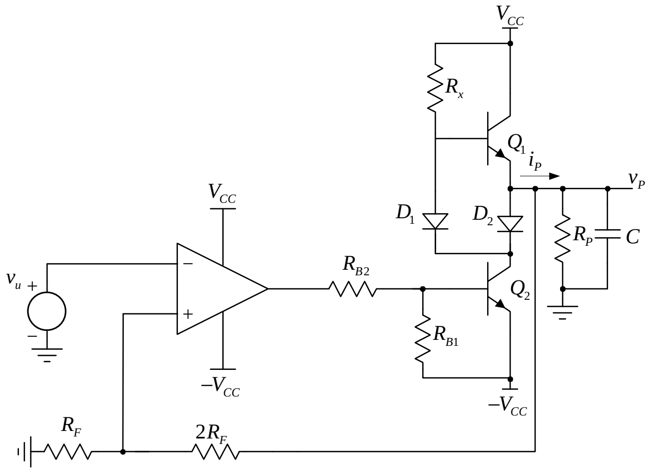
Zadatak. U kolu sa slike operacioni pojačavač se može smatrati idealnim, sa maksimalnom strujom $i_{OP\max} = 4\text{mA}$. Parametri tranzistora u kolu sa slike su $\beta_F = 100$, $V_{BE} = 0.7\text{V}$, $V_{CES} = 0.2\text{V}$ dok je $V_{CC} = 12\text{V}$, $R_P \to \infty$, $C = 2.5\mu\text{F}$, $R_x = 1\text{k}\Omega$, $R_{B1} = 1\text{k}\Omega$, $R_{B2} = 2\text{k}\Omega$. Napon na ulazu kola je trougaonog talasnog oblika periode T.



a) nacrtati i označiti dijagrame v_U, v_P, i_P, i_{C1} i_{C2}, v_{IOP} tokom jedne periode ulaznog napona, ako je $V_u = 3\text{V}$, $T = 1\text{ms}$.

b) Pod uslovima iz tačke b) izračunati snage disipacije tranzistora Q_1 i Q_2, i korisnu snagu koja se razvija na potrošaču.

c) Odrediti graničnu vrednost kapacitivnosti C tako da maksimalno moguća amplituda neizobličenog simetričnog napona na izlazu ne zavisi od vrednosti ove kapacitivnosti.

d) Pod uslovima iz prethodne tačke, i ako je $C = C_{gr}$ odrediti opseg mogućih vrednosti otpornosti R_{B2} tako da kolo i dalje ispravno radi

e) Ako je na ulazu kola sinusoidalni napon amplitude V_u, odrediti zavisnost srednje snage disipacije na tranzistorima Q_1 i Q_2 od V_u za $R_P = 100\Omega$, $C \to 0$, i $C \to \infty$

Rešenje:

a)

