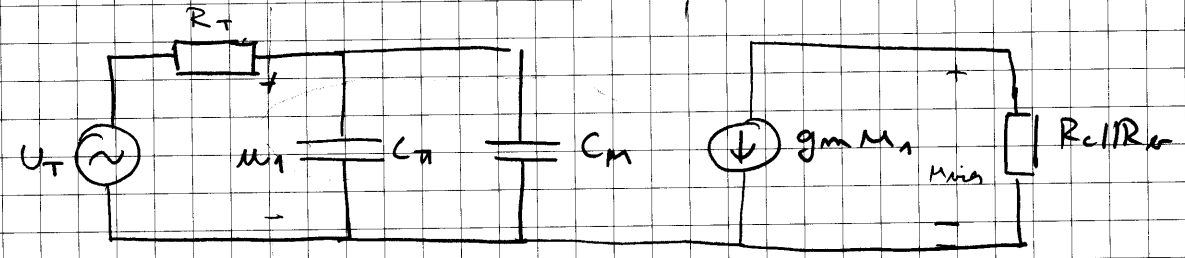
$$= -g_m R_L \frac{r_\pi}{r_\pi + j\omega C_t r_\pi (R_s + r_b) + R_s + r_b} =$$

$$(1 + j\omega C_t r_\pi)(R_s + r_b)$$

$$= -\frac{g_m R_L r_\pi}{r_\pi + R_s + r_b} \cdot \frac{1}{1 + j\omega \frac{C_t r_\pi (R_s + r_b)}{r_\pi + R_s + r_b}}$$

$$\omega_1 = \frac{r_\pi + R_s + r_b}{C_t r_\pi (R_s + r_b)}$$





$$u_s = I_1 (R_s + R_1 \| R_2) - I_2 (R_1 \| R_2)$$

$$0 = -I_1 (R_1 \| R_2) + I_2 (R_1 \| R_2 + r_{bb'} + r_\pi)$$

$$I_1 = \frac{I_2 (R_1 \| R_2 + r_{bb'} + r_\pi)}{R_1 \| R_2}$$

$$u_s = \frac{I_2 (R_1 \| R_2 + r_{bb'} + r_\pi)(R_s + R_1 \| R_2)}{R_1 \| R_2} - I_2 \cdot R_1 \| R_2$$

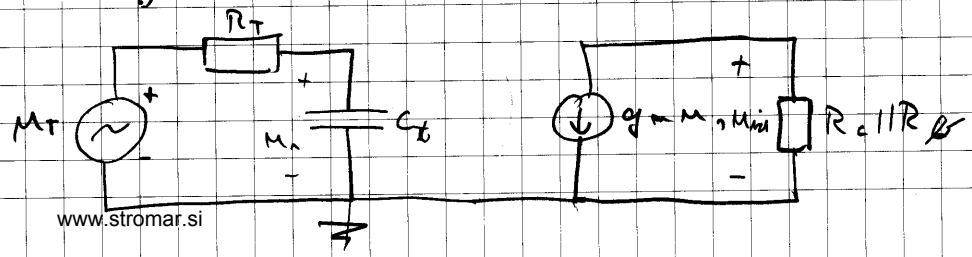
$$I_2 = \frac{u_s \cdot R_1 \| R_2}{R_s (R_1 \| R_2 + r_{bb'} + r_\pi) + R_1 \| R_2 (r_{bb'} + r_\pi)}$$

$$u_T = I_2 r_\pi = \frac{u_s \cdot R_1 \| R_2 \cdot r_\pi}{R_s (R_1 \| R_2 + r_{bb'} + r_\pi) + R_1 \| R_2 (r_{bb'} + r_\pi)}$$

$$R_T = (R_s \| (R_1 \| R_2) + r_{bb'}) \| r_\pi$$

$$C_M = (1 + |A_M|) C_\mu \qquad C_t = C_\pi + C_M$$

$$|A_M| = g_m R_c \| R_e$$



$$A_M = \frac{u_{izh}}{u_s} = \frac{u_{izh}}{u_T} \cdot \frac{u_T}{u_s}$$

$$u_{izh} = -g_m u_1 R_c \| R_b$$

$$u_1 = \frac{\frac{1}{j\omega C_t}}{\frac{1}{j\omega C_t} + R_T} u_T = \frac{1}{1 + j\omega C_t R_T} u_T$$

$$u_{izh} = -g_m R_c \| R_b \frac{1}{1 + j\omega C_t R_T} u_T$$

$$\frac{u_{izh}}{u_T} = -\frac{g_m R_c \| R_b}{1 + j\omega C_t R_T} = K \frac{1}{1 + \frac{j\omega}{\omega_p}}$$

$$K = -g_m R_c \| R_b$$

$$\omega_p = \frac{1}{C_t R_T}$$

$$A_M = \underbrace{-g_m R_c \| R_b \frac{R_1 \| R_2 \cdot r_\pi}{R_s (R_1 \| R_2 + r_b + r_\pi) + R_1 \| R_2 (r_b + r_\pi)}}_{K} \frac{1}{1 + \frac{j\omega}{\frac{1}{C_t R_T}}}$$

$$\omega_p = \frac{1}{(C_\pi + C_M) R_T} = \frac{1}{[C_\pi + (1 + g_m R_c \| R_b) C_{(M)}] [(R_s \| (R_1 \| R_2) + r_\pi) \| r_\pi]}$$

$$K = -27{,}27$$

$$\omega_p = 1{,}36 \cdot 10^7\ \Omega^{-1}$$