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

Elektronika 1

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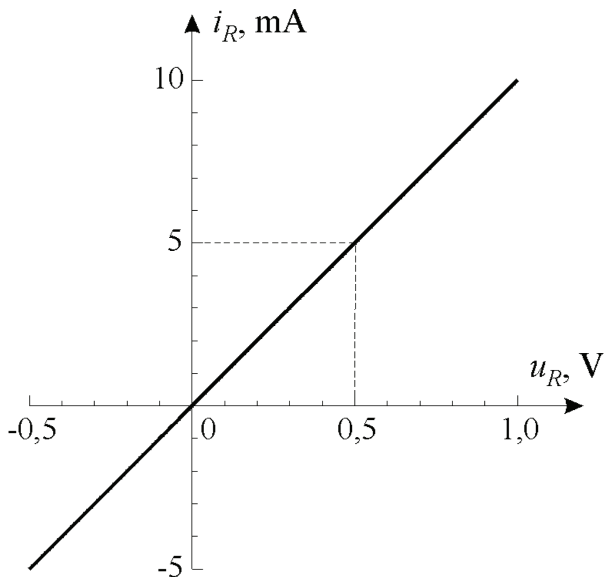
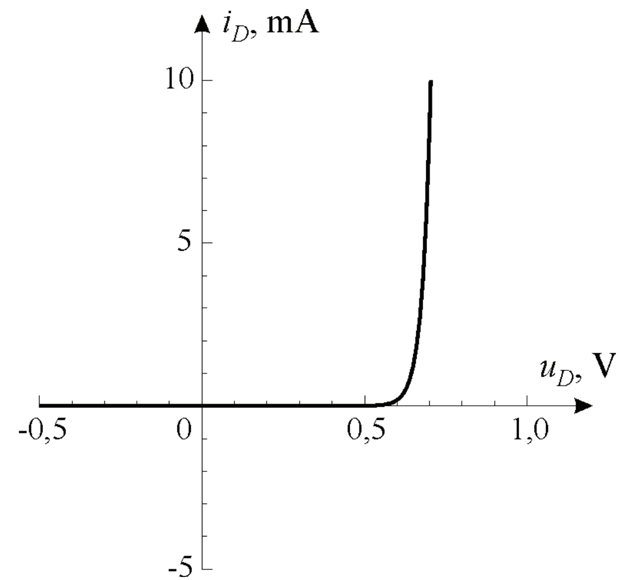
4. Sklopovi s diodama

Usporedba diode i otpornika

otpornik – 100 Ω



silicijska *pn*-dioda

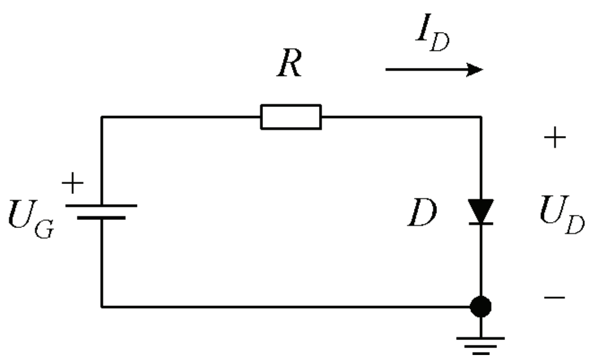


Specifičnost analize elektroničkih sklopova – zbog nelinearnih karakteristika elektroničkih elemenata

Statička analiza

Statičkom analizom proračunavaju se istosmjerne struje i naponi elektroničkih sklopova

Primjer sklopa



Iz strujnog kruga:

$$U_G = R\, I_D + U_D$$

Druga jednadžba:

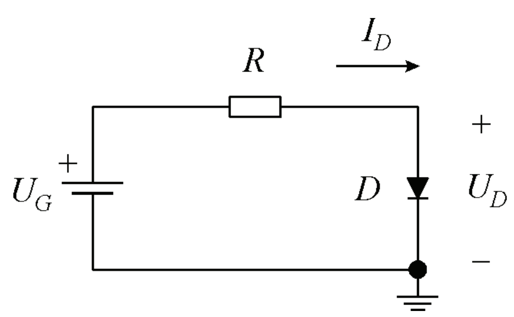
$$I_D = f(U_D)$$

npr. za propusnu polarizaciju

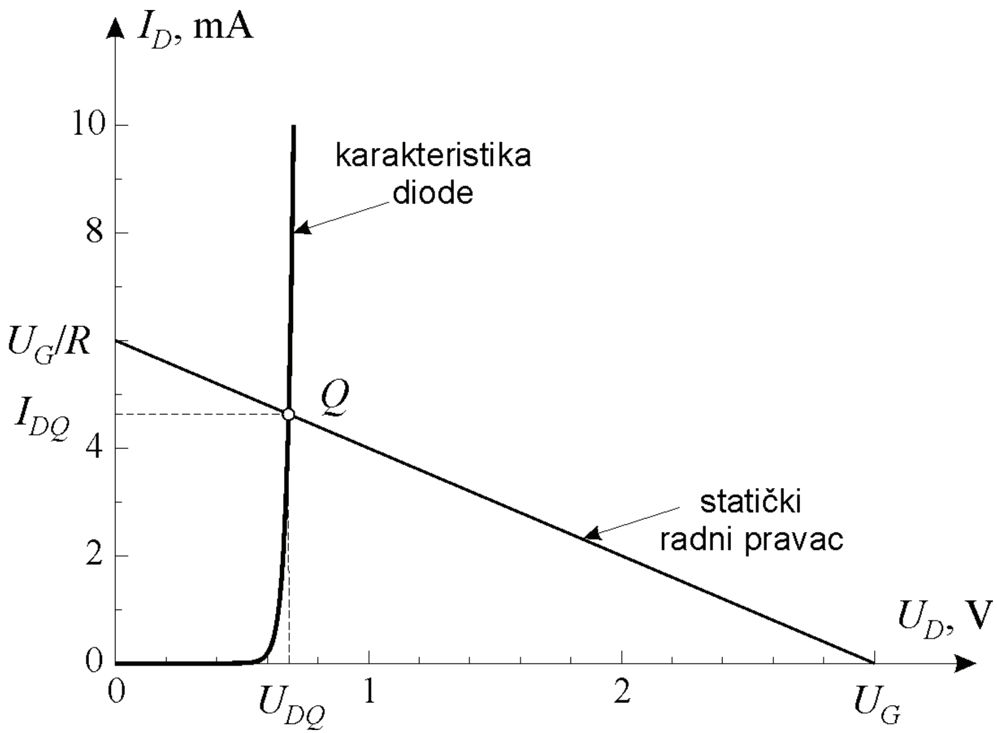
$$I_D = I_S \exp\,(U_D/U_T)$$

Primjer 4.1

Izračunati struju I_D i napon U_D za sklop prema slici. Napon $U_G = 3$ V, otpor $R = 500\ \Omega$, struja zasićenja diode $I_S = 10$ fA i temperatura je sobna, $U_T = 25$ mV.



Grafička analiza



Statički radni pravac:

$U_G = R\,I_D + U_D$

nagib - $-\,1/R$

Statička radna točka Q

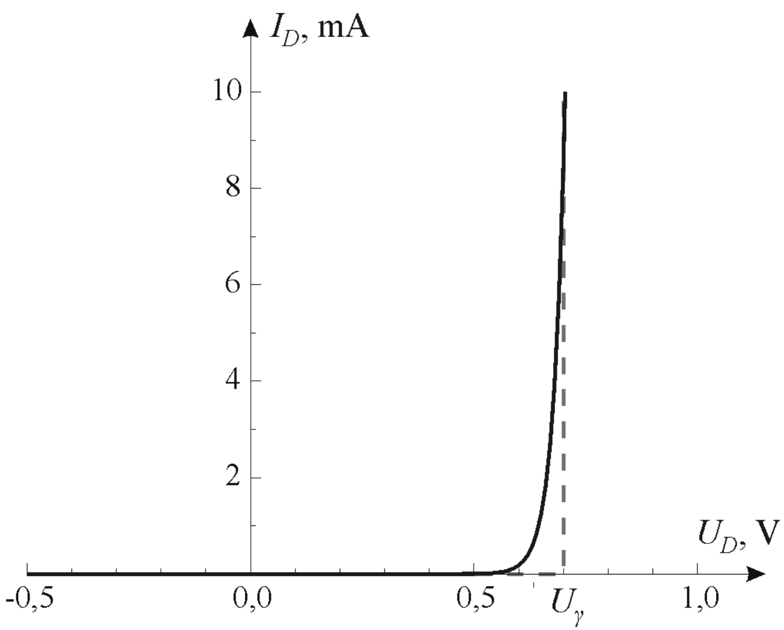
Primjer:

$U_G = 3\text{ V},\ R = 500\ \Omega$

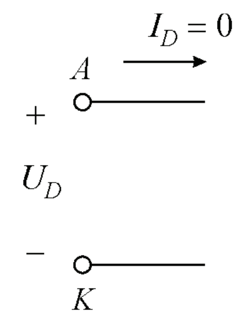
$U_{DQ} = 0{,}68\text{ V}$

$I_{DQ} = 4{,}6\text{ mA}$

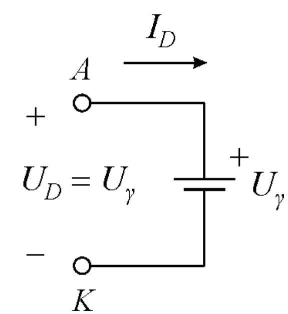
Model diode za statičku analizu



$U_D < U_\gamma$

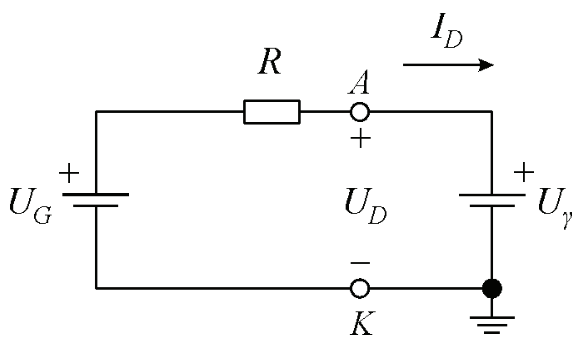


$U_D > U_\gamma$



Analitički postupak – Primjer 4.2

Za $U_D > U_\gamma$



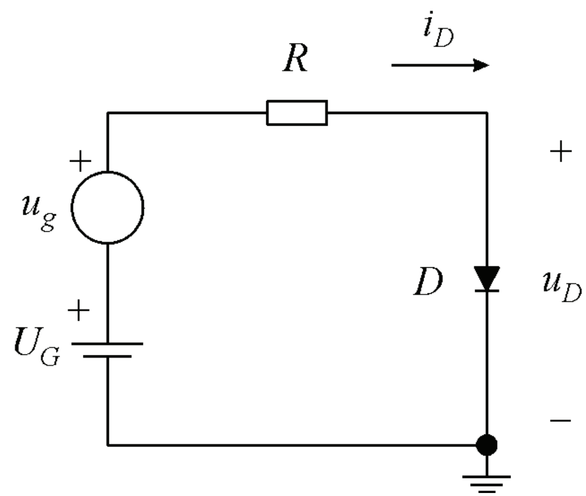
$$U_D = U_\gamma = U_{DQ}$$

$$I_D = \frac{U_G - U_\gamma}{R} = I_{DQ}$$

Primjer 4.2 - Ponoviti proračun struje i napona diode sklopa iz primjera 4.1 korištenjem modela diode za statičku analizu. Napon koljena diode $U_\gamma = 0{,}7\ \mathrm{V}$.

Analiza uz priključak malog signala

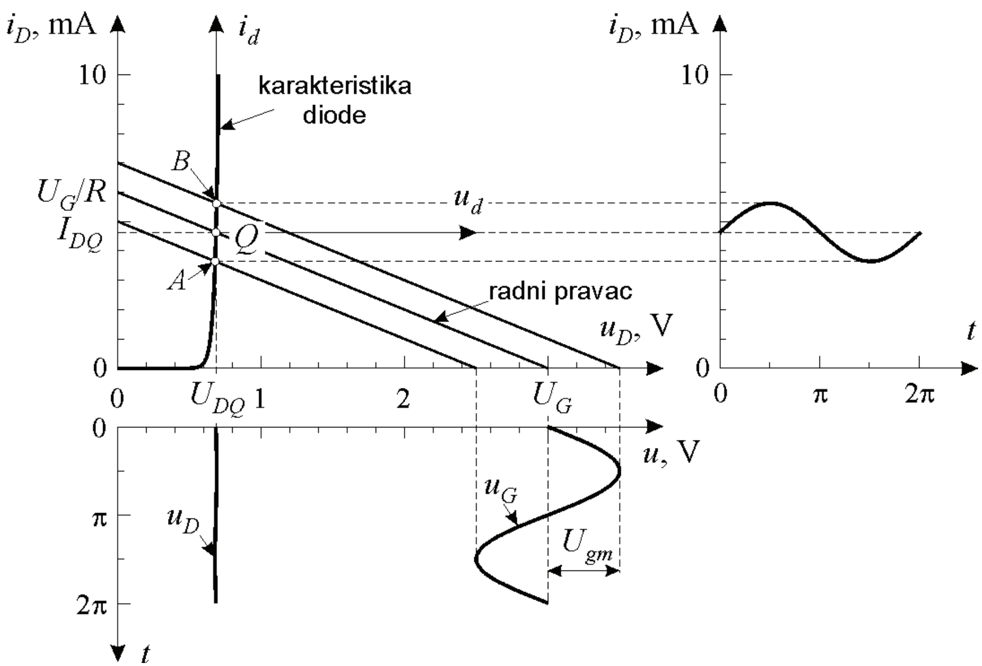
Primjer sklopa



Ulazni napon: $u_G = U_G + u_g = U_G + U_{gm} \sin \omega t$

Iz strujnog kruga: $u_G = R\, i_D + u_D$

Grafička analiza (1)



Radni pravac:

$$u_G = R\, i_D + u_D$$

pomiče se s primjenom u_G

Za mali signal

$$i_D = I_{DQ} + i_d = I_{DQ} + I_{dm} \sin \omega t$$

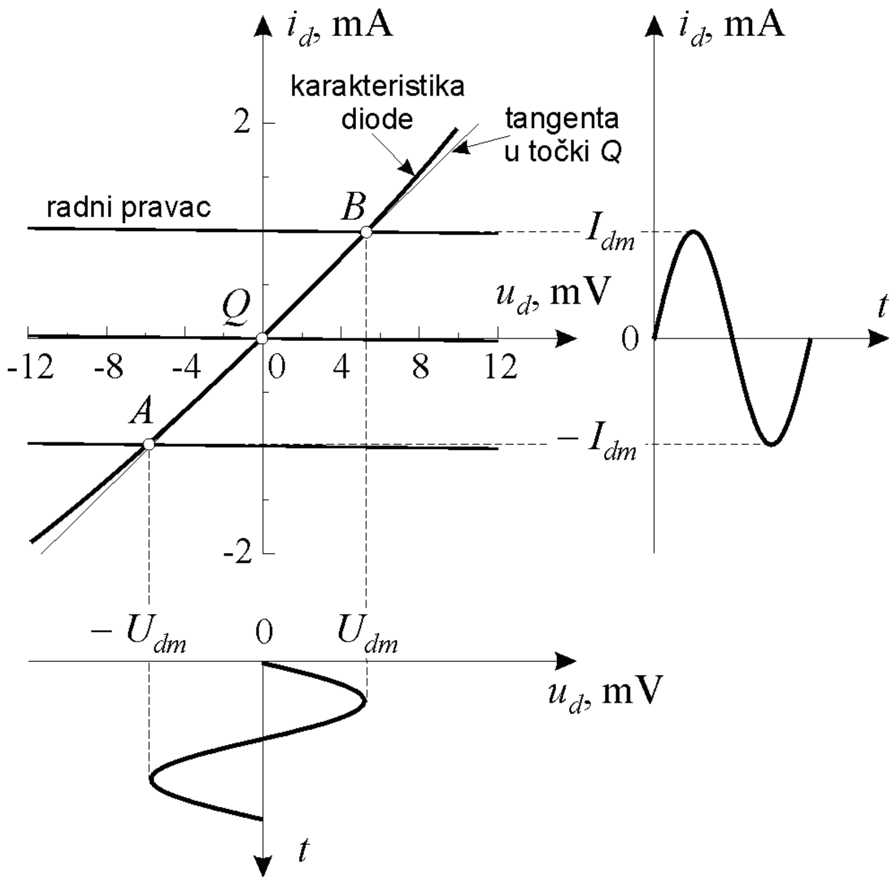
$$u_D = U_{DQ} + u_d = U_{DQ} + U_{dm} \sin \omega t$$

U statičkoj radnoj točki:

$$i_d = i_D - I_{DQ}$$

$$u_d = u_D - U_{DQ}$$

Grafička analiza (2)



Nagib karakteristike:

$$\left.\frac{\mathrm{d}\, i_D}{\mathrm{d}\, u_D}\right|_Q = \left.\frac{\Delta i_D}{\Delta u_D}\right|_Q = \frac{I_{dm}}{U_{dm}} = \frac{i_d}{u_d} = g_d$$

g_d – dinamička vodljivost

$r_d = 1/g_d$ – dinamički otpor

Primjer:

$U_{gm} = 0{,}5\ \mathrm{V}$

$I_{dm} = 1\ \mathrm{mA},\ U_{dm} = 5{,}6\ \mathrm{mV}$

$g_d = 0{,}18\ \mathrm{S},\ r_d = 5{,}6\ \Omega$

Uvjeti rada diode u režimu malog signala

Struja diode oko radne točke

$$i_D = i_D\big|_Q + \frac{\mathrm{d}\,i_D}{\mathrm{d}\,u_D}\bigg|_Q (u_D - U_{DQ}) + \frac{\mathrm{d}^2\,i_D}{\mathrm{d}\,u_D^2}\bigg|_Q \frac{(u_D - U_{DQ})^2}{2!} + \cdots$$

