

NEJLINEARNA ELEKTRONSKA VEŽJA - NEV

EV = Delitev po načinu analize: - rezistivna vezja (analitično ali grafično)
- dinamična vezja (reševanje dif. en)

+ v obeh primerih NUMERIČNA SIMULACIJA



LT SPICE

Analitično reševanje rezistivnih vezij:

a.) eksplicitno: $y = f(x)$

b.) implicitno: $h(x, y) = 0$

Grafično reševanje rezistivnih vezij:

odsekoma linearizirane nelin. elemente

Analitično reševanje dinamičnih vezij:

$\dot{x} = f(x, y)$ enačbe stanja

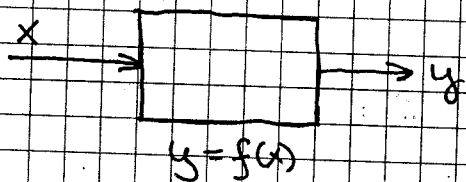
NEV = neselektivna NEV + selektivna NEV

1. NESELEKTIVNA NELINEARNA VEZJA ZA PREOBLIKOVANJE SIGNALOV

1.1. REZISTIVNA VEZJA Z ENIM VHODOM

- sistem je časovno invarianten

matematični zapis:



$$\begin{cases} u_2 = f(u_1) & \text{ali } f(i_1) \\ i_2 = f(i_1) & \text{ali } f(u_1) \end{cases}$$

elektronski model (zapis):

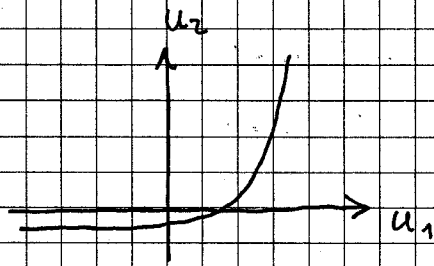


- prenosna funkcija (PF) : $i_2(i_1)$ ali $i_2(u_1)$
 $u_2(u_1)$ ali $u_2(i_1)$

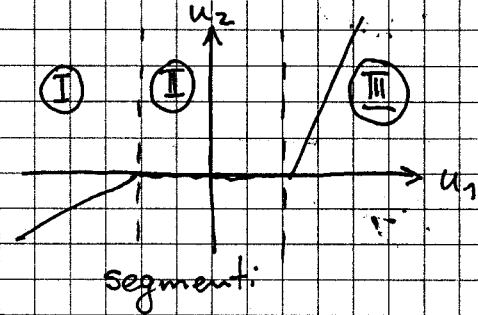
- vhodna funkcija (VF) : $i_1(u_1)$ ali $u_1(i_1)$

- izhodna funkcija (IF) : $u_2(i_2)$ ali $i_2(u_2)$

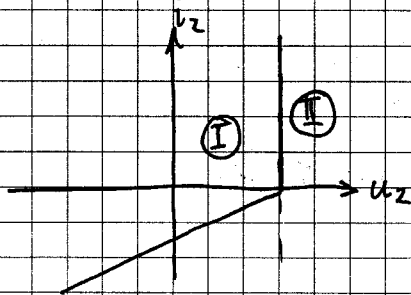
primer PF:



primer VF:



primer IF:

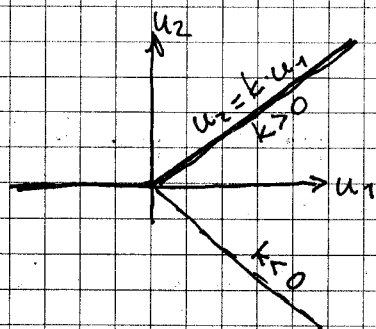


1.1.1. R-USMERNIKI (usmerniki z Ohmskim bremenom)

gre. za signalne usmernike in NE za napajalne usmernike

• POKVALNI R-USMERNIK

PF:



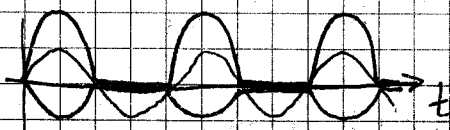
grafično

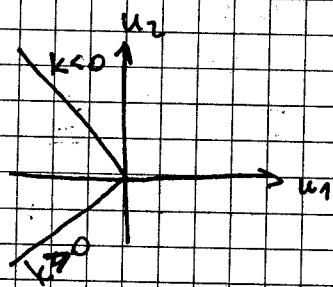
$k > 0$: neinvertivajoč en polvalnem R-USM

$k < 0$: invertivajoči polvalni R-USM

analitično

$$u_2 = \begin{cases} k \cdot u_1 & ; u_1 \geq 0 \\ 0 & ; u_1 < 0 \end{cases}$$

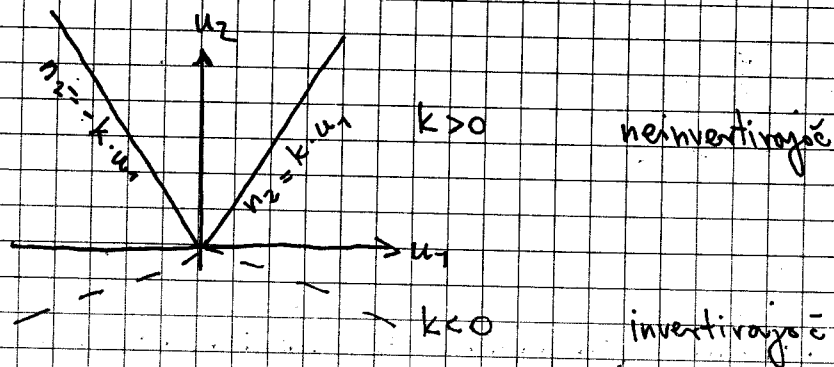




$$u_2 = \begin{cases} k \cdot u_1 & ; u_1 < 0 \\ 0 & ; u_1 > 0 \end{cases}$$

● POLNOVALNI R - USMERNIK

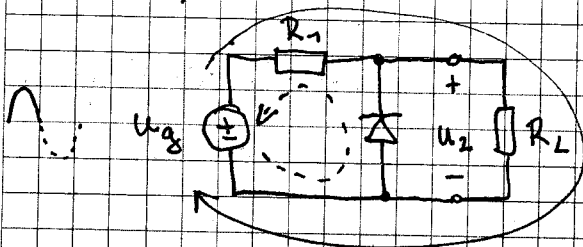
PF:



analitično: $u_2 = k \cdot |u_1|$

REALIZACIJE:

a.) paralelna vezava diode:



V pozitivni polperiodi dioda ne prevaja

V negativni pa prevaja

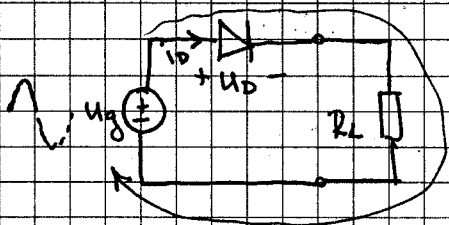
$$k = \frac{R_L}{R_1 + R_L} < 1$$

za pozitivni polval dioda je zaprta

$$u_2 = U_K$$

za negativni polval dioda prevaja

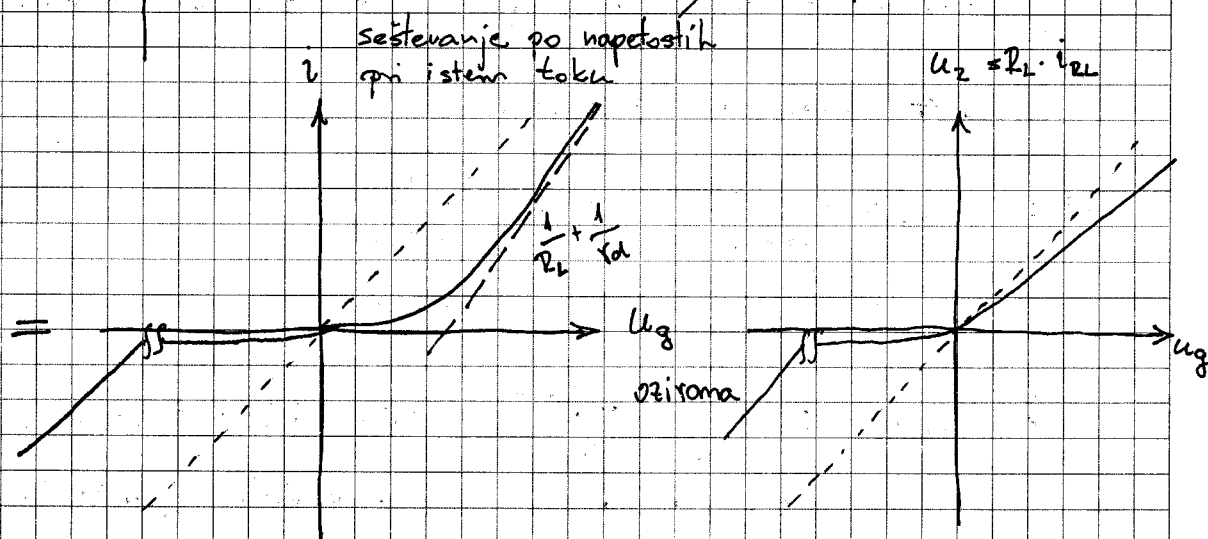
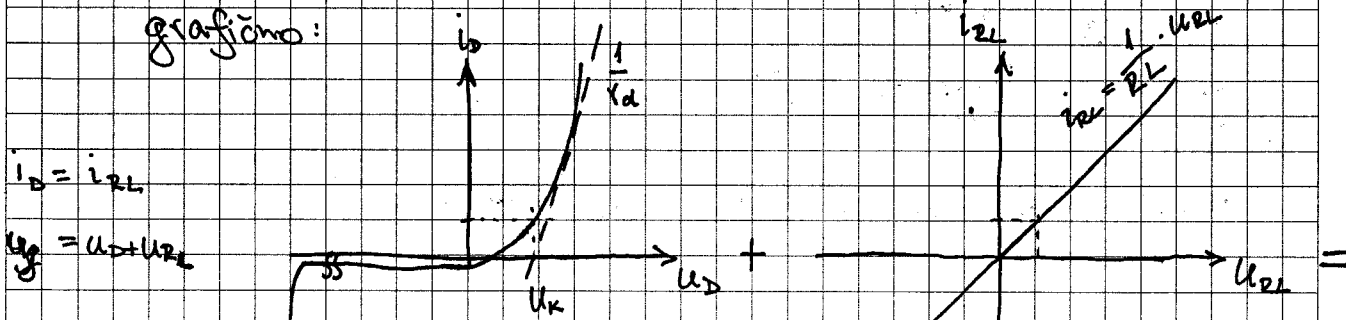
b.) serijska vezava diode:



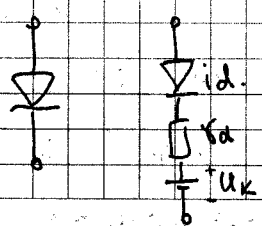
prevaja le za pozitivni polval

Analiza za realno diodo:

grafično:



pocnostavitev: lineariziran model diode

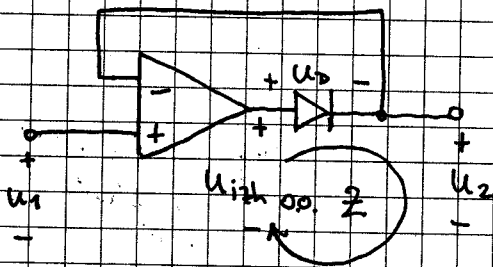


REALIZACIJE 2-USM z O.O. (op. amp) :

- uporaba neg. PS, ki bo dioda idealiziral

- neinvertirajoč polvalni 2-USM ($k \approx +1$)

izhaja iz nap. sledilnika



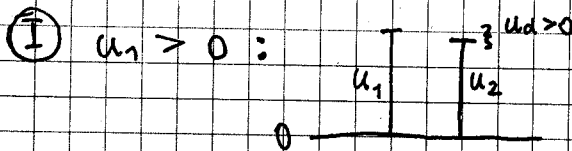
Analiza za idealni O.O. ($A_u \rightarrow \infty$)

z: $u_{izh\ o.o.} = u_D + u_2$

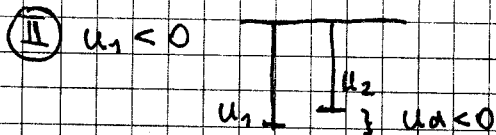
$u_{izh\ o.o.} = A_u \cdot (u_1 - u_2)$; samo za LIN območje delovanja

$u_D + (1 + A_u) \cdot u_2 = A_u \cdot u_1$

PF: $u_2 = \frac{A_u}{(1 + A_u)} \cdot u_1 - \frac{u_D}{1 + A_u}$



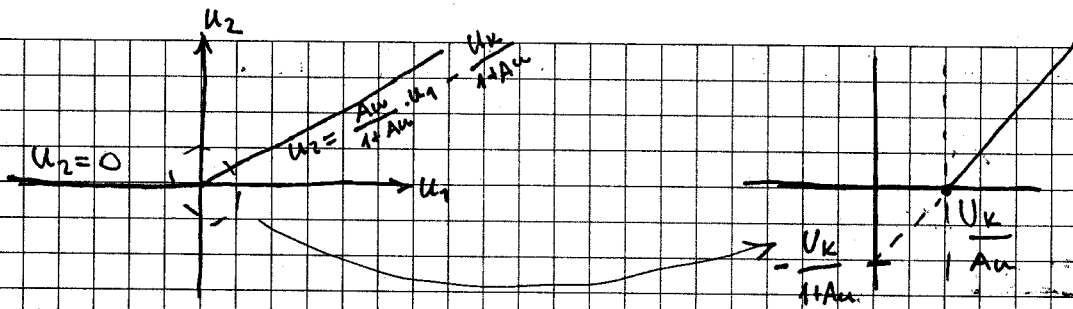
O.O. sili v $+U_{sat}$, a mi dioda preprečuje ($u_D = +U_K$), zato $u_{izh\ o.o.} = +U_K + u_K$ dioda prevaja



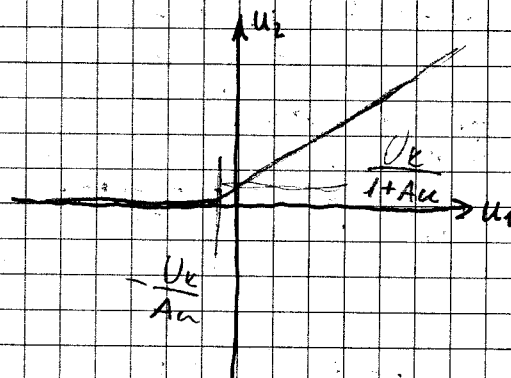
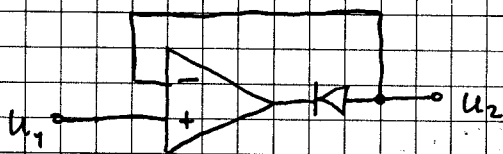
O.O. sili v $-U_{sat}$, $u_{izh\ o.o.} = -U_{sat}$ zato je dioda zaporno polarizirana

$u_2 = R_L \cdot i_{R_L} = 0$

PF:

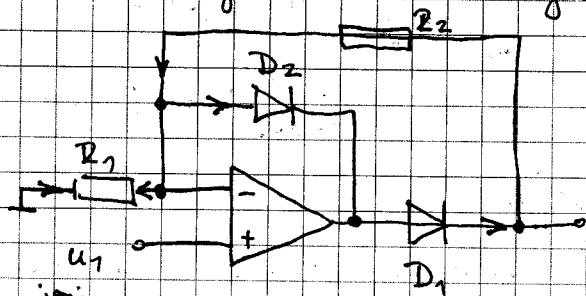


2a D.N. PF = ?



• neinvertirajoče polovalni R-VSM ($k > 1$)

- temelji na neinvertirajočem OJAČ z O.O.



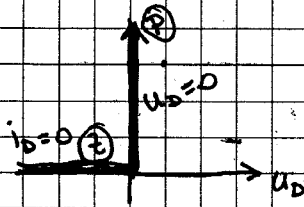
D_2 ... preprečija, da gre O.O.
V - Usat

opis delovanja:

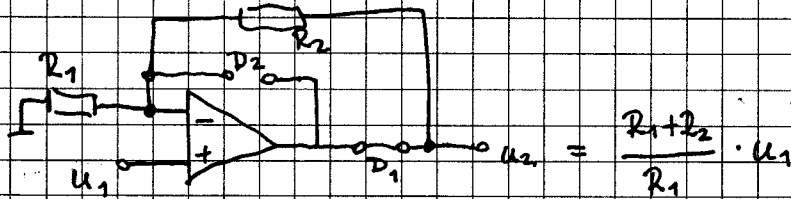
$u_1 > 0$: D_1 prevodna, D_2 zaporna

$u_1 < 0$: $u^- = u^+ < 0$, D_2 prevaja, D_1 zaporna

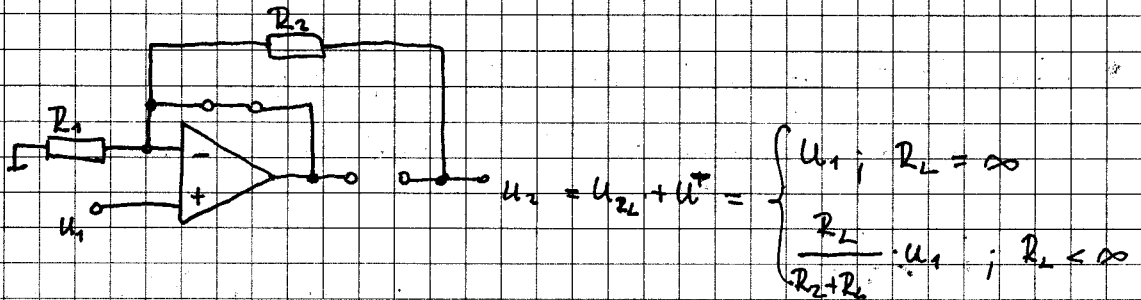
Analiza za idealni O.O. in idealni D_1, D_2



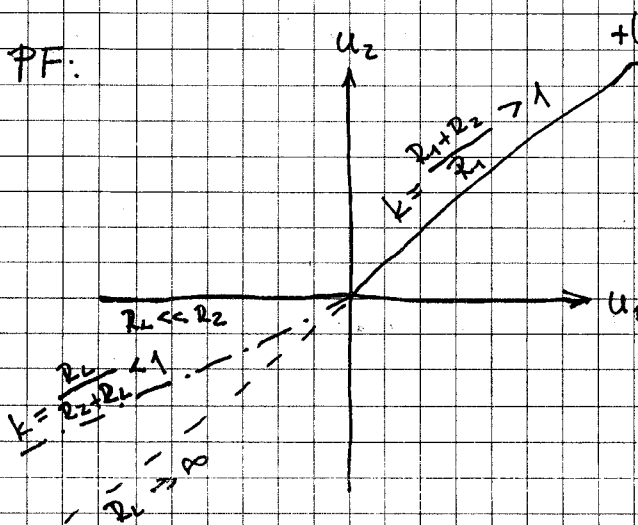
I $u_1 > 0$: P_1 & Z_2



II $u_1 < 0$: Z_1 & P_2

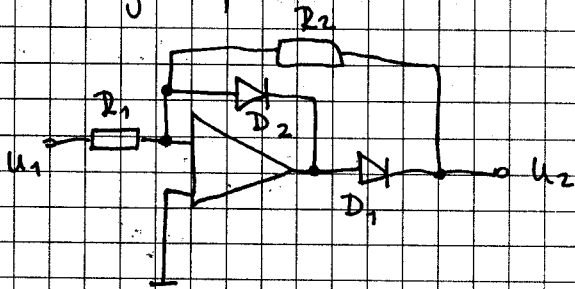


PF:



polvalni R-VSM samo ob izpolnitvi pogoja $R_L \ll R_2$

● Invertirajoči polvalni R-USM



D_2 ... preprečuje uhajanje v kosičenje

Analiza za idealni O.O. in idealne D_1 in D_2 :

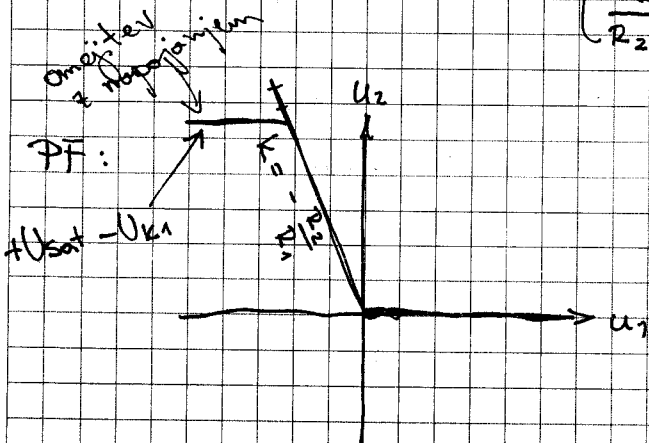
Ⓘ $u_1 < 0$: (R_1) , (R_2) , vezje deluje kot invertirajoči ojač.

$$u_2 = -\frac{R_2}{R_1} \cdot u_1 \quad \text{in} \quad u_{izh. o.o.} = U_{ki} + u_2$$