$$v_P = 3v_U = 3V_u\Delta(t)$$

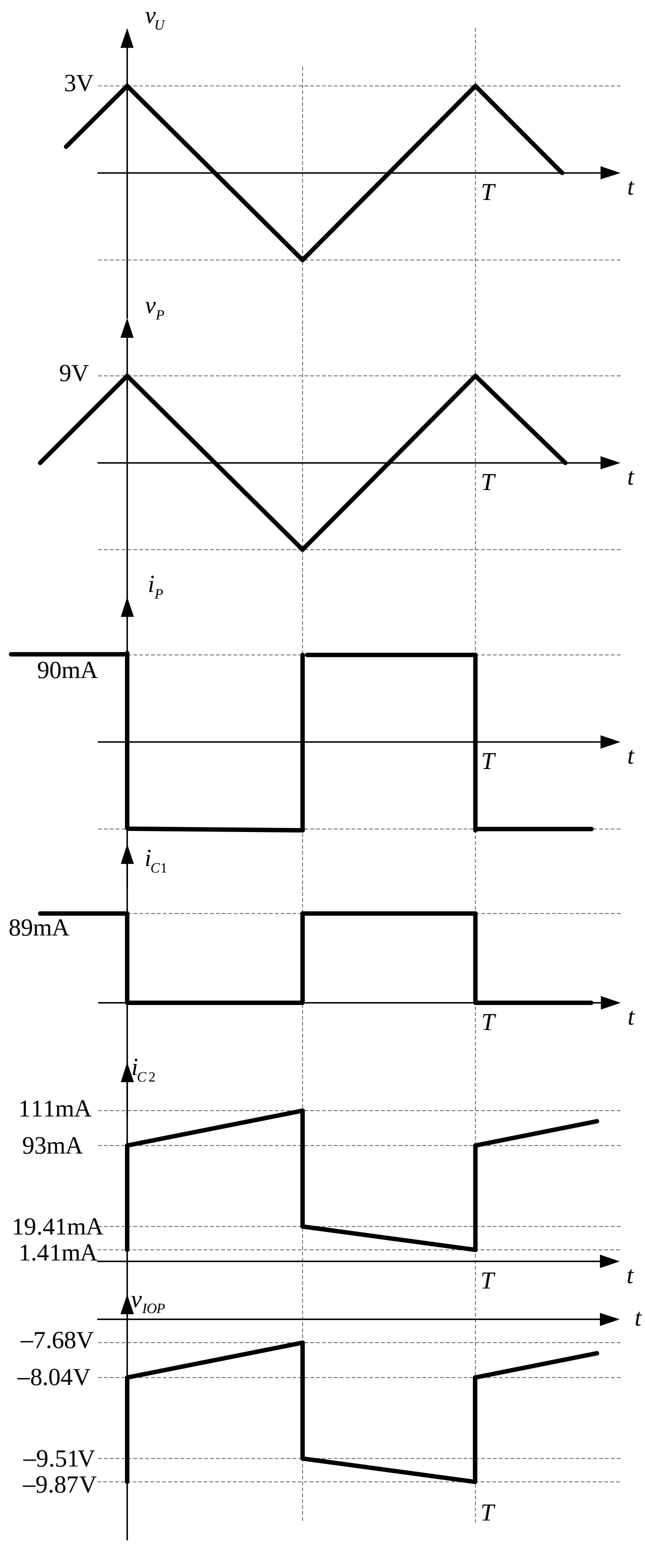
$$i_P = C\frac{dv_P}{dt} = 3CV_u\frac{d\Delta(t)}{dt} = -\frac{12CV_u}{T}\Pi(t) = -90\,\text{mA}\Pi(t)$$

$$i_{C1} = \begin{cases} \dfrac{\beta}{1+\beta}i_P, & i_P > 0 \\ 0 & i_P < 0 \end{cases} = \begin{cases} 0 & nT \le t \le \dfrac{2n+1}{2}T \\ 89\text{mA} & \dfrac{2n+1}{2}T \le t \le (n+1)T \end{cases}$$

$$i_{C2} = \begin{cases} \dfrac{V_{CC} - v_P}{R_x} - i_P, & nT \le t \le \dfrac{2n+1}{2}T \\ \dfrac{V_{CC} - V_{BE}}{R_x} - \dfrac{v_P}{R_x} - \dfrac{i_P}{1+\beta}, & \dfrac{2n+1}{2}T \le t \le (n+1)T \end{cases}$$

$$i_{C2} = \begin{cases} 102\,mA - 9\,mA\Delta(t) & nT \le t \le \dfrac{2n+1}{2}T \\ 10.41\,mA - 9mA\Delta(t) & \dfrac{2n+1}{2}T \le t \le (n+1)T \end{cases}$$

$$v_{IOP} = -V_{CC} + V_{BE} + R_{B2}\left(\frac{V_{BE}}{R_{B1}} + \frac{i_{C2}}{\beta}\right) = \begin{cases} -7.86\,V - 0.18\,V\Delta(t) & nT \le t \le \dfrac{2n+1}{2}T \\ -9.69\,V - 0.18\,V\Delta(t) & \dfrac{2n+1}{2}T \le t \le (n+1)T \end{cases}$$