Uz $i_D = I_S \exp\,(u_D/U_T)$

$$\frac{\mathrm{d}\,i_D}{\mathrm{d}\,u_D}\bigg|_Q = \frac{I_S}{U_T}\exp\left(\frac{u_D}{U_T}\right)\bigg|_Q = \frac{I_{DQ}}{U_T} \qquad \frac{\mathrm{d}^2\,i_D}{\mathrm{d}\,u_D^2}\bigg|_Q = \frac{I_S}{U_T^2}\exp\left(\frac{u_D}{U_T}\right)\bigg|_Q = \frac{I_{DQ}}{U_T^2}$$

$$\text{uz}\; u_D - U_{DQ} = u_d \rightarrow \quad i_D = I_{DQ}\left[1 + \frac{u_d}{U_T} + \frac{1}{2!}\left(\frac{u_d}{U_T}\right)^2 + \cdots\right]$$

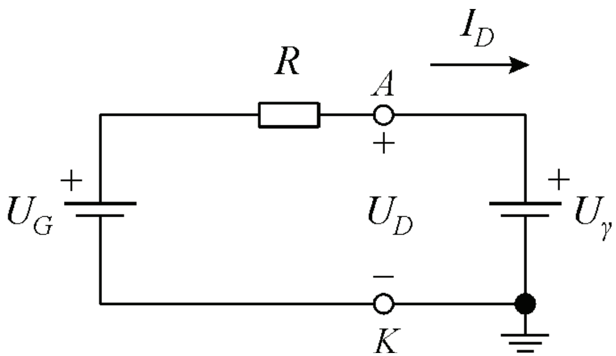
Uvjet za režim malog signala: $u_d << U_T \;\; (U_{dm} << U_T)$

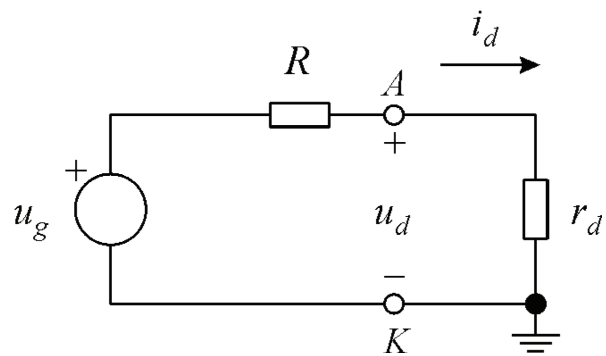
$$\frac{\mathrm{d}\,i_D}{\mathrm{d}\,u_D}\bigg|_Q = \frac{I_{DQ}}{U_T} = g_d = \frac{1}{r_d} \qquad \text{uz linearni rad} \rightarrow i_D = I_{DQ} + i_d = I_{DQ} + \frac{u_d}{r_d}$$

Analitički postupak

Metoda superpozicije

uz: $u_G = U_G + u_g$ - analiza posebno za statiku, a posebno za dinamiku





statička analiza

dinamička analiza

$$U_D = U_\gamma = U_{DQ}$$

$$I_D = \frac{U_G - U_\gamma}{R} = I_{DQ}$$

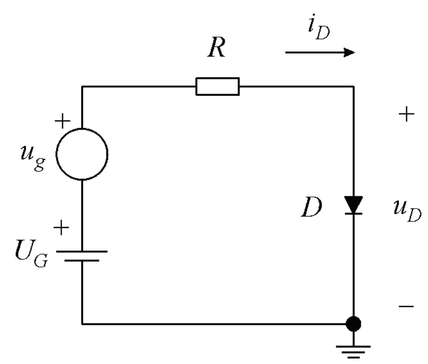
$$r_d = \frac{U_T}{I_{DQ}}$$

$$i_d = \frac{u_g}{R + r_d}$$

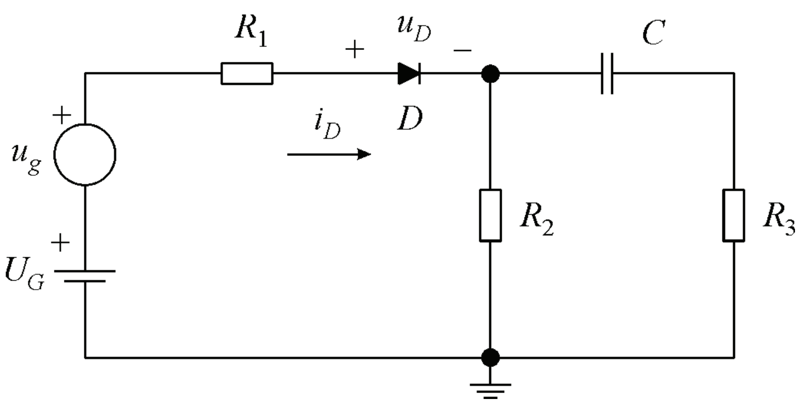
$$u_d = r_d \, i_d$$

Primjer 4.3

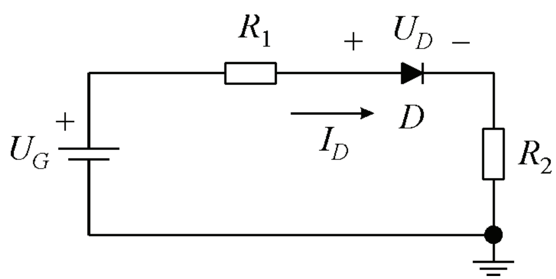
Za sklop sa slike analitički proračunati napon u_D i struju i_D diode. Napon $u_G = 3 + 0{,}5 \sin\omega t$ V, otpor $R = 500\ \Omega$, napon koljena diode $U_\gamma = 0{,}7$ V i temperatura je sobna, $U_T = 25$ mV.



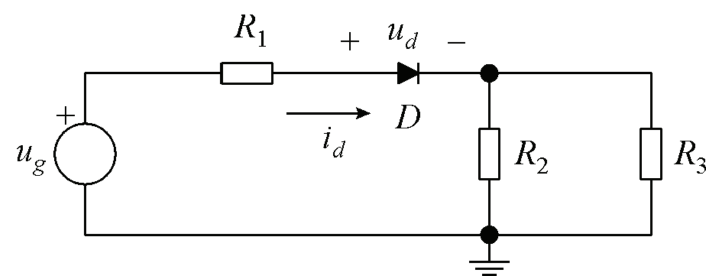
Utjecaj reaktivnih elemenata



Reaktivne komponente se različito ponašaju u statičkim i dinamičkim uvjetima.

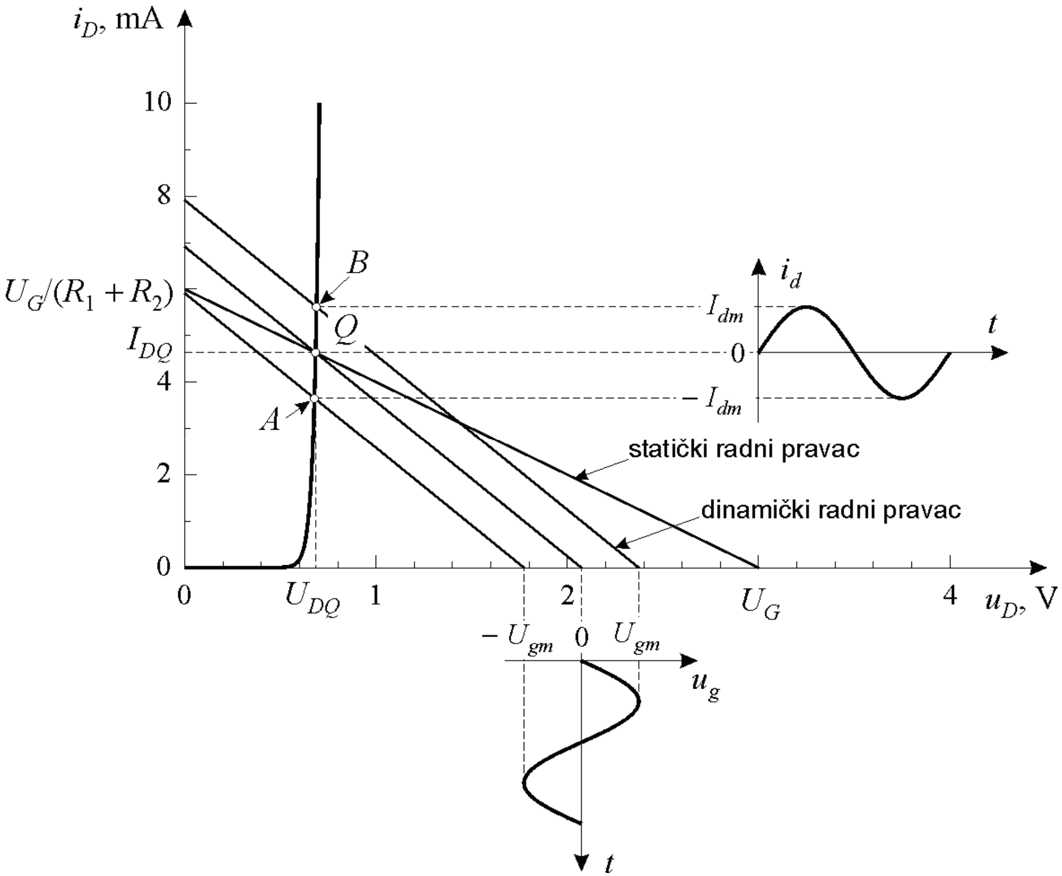


statička analiza



dinamička analiza

Grafička analiza



Statički radni pravac:

$$U_G = (R_1 + R_2)\, I_D + U_D$$

nagib: $-1/(R_1 + R_2)$

Dinamički radni pravac:

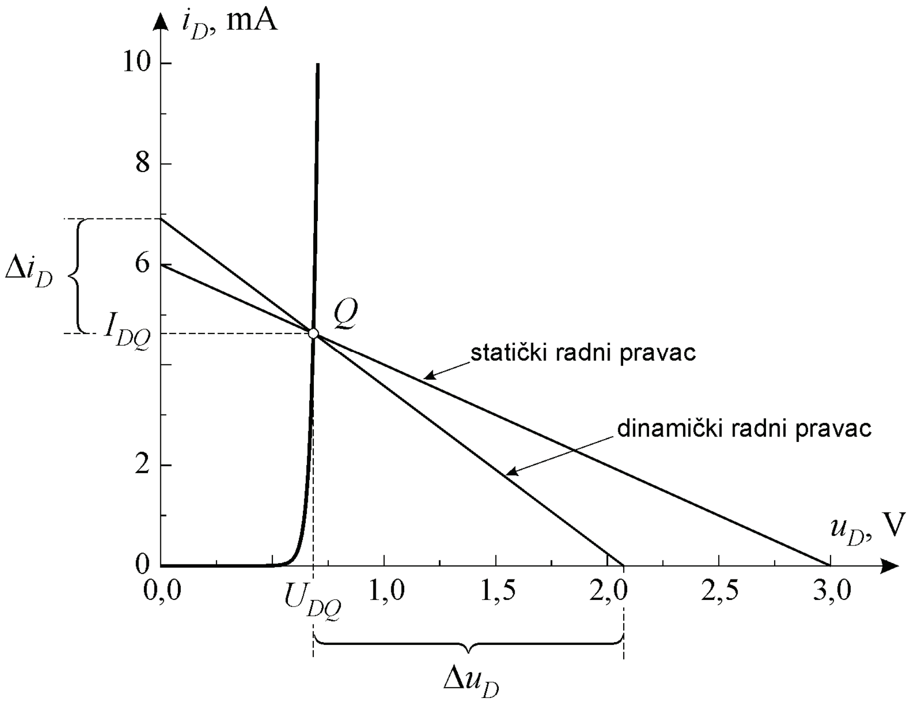
$$u_g = (R_1 + R_2 \| R_3)\, i_d + u_d$$

nagib: $-1/(R_1 + R_2 \| R_3)$

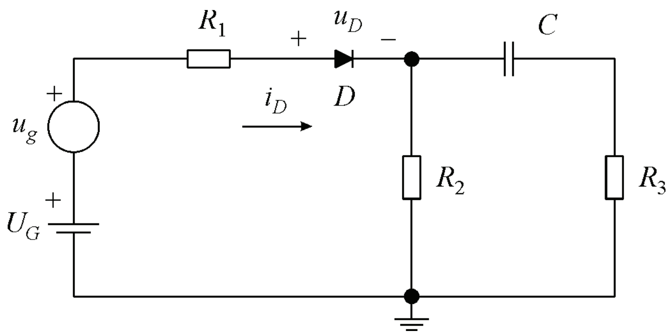
Primjer 4.4

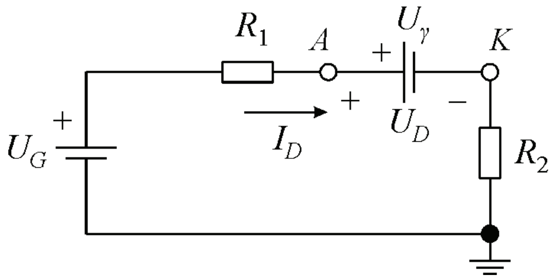
Konstruirati statički radni pravac i dinamički radni pravac za napon $u_g = 0$ za primjer sa zadnjeg grafičkog prikaza. Zadano je: $U_G = 3$ V, $R_1 = 100\ \Omega$ i $R_2 = R_3 = 400\ \Omega$.

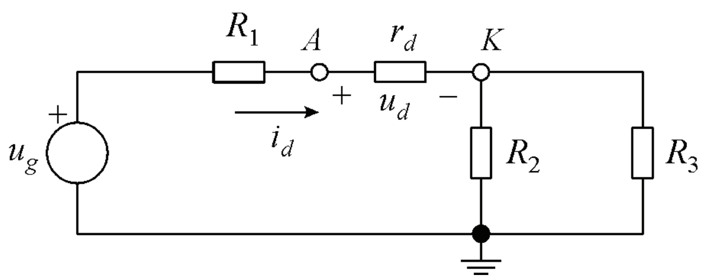
Rješenje:



Analitički postupak







statička analiza

$$U_D = U_{DQ} = U_\gamma$$

$$I_D = I_{DQ} = \frac{U_G - U_\gamma}{R_1 + R_2}$$

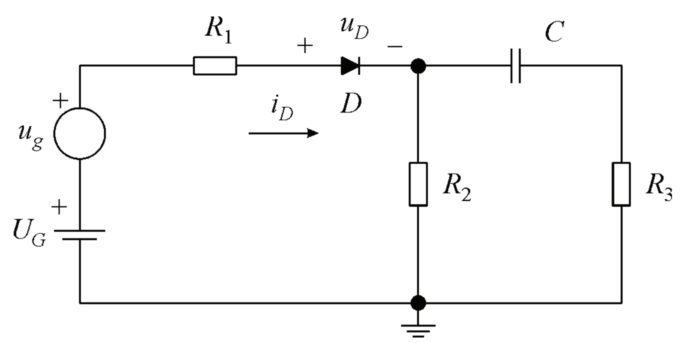
dinamička analiza

$$i_d = \frac{u_g}{R_1 + r_d + R_2 \| R_3}$$

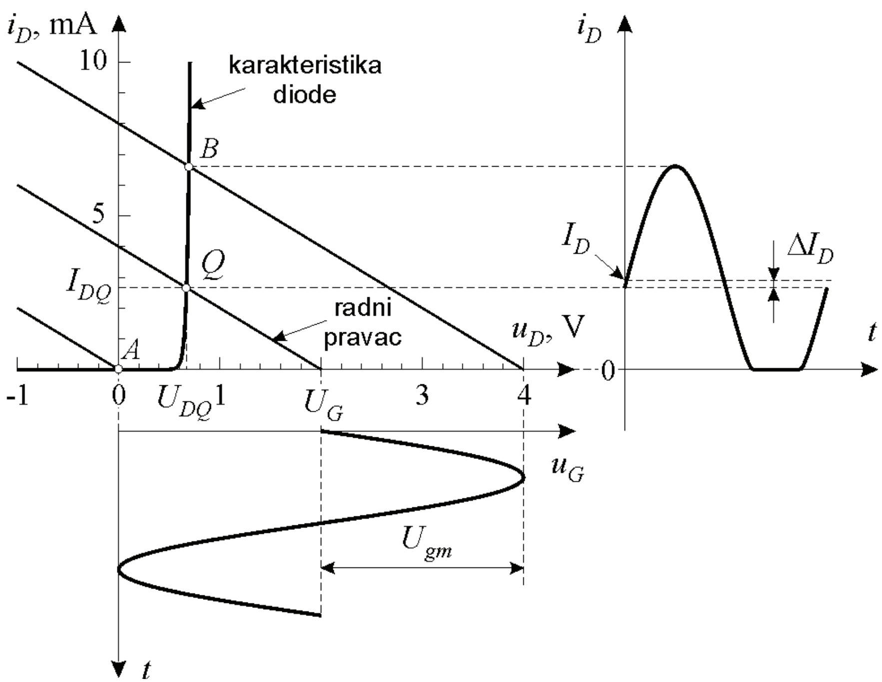
$$u_d = r_d \, i_d$$

Primjer 4.5

Za sklop sa slike analitički proračunati napon u_D i struju i_D diode. Napon $u_G = 3 + 0{,}3\ \sin\omega t$ V, otpori $R_1 = 100\ \Omega$, $R_2 = R_3 = 400\ \Omega$, napon koljena diode $U_\gamma = 0{,}7$ V i temperatura je sobna, $U_T = 25$ mV.