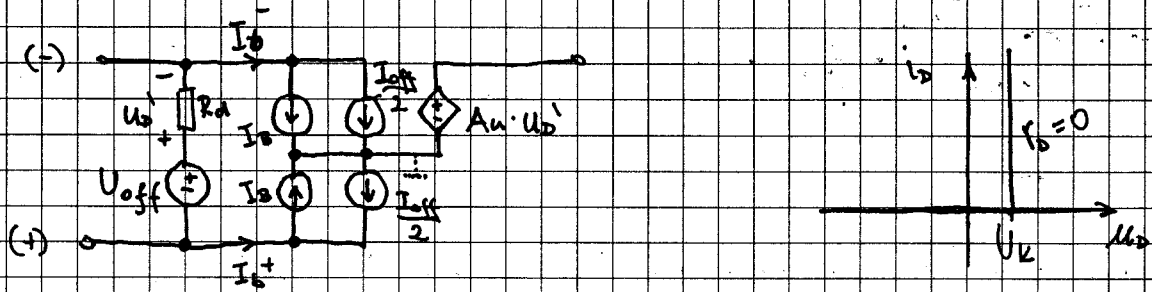
Ⓜ $u_1 > 0$: (D_1) & (D_2)

$$u_{izh. o.o.} = -u_{D2} + u^- = -U_k + 0 = -U_k$$

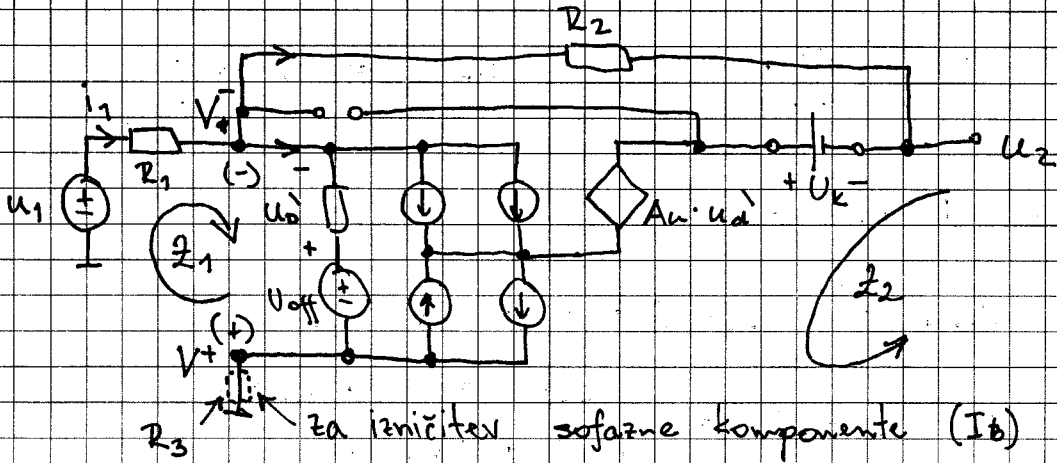
$$u_2 = u_{R2} + u^- = \begin{cases} u_{R2} + u^- = 0 & ; R_L \rightarrow \infty \\ \frac{R_L}{R_2 + R_L} \cdot u^- = 0 & ; R_L < \infty \end{cases}$$



Analiza za realni O.O. ($A_u \rightarrow \infty$, U_{off} , I_B , I_{off}) in linearnimi obkodi D_1, D_2
 ($U_K, r_{u2} = 0$)



① ② in ③



$$\textcircled{2}: U_2 = -U_{K1} + A_u \cdot U_D'$$

neznanke

$$\textcircled{1}: U_D' = U_{off} - U_1 + R_1 \cdot i_1$$

$$V^-: \frac{U_1 - U^-}{R_1} = \frac{U^- + U_2}{R_2} + I_B^-$$

$$V^+: -\frac{U^+}{R_3} = I_B^+$$

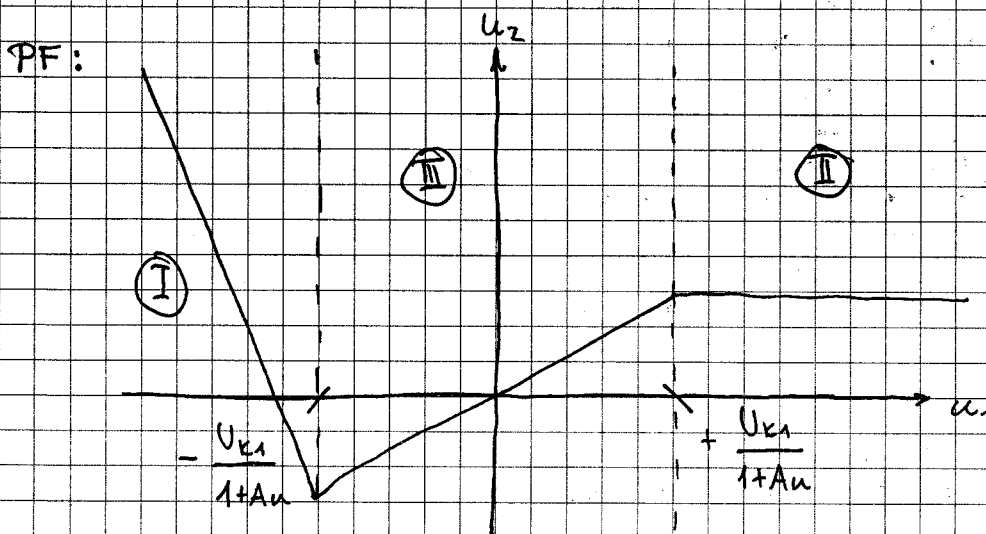
$$U_2 = -\frac{R_2}{R_1} \cdot U_1 - \frac{U_{K1}}{A_u} \left(1 + \frac{R_2}{R_1}\right) + U_{off} \left(1 + \frac{R_2}{R_1}\right) + \left(1 + \frac{R_2}{R_1}\right) \cdot \left[R_1 \parallel R_2 - R_3 \right] \cdot I_B + \left[R_1 \parallel R_2 + R_3 \right] \cdot I_B$$

$$D_1 < -\frac{U_{K1}}{1 + A_u} \quad (\text{manjše od } \sim f_{GBW})$$

$$\textcircled{\text{I}} \quad u_2 = \frac{r_{D2} \cdot u_1}{A_u \cdot R_1} + \frac{U_{K1}}{A_u} + U_{\text{off}} - R_3 \cdot I_0^+ - r_{D2} \cdot I_B^- ; \quad u_1 > + \frac{U_{K1}}{1+A_u}$$

III) omejeno območje med I in II

$$u_2 = u_1 - R_1 \cdot I_B^- ; \quad - \frac{U_{K1}}{1+A_u} < u_1 < + \frac{U_{K1}}{1+A_u}$$



Konkretni primer:

- $R_1 = R_2 = 10 \text{ k}\Omega$
- $R_3 = 5 \text{ k}\Omega$
- $U_{\text{off}} = 3 \text{ mV}$
- $I_{\text{off}} = 50 \text{ nA}$
- $I_B = 475 \text{ nA}$
- $U_K = 0.7 \text{ V}$
- $A_u = 10^5$
- $r_{D2} = 10 \Omega$

vpliv ničelne napetosti

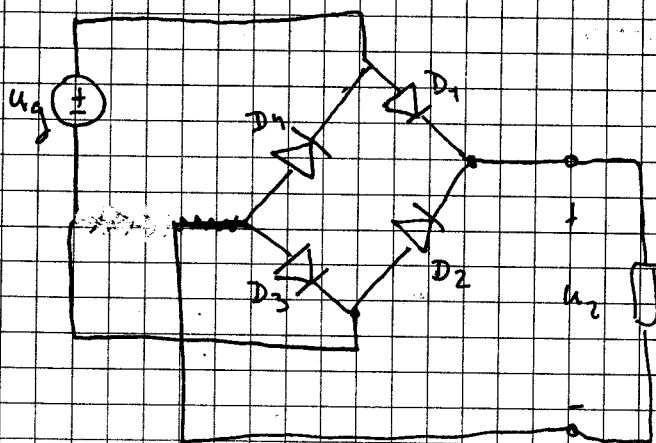
$$u_2 = \begin{cases} -1 \cdot u_1 - 2.7 \mu\text{V} + 2.3 \text{ mV} - 10 \text{ k}\Omega \cdot 30 \text{ nA} ; & u_1 < -7 \mu\text{V} \\ 10^{-8} \cdot u_1 + 7 \mu\text{V} + 3 \text{ mV} + 2.5 \text{ mV} + 4.5 \mu\text{V} & \\ u_1 = 4.5 \text{ mV} & \end{cases}$$

vpliv vhodnih tokov

18.10.2013

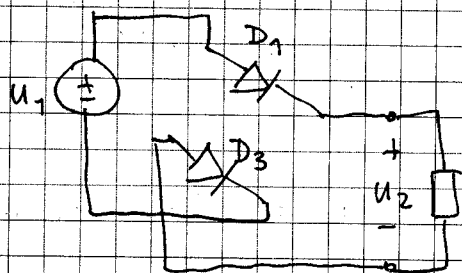
REALIZACIJE POLNOVALNEGA 2-USM S PLAVAJOČIM BREMENOM

- mostično / Graetzovo vezje



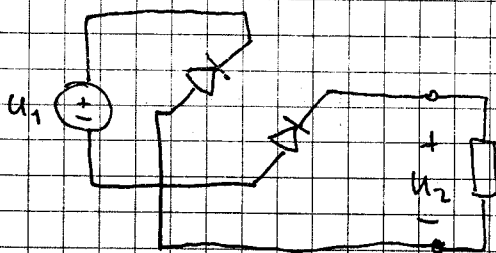
Analiza:

$u_1 > 0$ D_1, D_3 in Z_2, Z_4



$$u_2 = u_1 - U_{k1} - U_{k3}$$

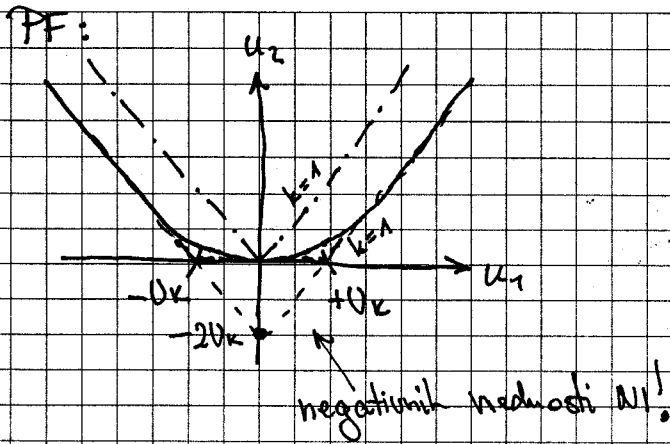
$u_1 < 0$ Z_1, Z_3 in D_2, D_4



$$u_2 = -u_1 - U_{k2} - U_{k4}$$

za enake diode

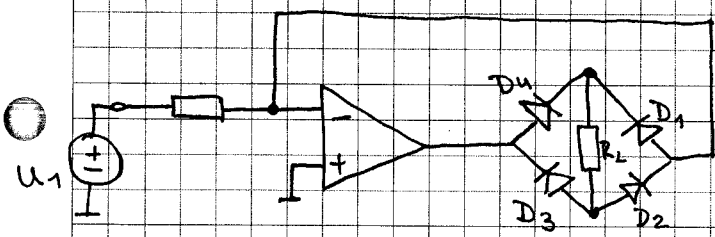
$$u_2 = |u_1| - 2U_k$$



⇒ slab polnomočni R-UM

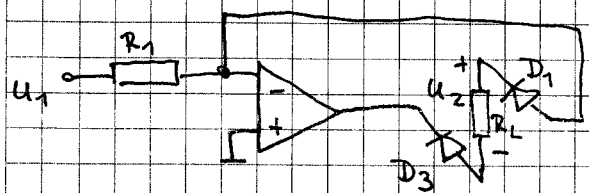
⇒ zadovoljiv R-UM

• mostično / Graetzovo vezje v negativnem Parotnem Sklopu O.O.



