Zadatak. Na slici je prikazan pojačavač snage u klasi A. Poznato je: $R_1 = 111\Omega$, $R_2 = 39\Omega$, $R_E = 8\Omega$, $R_P = 4\Omega$, $V_{CC} = 15\text{V}$, $\beta_F = 50$, $V_{BE} = 0.7\text{V}$, $V_{CES} = 0.5\text{V}$, $L_m \to \infty$, $C_G \to \infty$, $C_E \to \infty$, $n = 2$. Napon na izlazu je trougaonog talasnog oblika maksimalne moguće amplitude za zadate parametre.

a) Nacrtati jednosmernu i dinamičku radnu pravu pojačavača.

b) Odrediti i nacrtati vremenske oblike napona v_{CE}, struje i_C i snaga p_D, p_{OUT}, p_L i p_{CC}.

c) Izračunati koeficijent korisnog dejstva pojačavača .

d) ponoviti tačku a) ako je $n = 3$

e) ponoviti tačku b) ako je $n = 3$

f) ponoviti tačku c) ako je $n = 3$

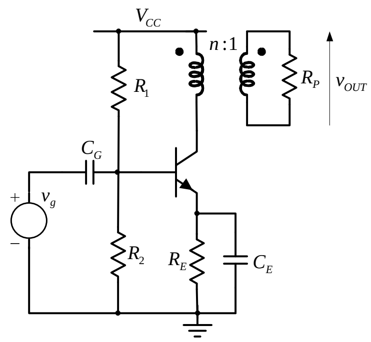
g) izvesti izraz za optimalnu vrednost parametra n, tako da se na izlazu dobija najveća moguća amplituda neizobličenog napona.

h) ako je $L_m = 20\text{mH}$ i $T = 1\text{ms}$, $n = n_{OPT}$, $V_{CES} = 0\text{V}$, pod pretpostavkom da je napon na izlazu pravougaonog talasnog oblika maksimalne moguće amplitude nacrtati jednosmernu radnu pravu pojačavača i putanju radne tačke pojačavača.

i) pod uslovima iz tačke h), odrediti i nacrtati vremenske oblike napona v_{CE}, struja i_C i i_L i snaga p_D, p_{OUT}, p_L i p_{CC}

j) pod uslovima iz tačke h), odrediti amplitudsku i faznu karakteristiku pojačanja

k) pod uslovima iz tačke h) uz $n = 4$ odrediti koeficijent korisnog dejstva pojačavača u zavisnosti od T.



Rešenje:

a)

Jednosmerna radna prava:

$$V_{CEQ} = V_{CC} - R_E \frac{\beta_F + 1}{\beta_F} I_{CQ}$$

Određivanje I_{CQ} i V_{CEQ}:

$$\frac{V_{CC} - V_B}{R_1} = \frac{V_B}{R_2} + I_B$$

$$I_E = \frac{V_B - V_{BE}}{R_E} = (1 + \beta_F) I_B$$

$$V_B = \frac{\frac{V_{BE}}{R_E} + \frac{(1+\beta_F)V_{CC}}{R_1}}{\frac{1}{R_E} + \frac{(1+\beta_F)}{R_1 \parallel R_2}} = 3.7\text{V}$$

$$V_E = V_B - V_{BE} = 3\text{V}$$

$$I_E = \frac{V_E}{R_E} = 375\text{mA}$$

$$I_{CQ} = \frac{\beta_F}{\beta_F + 1} I_E = 368\text{mA}$$

$$V_{CEQ} = V_{CC} - R_E I_{EQ} = 12\text{V}$$

Dinamička radna prava:

$$i_C - I_{CQ} = -\frac{1}{n^2 R_P}\left(v_{CE} - V_{CEQ}\right)$$

$$i_C = I_{CQ} - \frac{1}{n^2 R_P}\left(v_{CE} - V_{CEQ}\right)$$

<u>Uslov da se tranzistor ne isključi:</u>

$$i_C > 0$$

$$I_{CQ} - \frac{1}{n^2 R_P}\left(v_{CE} - V_{CEQ}\right) > 0$$

$$v_{CE} < n^2 R_P I_{CQ} + V_{CEQ}\text{, } v_{CE\max} = 17.888\text{V}$$

$$V_{ce\max} = 5.888\text{V}\left(< V_{CEQ} - V_{CES}\right) \text{ - ograničenje}$$