b)

$$P_{D1} = \frac{1}{T}\int_{\frac{T}{2}}^{T} 89\ \text{mA}\left(12 - 9\Delta(t)\right)\text{V}\,dt = \frac{1}{T}\left(1068\ \text{mW}\int_{\frac{T}{2}}^{T} dt - 801\ \text{mW}\int_{\frac{T}{2}}^{T}\Delta(t)\,dt\right) = \ldots = 0.534\ \text{W}$$

$$P_{D2} = \frac{1}{T}\int_0^{\frac{T}{2}} (11.3\text{ V} + 9\text{ V}\Delta(t))(102\text{ mA} - 9\text{ mA}\Delta(t))dt + \frac{1}{T}\int_{\frac{T}{2}}^{T} (12\text{ V} + 9\text{ V}\Delta(t))(10.41\text{ mA} - 9\text{ mA}\Delta(t))dt =$$

$$= \left(\frac{1}{T}\int_0^{\frac{T}{2}} 1152.6\text{ mW}dt - \frac{1}{T}\int_0^{\frac{T}{2}} 101.7\text{ mW}\Delta(t)dt + \frac{1}{T}\int_0^{\frac{T}{2}} (918\text{ mW}\Delta(t))dt - \frac{1}{T}\int_0^{\frac{T}{2}} 81\text{ mW}\Delta^2(t)dt \right) +$$

$$+ \left(\frac{1}{T}\int_{\frac{T}{2}}^{T} 124.92\text{ mW}dt - \frac{1}{T}\int_{\frac{T}{2}}^{T} 10812\text{ mW}\Delta(t)dt + \frac{1}{T}\int_{\frac{T}{2}}^{T} 93.69\text{ mW}\Delta(t)dt - \frac{1}{T}\int_{\frac{T}{2}}^{T} 81\text{ mW}\Delta^2(t)dt \right) =$$

$$= 0.61\text{ W}$$

$$P_{OUT} = 0$$

c)

Strujno ograničenje tranzistora Q_1, kada sva struja iz otpornika R_x ode u bazu tranzistora Q_1:

$$V_{CC} = \frac{R_x I_p}{1+\beta} + V_{BE} + v_{P\max}$$

$$V_{CC} = \frac{R_x}{1+\beta}\frac{4C}{T} v_{P\max} + V_{BE} + v_{P\max}$$

$$v_{P\max 1} = \frac{V_{CC} - V_{BE}}{1 + \frac{R_x}{1+\beta}\frac{4C}{T}}$$

Strujno ograničenje operacionog pojačavača:

$$i_{OP} = \frac{V_{BE}}{R_{B1}} + \frac{i_{C2}}{\beta} \le i_{OP\max}$$

Kritično je kada je struja kolektora Q_2 veća, a to je prva poluperioda

$$i_{P\min} = -\left(\beta\left(i_{OP\max} - \frac{V_{BE}}{R_{B1}} - \right) - \frac{V_{CC} - v_{P\min 1}}{R_x} \right)$$

$$\frac{4Cv_{p\min 1}}{T} = -\left(\beta\left(i_{OP\max} - \frac{V_{BE}}{R_{B1}} \right) - \frac{V_{CC} - v_{P\min 1}}{R_x} \right) = -\beta\left(i_{OP\max} - \frac{V_{BE}}{R_{B1}} \right) + \frac{V_{CC}}{R_x} - \frac{v_{P\min 1}}{R_x}$$

$$v_{P\min 1} = -\frac{\beta\left(i_{OP\max} - \frac{V_{BE}}{R_{B1}} \right) - \frac{V_{CC}}{R_x}}{\frac{4C}{T} + \frac{1}{R_x}}$$