Analiza:

$u_1 > 0$: D_1, D_3 in i_{22}, i_{24}

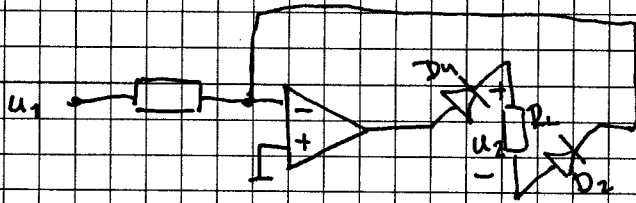


$$u_2 = R_L \cdot i_{2L}$$

$$i_{2L} = i_{21} ; i^- = 0$$

$$u_2 = R_L \cdot \frac{u_1 - u^-}{R_1} = R_L \cdot \frac{u_1}{R_1}$$

$u_1 < 0$: i_1, i_2 in P_2, P_4



$$u_2 = R_L \cdot i_{R_L} = R_L \left(-\frac{u_1}{R_1} \right)$$

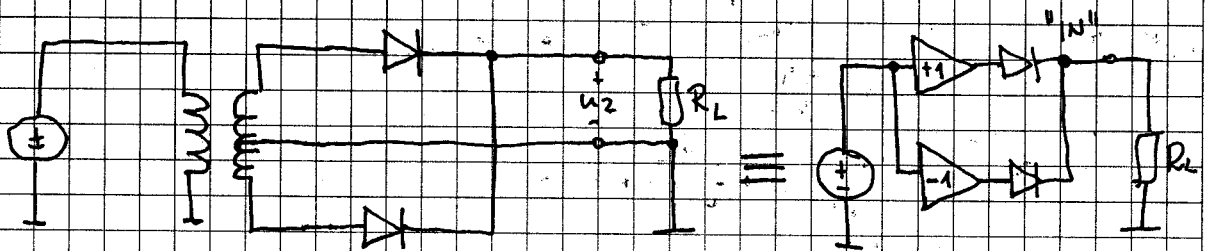
Če enačbi zohranimo ($u_1 > 0$ & $u_1 < 0$), dobimo:

$$u_2 = \frac{R_L}{R_1} |u_1|$$

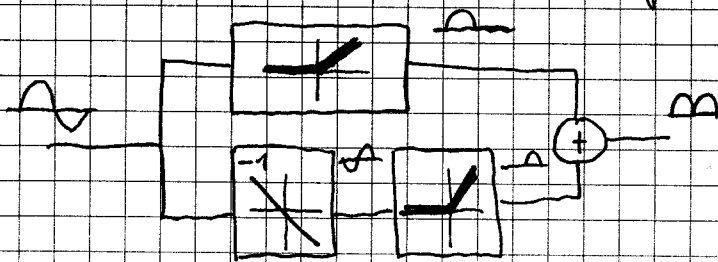
slabost: breme ni ozemljeno!

REALIZACIJE POLNOVALNEGA 2-USM 2 OZEMLJENIM BREMENOM

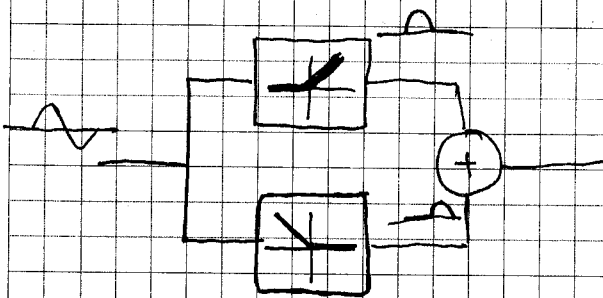
- protitaktna vezava z uporabo transformatorja s srednjim odcepom

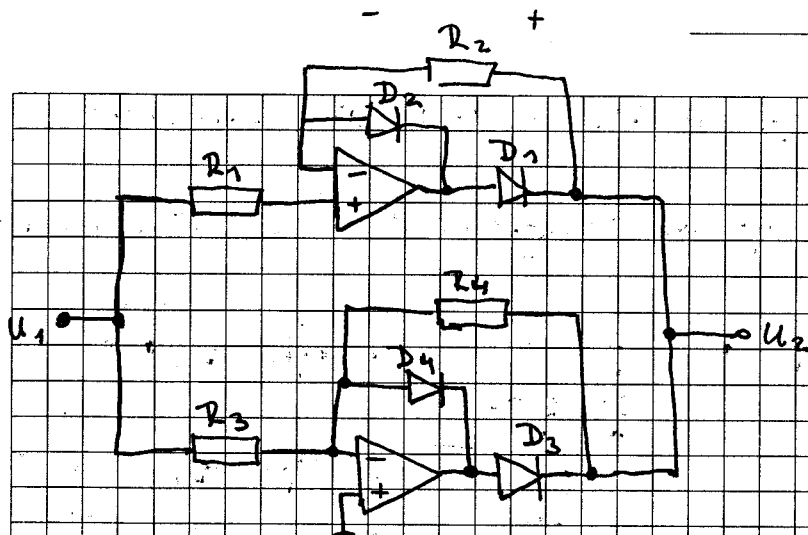


simbolični prikaz delovanja:



- z dvema O.O. in 4 diodami

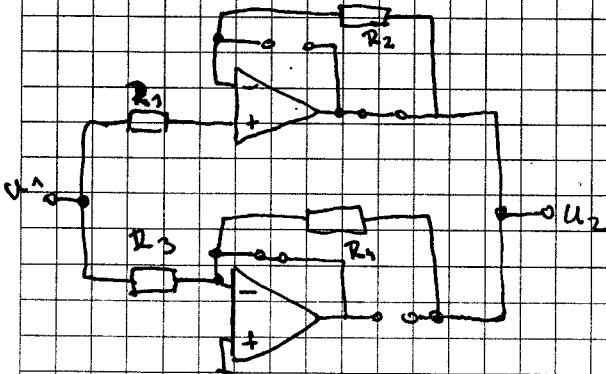




R_1 ... za uporabo simetrije
plačevalnih plov

Analiza za id. diode

$U_1 > 0$: P_1, Z_2, Z_3, P_4

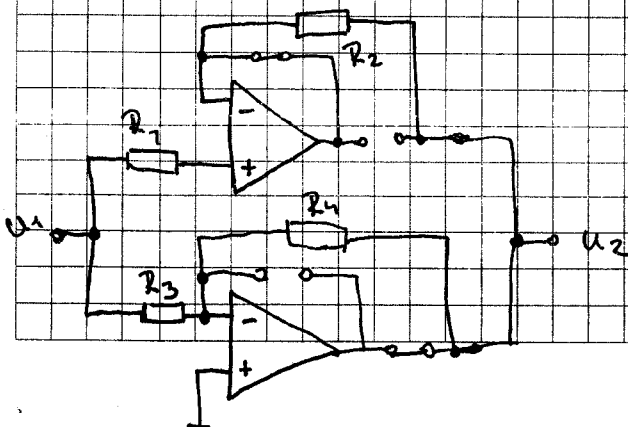


iz zgornjega polvezja : nap. sledilnik : $u_2 = u_1$

iz spodnjega polvezja : dioda D_4 preprečuje, da bi o.o. 2
šel v $-U_{sat}$

$$u_{izh.o.o.} = -U_{K4} - u^- = 0$$

$U_1 < 0$: Z_1, P_2, P_3, Z_4



iz spodnjega polvezja : $u_2 = -\frac{R_2}{R_1} \cdot u_1$

iz zgornjega polvezja :

D_2 preprečuje, da bi o.o. 1 šel v $-U_{sat}$

$$u_{izh.o.o.1} = -U_{K1} - u^- = u_1$$

Zakaj $R_2 > 0$?

R_2 omejuje ~~izhodni tok~~ izhodni tok 0.0.2

$$u_{R2} = u_2 - u_{0.0.1} = -\frac{R_4}{R_3} \cdot u_1 - u_1 = -\left(1 + \frac{R_4}{R_3}\right) \cdot u_1$$

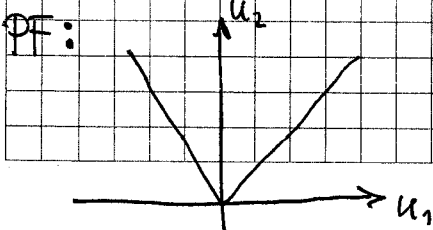
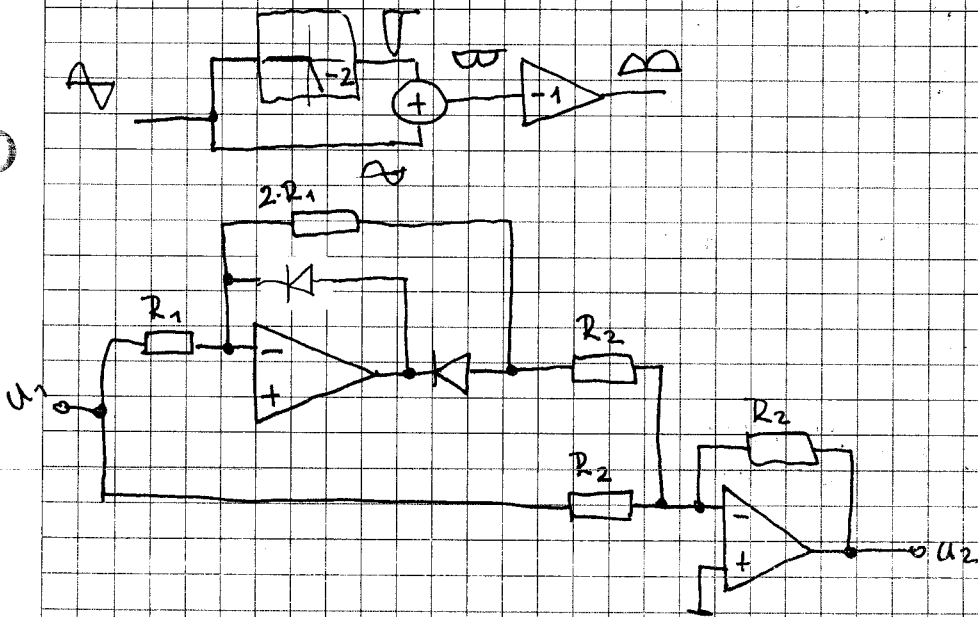
$$i_{R2} < \underbrace{I_{izh_{0.0.2 \max}}}_{\text{kataloški podatok}}$$