<u>Uslov da se tranzistor ne zasiti:</u>

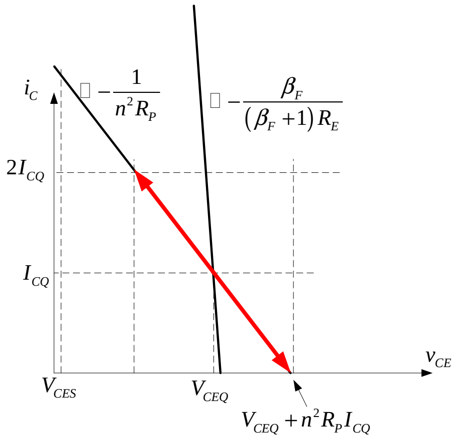
$$v_{CE} > V_{CES}$$

$$V_{CEQ} - n^2 R_P \left(i_C - I_{CQ}\right) > V_{CES}$$

$$i_C < I_{CQ} + \frac{V_{CEQ} - V_{CES}}{n^2 R_P}\text{, } i_{C\max} = 1.08675\text{A}$$

$$I_{c\max} = 0.71875\text{A}\left(> I_{CQ}\right) \text{ - nema ograničenja}$$

NA DELU JE OGRANIČENJE USLED ISKLJUČENJA



$$V_m=\frac{V_{ce\max}}{n}=2.944\,\mathrm{V}$$

b)

$$v_{OUT}=V_m\Delta(t)=2.944\,\mathrm{V}\Delta(t)$$

$$v_{CE}=V_{CEQ}-nv_{OUT}=V_{CEQ}-nV_m\Delta(t)=12\,\mathrm{V}-5.888\,\mathrm{V}\Delta(t)$$

$$i_C=I_{CQ}+\frac{1}{n}\frac{v_{OUT}}{R_P}=I_{CQ}+\frac{V_m}{nR_P}\Delta(t)=0.368\,\mathrm{A}\left(1+\Delta(t)\right)$$

$$p_{OUT}=\frac{{v_{OUT}}^2}{R_P}=\frac{{V_m}^2}{R_P}\Delta^2(t)=2.167\,\mathrm{W}\Delta^2(t)$$

$$p_D=v_{CE}i_C=\left(V_{CEQ}-nV_m\Delta(t)\right)\left(I_{CQ}+\frac{V_m}{nR_P}\Delta(t)\right)=V_{CEQ}I_{CQ}+V_m\left(\frac{V_{CEQ}}{nR_P}-nI_{CQ}\right)\Delta(t)-\frac{{V_m}^2}{R_P}\Delta^2(t)$$

$$=4.416\,\mathrm{W}+2.249\Delta(t)\,\mathrm{W}-2.167\Delta^2(t)\,\mathrm{W}$$

$$p_D(0)=4.498\,\mathrm{W}$$

$$p_D\left(\frac{T}{4}\right)=4.416\,\mathrm{W}$$

$$p_D\left(\frac{T}{2}\right)=0\,\mathrm{W}$$

Traženje ekstremuma funkcije:

$$p_D{}'=-\frac{4}{T}V_m\left(\frac{V_{CEQ}}{nR_P}-nI_{CQ}\right)\Pi(t)+\frac{8}{T}\frac{{V_m}^2}{R_P}\Delta(t)=0$$

U prvoj poluperiodi:

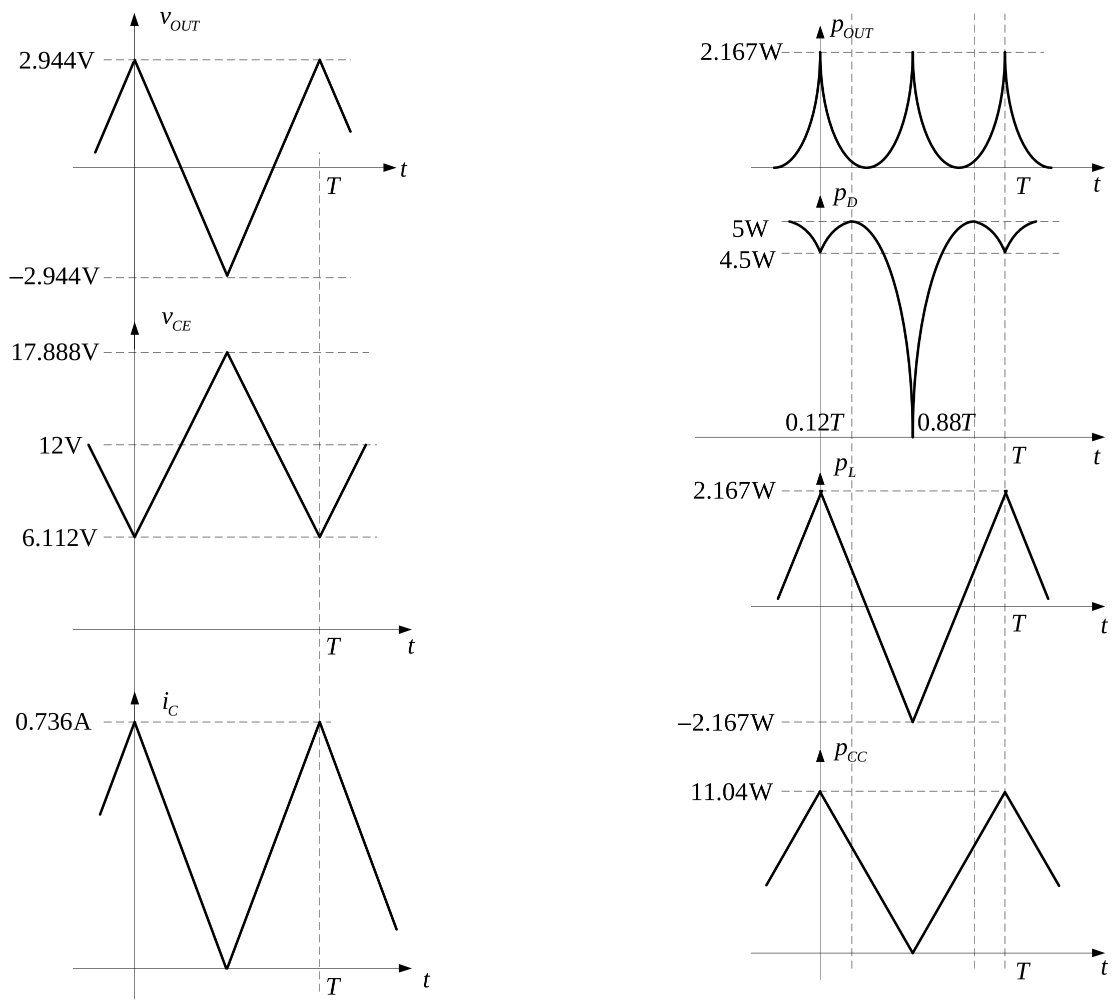
$$2\frac{V_m}{R_P}\left(1-\frac{4t}{T}\right)=\frac{V_{CEQ}}{nR_P}-nI_{CQ}$$

