Fakultet elektrotehnike i računarstva
Zavod za elektroniku, mikroelektroniku,
računalne i inteligentne sustave

Elektronika 2

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2. Kaskadna pojačala

Kaskadna pojačala

Osnovni spojevi pojačala → s jednim aktivnim elementom (unipolarni ili bipolarni tranzistor).

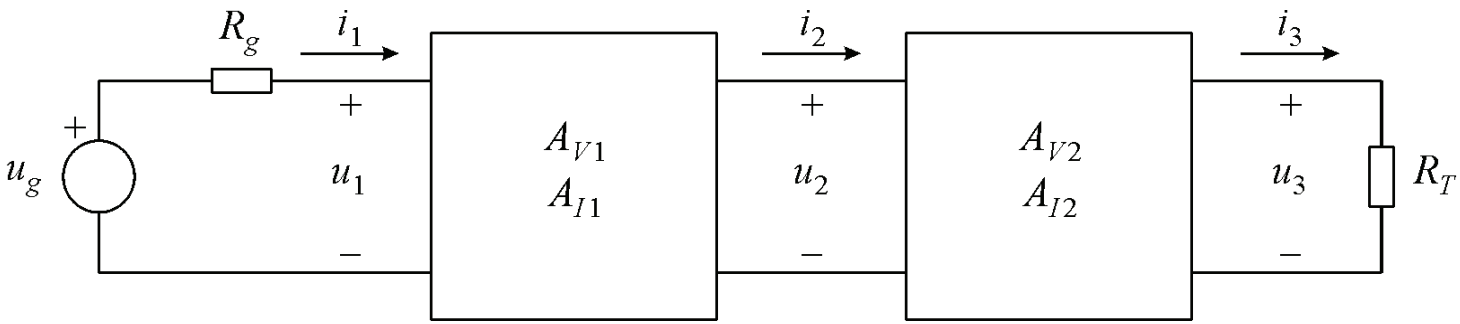
Ograničenja osnovnih spojeva pojačala:

- ograničene vrijednosti pojačanja,
- ograničene mogućnosti kombiniranja pojačanja s ulaznim i izlaznim otporima

Rješenje – povezivanje više osnovnih spojeva pojačala serijski u lanac ili u kaskadu – kaskadna pojačala

Osnovni spojevi pojačala su stupnjevi kaskadnog pojačala → kaskadno pojačalo je višestupanjsko pojačalo

Princip kaskadiranja



$$A_V = \frac{u_3}{u_1} = \frac{u_3}{u_2}\frac{u_2}{u_1} = A_{V2}\,A_{V1} \qquad A_I = \frac{i_3}{i_1} = \frac{i_3}{i_2}\frac{i_2}{i_1} = A_{I2}\,A_{I1}$$

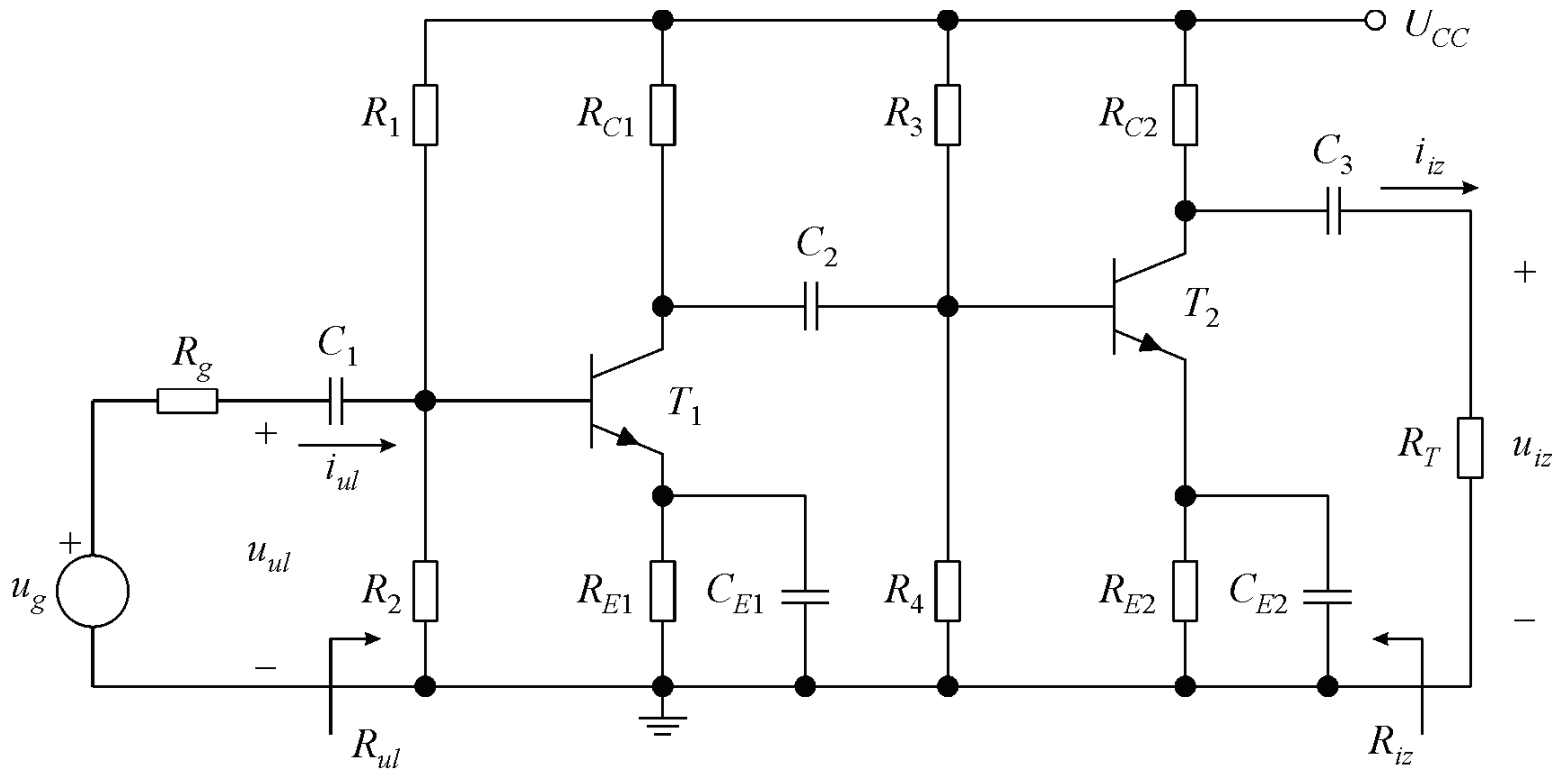
općenito:

$$A_V = A_{Vn}\,A_{Vn-1}\cdots A_{V2}\,A_{V1} = \prod_{k=1}^{n} A_{Vk} \qquad A_I = A_{In}\,A_{In-1}\cdots A_{I2}\,A_{I1} = \prod_{k=1}^{n} A_{Ik}$$