$$i_{R2} = \frac{u_{R2}}{R_2} < I_{izh_{0.0.2 \max}}$$

$$R_2 > \frac{u_{R2}}{I_{izh_{0.0.2 \max}}} = \frac{\left(1 + \frac{R_4}{R_3}\right) \cdot u_1 \max}{I_{izh_{0.0.2 \max}}}$$

amplituda

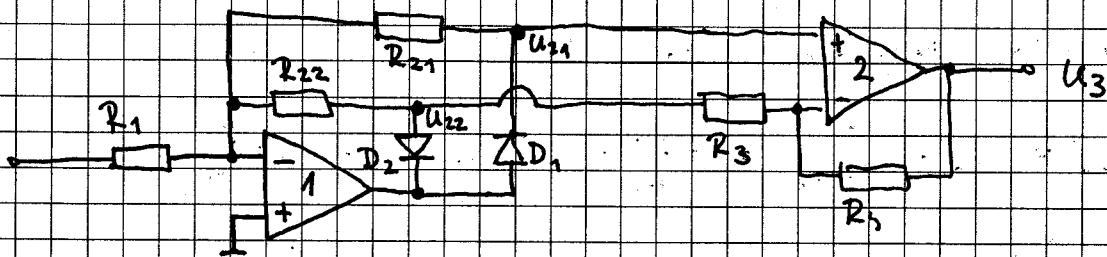
• 2 dvema J.O. iz 2 diodama



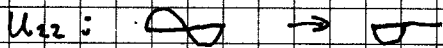
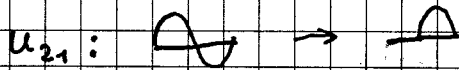
ali $u_2 = |u_1|$

za DN da bo 1 stopnja
 pojačanje 1. in popravnino
 na 2. stopnji (inv. sestava blok)

• 2 dienna 0.0. in dienna diodama

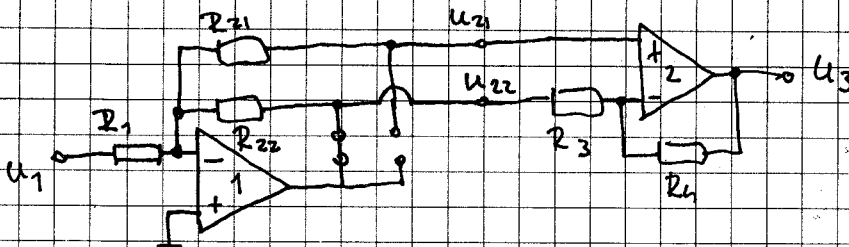


brez 0.0.2 :



Analiza: (za idealni diodi)

$u_1 > 0$: D_1 in D_2



$$u_{21} = R_{21} \cdot i_{R_{21}} + u^- = 0 + 0 = 0$$

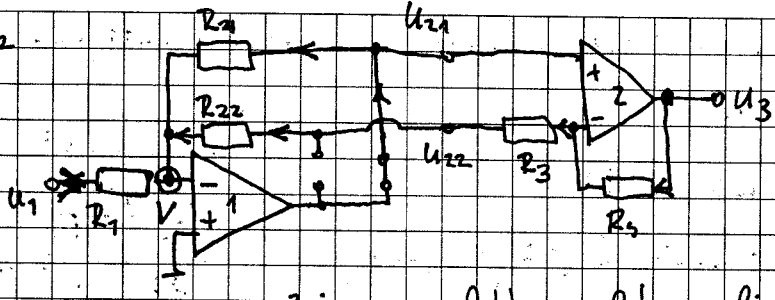
$$u_{22} = -\frac{R_{22}}{R_1} \cdot u_1$$

$$u_3 = -\frac{R_4}{R_3} \cdot u_{22} = +\frac{R_4}{R_3} \cdot \frac{R_{22}}{R_1} \cdot u_1$$

$u_1 < 0$: P_1 in I_2

$$u_{21} = -\frac{R_{21}}{R_1} \cdot u_1$$

$$u_{22} = ?$$



zajamemo lahko celotno linijo, ker ni odjemov toka

$$V: \frac{u_1 - u^-}{R_1} + \frac{u_{21} - u^-}{R_{21}} + \frac{u_3 - u^-}{R_{22} + R_3 + R_4} =$$

$$u^- = u^+ = 0$$

zaradi $u_{0.0.2} = u_{0.0.2}^+ \Rightarrow u_{21} = u_{0.0.2}^- = \frac{R_{22} + R_3}{R_{22} + R_3 + R_4} \cdot u_3$

$$u_3 = -\frac{(R_{22} + R_3 + R_4) \cdot R_{21}}{(R_{21} + R_{22} + R_3) \cdot R_1} \cdot u_1$$

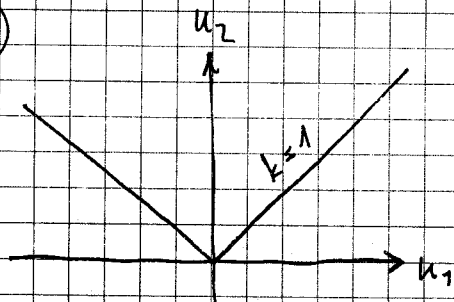
za polnvalni R-USM želimo $u_2 = k \cdot |u_1|$

rešitev za $k=1$: vsi upori enaki: $u_2 = |u_1|$

poljubna rešitev za izbrani k :

$$\frac{R_4}{R_3} \cdot \frac{R_{22}}{R_1} = k \quad \text{in} \quad \frac{(R_{22} + R_3 + R_4) \cdot R_{21}}{(R_{21} + R_{22} + R_3) \cdot R_1} = k$$

PF (za $k=1$)



1.1.2. REZALNIKI (angl. CLIPPERS)

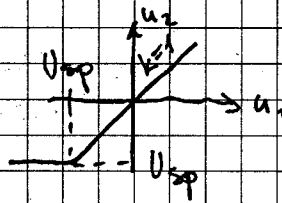
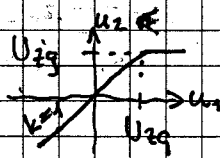
Delitev:

- enostranski:

- pozitivni (režejo nadzor)

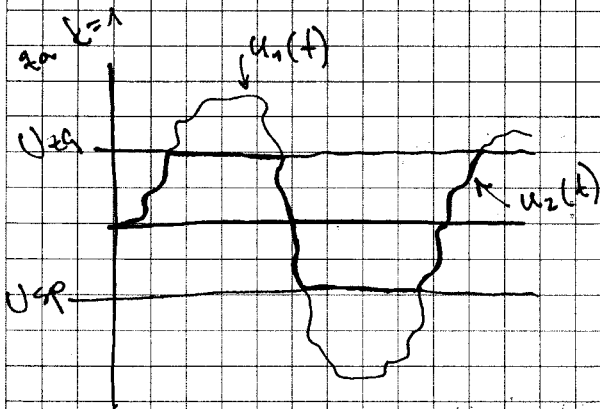
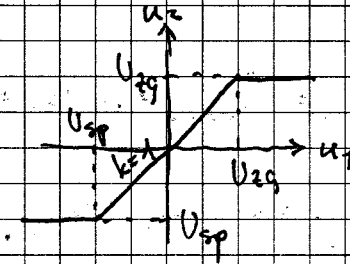
- negativni (režejo nadobol)

idealne PF



- dvostranski:

režejo v obeh smeri

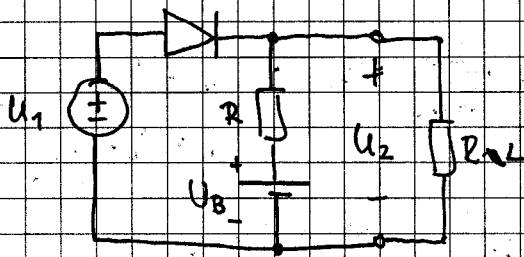


Zahtevano linearno zvezo

$$u_2 = k \cdot u_1$$

Realizacije diodnih rezalnikov

- dvostranski rezalnik s serijsko vezavo diode



② dioda zaprta: $U_2 = \frac{R_L}{R+R_L} \cdot U_3$;

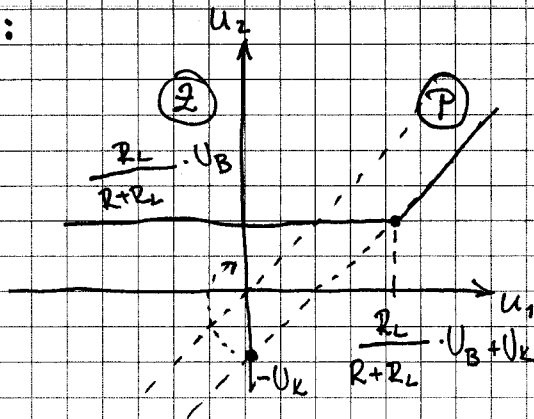
$$\left. \begin{array}{l} U_3 < U_K \\ U_3 = U_1 + U_2 \end{array} \right\} \Rightarrow U_1 < U_2 + U_K$$

$$U_1 < \frac{R_L}{R+R_L} \cdot U_3 + U_K$$

① dioda prevaja: $U_2 = U_1 - U_0 \approx U_1 - U_K$;

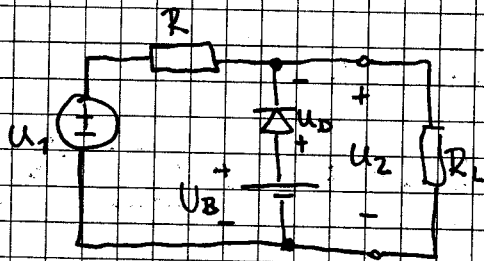
$$U_1 > \frac{R_L}{R+R_L} \cdot U_3 + U_K$$

PF:



DN / Dolžite PF za obrnjeno diodo

• Enostranski rezačnik s paralelno vezano diodo



⊖ dioda zaprta:

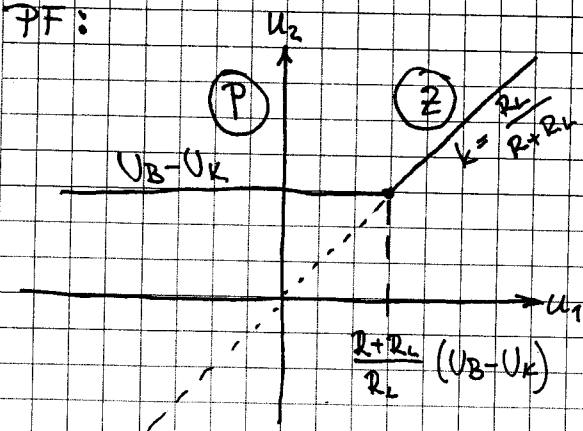
$$u_2 = \frac{R_L}{R+R_L} \cdot u_1 ; \left. \begin{array}{l} u_D < U_K \\ u_D = U_B - u_2 \end{array} \right\} \Rightarrow$$

$$\Rightarrow u_1 > \frac{R+R_L}{R_L} (U_B - U_K)$$

⊕ dioda prevaja:

$$u_2 = U_B - U_K - r_D \cdot i_D ; u_1 < \frac{R+R_L}{R_L} (U_B - U_K)$$

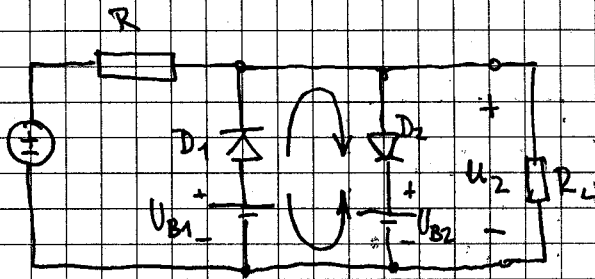
PF:



$$Z_{iZH} = R \parallel r_D \approx 0$$

$$Z_{iZH} = R$$

● dvostranski rezačnik (s paralelno vezavo diod)

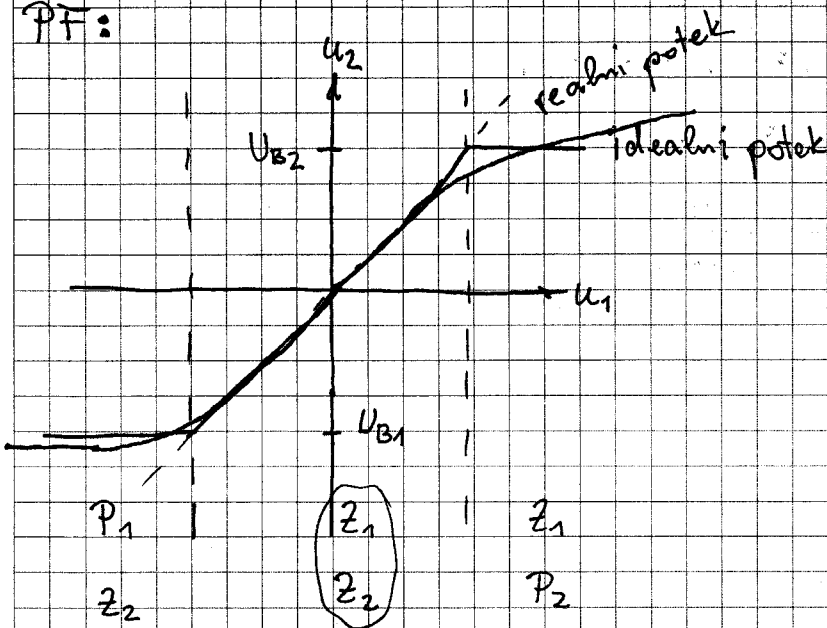


$$U_{B1} - U_{B2} = U_{D1} + U_{D2} < \underline{U_{K1} + U_{K2}}$$

$$U_{B1} - U_{B2} < 0$$

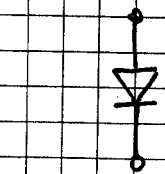
$$\underline{U_{B1} < U_{B2}}$$

PF:

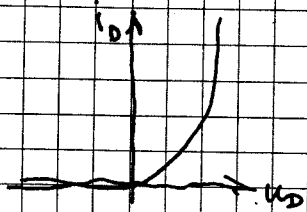
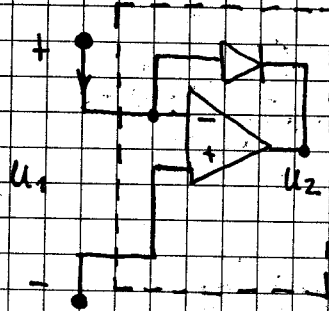


Realizacije idealiziranih diodnih vezalnikov

• IDEALIZIRANA DIODA



idealizacija
s pomočjo
O.D.



$$u_1 = u_D + u_2$$

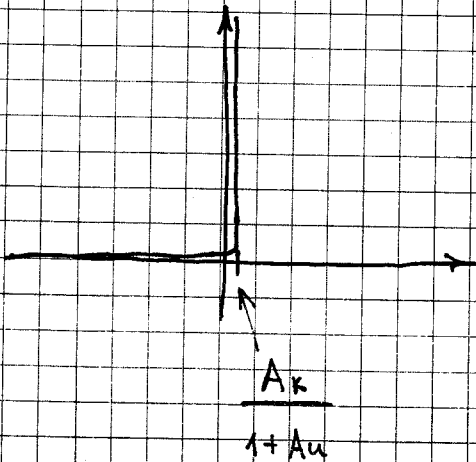
$$u_2 = -A_u \cdot u_1$$

$$u_1 = u_D - A_u \cdot u_1$$

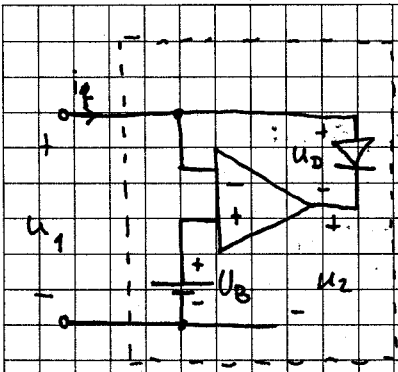
$$(A_u + 1) u_1 = u_D$$

$$u_1 = \frac{u_D}{1 + A_u}$$

$$u_1(i_D) = \frac{u_D(i_D)}{1 + A_u}$$



25.10.2013



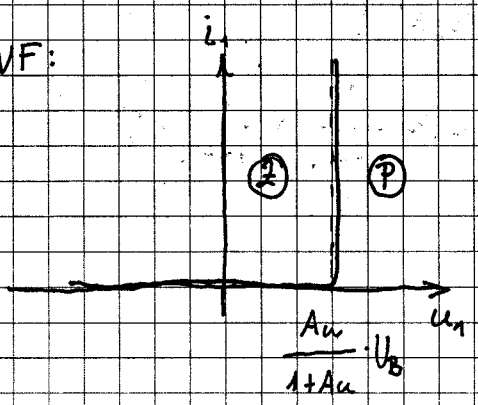
$$u_{01} = u_D + u_{z2}$$

$$u_{z2} = -A_u (u^- - u^+) = -A_u (u - U_B)$$

$$u_1 = \frac{u_D}{1+A_u} + \frac{A_u}{1+A_u} \cdot U_B$$

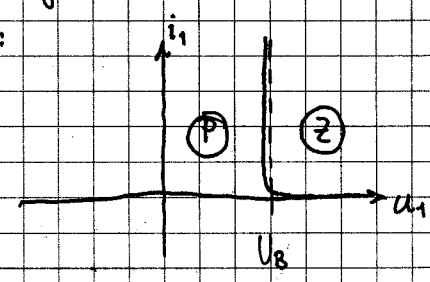
$$u_1(i_1) = \frac{u_D(i_1)}{1+A_u} + \frac{A_u}{1+A_u} \cdot U_B$$

VF:

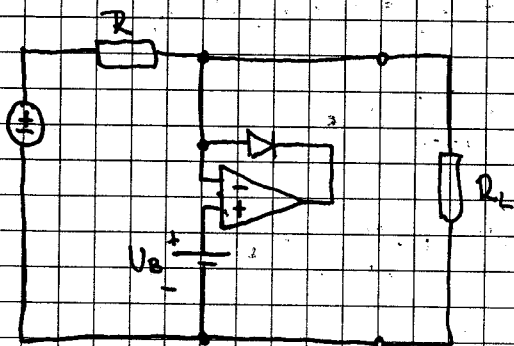


za obrnjeno diodo : DN

VF:



• enostranski diodni rezalnik z D.O.



Ⓐ dioda zaprta:

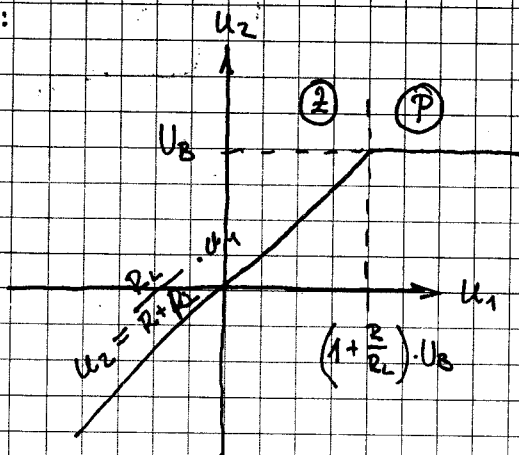
$$u_2 = \frac{R_L}{R_L + R} \cdot u_1$$

Ⓑ dioda prevaja:

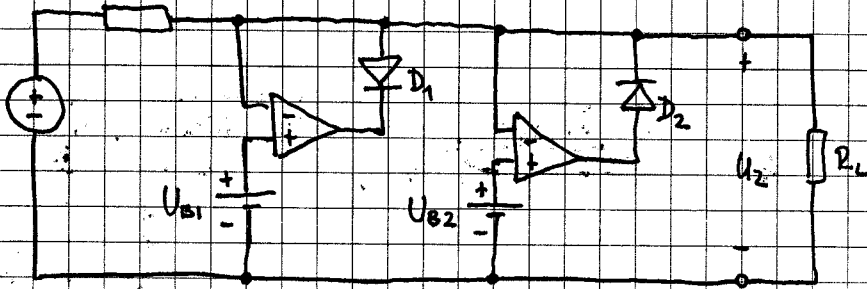
$$u_2 \approx U_B$$

$$u_2 = \frac{U_k}{1 + A_u} + \frac{A_u}{1 + A_u} \cdot U_B$$

PF:

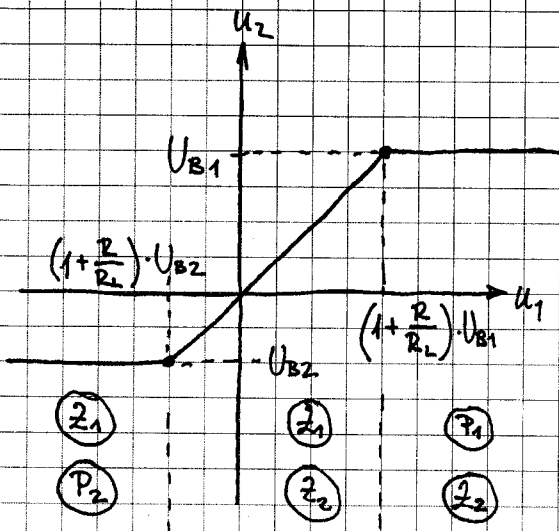


• dvostranski diodni rezalnik z D.O.