Naponsko zasićenje operacionog pojačavača:

$$-V_{CC} \le -V_{CC} + V_{BE} + R_{B2}\left(\frac{V_{BE}}{R_{B1}} + \frac{i_{C2}}{\beta} \right) \le V_{CC}$$

Negativno zasićenje se nikada neće dostići. Preostaje pozitivno:

$$-V_{CC} + V_{BE} + R_{B2}\left(\frac{V_{BE}}{R_{B1}} + \frac{i_{C2}}{\beta} \right) \le V_{CC}$$

$$i_{C2} \le \beta\left(\frac{2V_{CC}}{R_{B2}} - V_{BE}\left(\frac{1}{R_{B1}} + \frac{1}{R_{B2}}\right)\right)$$

$$\frac{V_{CC} - v_{P\min 3}}{R_x} - \beta\left(\frac{2V_{CC}}{R_{B2}} - V_{BE}\left(\frac{1}{R_{B1}} + \frac{1}{R_{B2}}\right)\right) \le \frac{4Cv_{p\min 3}}{T}$$

$$v_{P\min 3} = \frac{\frac{V_{CC}}{R_x} - \beta\left(\frac{2V_{CC}}{R_{B2}} - V_{BE}\left(\frac{1}{R_{B1}} + \frac{1}{R_{B2}}\right)\right)}{\frac{1}{R_x} + \frac{4C}{T}}$$

Naponska ograničenja:

$$v_{P\max 2} = V_{CC} - V_{CES} = 11.8\text{V}$$

$$v_{P\min 2} = -V_{CC} + V_{CES} + V_D = -11.1\text{V}$$

Treba da strožiji od naponskih uslova bude strožiji od strožijeg strujnog uslova:

$$\left|v_{P\min 2}\right| \le v_{P\max 1}$$

$$C \le \frac{(1+\beta)T}{4R_x}\left(\frac{V_{CC} - V_{BE}}{\left|v_{P\min 2}\right|} - 1\right) = 455\text{nF}$$

$$\left|v_{P\min 2}\right| \le \left|v_{P\min 1}\right|$$

$$C \le \frac{T}{4}\left(\frac{\beta\left(i_{OP\max} - \frac{V_{BE}}{R_{B1}}\right) - \frac{V_{CC}}{R_x}}{\left|v_{P\min 2}\right|} - \frac{1}{R_x}\right) = 6.91\mu\text{F}$$

$$\left|v_{P\min 2}\right| \le \left|v_{P\min 3}\right|$$

$$C \le \frac{T}{4}\left(\frac{\beta\left(\frac{2V_{CC}}{R_{B2}} - V_{BE}\left(\frac{1}{R_{B1}} + \frac{1}{R_{B2}}\right)\right) - \frac{V_{CC}}{R_x}}{\left|v_{P\min 2}\right|} - \frac{1}{R_x}\right) = 24.1\, mH$$

d)

$$v_{IOP} = -V_{CC} + V_{BE} + R_{B2}\left(\frac{V_{BE}}{R_{B1}} + \frac{i_{C2}}{\beta}\right)$$

$$v_{IOP\max} = -V_{CC} + V_{BE} + R_{B2}\left(\frac{V_{BE}}{R_{B1}} + \frac{i_{C2\max}}{\beta}\right) \le V_{CC}$$

$$i_{C2\max} = \frac{V_{CC} - v_{P\min}}{R_x} - i_{P\min} = \frac{V_{CC} - v_{P\min}}{R_x} - \frac{4Cv_{P\min}}{T} = \left\langle \begin{matrix} v_{P\min} = -11.1\text{V} \\ C = 454\text{nF} \end{matrix} \right\rangle = 43\text{mA}$$

$$R_{B2} \le \frac{2V_{CC} - V_{BE}}{\frac{V_{BE}}{R_{B1}} + \frac{i_{C2\max}}{\beta}} = 20.62\text{k}\Omega$$

e)