Povezivanje stupnjeva

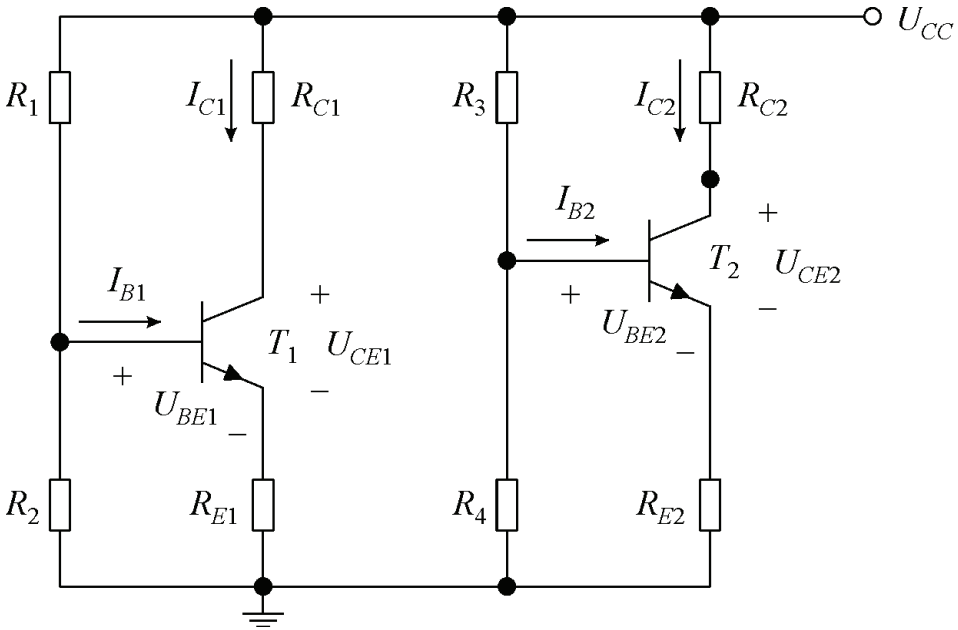
- RC-vezana ili izmjenična pojačala
  - povezivanje stupnjeva veznim kondenzatorima
  - kondenzatori prekidaju istosmjernu vezu među stupnjevima pojačala
  - postavljanja statičkih radnih točaka pojedinih stupnjeva međusobno su neovisna
  - na nižim frekvencijama vezni kondenzatori guše prolazak signala među stupnjevima
- izravno vezana ili istosmjerna pojačala
  - izravno povezivanja stupnjeva pojačala
  - među pojačalima uspostavlja se istosmjerna i izmjenična veza
  - statičke radne točke pojedinih stupnjeva međusobno su ovisne
  - teže se osigurava stabilizacija statičke radne točke

Izmjenično pojačalo



izmjenična veza → kondenzatori C_1, C_2 i C_3

Statička analiza



za statiku → odvojeni stupnjevi

$$U_{BB1} = \frac{R_2}{R_1 + R_2} U_{CC} \qquad R_{B1} = R_1 \| R_2$$

$$I_{BQ1} = \frac{U_{BB1} - U_{BEQ1}}{R_{B1} + (1+\beta) R_{E1}}$$

$$U_{CEQ1} = U_{CC} + R_{C1} I_{CQ1} - R_{E1}\left(I_{BQ1} + I_{CQ1}\right) \approx$$
$$\approx U_{CC} - \left(R_{C1} + R_{E1}\right) I_{CQ1}$$

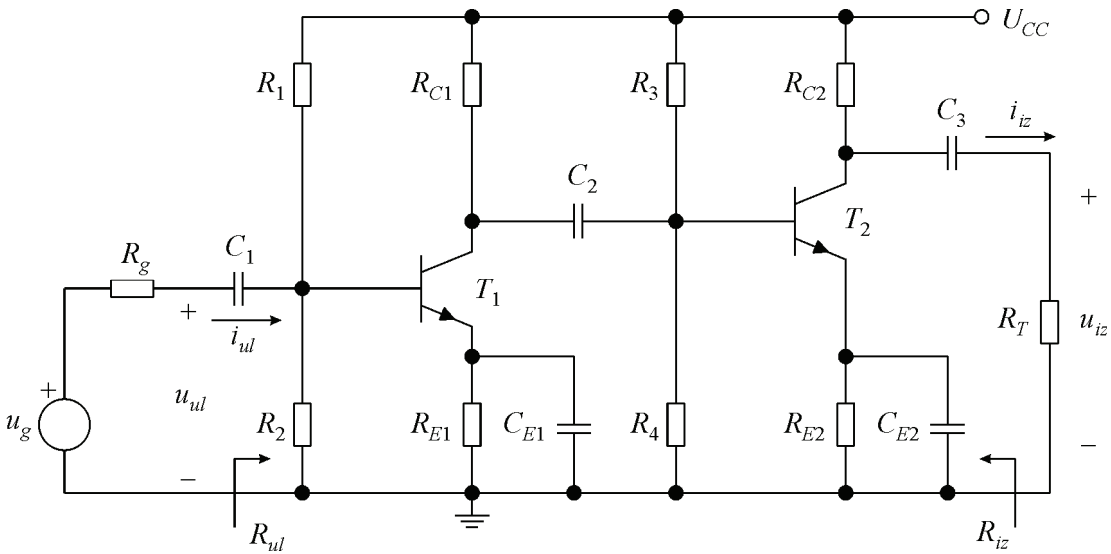
$$U_{BB2} = \frac{R_4}{R_3 + R_4} U_{CC} \qquad R_{B2} = R_3 \| R_4$$

$$I_{BQ2} = \frac{U_{BB2} - U_{BEQ2}}{R_{B2} + (1+\beta) R_{E2}}$$

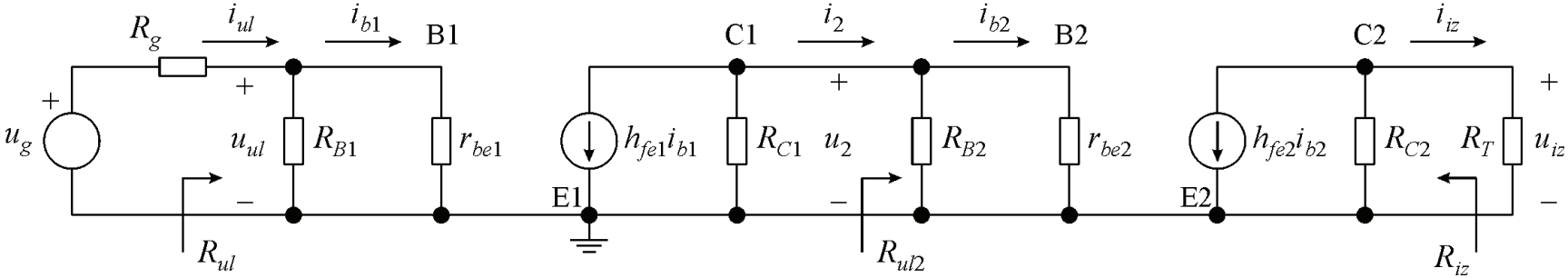
$$U_{CEQ2} = U_{CC} - R_{C2} I_{CQ2} - R_{E2}\left(I_{BQ2} + I_{CQ2}\right) \approx$$
$$\approx U_{CC} - \left(R_{C2} + R_{E2}\right) I_{CQ2}$$

Primjer 2.1

U pojačalu sa slike zadano je: $U_{CC} = 15$ V, $R_g = 500\ \Omega$, $R_1 = 300$ kΩ, $R_2 = 50$ kΩ, $R_{C1} = 8$ kΩ, $R_{E1} = 1$ kΩ, $R_3 = 160$ kΩ, $R_4 = 40$ kΩ, $R_{C2} = 5$ kΩ, $R_{E2} = 1{,}5$ kΩ i $R_T = 5$ kΩ. Parametri oba *npn* bipolarna tranzistora su $\beta = 100$ i $U_\gamma = 0{,}7$ V. Odrediti struje i napone tranzistora u statičkoj radnoj točki. točki.