$$\frac{1-\left(\frac{V_{CEQ}}{nR_P}-nI_{CQ}\right)\frac{R_P}{2V_m}}{4}=\frac{t}{T}\Rightarrow t=0.12T$$

$$p_D(0.12T)=5\,\mathrm{W}\ \text{(maksimum)}$$

Druga poluperioda je simetrična u odnosu na $t = \frac{T}{2}$

$$p_L = n v_{OUT} I_{CQ} = n V_m I_{CQ} \Delta(t) = 2.167\,\mathrm{W}\Delta(t)$$
$$p_{CC} = V_{CC} i_C = V_{CC}\left(I_{CQ} + \frac{V_m}{nR_P}\Delta(t)\right) = 5.52\,\mathrm{W}\left(1 + \Delta(t)\right)$$



c)

$$P_{OUT} = \overline{p_{OUT}} = \overline{\frac{V_m^{\ 2}}{R_P}\Delta^2(t)} = \frac{V_m^{\ 2}}{R_P}\overline{\Delta^2(t)} = \frac{V_m^{\ 2}}{3R_P} = 0.72\,\mathrm{W}$$

$$P_{CC}=\overline{p_{CC}}=\overline{V_{CC}\left(I_{CQ}+\frac{V_m}{nR_P}\Delta(t)\right)}=V_{CC}\overline{\left(I_{CQ}+\frac{V_m}{nR_P}\Delta(t)\right)}=V_{CC}\left(I_{CQ}+\frac{V_m}{nR_P}\overline{\Delta(t)}\right)=$$
$$=V_{CC}I_{CQ}=5.52\,\text{W}$$

$$\eta=\frac{P_{OUT}}{P_{CC}}=13\%$$

d)
Jednosmerna radna prava i mirna radna tačka ostaju iste:

$$I_{CQ}=\frac{\beta_F}{\beta_F+1}I_E=368\text{mA}$$

$$V_{CEQ}=V_{CC}-R_EI_{CQ}=12\text{V}$$

Dinamička radna prava (isti opšti izraz)**:**

$$i_C=I_{CQ}-\frac{1}{n^2R_P}\left(v_{CE}-V_{CEQ}\right)$$

Uslov da se tranzistor ne isključi:

$$v_{CE}<n^2R_PI_{CQ}+V_{CEQ}\,,\; v_{CE\max}=25.248\text{V}$$

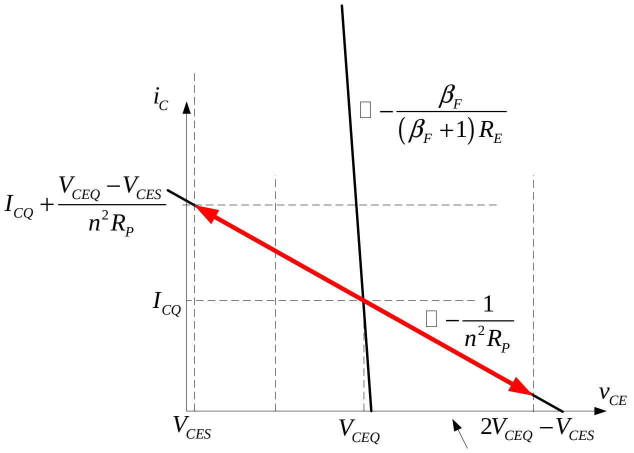
$$V_{ce\max}=13.248\text{V}\left(>V_{CEQ}-V_{CES}\right)\text{ - nema ograničenja}$$