$C \to 0$ je ekvivalentno kao da je otpornik sam

$$v_P = 3v_U = 3V_u \sin\omega t$$

$$i_P = \frac{3V_u}{R_P}\sin\omega t$$

$$i_{C1} = \begin{cases} \frac{\beta}{1+\beta}\frac{3V_u}{R_P}\sin\omega t, & i_P > 0 \\ 0 & i_P < 0 \end{cases}$$

$$i_{C2} = \begin{cases} \frac{V_{CC}-V_{BE}}{R_x} - \frac{3V_u}{R_x}\sin\omega t - \frac{1}{1+\beta}\frac{3V_u}{R_P}\sin\omega t, & i_P > 0 \\ \frac{V_{CC}-3V_u\sin\omega t}{R_x} - \frac{3V_u}{R_P}\sin\omega t & i_P < 0 \end{cases}$$

$$P_{D1} = \frac{1}{T}\int_0^{\frac{T}{2}}\frac{V_p}{R_P}\sin\omega t\left(V_{CC}-V_p\sin\omega t\right)dt = \frac{V_{CC}V_p}{R_P}\frac{1}{T}\int_0^{\frac{T}{2}}\sin\omega t dt - \frac{{V_p}^2}{R_P}\frac{1}{T}\int_0^{\frac{T}{2}}\sin^2\omega t dt =$$

$$= \frac{V_{CC}V_p}{R_P}\frac{1}{\pi} - \frac{{V_p}^2}{R_P}\frac{1}{4} = \frac{3V_{CC}V_u}{\pi R_P} - \frac{\left(3V_u\right)^2}{4R_P} = 0.115V_u - 0.022{V_u}^2$$

$$P_{D2} = \frac{1}{T}\int_0^{\frac{T}{2}}\left(\frac{V_{CC}-V_{BE}}{R_x} - \frac{V_p}{R_x}\sin\omega t - \frac{1}{1+\beta}\frac{V_p}{R_P}\sin\omega t\right)\left(V_p\sin\omega t + V_{CC}\right)dt$$

$$+\frac{1}{T}\int_{\frac{T}{2}}^{T}\left(\frac{V_{CC}-V_p\sin\omega t}{R_x} - \frac{V_p}{R_P}\sin\omega t\right)\left(V_p\sin\omega t + V_{CC} - V_D\right)dt$$

$$P_{D2} = \frac{1}{T}\int_0^{\frac{T}{2}}\left(\frac{V_{CC}-V_{BE}}{R_x}V_p\sin\omega t - V_p\left(\frac{V_p}{R_x} + \frac{1}{1+\beta}\frac{V_p}{R_P}\right)\sin^2\omega t\right)dt$$

$$+\frac{1}{T}\int_0^{\frac{T}{2}}\left(V_{CC}\frac{V_{CC}-V_{BE}}{R_x} - V_{CC}\left(\frac{V_p}{R_x} + \frac{1}{1+\beta}\frac{V_p}{R_P}\right)\sin\omega t\right)dt$$

$$+\frac{1}{T}\int_{\frac{T}{2}}^{T}\left(\frac{V_{CC}V_p\sin\omega t}{R_x} - \left(\frac{{V_p}^2}{R_x} + \frac{{V_p}^2}{R_P}\right)\sin^2\omega t\right)dt$$

$$+\frac{1}{T}\int_{\frac{T}{2}}^{T}\left(\frac{V_{CC}\left(V_{CC}-V_D\right)}{R_x} - \left(V_{CC}-V_D\right)\left(\frac{V_p}{R_x} + \frac{V_p}{R_P}\right)\sin\omega t\right)dt$$

$$P_{D2}=\left(V_{CC}\frac{V_{CC}-V_{BE}}{R_x}\right)\frac{1}{T}\int_0^{\frac{T}{2}}dt+\left(\frac{V_{CC}-V_{BE}}{R_x}V_p-V_{CC}\left(\frac{V_p}{R_x}+\frac{1}{1+\beta}\frac{V_p}{R_P}\right)\right)\frac{1}{T}\int_0^{\frac{T}{2}}\sin\omega t dt-$$