Dinamička analiza (1)



Pojačanja i ulazni otpori pojedinih stupnjeva određuju od zadnjeg stupnja prema prvom, a izlazni otpori računaju se od prvog stupnja prema zadnjem

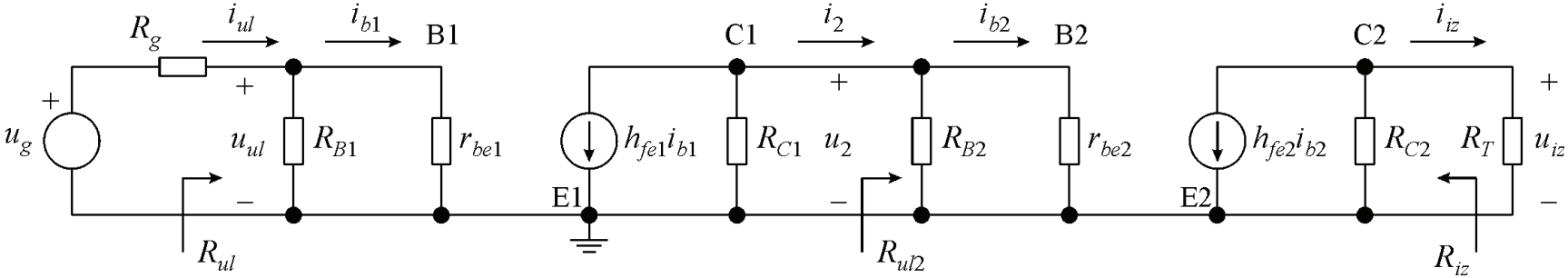
2. stupanj:

$$A_{V2} = \frac{u_{iz}}{u_2} = \frac{u_{iz}}{i_{b2}} \frac{i_{b2}}{u_2} = -h_{fe2} \frac{R_{C2} \| R_T}{r_{be2}}$$

$$R_{ul2} = R_{B2} \| r_{be2}$$

$$A_{I2} = \frac{i_{iz}}{i_2} = \frac{i_{iz}}{i_{b2}} \frac{i_{b2}}{i_2} = -h_{fe2} \frac{R_{C2}}{R_{C2} + R_T} \frac{R_{B2}}{R_{B2} + r_{be2}}$$

Dinamička analiza (2)



1. stupanj:

$$A_{V1} = \frac{u_2}{u_{ul}} = \frac{u_2}{i_{b1}} \frac{i_{b1}}{u_{ul}} = -\, h_{fe1} \frac{R_{C1} \,\|\, R_{ul2}}{r_{be1}}$$

$$R_{ul1} = R_{B1} \,\|\, r_{be1} = R_{ul} \qquad A_{I1} = \frac{i_2}{i_{ul}} = \frac{i_2}{i_{b1}} \frac{i_{b1}}{i_{ul}} = -\, h_{fe1} \frac{R_{C1}}{R_{C1} + R_{ul2}} \frac{R_{B1}}{R_{B1} + r_{be1}}$$

ukupno pojačanje:

$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{u_{iz}}{u_2} \frac{u_2}{u_{ul}} = A_{V2}\, A_{V1} \qquad A_I = \frac{i_{iz}}{i_{ul}} = \frac{i_{iz}}{i_2} \frac{i_2}{i_{ul}} = A_{I2}\, A_{I1}$$

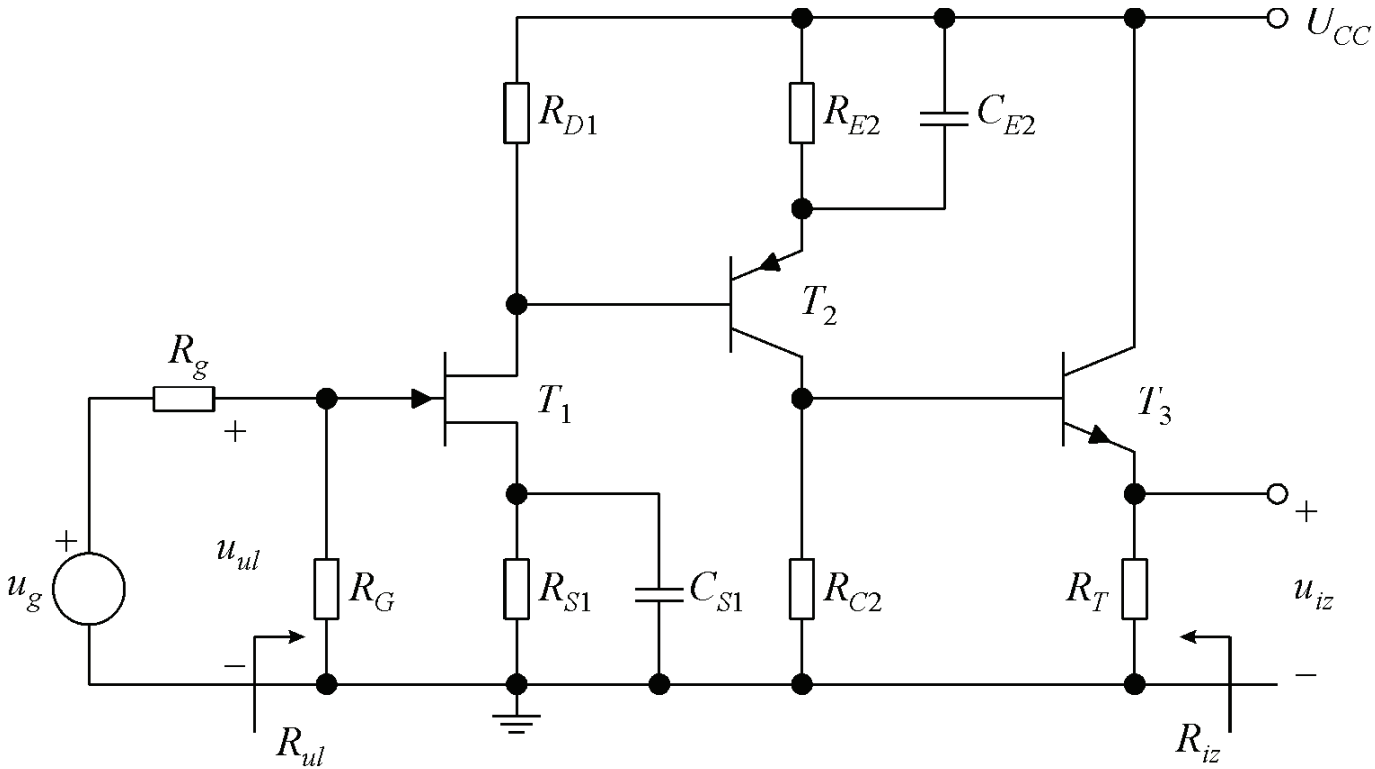
izlazni otpor:

$$R_{iz} = R_{C2}$$

Primjer 2.2

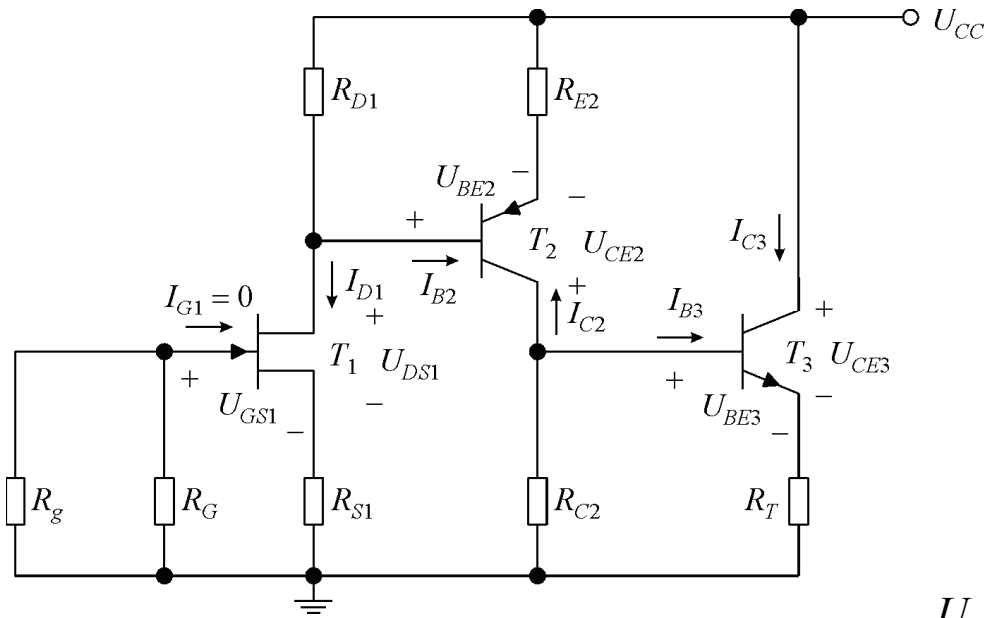
Za kaskadno pojačalo iz primjera 2.1 odrediti pojačanja $A_V = u_{iz}/u_{ul}$ i $A_I = i_{iz}/i_{ul}$, te ulazni i izlazni otpor pojačala. Za oba *npn* bipolarna tranzistora $h_{fe} = 100$. Zanemariti porast struje kolektora u normalnom aktivnom području. Naponski ekvivalent temperature $U_T = 25\ \mathrm{mV}$.

Istosmjerno pojačalo



izravna veza među stupnjevima

Statička analiza



za statiku → veza među stupnjevima

$$0 = U_{GS1} + I_{D1} R_S \qquad I_{D1} = I_{DSS1}\left(1 - \frac{U_{GS1}}{U_{P1}}\right)^2$$

$$\left(I_{D1} + I_{B2}\right) R_{D1} = -\left(I_{B2} + I_{C2}\right) R_{E2} - U_{BE2}$$

$$I_{BQ2} = -\frac{I_{DQ1} R_{D1} + U_{BEQ2}}{R_{D1} + \left(1 + \beta_2\right) R_{E2}}$$

$$-\left(I_{C2} + I_{B3}\right) R_{C2} = U_{BE3} + \left(I_{B3} + I_{C3}\right) R_T$$

$$I_{BQ3} = \frac{-I_{CQ2} R_{C2} - U_{BEQ3}}{R_{C2} + \left(1 + \beta_3\right) R_T}$$

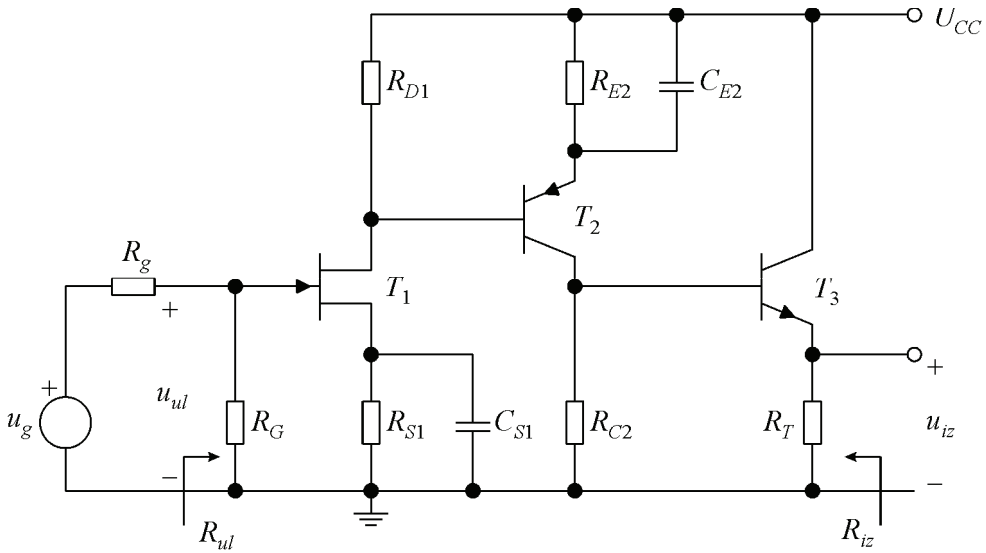
$$U_{DSQ1} = U_{CC} - I_{DQ1}\left(R_{D1} + R_{S1}\right) - I_{BQ2} R_{D1}$$

$$U_{CEQ2} \approx -U_{CC} - I_{CQ2}\left(R_{E2} + R_{C2}\right) - I_{BQ3} R_{C2}$$

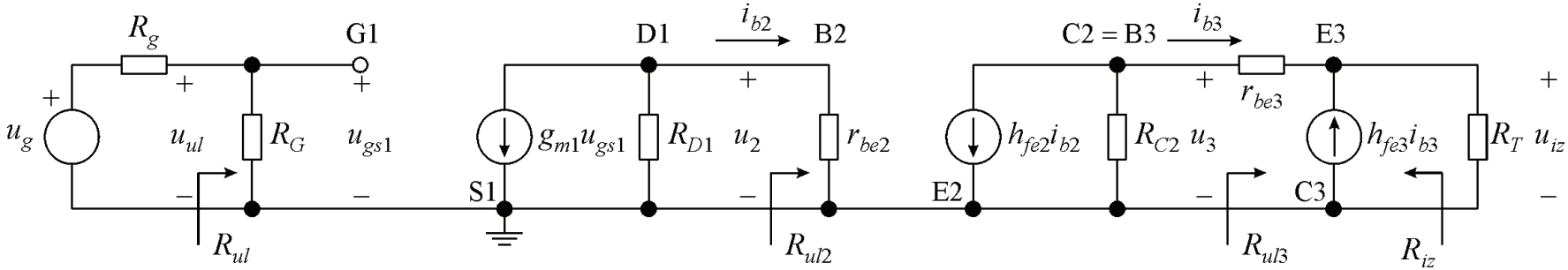
$$U_{CEQ3} \approx U_{CC} - I_{CQ3} R_T$$

Primjer 2.3

U pojačalu sa slike zadano je: $U_{CC} = 15\ \text{V}$, $R_g = 1\ \text{k}\Omega$, $R_G = 1\ \text{M}\Omega$, $R_{D1} = 1\ \text{k}\Omega$, $R_{S1} = 300\ \Omega$, $R_{E2} = 500\ \Omega$ i $R_{C2} = R_T = 2\ \text{k}\Omega$. Parametri *n*-kanalnog spojnog FET-a su $I_{DSS} = 10\ \text{mA}$ i $U_P = -2\ \text{V}$. Za oba bipolarna tranzistora $\beta = 100$ i $U_\gamma = 0{,}7\ \text{V}$ i . Odrediti struje i napone tranzistora u statičkoj radnoj točki.