Uslov da se tranzistor ne zasiti:

$$i_C<I_{CQ}+\frac{V_{CEQ}-V_{CES}}{n^2R_P}\,,\; i_{C\max}=0.6874\text{A}$$

$$I_{c\max}=0.3194\text{A}\left(<I_{CQ}\right)\text{ - ograničenje}$$

NA DELU JE OGRANIČENJE USLED ZASIĆENJA



$$V_m=\frac{V_{CEQ}-V_{CES}}{n}=3.833\,\text{V}$$

e)

$$v_{OUT}=V_m\Delta(t)=3.833\,\text{V}\Delta(t)$$

$$v_{CE} = V_{CEQ} - n v_{OUT} = V_{CEQ} - nV_m \Delta(t) = 12\,\mathrm{V} - 11.5\,\mathrm{V}\Delta(t)$$

$$i_C = I_{CQ} + \frac{1}{n}\frac{v_{OUT}}{R_P} = I_{CQ} + \frac{V_m}{nR_P}\Delta(t) = 0.368\,\mathrm{A} + 0.319\,\mathrm{A}\Delta(t)$$

$$p_{OUT} = \frac{{v_{OUT}}^2}{R_P} = \frac{{V_m}^2}{R_P}\Delta^2(t) = 3.673\,\mathrm{W}$$

$$p_D = v_{CE} i_C = \left(V_{CEQ} - nV_m\Delta(t)\right)\left(I_{CQ} + \frac{V_m}{nR_P}\Delta(t)\right) = V_{CEQ} I_{CQ} + V_m\left(\frac{V_{CEQ}}{nR_P} - nI_{CQ}\right)\Delta(t) - \frac{{V_m}^2}{R_P}\Delta^2(t) =$$

$$= 4.416\,\mathrm{W} - 0.399\Delta(t)\,\mathrm{W} - 3.673\Delta^2(t)\,\mathrm{W}$$

$$p_D(0) = 0.344\mathrm{W}$$

$$p_D\left(\frac{T}{4}\right) = 4.416\,\mathrm{W}$$

$$p_D\left(\frac{T}{2}\right) = 1.142\,\mathrm{W}$$

Traženje ekstremuma funkcije:

$$p_D{}' = -\frac{4}{T}V_m\left(\frac{V_{CEQ}}{nR_P} - nI_{CQ}\right)\Pi(t) + \frac{8}{T}\frac{{V_m}^2}{R_P}\Delta(t) = 0$$

U prvoj poluperiodi:

$$2\frac{V_m}{R_P}\left(1 - \frac{4t}{T}\right) = \frac{V_{CEQ}}{nR_P} - nI_{CQ}$$

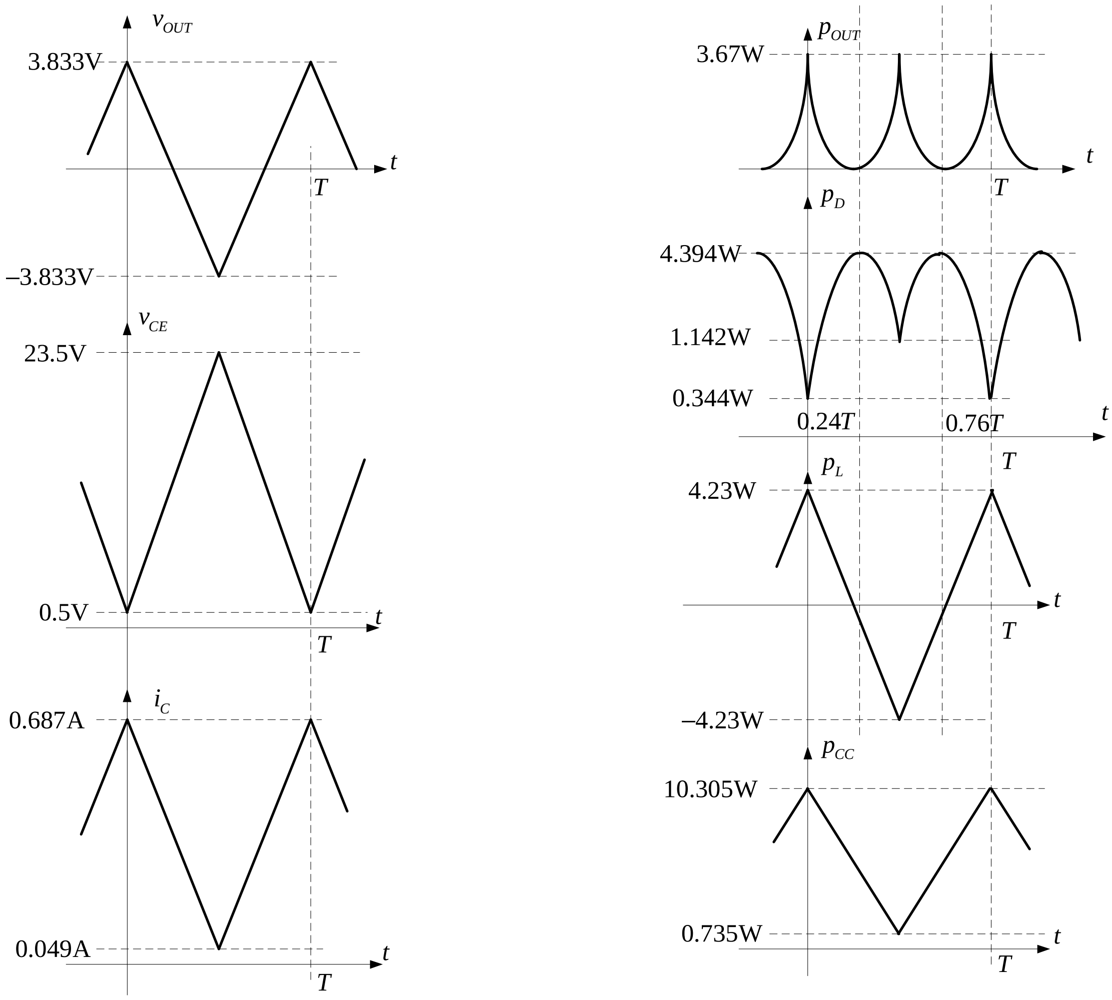
$$\frac{1 - \left(\frac{V_{CEQ}}{nR_P} - nI_{CQ}\right)\frac{R_P}{2V_m}}{4} = \frac{t}{T} \Rightarrow t = 0.24T$$