Priključak velikog signala



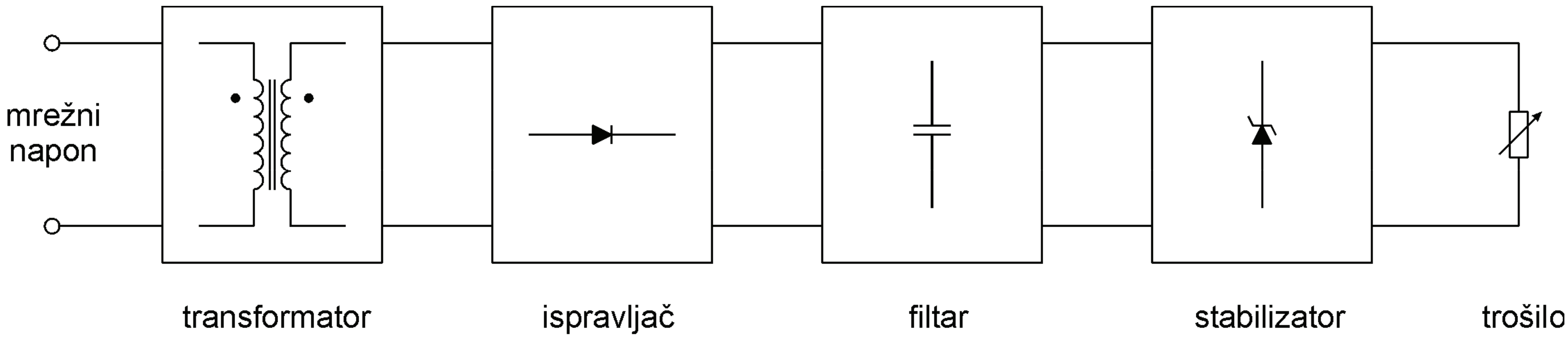
Hod radne točke po nelinearnom dijelu karakteristike

Posljedica nelinearnog rada:

- izobličenje struje
- dodatna istosmjerna struja ΔI_D

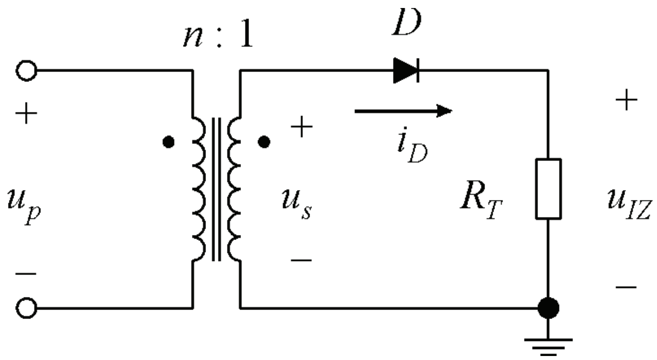
$I_D = I_{DQ} + \Delta I_D$

Izvor napajanja



- Mrežni napon – $f = 50\ \mathrm{Hz}$, $U_{pef} = 220\ \mathrm{V}$, $U_{pm} = 310\ \mathrm{V}$
- Transformator – smanjuje ulazni napon, izolira izvor od napona u primaru
- Ispravljač – ispravlja izmjenični napon, daje istosmjerni pulsirajući napon
- Filtar – guši izmjenične komponente
- Stabilizator – održava stalni istosmjerni napon
- Trošilo – elektronički sklopovi i uređaji

Polualni ispravljač (1)



Mrežni napon – $u_p = U_{pm} \sin \omega t$

Napon sekundara – $u_s = U_{sm} \sin \omega t$ Omjer transformacije: $n = U_{pm}/U_{sm}$

Za $u_D = u_s - u_{IZ} > U_\gamma$ $\rightarrow$ dioda vodi $\rightarrow$ $u_D = U_\gamma$, $u_{IZ} = u_s - U_\gamma$

Za $u_D < U_\gamma$ $\rightarrow$ dioda ne vodi $\rightarrow$ $i_D = 0$, $u_D = u_s$, $u_{IZ} = 0$

Poluvalni ispravljač (2)

Uz idealnu diodu:

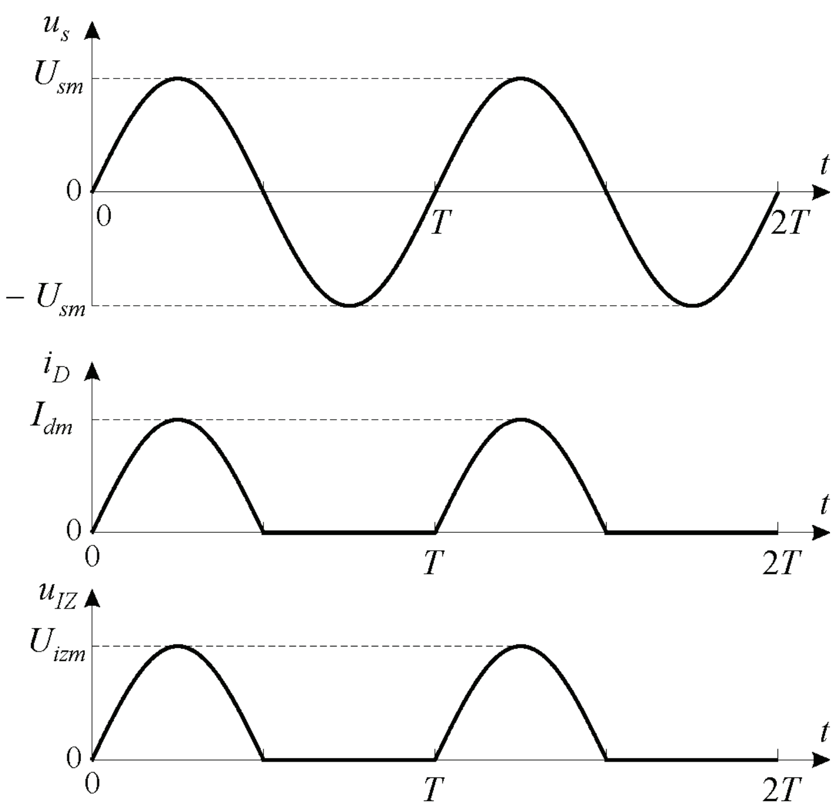
za $u_D < 0 \rightarrow i_D = 0$

za $u_D > 0 \rightarrow u_D = 0$

$$i_D = \begin{cases} u_s / R_T & \text{za} \quad u_s > 0 \\ 0 & \text{za} \quad u_s < 0 \end{cases}$$

$$u_{IZ} = i_D R_T$$

$$u_{IZ} = \begin{cases} u_s & \text{za} \quad u_s > 0 \\ 0 & \text{za} \quad u_s < 0 \end{cases}$$



Poluvalno ispravljeni napon (1)

Srednja vrijednost

$$U_{IZ} = \frac{1}{T}\int_0^T u_{IZ}(t)\,\mathrm{d}t = \frac{1}{2\pi}\left(U_{sm}\int_0^{\pi} \sin\omega t\,\mathrm{d}\omega t + \int_{\pi}^{2\pi} 0\,\mathrm{d}\omega t\right) = \frac{U_{sm}}{\pi} = 0{,}318\,U_{sm}$$

Efektivna vrijednost

$$U_{izef} = \left[\frac{1}{T}\int_0^T u_{IZ}^2(t)\,\mathrm{d}t\right]^{1/2} = \left[\frac{1}{2\pi}\left(U_{sm}^2\int_0^{\pi} \sin^2\omega t\,\mathrm{d}\omega t + \int_{\pi}^{2\pi} 0\,\mathrm{d}\omega t\right)\right]^{1/2} = \frac{U_{sm}}{2}$$

Razvojem poluvalno ispravljenog napona u Fourierov red

$$u_{IZ} = U_{sm}\left[\frac{1}{\pi} + \frac{\sin\omega t}{2} - \frac{2}{\pi}\left(\frac{\cos 2\omega t}{1\cdot 3} + \frac{\cos 4\omega t}{3\cdot 5} + \ldots\right)\right] = U_{IZ} + u_{izv}$$

Poluvalno ispravljeni napon (2)

Uz $U_{izef} = \sqrt{U_{IZ}^2 + U_{izvef}^2}$

Efektivna vrijednost napona valovitosti

$$U_{izvef} = \sqrt{U_{izef}^2 - U_{IZ}^2} = U_{sm}\sqrt{\frac{1}{4} - \frac{1}{\pi^2}} = 0{,}386\,U_{sm}$$

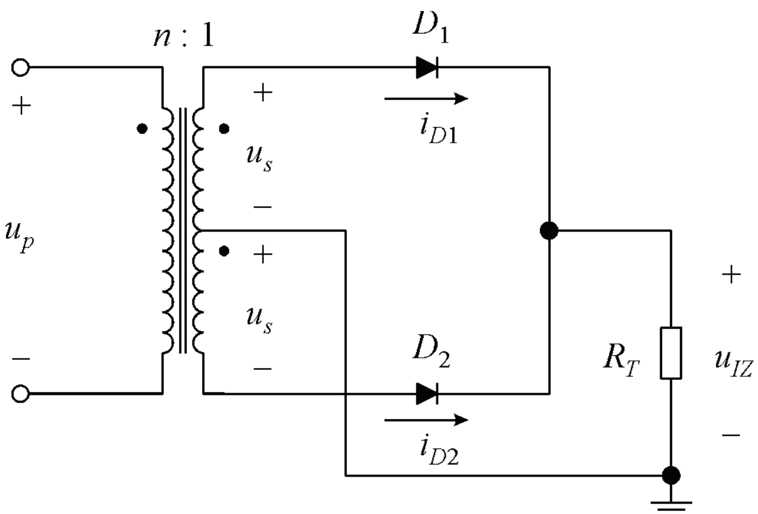
Faktor valovitosti

$$r = \frac{U_{izvef}}{U_{IZ}} = \sqrt{\left(\frac{U_{izef}}{U_{IZ}}\right)^2 - 1} = \sqrt{\frac{\pi^2}{4} - 1} = 1{,}21$$