Dinamička analiza (1)



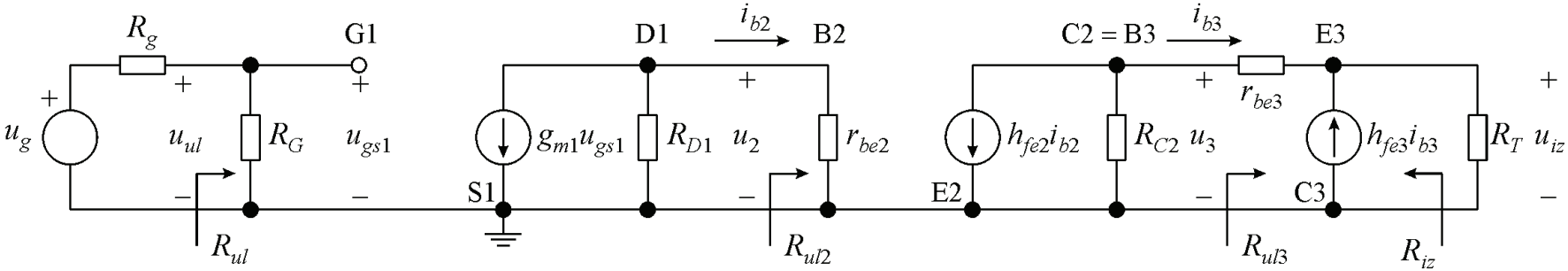
3. stupanj – spoj zajedničkog kolektora:

$$A_{V3} = \frac{u_{iz}}{u_3} = \frac{u_{iz}}{i_{b3}}\frac{i_{b3}}{u_3} = \frac{\left(1+h_{fe3}\right)R_T}{r_{be3}+\left(1+h_{fe3}\right)R_T} \qquad R_{ul3} = \frac{u_3}{i_{b3}} = r_{be3}+\left(1+h_{fe3}\right)R_T$$

2. stupanj – spoj zajedničkog emitera:

$$A_{V2} = \frac{u_3}{u_2} = \frac{u_3}{i_{b2}}\frac{i_{b2}}{u_2} = -h_{fe2}\frac{R_{C2}\,\|\,R_{ul3}}{r_{be2}} \qquad R_{ul2} = \frac{u_2}{i_{b2}} = r_{be2}$$

Dinamička analiza (2)



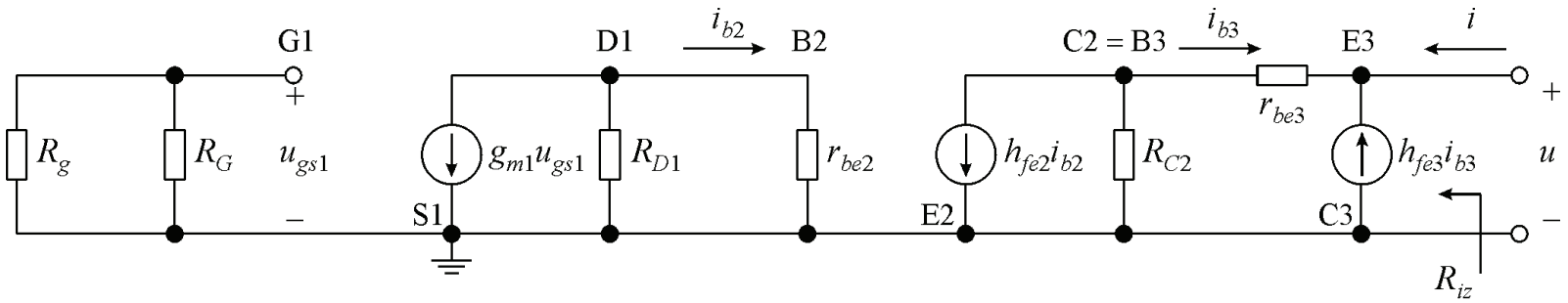
1. stupanj – spoj zajedničkog uvoda:

$$A_{V1} = \frac{u_2}{u_{ul}} = \frac{u_2}{i_{gs1}} = -g_{m1}\left(R_{D1} \,\|\, R_{ul2}\right) \qquad R_{ul1} = R_{ul} = R_G$$

ukupno pojačanje:

$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{u_{iz}}{u_3}\frac{u_3}{u_2}\frac{u_2}{u_{ul}} = A_{V3}\,A_{V2}\,A_{V1}$$

Dinamička analiza – izlazni otpor



$$u = -i_{b3}\left(R_{C2} + r_{be3}\right)$$

$$i = -\left(1 + h_{fe3}\right)i_{b3}$$

$$R_{iz} = \frac{u}{i} = \frac{R_{C2} + r_{be3}}{1 + h_{fe3}}$$

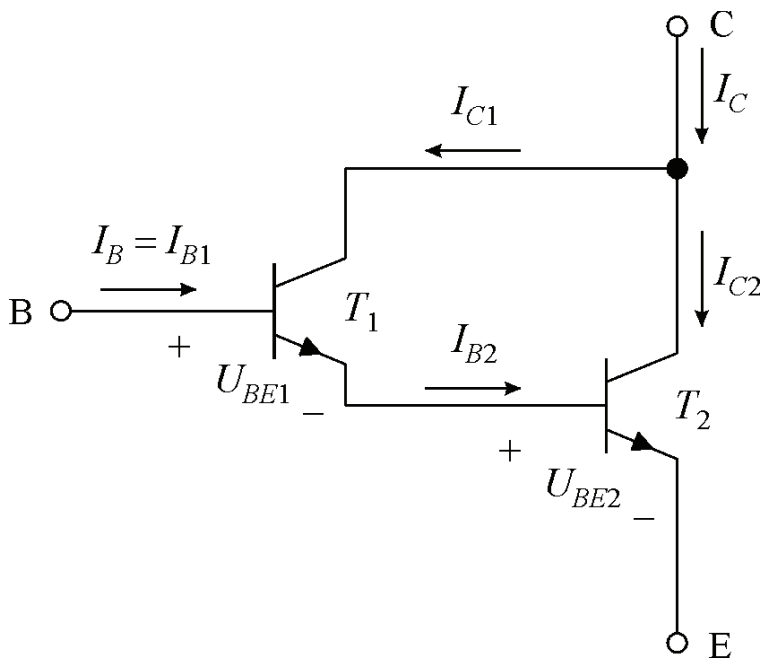
Primjer 2.4

Za kaskadno pojačalo iz primjera 2.3 odrediti naponsko pojačanje $A_V = u_{iz}/u_{ul}$, te ulazni i izlazni otpor pojačala. Za oba bipolarna tranzistora $h_{fe} = 100$. Zanemariti porast struje odvoda FET-a u području zasićenja, te struja kolektora bipolarnih tranzistora u normalnom aktivnom području. Naponski ekvivalent temperature $U_T = 25\ \mathrm{mV}$.

Darlingtonov spoj tranzistora

Koristi se za veća strujna pojačanja

Djeluje kao složeni bipolarni tranzistor između priključaka B, C i E



$$I_{C1} = \beta_1 I_{B1} = \beta_1 I_B$$

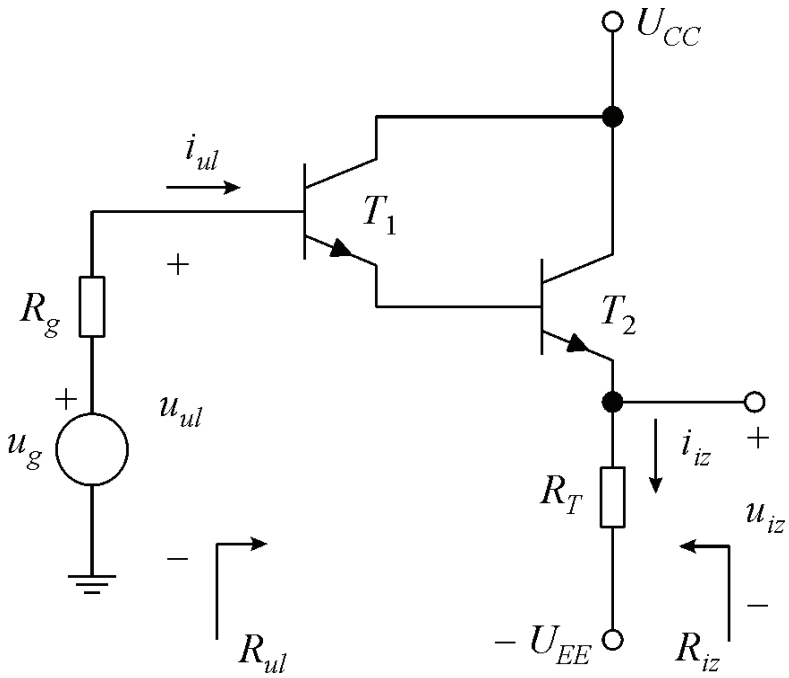
$$I_{C2} = \beta_2 I_{B2} = \beta_2 \left(I_{B1} + I_{C1} \right) = \beta_2 \left(1 + \beta_1 \right) I_B$$

$$I_C = I_{C1} + I_{C2} = \beta_1 I_B + \beta_2 \left(1 + \beta_1 \right) I_B \approx \beta_1 \beta_2 I_B$$