$$p_D(0.24T) = 4.394\,\mathrm{W} \quad \text{(maksimum)}$$

Druga poluperioda je simetrična u odnosu na $t = \frac{T}{2}$

$$p_L = n v_{OUT} I_{CQ} = nI_{CQ}V_m\Delta(t) = 4.232\,\mathrm{W}\Delta(t)$$

$$p_{CC} = V_{CC} i_C = V_{CC}\left(I_{CQ} + \frac{V_m}{nR_P}\Delta(t)\right) = 5.52\,\mathrm{W} + 4.785\,\mathrm{W}\Delta(t)$$



f)

$$P_{OUT}=\overline{p_{OUT}}=\overline{\frac{V_m^{\ 2}}{R_P}\Delta^2(t)}=\frac{V_m^{\ 2}}{R_P}\overline{\Delta^2(t)}=\frac{V_m^{\ 2}}{3R_P}=1.224\,\text{W}$$

$$P_{CC}=\overline{p_{CC}}=\overline{V_{CC}\left(I_{CQ}+\frac{V_m}{nR_P}\Delta(t)\right)}=V_{CC}I_{CQ}=5.52\,\text{W}$$

$$\eta=\frac{P_{OUT}}{P_{CC}}=22\%$$

g)

Maksimalna amplituda neizobličenog napona dobija se kada se mirna radna tačka nalazi na polovini dinamičke radne prave, odnosno ako se istovremeno dostižu naponsko i strujno ograničenje:

$$i_{C\max}=2I_{CQ}=I_{CQ}+\frac{V_{CEQ}-V_{CES}}{n^2R_P}$$

$$v_{CE\min}=V_{CES}=V_{CEQ}-n^2R_PI_{CQ}$$

$$n^2 = \frac{V_{CC} - R_E \frac{\beta_F + 1}{\beta_F} I_{CQ} - V_{CES}}{I_{CQ} R_P}$$

$$n_{OPT} = \sqrt{\frac{1}{R_P}\left(\frac{V_{CC} - V_{CES}}{I_{CQ}} - \frac{\beta_F + 1}{\beta_F} R_E\right)} = 2.8$$

h)

Jednosmerna radna prava i mirna radna tačka ostaju iste:

$$I_{CQ} = \frac{\beta_F}{\beta_F + 1} I_E = 368\text{mA}$$

$$V_{CEQ} = V_{CC} - R_E I_{EQ} = 12\text{V}$$

Kako bi odredili putanju radne tačke, potrebno je odrediti opšte izraze za napone i struje…

$$v_{OUT} = \frac{V_{ce}}{n} \Pi(t)$$

$$v_{CE} = V_{CEQ} - V_{ce} \Pi(t)$$

$$i_L = I_{CQ} + \frac{n}{L} \int v_{OUT} dt = I_{CQ} + \frac{V_{ce}}{L} \int \Pi(t) dt = I_{CQ} - \frac{V_{ce} T}{4L} \Delta(t)$$

$$i_C = i_L + \frac{v_{OUT}}{n R_P} = I_{CQ} - \frac{V_{ce} T}{4L} \Delta(t) + \frac{V_{ce}}{n^2 R_P} \Pi(t)$$

NAPONSKO OGRANIČENJE:

Kada je $v_{CE} = 0, V_{ce} = V_{CEQ} - V_{CES} \approx V_{CEQ}$:

$$i_{C\max} = I_{CQ} + \frac{V_{ce}}{n^2 R_P} + \frac{V_{ce} T}{4L} = I_{CQ} + V_{CEQ}\left(\frac{1}{n^2 R_P} + \frac{T}{4L}\right)$$

$i_{C\max} = 0.9\text{A} > 2 I_{CQ}$ - nema problema

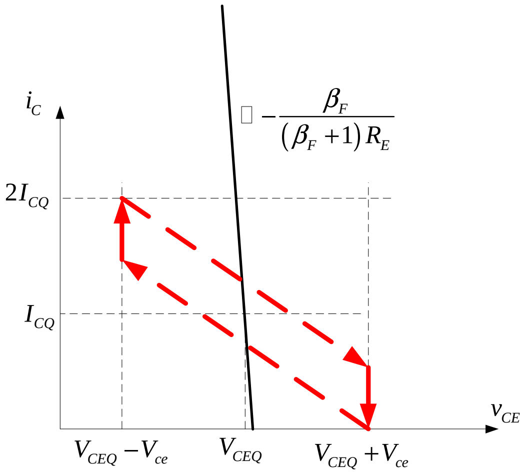
STRUJNO OGRANIČENJE:

Kada je $i_C = 0$:

$$i_{C\min} = I_{CQ} - \frac{V_{ce}}{n^2 R_P} - \frac{V_{ce} T}{4L} = 0$$

$V_{ce\max} = \dfrac{I_{CQ}}{\dfrac{T}{4L} + \dfrac{1}{n^2 R_P}} = 8.29\text{V}$ ograničenje, pošto je $\le V_{CEQ} - V_{CES}$!

Konačno: $V_{ce} = 8.29\text{V}$, $V_m = \dfrac{V_{ce}}{n} = 2.96\text{V}$



i)

$$v_{OUT} = V_m \Pi(t) = 2.96\,\mathrm{V}\Pi(t)$$

$$v_{CE} = V_{CEQ} - n v_{OUT} = V_{CEQ} - n V_m \Pi(t) = 12\,\mathrm{V} - 8.29\,\mathrm{V}\Pi(t)$$

$$i_L = I_{CQ} - \frac{V_{ce}T}{4L}\Delta(t) = 0.368\,\mathrm{A} - 0.104\,\mathrm{A}\Delta(t)$$

$$i_C = I_{CQ} - \frac{V_{ce}T}{4L}\Delta(t) + \frac{V_{ce}}{n^2 R_P}\Pi(t) = 0.368\,\mathrm{A} - 0.104\,\mathrm{A}\Delta(t) + 0.262\,\mathrm{A}\Pi(t)$$

$$i_C(0) = I_{CQ} + \frac{V_{ce}}{n^2 R_P} - \frac{V_{ce}T}{4L} = 0.529\mathrm{A}$$

$$i_C(T/2^-) = I_{CQ} + \frac{V_{ce}}{n^2 R_P} + \frac{V_{ce}T}{4L} = 0.736\mathrm{A}$$

$$i_C(T/2^+) = I_{CQ} - \frac{V_{ce}}{n^2 R_P} + \frac{V_{ce}T}{4L} = 0.207\mathrm{A}$$

$$i_C(T) = I_{CQ} - \frac{V_{ce}}{n^2 R_P} - \frac{V_{ce}T}{4L} = 0\mathrm{A}$$

$$p_{OUT} = \frac{{v_{OUT}}^2}{R_P} = \frac{{V_m}^2}{R_P}\Pi^2(t) = \frac{{V_m}^2}{R_P} = 2.19\,\mathrm{W}$$

$$p_D = v_{CE} i_C = \left(V_{CEQ} - nV_m \Pi(t)\right)\left(I_{CQ} - \frac{V_{ce}T}{4L}\Delta(t) + \frac{V_{ce}}{n^2 R_P}\Pi(t)\right) =$$