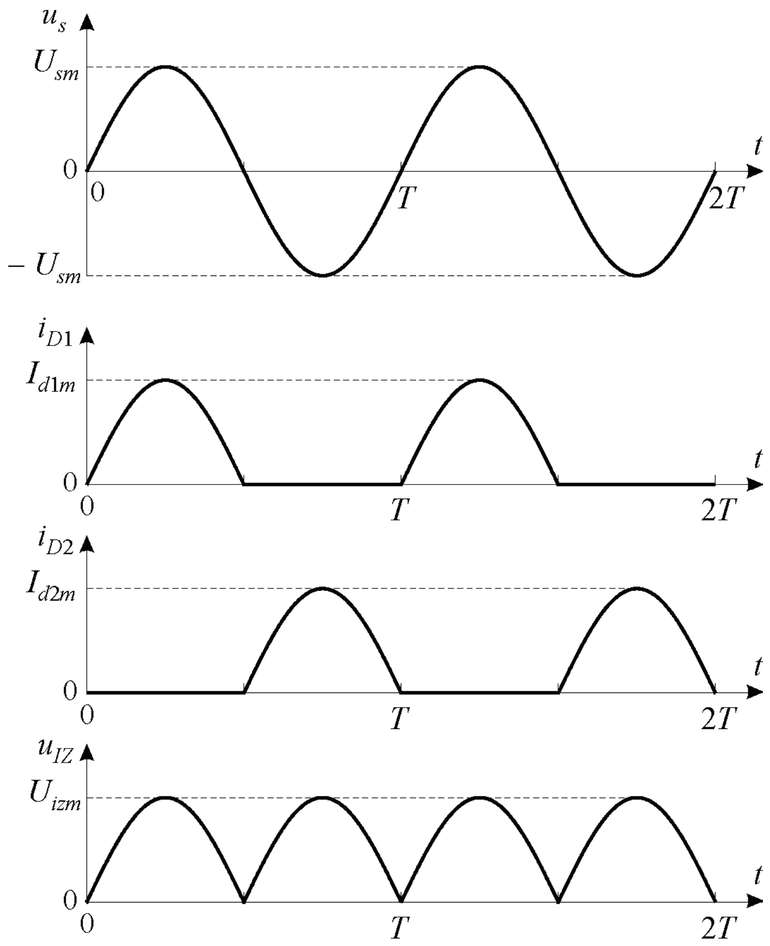
Maksimalna struja diode u vođenju – U_{sm}/R_T

Maksimalni zaporni napon diode – U_{sm}

Punovalni ispravljač



$$u_{IZ} = (i_{D1} + i_{D2})\,R_T$$



Punovalno ispravljeni napon (1)

Srednja vrijednost

$$U_{IZ} = \frac{2}{T}\int_0^{T/2} u_{IZ}(t)\,\mathrm{d}t = \frac{U_{sm}}{\pi}\int_0^{\pi} \sin\omega t\,\mathrm{d}\omega t = \frac{2U_{sm}}{\pi} = 0{,}637\,U_{sm}$$

Efektivna vrijednost

$$U_{izef} = \left[\frac{2}{T}\int_0^{T/2} u_{IZ}^2(t)\,\mathrm{d}t\right]^{1/2} = \left(\frac{U_{sm}^2}{\pi}\int_0^{\pi} \sin^2\omega t\,\mathrm{d}\omega t\right)^{1/2} = \frac{U_{sm}}{\sqrt{2}} = 0{,}707\,U_{sm}$$

Razvojem punovalno ispravljenog napona u Fourierov red

$$u_{IZ} = U_{sm}\left[\frac{2}{\pi} - \frac{4}{\pi}\left(\frac{\cos 2\omega t}{1\cdot 3} + \frac{\cos 4\omega t}{3\cdot 5} + \ldots\right)\right] = U_{IZ} + u_{izv}$$

Punovalno ispravljeni napon (2)

Efektivna vrijednost napona valovitosti

$$U_{izvef} = \sqrt{U_{izef}^2 - U_{IZ}^2} = U_{sm}\sqrt{\frac{1}{2} - \frac{4}{\pi^2}} = 0{,}308\,U_{sm}$$

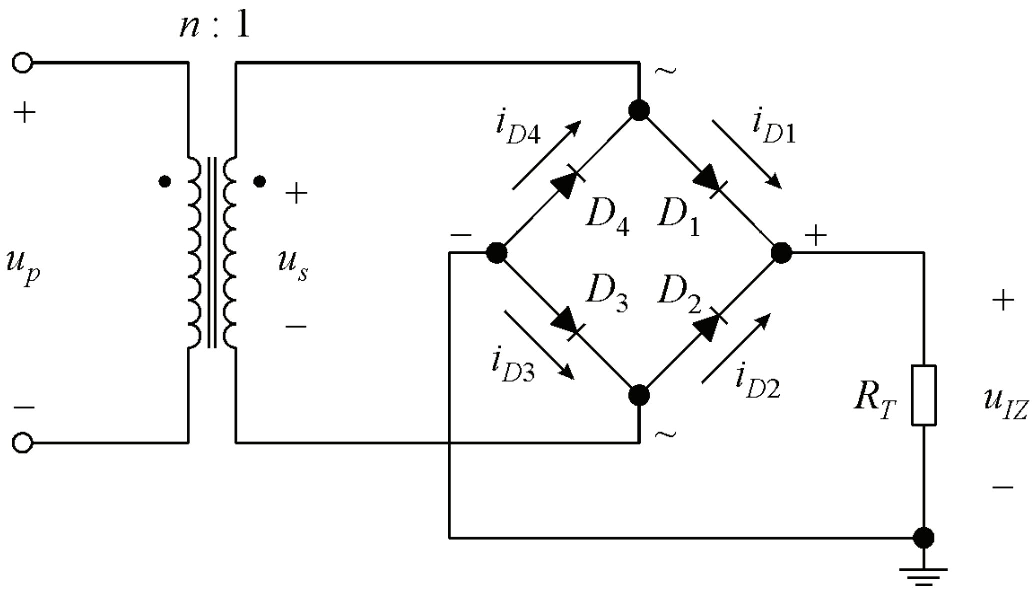
Faktor valovitosti

$$r = \frac{U_{izvef}}{U_{IZ}} = \sqrt{\left(\frac{U_{izef}}{U_{IZ}}\right)^2 - 1} = \sqrt{\frac{\pi^2}{8} - 1} = 0{,}483$$

Maksimalna struja dioda u vođenju – U_{sm}/R_T

Maksimalni zaporni napon dioda – $2U_{sm}$

Punovalni ispravljač – mosni ili Graetzov spoj

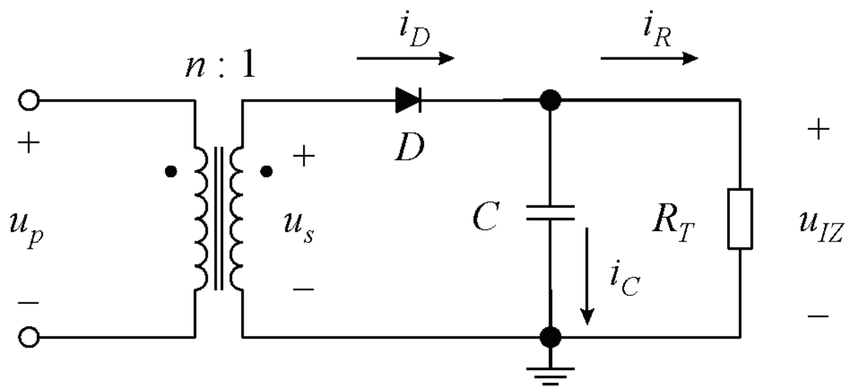


- Valni oblici – isti kao i kod prethodnog punovalnog ispravljača
- Maksimalna struja dioda u vođenju – U_{sm}/R_T
- Maksimalni zaporni napon dioda – U_{sm}
- Realizacija – sve 4 diode u istom kućištu

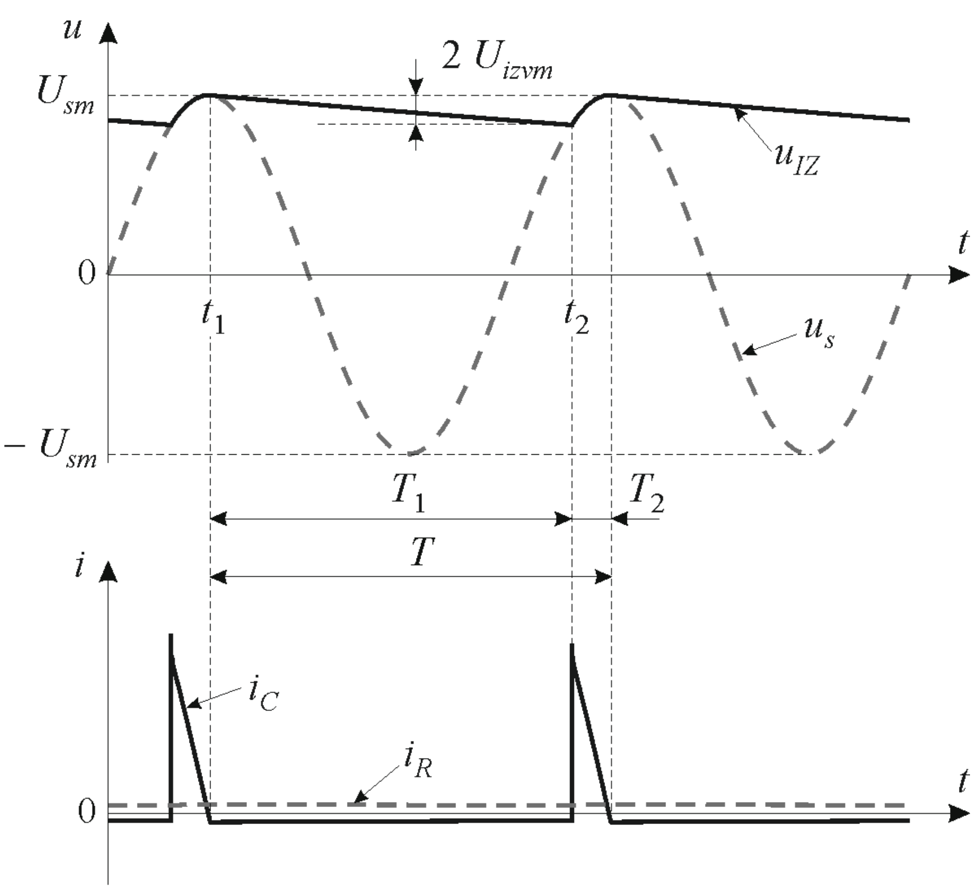
Ispravljač s kapacitivnim opterećenjem (1)