$I_B = I_{B1} \approx I_{B2}/\beta_2 \rightarrow$ veliki ulazni otpor

$$U_{BE} = U_{BE1} + U_{BE2}$$

Darlingtonov spoj u pojačalu u spoju sljedila



Statička analiza

$$U_{EE} = I_{B1} R_g + U_{BE1} + U_{BE2} + (1+\beta_2) I_{B2} R_T$$

$$I_{B2} = I_{B1} + I_{C1} = (1+\beta_1) I_{B1}$$

$$I_{BQ1} = \frac{U_{EE} - U_{BE1} - U_{BE2}}{R_g + (1+\beta_1)(1+\beta_2) R_T} \approx$$

$$\approx \frac{U_{EE} - U_{BE1} - U_{BE2}}{\beta_1 \beta_2 R_T}$$

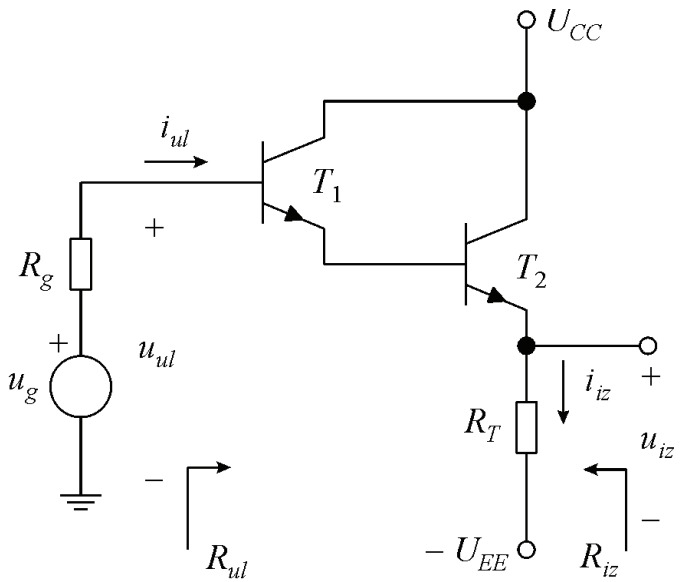
$$I_{CQ1} = \beta_1 I_{BQ1} \quad I_{CQ2} = \beta_2 I_{BQ2}$$

$$U_{CEQ1} \approx U_{CC} + U_{EE} - U_{BEQ2} - I_{CQ2} R_T$$

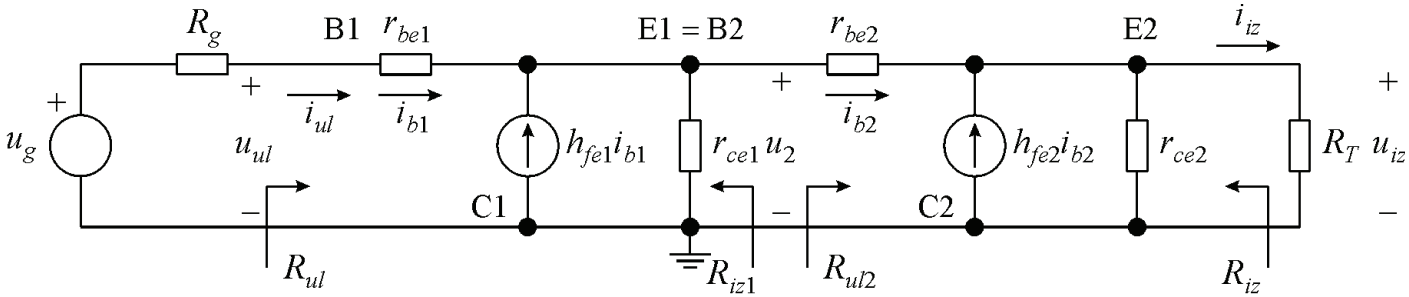
$$U_{CEQ2} \approx U_{CC} + U_{EE} - I_{CQ2} R_T$$

Primjer 2.5

Odrediti statičku radnu točku pojačala sa slike. Zadano je: $U_{CC} = U_{EE} = 10$ V, $R_g = 1$ kΩ i $R_T = 2$ kΩ. Parametri tranzistora su $\beta_1 = 60$, $\beta_2 = 80$ i $U_{\gamma 1} = U_{\gamma 2} = 0{,}7$ V.



Dinamička analiza (1)



2. stupanj – spoj zajedničkog kolektora:

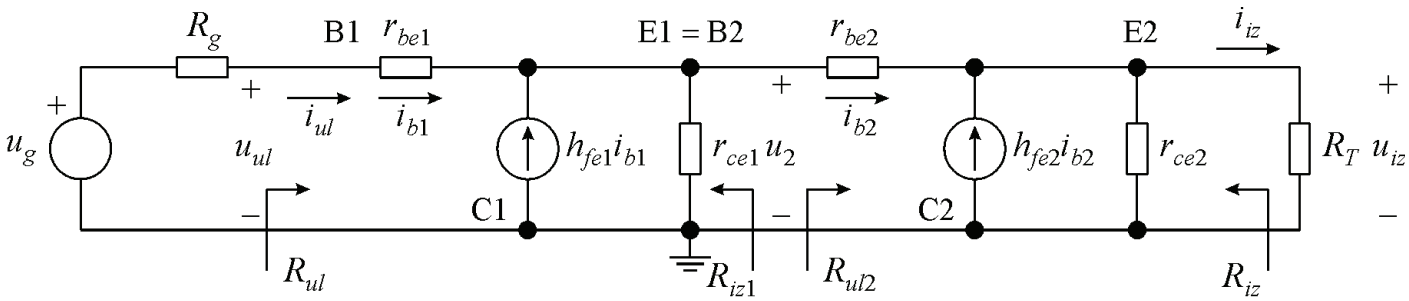
$$A_{I2} = \frac{i_{iz}}{i_{b2}} = \left(1 + h_{fe2}\right)\frac{r_{ce2}}{r_{ce2} + R_T} \approx \left(1 + h_{fe2}\right) \approx h_{fe2}$$

$$R_{ul2} = \frac{u_2}{i_{b2}} = r_{be2} + \left(1 + h_{fe2}\right)\left(r_{ce2} \,\|\, R_T\right) \approx r_{be2} + \left(1 + h_{fe2}\right)R_T \approx h_{fe2}\,R_T$$

1. stupanj – spoj zajedničkog kolektora:

$$A_{I1} = \frac{i_{b2}}{i_{b1}} = \frac{i_{b2}}{i_{ul}} = \left(1 + h_{fe1}\right)\frac{r_{ce1}}{r_{ce1} + R_{ul2}} \approx h_{fe1}\frac{r_{ce1}}{r_{ce1} + R_{ul2}}$$