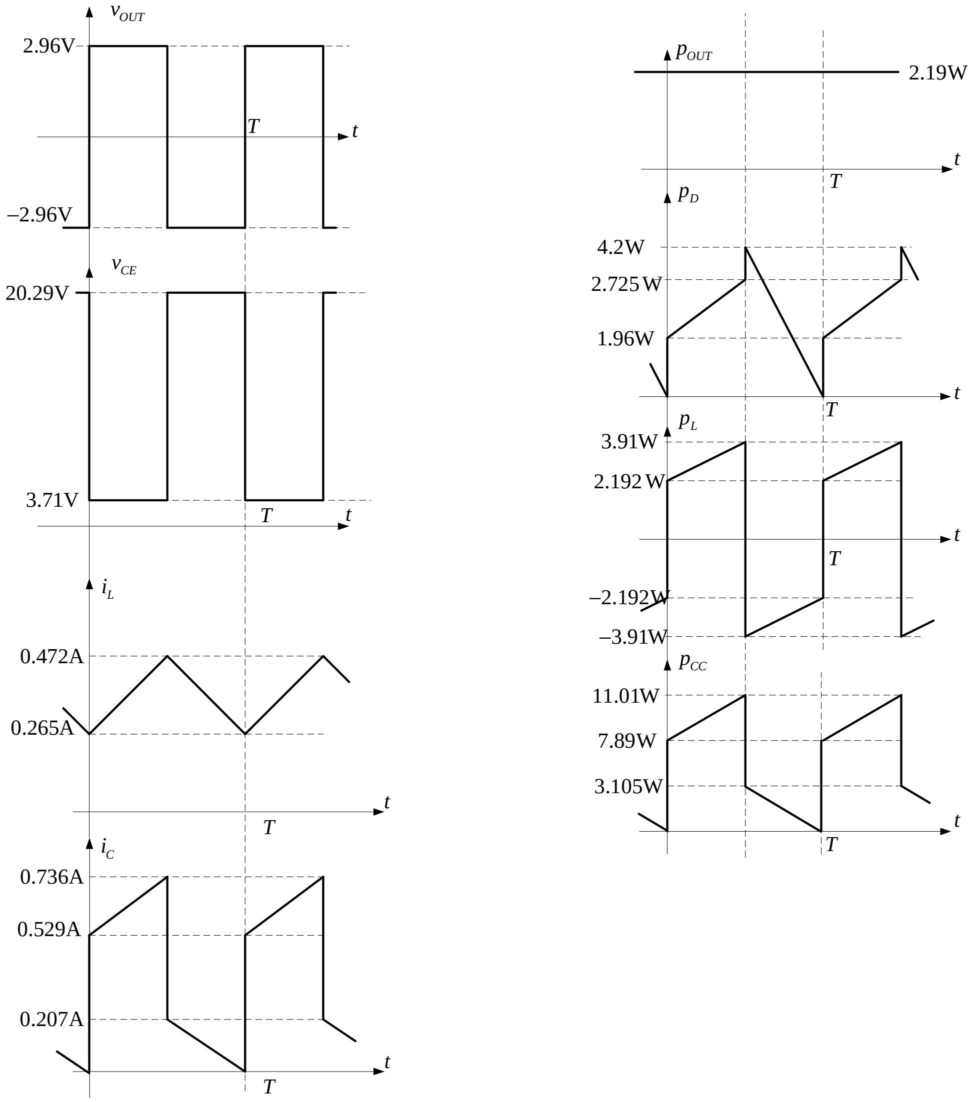
$$= V_{CEQ} I_{CQ} - \frac{{V_{ce}}^2}{n^2 R_P} - V_{ce}\frac{V_{CEQ}T}{4L}\Delta(t) + V_{ce}\left(\frac{V_{CEQ}}{n^2 R_P} - I_{CQ}\right)\Pi(t) + \frac{{V_{ce}}^2 T}{4L}\Pi(t)\Delta(t) =$$

$$= 2.24\,\mathrm{W} - 1.244\,\mathrm{W}\Delta(t) + 0.1\,\mathrm{W}\Pi(t) + 0.859\,\mathrm{W}\Pi(t)\Delta(t)$$

$$p_L = n v_{OUT} i_L = nV_m \Pi(t)\left(I_{CQ} - \frac{V_{ce}T}{4L}\Delta(t)\right) = V_{ce}\Pi(t)\left(I_{CQ} - \frac{V_{ce}T}{4L}\Delta(t)\right) =$$

$$= 3.051\,\mathrm{W}\Pi(t) - 0.859\,\mathrm{W}\Pi(t)\Delta(t)$$

$$p_{CC} = V_{CC} i_C = V_{CC}\left(I_{CQ} - \frac{V_{ce}T}{4L}\Delta(t) + \frac{V_{ce}}{n^2 R_P}\Pi(t)\right) = 5.52\,\mathrm{W} - 1.56\,\mathrm{W}\Delta(t) + 3.93\,\mathrm{W}\Pi(t)$$



j)

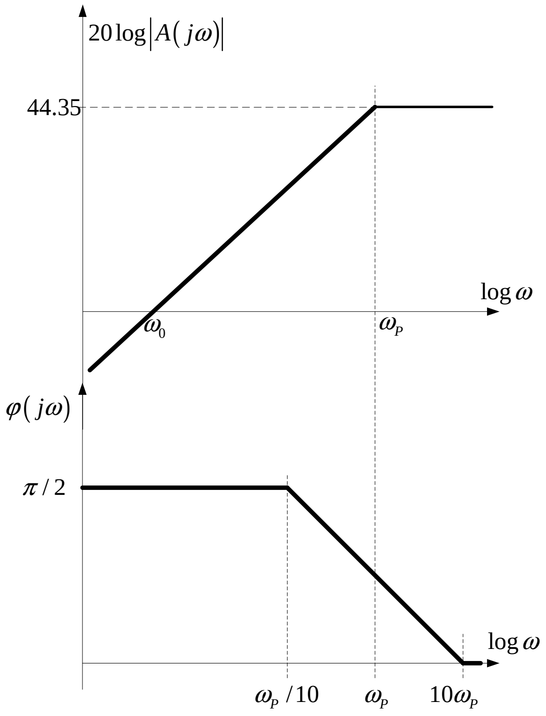
$$A(s)=\frac{v_p(s)}{v_u(s)}=\frac{1}{n}g_m n^2R_P \| sL=\frac{1}{n}g_m\frac{sLn^2R_P}{sL+n^2R_P}=\frac{1}{n}g_m\frac{sL}{sL\frac{1}{n^2R_P}+1}$$