Smanjuje valovitost ispravljenog napona

C i R_T – niskopropusni filtar koji guši izmjenične komponente ispravljenog napona



Ispravljač s kapacitivnim opterećenjem (2)



Kroz T_1 – $u_s < u_{IZ}$ dioda ne vodi, kondenzator se izbija

$$u_{IZ}(t) = U_{sm} \exp\left(-\frac{t - t_1}{\tau}\right) \qquad \tau = R_T\, C$$

Za $t = t_2$ – $u_s = u_{IZ}$ dioda provede

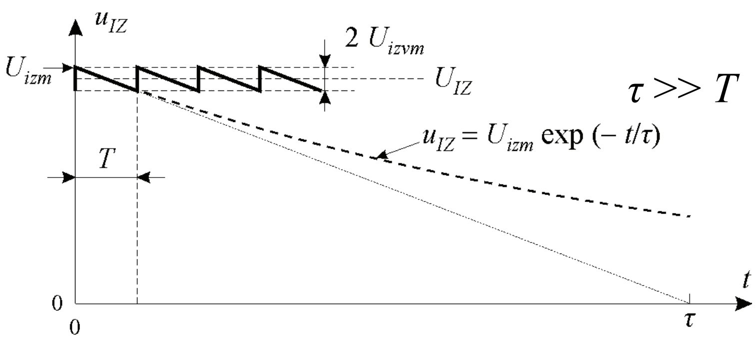
$$U_{sm} \cos\omega(t_2 - t_1) = U_{sm} \exp\left(-\frac{t_2 - t_1}{\tau}\right)$$

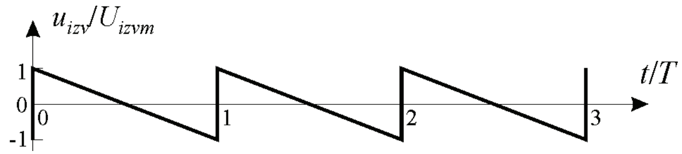
Kroz T_2 – $u_s = u_{IZ}$ dioda vodi, kondenzator se nabija

$$u_{IZ}(t) = u_s(t) = U_{sm} \cos\omega(t - t_1)$$

Maksimalni zaporni napon diode – $2U_{sm}$

Pojednostavljeni valni oblik napona trošila





Za $t = 0 \qquad u_{IZ}(0) = U_{izm} = U_{sm}$

Za $t = T_2 \approx T$

$$u_{IZ}(T) = U_{izm} \exp\left(-\frac{T}{\tau}\right) \approx U_{izm}\left(1 - \frac{T}{\tau}\right)$$

$$u_{IZ}(0) - u_{IZ}(T) = 2U_{izvm}$$

$$U_{izvm} = U_{izm} \frac{T}{2\tau}$$

Srednja vrijednost $\quad U_{IZ} = u_{IZ} - u_{izv} = U_{izm} - U_{izvm} = U_{izm}\left(1 - \dfrac{T}{2\tau}\right)$

Izmjenični napon valovitosti $\quad u_{izv} = U_{izvm}\left(1 - \dfrac{2t}{T}\right) \qquad U_{izvef} = \left[\dfrac{1}{T}\displaystyle\int_0^T u_{izv}^2(t)\,\mathrm{d}t\right]^{1/2} = \dfrac{U_{izvm}}{\sqrt{3}}$

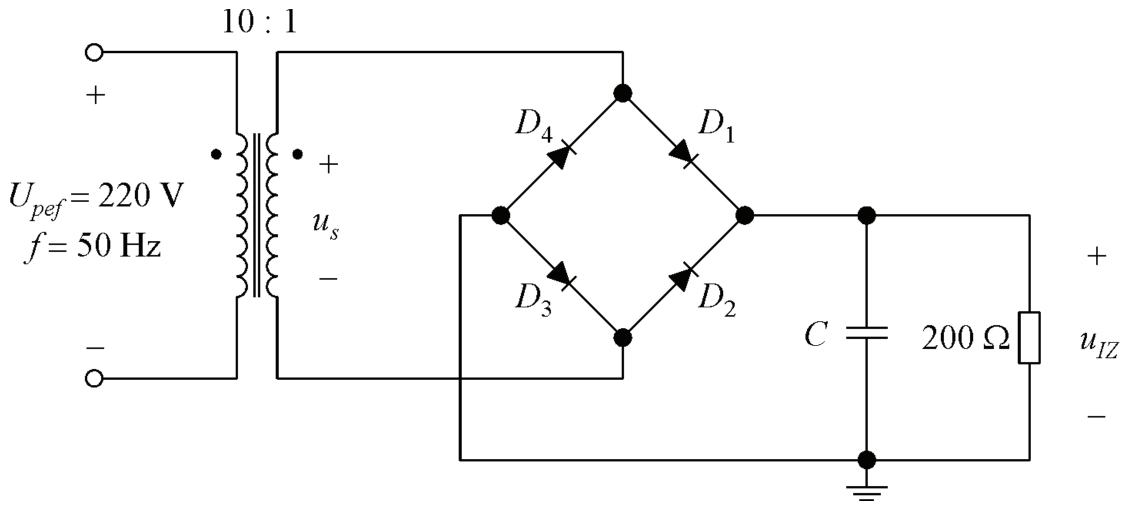
Faktor valovitosti $\quad r = \dfrac{U_{izvef}}{U_{IZ}} = \dfrac{T/(2\,\tau)}{\sqrt{3}\left[1 - T/(2\,\tau)\right]}$

Primjer 4.6 (1)

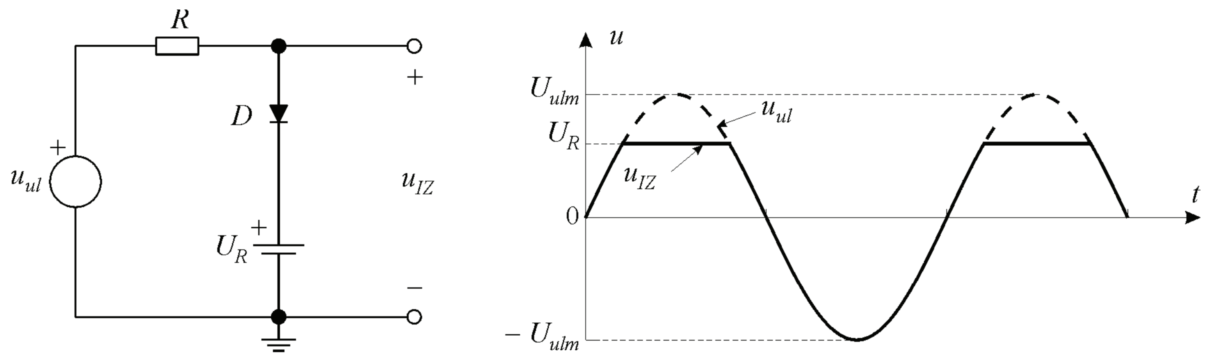
Za punovalni ispravljač u Graetzovom spoju s kapacitivnim opterećenjem na slici izračunati srednju vrijednost napona trošila i faktor valovitosti uz:

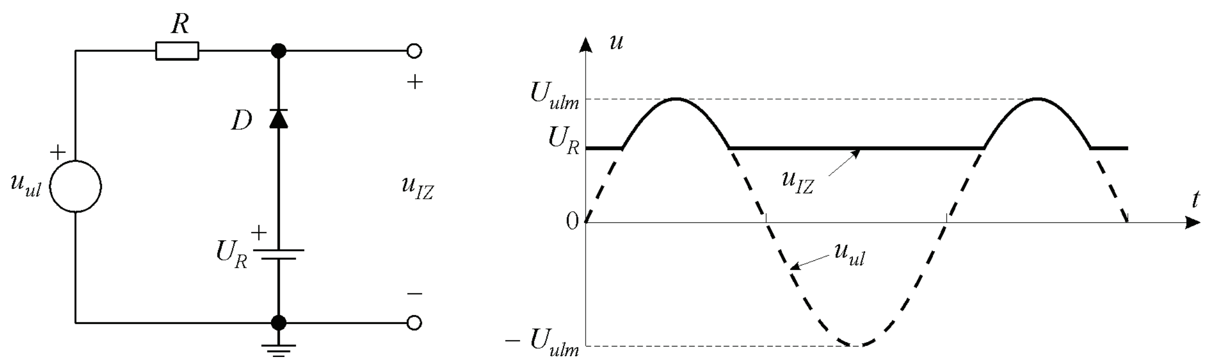
a) $C = 0$,

b) $C = 1000\ \mu\text{F}$.