$$-V_p\left(\frac{V_p}{R_x}+\frac{1}{1+\beta}\frac{V_p}{R_P}\right)\frac{1}{T}\int_0^{\frac{T}{2}}\sin^2\omega t dt+$$

$$+\frac{V_{CC}\left(V_{CC}-V_D\right)}{R_x}\frac{1}{T}\int_{\frac{T}{2}}^{T}dt-\left(\left(V_{CC}-V_D\right)\left(\frac{V_p}{R_x}+\frac{V_p}{R_P}\right)-\frac{V_{CC}V_p}{R_x}\right)\frac{1}{T}\int_{\frac{T}{2}}^{T}\sin\omega t dt-\left(\frac{V_p^{\ 2}}{R_x}+\frac{V_p^{\ 2}}{R_P}\right)\frac{1}{T}\int_{\frac{T}{2}}^{T}\sin^2\omega t dt=$$

$$=\left(V_{CC}\frac{V_{CC}-V_{BE}}{R_x}\right)\frac{1}{2}+\left(\frac{V_{CC}-V_{BE}}{R_x}V_p-V_{CC}\left(\frac{V_p}{R_x}+\frac{1}{1+\beta}\frac{V_p}{R_P}\right)\right)\frac{1}{\pi}-V_p\left(\frac{V_p}{R_x}+\frac{1}{1+\beta}\frac{V_p}{R_P}\right)\frac{1}{4}+$$

$$+\frac{V_{CC}\left(V_{CC}-V_D\right)}{R_x}\frac{1}{2}+\left(\left(V_{CC}-V_D\right)\left(\frac{V_p}{R_x}+\frac{V_p}{R_P}\right)-\frac{V_{CC}V_p}{R_x}\right)\frac{1}{\pi}-\left(\frac{V_p^{\ 2}}{R_x}+\frac{V_p^{\ 2}}{R_P}\right)\frac{1}{4}$$

$$P_{D2}=-\frac{V_p^{\ 2}}{4}\left(\frac{2}{R_x}+\frac{\beta+2}{\beta+1}\frac{1}{R_P}\right)-\frac{V_p}{\pi}\left(V_{BE}\left(\frac{1}{R_P}+\frac{2}{R_x}\right)-\frac{\beta}{1+\beta}\frac{V_{CC}}{R_P}\right)+\frac{V_{CC}\left(V_{CC}-V_D\right)}{R_x}$$

$$P_{D2}=-0.027V_u^{\ 2}+0.105V_u+0.136$$

$C\to\infty$ je ekvivalentno kao da je otpornik u kratkom spoju, negativna povratna sprega je raskinuta, operacioni pojačavač će biti u naponskom zasićenju.

Kada je $v_U>0$ operacioni pojačavač je u negativnom zasićenju i tranzistor Q_2 je isključen

$$p_{D2}=0$$

Važi $i_{C1}=\beta\frac{V_{CC}-V_{BE}}{R_x}=1.13\text{A}$

$$p_{D1}=V_{CC}i_{C1}=13.56\text{W}$$

Kada je $v_U<0$ operacioni pojačavač je u pozitivnom zasićenju i tranzistor Q_2 je uključen. Tranzistor Q_1 je isključen jer je $v_{BE1}=\left(v_P-V_D+V_D\right)-v_P=0$.

$$i_{B2}=\frac{2V_{CC}-V_{BE}}{R_{B2}}-\frac{V_{BE}}{R_{B1}}=10.95\text{mA}$$

$$i_{C2}=\beta i_{B2}=1.095\text{A}$$

$$p_{D2}=\left(-V_D+V_{CC}\right)i_{C2}=12.3735\text{W}$$

$$p_{D1}=0$$

$$P_{D1}=\frac{13.56+0}{2}=6.78\text{W}$$

$$P_{D2}=\frac{12.3735}{2}=6.18675\text{W}$$