Dinamička analiza (2)



$$R_{ul1} = R_{ul} = \frac{u_{ul}}{i_{b1}} = \frac{u_{ul}}{i_{ul}} = r_{be1} + \left(1 + h_{fe1}\right)\left(r_{ce1} \,\|\, R_{ul2}\right) = r_{be1} + A_{I1}\, R_{ul2}$$

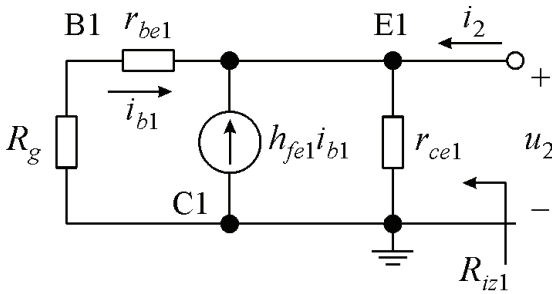
$$R_{ul} \approx A_{I1}\, R_{ul2} \approx \frac{h_{fe1}\, h_{fe2}\, r_{ce1}\, R_T}{r_{ce1} + h_{fe2}\, R_T} \approx h_{fe1}\left(r_{ce1} \,\|\, h_{fe2}\, R_T\right)$$

$$A_I = \frac{i_{iz}}{i_{ul}} = \frac{i_{iz}}{i_{b2}} \frac{i_{b1}}{i_{ul}} = A_{I2}\; A_{I2} \approx \frac{h_{fe1}\, h_{fe2}\, r_{ce1}}{r_{ce1} + h_{fe2}\, R_T}$$

$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{i_{iz}\, R_T}{i_{ul}\, R_{ul}} = A_I\, \frac{R_T}{R_{ul}}$$

Dinamička analiza – izlazni otpor

1. stupanj

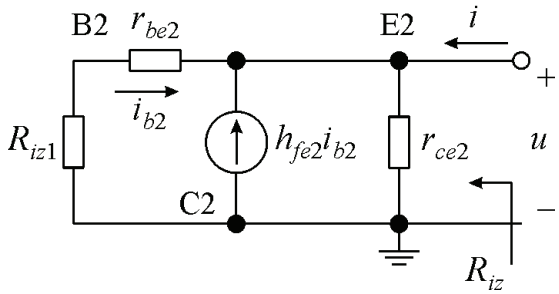


$$u_2 = -\left(R_g + r_{be1}\right) i_{b1}$$

$$\frac{i_2}{u_2} = \frac{1}{r_{ce1}} - \frac{\left(1 + h_{fe1}\right) i_{b1}}{u_2} = \frac{1}{r_{ce1}} + \frac{\left(1 + h_{fe1}\right)}{R_g + r_{be1}}$$

$$R_{iz1} = \frac{u_2}{i_2} = r_{ce1} \left\| \frac{R_g + r_{be1}}{1 + h_{fe1}} \right.$$

2. stupanj

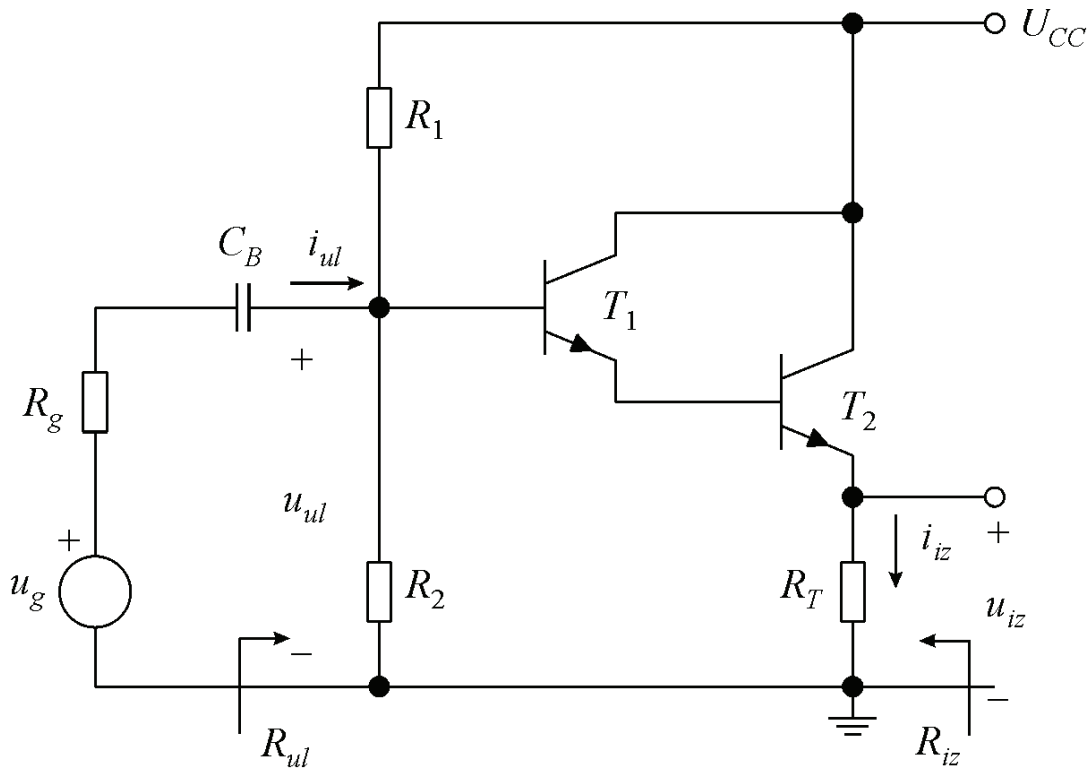


$$R_{iz} = R_{iz2} = \frac{u}{i} = r_{ce2} \left\| \frac{R_{iz1} + r_{be2}}{1 + h_{fe2}} \right.$$

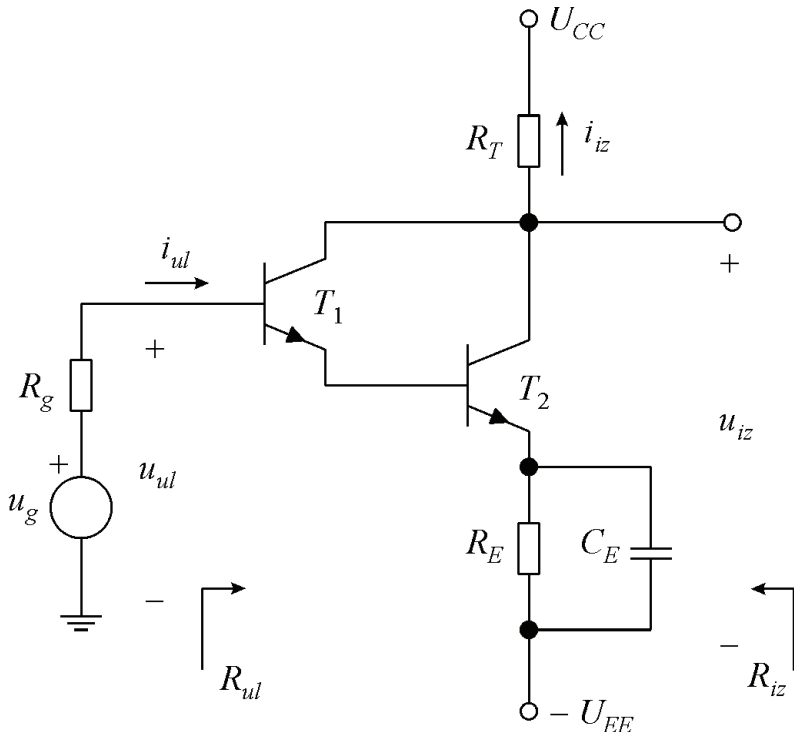
Primjer 2.6

Za pojačalo u spoju zajedničkog kolektora s Darlingtonovim spojem tranzistora iz primjera 2.5 odrediti pojačanja $A_V = u_{iz}/u_{ul}$ i $A_I = i_{iz}/i_{ul}$, te ulazni i izlazni otpor pojačala. Parametri tranzistora su $h_{fe1} = 60$, $h_{fe2} = 80$ i $U_{A1} = U_{A2} = 200\ \mathrm{V}$, a naponski ekvivalent temperature $U_T = 25\ \mathrm{mV}$.