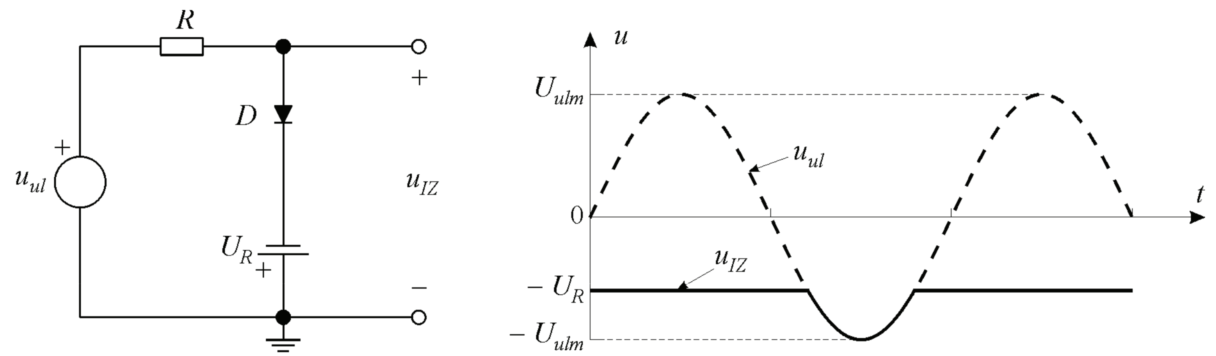


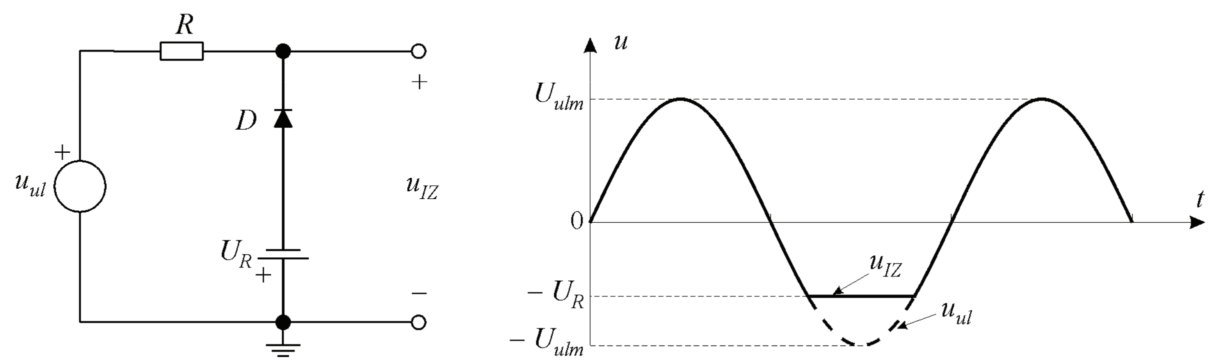
Paralelni diodni ograničavači (1)



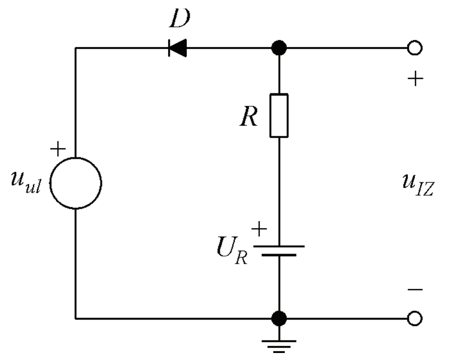


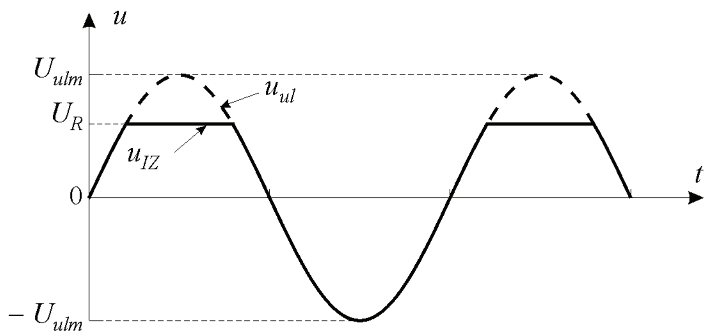
Paralelni diodni ograničavači (2)





Serijski diodni ograničavač

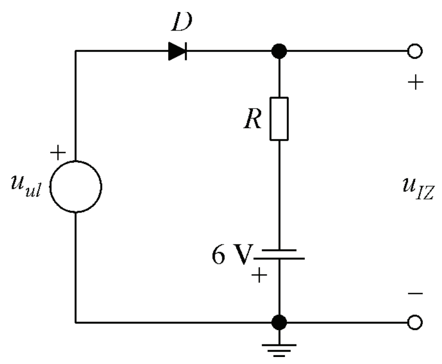


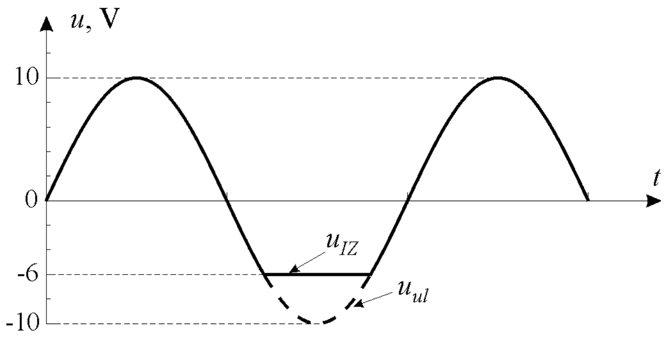


Primjer 4.7

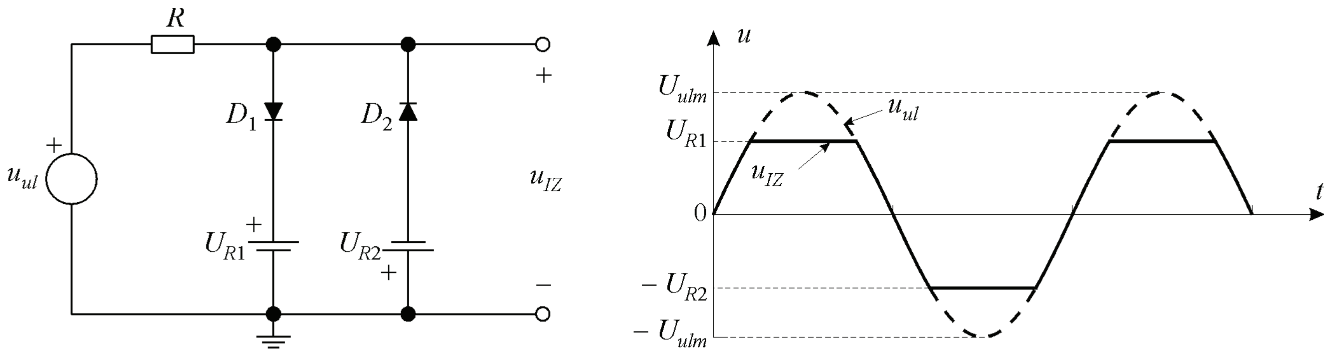
Nacrtati spoj serijskog diodnog ograničavača koji će ulazni napon $u_{ul} = 10 \sin \omega t$ V ograničiti ispod razine od -6 V.

Rješenje:

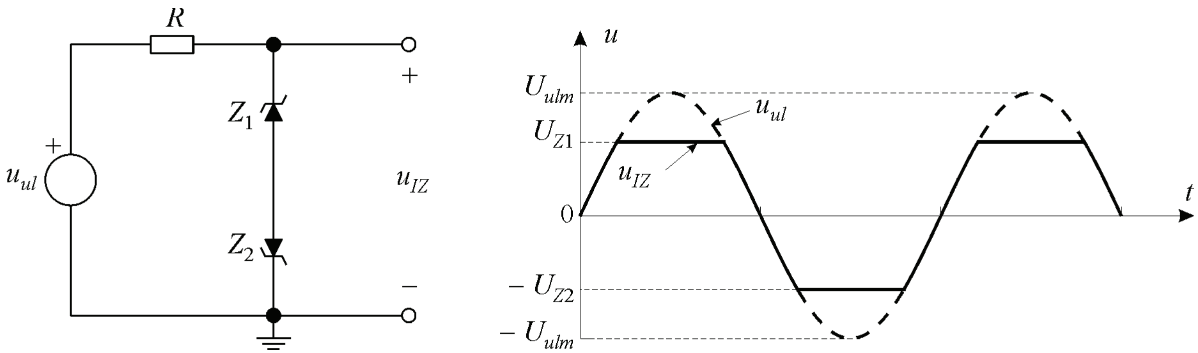




Dvostrani ograničavači



Dvostrani paralelni diodni ograničavač



Dvostrani ograničavač sa Zenerovim diodama