$$A(j\omega)=\frac{1}{n}g_m\frac{j\omega L}{j\omega L\frac{1}{n^2R_P}+1}=\frac{j\frac{\omega}{\omega_0}}{j\frac{\omega}{\omega_P}+1}$$

$$\omega_0=\frac{n}{g_mL}=9.51\text{rad/s},\omega_P=\frac{n^2R_P}{L}=1568\text{rad/s}$$

$$g_m=I_{CQ}/V_T=14.72\text{S}$$

$$A(\infty)=\frac{\omega_P}{\omega_0}\approx 165$$



k)

ZASIĆENJE TRANZISTORA:

Kada je $v_{CE}=v_{CE\min}=V_{CEQ}-V_{ce}(\geq V_{CES})$:

$$i_{C\max}=I_{CQ}+\frac{V_{ce}}{n^2R_P}+\frac{T}{4L}V_{ce}=I_{CQ}+V_{ce}\left(\frac{1}{n^2R_P}+\frac{T}{4L}\right)$$

$$V_{ce}=\frac{i_{C\max}-I_{CQ}}{\frac{1}{n^2R_P}+\frac{T}{4L}}\leq V_{CEQ}-V_{CES}\left(\approx V_{CEQ}\right)$$

Najgori slučaj je kada je struja najveća: $i_{C\max}=2I_{CQ}$

$$V_{ce\max}=\frac{I_{CQ}}{\frac{1}{n^2R_P}+\frac{T}{4L}}\leq V_{CEQ}-V_{CES}\left(\approx V_{CEQ}\right)$$

granična vrednost periode:

$$T\geq 4L\left(\frac{I_{CQ}}{V_{CEQ}}-\frac{1}{n^2R_P}\right)=1.2\text{ms}$$

$$V_{ce} = \begin{cases} V_{CEQ}, & T \le 4L\left(\dfrac{I_{CQ}}{V_{CEQ}} - \dfrac{1}{n^2 R_P}\right) \\ \dfrac{I_{CQ}}{\dfrac{1}{n^2 R_P} + \dfrac{T}{4L}}, & T > 4L\left(\dfrac{I_{CQ}}{V_{CEQ}} - \dfrac{1}{n^2 R_P}\right) \end{cases}$$

ZAKOČENJE TRANZISTORA:

Kada je $v_{CE} = v_{CE\max} = V_{CEQ} + V_{ce}$:

$$i_{C\min} = I_{CQ} - \frac{V_{ce}}{n^2 R_P} - \frac{T}{4L} V_{ce} = I_{CQ} - V_{ce}\left(\frac{1}{n^2 R_P} + \frac{T}{4L}\right) \ge 0$$

$$V_{ce} \le \frac{I_{CQ}}{\dfrac{1}{n^2 R_P} + \dfrac{T}{4L}} \le V_{CEQ} - V_{CES} \left(\approx V_{CEQ}\right)$$

Dobija se isti rezultat kao i za naponsko ograničenje

Kada je $T \le 4L\left(\dfrac{I_{CQ}}{V_{CEQ}} - \dfrac{1}{n^2 R_P}\right)$

$$P_{CC} = V_{CC} I_{CQ}$$

$$P_{OUT} = \frac{V_m^{\ 2}}{R_P} = \frac{V_{ce}^{\ 2}}{n^2 R_P} = \frac{V_{CEQ}^{\ 2}}{n^2 R_P}$$

$$\eta = \frac{V_{CEQ}^{\ 2}}{n^2 R_P I_{CQ} V_{CC}} = 41\%$$

Kada je $T > 4L\left(\dfrac{I_{CQ}}{V_{CEQ}} - \dfrac{1}{n^2 R_P}\right)$

$$P_{CC} = V_{CC} I_{CQ}$$

$$P_{OUT} = \frac{V_m^{\ 2}}{R_P} = \frac{V_{ce}^{\ 2}}{n^2 R_P} = \frac{1}{n^2 R_P}\left(\frac{I_{CQ}}{\dfrac{1}{n^2 R_P} + \dfrac{T}{4L}}\right)^2$$

$$\eta = \frac{I_{CQ}}{n^2 R_P V_{CC}}\left(\frac{1}{\dfrac{1}{n^2 R_P} + \dfrac{T}{4L}}\right)^2 = 0.00038\left(\frac{1}{0.015625 + 12.5T}\right)^2$$