Podešavanje radne točke s jednim naponom napajanja



Darlingtonov spoj u pojačalu u spoju zajedničkog emitera



Statička analiza

$$I_{BQ1} = \frac{U_{EE} - U_{BE1} - U_{BE2}}{R_g + (1+\beta_1)(1+\beta_2)R_T}$$

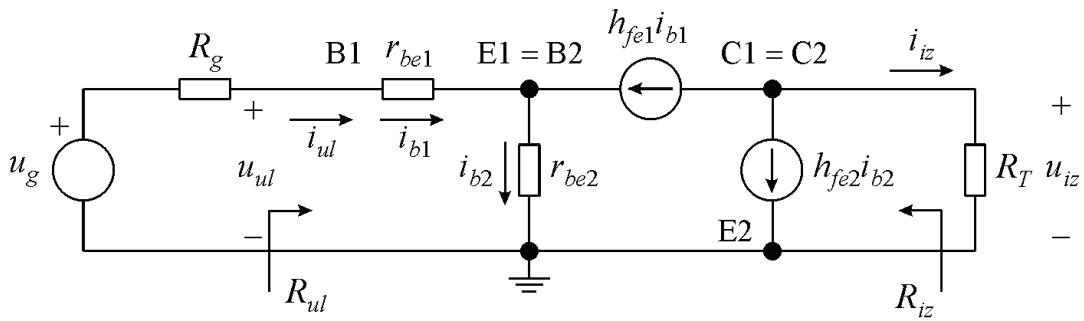
$$I_{BQ2} = (1+\beta_1) I_{BQ1}$$

$$I_{CQ1} = \beta_1 I_{BQ1} \quad I_{CQ2} = \beta_2 I_{BQ2}$$

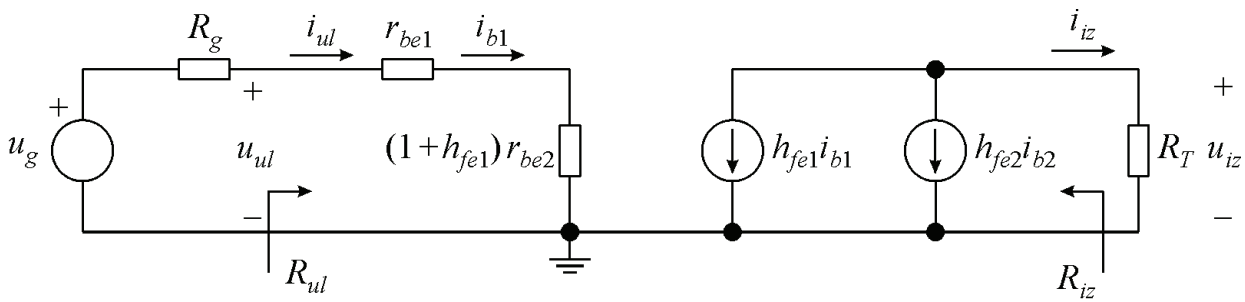
$$U_{CEQ1} \approx U_{CC} + U_{EE} - U_{BEQ2} - I_{CQ2}(R_T + R_E)$$

$$U_{CEQ2} \approx U_{CC} + U_{EE} - I_{CQ2}(R_T + R_E)$$

Dinamička analiza (1)



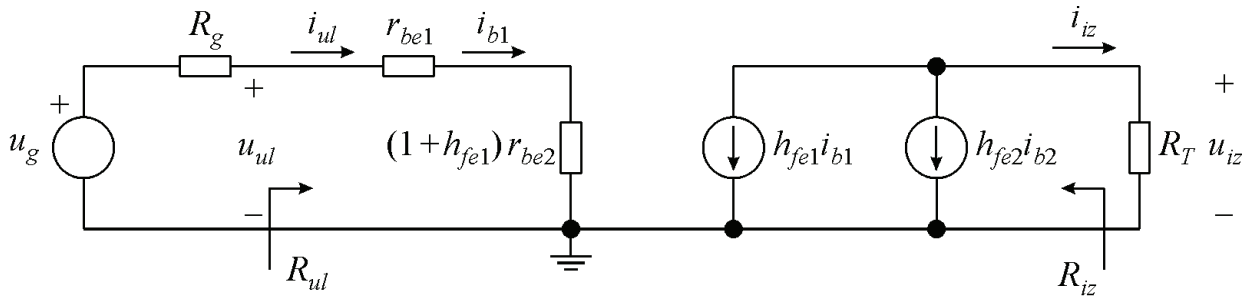
Pojednostavljena shema



$$i_{b2} = \left(1 + h_{fe1}\right) i_{b1}$$

$$i_{iz} = -\,h_{fe1}\,i_{b1} - h_{fe2}\,i_{b2} = -\left[h_{fe1} + h_{fe2}\left(1 + h_{fe1}\right)\right] i_{b1} \approx -\,h_{fe1}\,h_{fe2}\,i_{b1}$$

Dinamička analiza (2)



$$A_I = \frac{i_{iz}}{i_{ul}} = \frac{i_{iz}}{i_{b1}} = -h_{fe1} - h_{fe2}\left(1 + h_{fe1}\right) \approx -h_{fe1}\,h_{fe2}$$

$$R_{ul} = \frac{u_{ul}}{i_{ul}} = \frac{u_{ul}}{i_{b1}} = r_{be1} + \left(1 + h_{fe1}\right) r_{be2}$$

$$I_{BQ2} = \left(1 + \beta_1\right) I_{BQ1} \quad \rightarrow \quad r_{be2} = \frac{U_T}{I_{BQ2}} = \frac{U_T}{\left(1 + \beta_1\right) I_{BQ1}} \approx \frac{r_{be1}}{1 + h_{fe1}} \quad \rightarrow \quad R_{ul} \approx 2\,r_{be1}$$

$$A_V \approx -h_{fe1}\,h_{fe2}\,\frac{R_T}{2\,r_{be1}} \approx -h_{fe2}\,\frac{R_P}{2\,r_{be2}}$$

Primjer 2.7

U pojačalu sa slike zadano je $U_{CC} = U_{EE} = 10\ \text{V}$, $R_g = 1\ \text{k}\Omega$ i $R_T = R_E = 2\ \text{k}\Omega$. Parametri tranzistora su $\beta_1 \approx h_{fe1} = 60$, $\beta_2 \approx h_{fe2} = 80$ i $U_{\gamma 1} = U_{\gamma 2} = 0{,}7\ \text{V}$. Za oba tranzistora zanemariti porast struje kolektora u normalnom aktivnom području. Naponski ekvivalent temperature $U_T = 25\ \text{mV}$.

Izračunati pojačanja $A_V = u_{iz}/u_{ul}$ i $A_I = i_{iz}/i_{ul}$, te ulazni otpor pojačala.