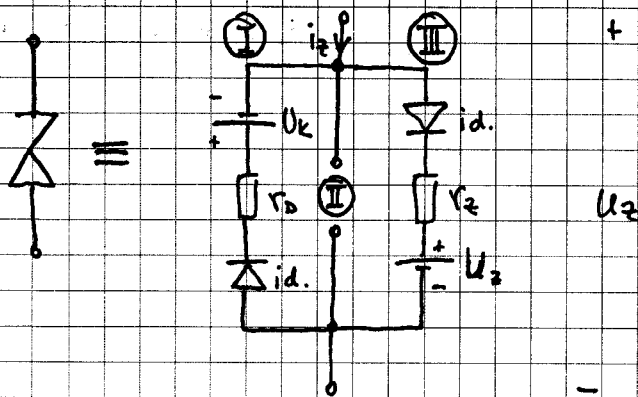
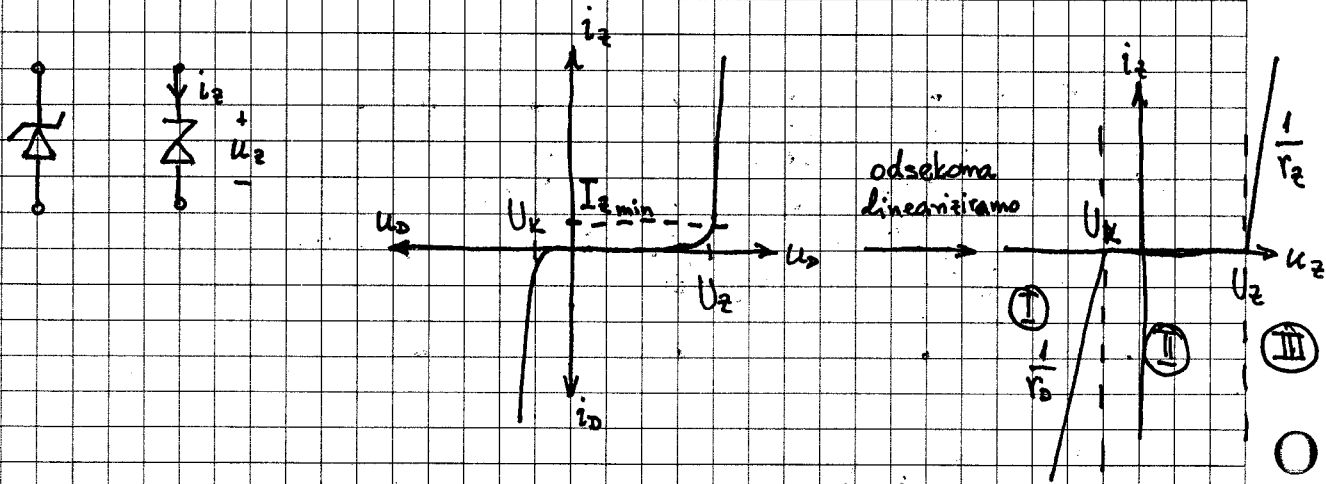
$$u_{D2} + u_{D1} = U_{B2} - U_{B1} < 0$$

$U_{B2} < U_{B1}$, pogoj, da obe diodi nikoli ne prevajata skupaj



$\begin{pmatrix} z_1 \\ p_2 \end{pmatrix}$
 $\begin{pmatrix} z_1 \\ z_2 \end{pmatrix}$
 $\begin{pmatrix} p_1 \\ z_2 \end{pmatrix}$

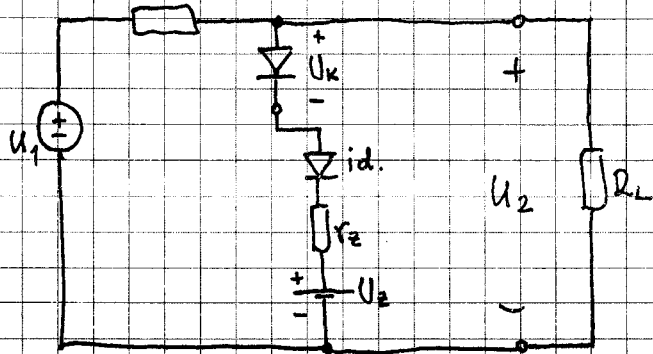
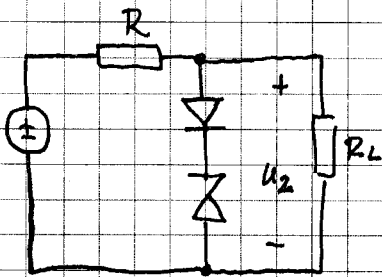
Realizacije prebojno - diodnih rezalnikov



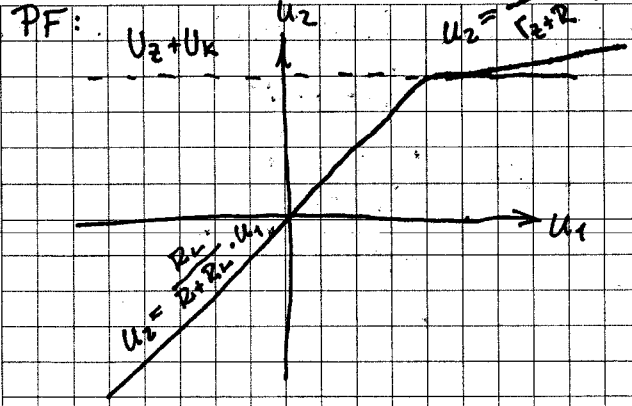
• enostranski rezalnik

prebojna dioda nadomešča U_B

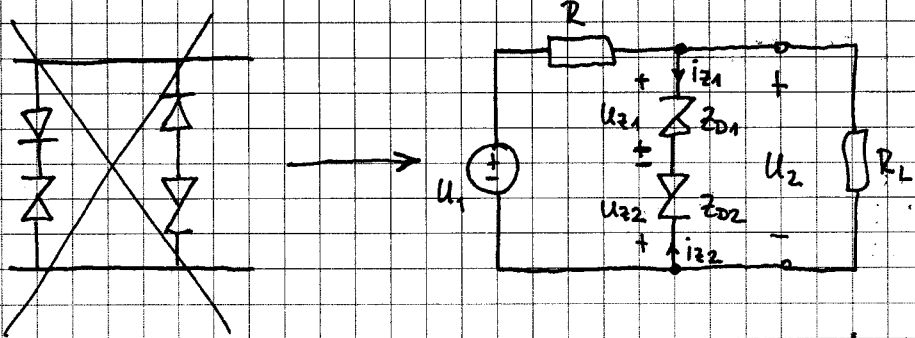
za področje preboja ($i_z > I_{z\min}$):



$$U_2 = \frac{R}{R+r_2} (U_2+U_k) + \frac{r_2}{R+r_2} \cdot U_1$$

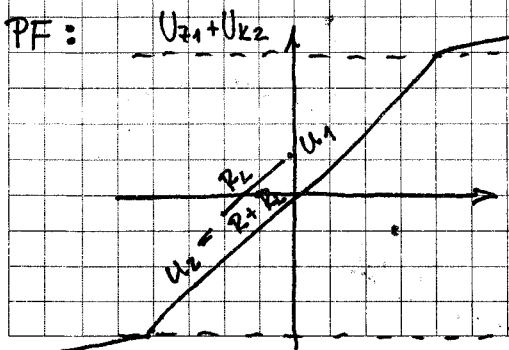
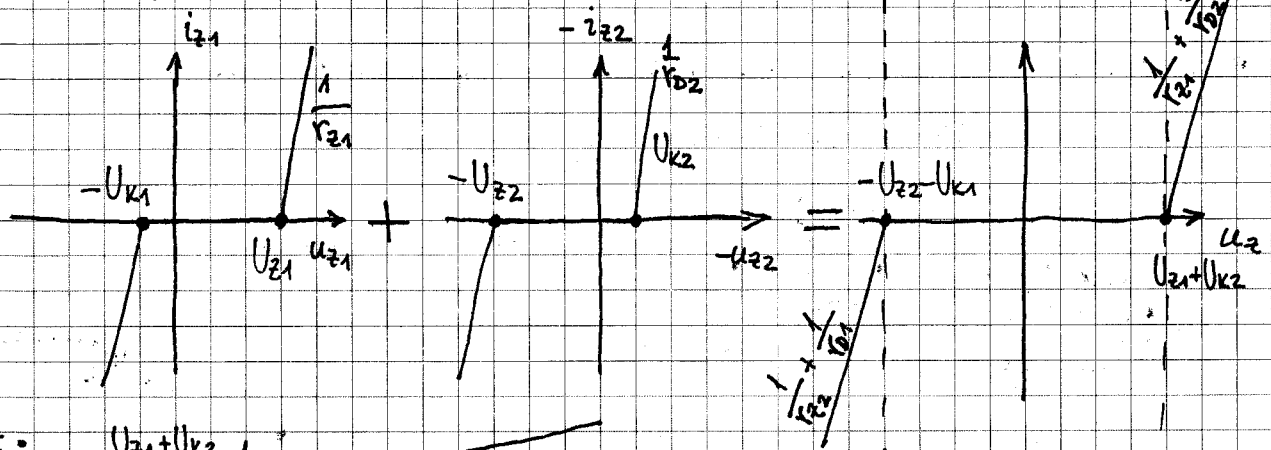


• dvostranski rezalnik

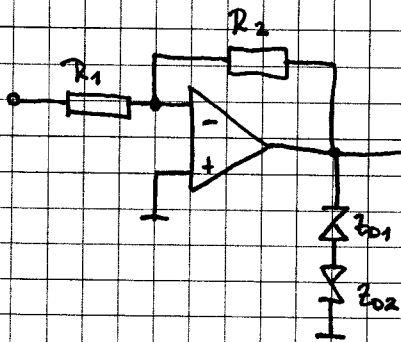


*tudi če diodi zamenjamo j isto

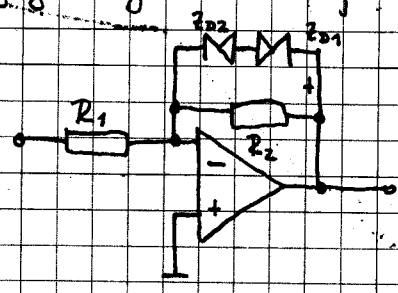
antiserijska vezava dveh zener diod:



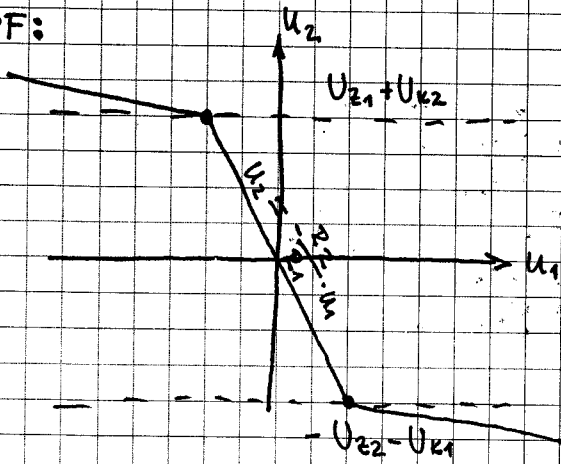
• dvostranski rezalnik v konfiguraciji invertirajočega ojačevalnika



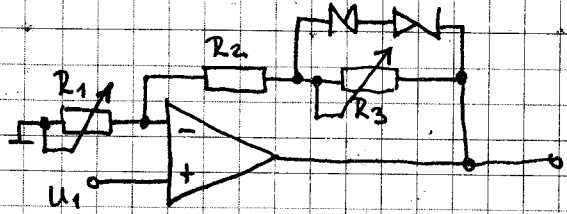
ali



PF:

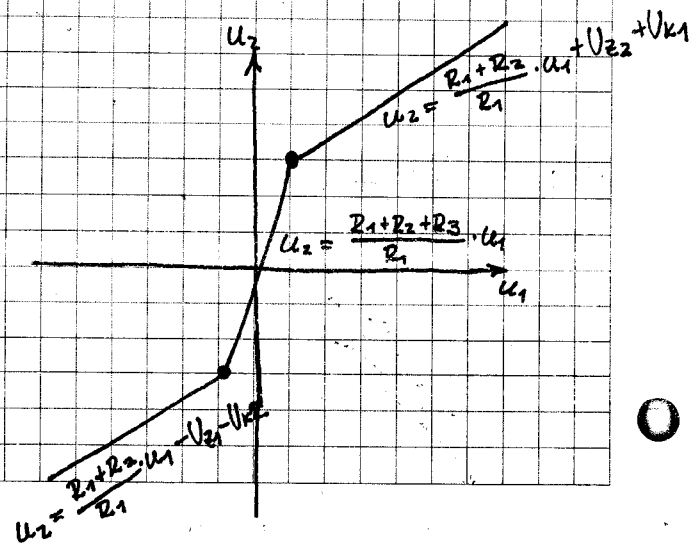


• uporaba 2D rezalnika za nastanitev amplitude oscilatorja v konfiguraciji neinvertirajočega ojačevalnika



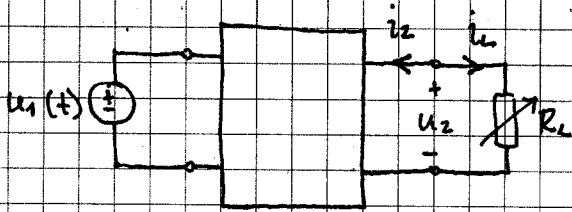
za določanje amplitude oscilatorja

PF za $r_0 = r_3 = 0$



1.1.3. NAPETOSTNI REGULATORJI / STABILIZATORJI

- za stabilizacijo enosmerne napetosti
- shematski prikaz:

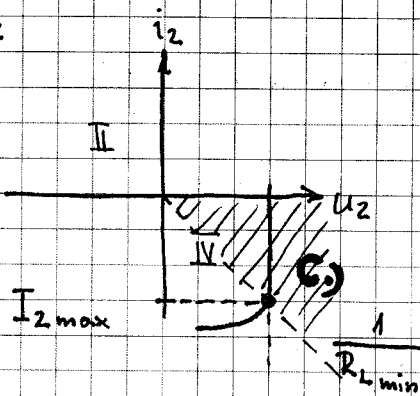


- idealni napetostni regulator ohranja u_2 konstantno ne glede na spremembe

- vhodne napetosti $u_1(t)$
- harmonskih komponent $u_1(t)$
- bremenskega toka $i_2(t)$ oz. bremenske upornosti $R_L(t)$

izhodna funkcija IF:

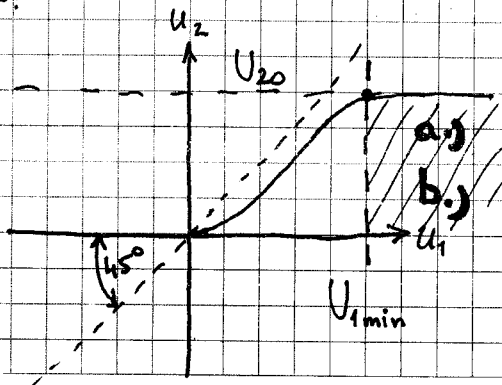
II in IV kvadrant \rightarrow generatorski režim



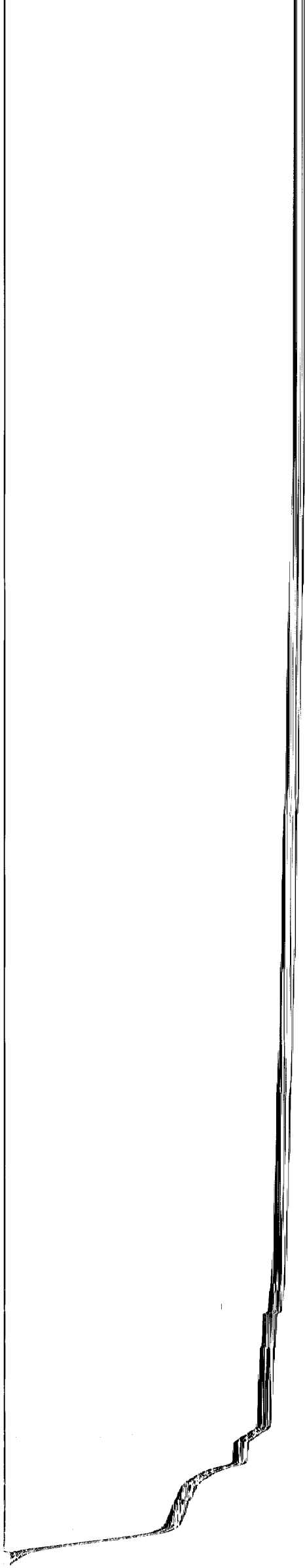
$$R_L \geq R_{L \min}$$

$$i_2(t) \leq I_{2 \max}$$

PF:

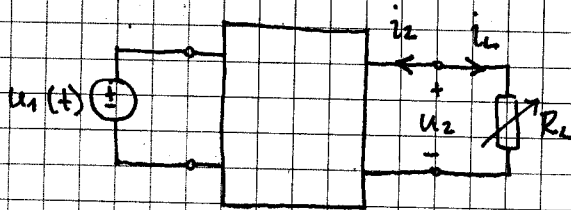


$$u_1(t) \geq U_{1 \min}$$



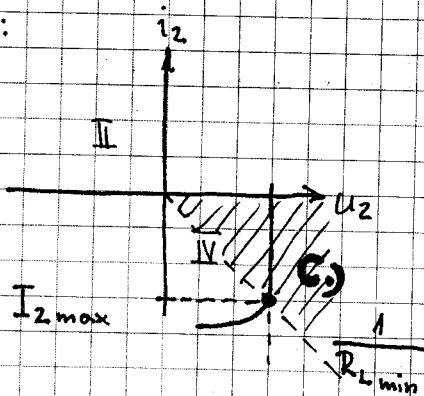
1.1.3. NAPETOSTNI REGULATORJI / STABILIZATORJI

- za stabilizacijo enosmerne napetosti
- shematski prikazi



- idealni napetostni regulator ohranja u_2 konstantno ne glede na spremembe
 - vhodne napetosti $u_1(t)$
 - harmonskih komponent $u_1(t)$
 - bremenskega toka $i_L(t)$ oz. bremenske upornosti $R_L(t)$

izhodna funkcija IF:

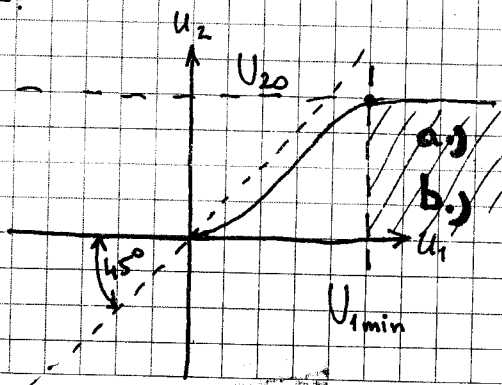


II in IV kvadrant \rightarrow generatorski režim

$$R_L \geq R_{L \min}$$

$$i_2(t) \leq I_{2 \max}$$

PF:



$$u_1(t) \geq U_{1 \min}$$

Kriteriji sposobnosti / kvalitete:

a) \rightarrow 1. "line regulation" / regulacija napajanja

$$LR = \begin{cases} \frac{\Delta U_2}{U_{20}} \Big|_{\Delta U_1 = 10\% U_1} \cdot 100\% & \text{idealno: } 0\% \\ \frac{1}{\Delta U_1} \cdot \frac{\Delta U_2}{U_{20}} \cdot 100\% & \text{idealno: } 0\% / V \end{cases}$$

b) \rightarrow 2. faktor stabilizacije:

$$S = \frac{1}{\frac{\partial U_2}{\partial U_1}} = \frac{1}{A_u(\omega)}$$

ojačenje širokopasovnega ojača

idealno: $A_u(\omega) = 0$

$S \rightarrow \infty$

b) \rightarrow 3. "ripple rejection" / rejekcijski faktor valovitosti

$$RR = 20 \log \left[\frac{U_1 \text{ ripple}}{U_2 \text{ ripple}} \right] @ \text{izbrani } \omega$$

idealno: $\rightarrow \infty$ dB

c) → 4. "load regulation" / regulacija bremena

$$\text{Load R} = \left\{ \begin{array}{l} \frac{\Delta U_2 \Big|_{\Delta i_L = I_{L\max} - 0}}{U_{20}} \cdot 100\% \quad \text{idealno: } 0\% \\ \frac{1}{\Delta i_L} \frac{\Delta U_2}{U_2} \cdot 100\% \quad \text{idealno: } 0\% / A \end{array} \right.$$

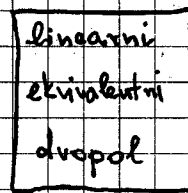
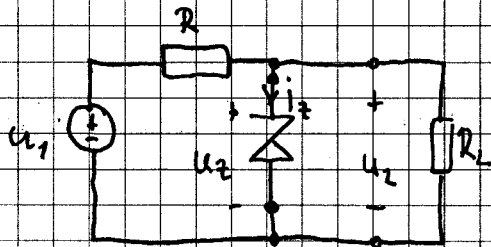
c) → 5. dinamična izhodna upornost

$$r_{izh} = \frac{\partial U_2}{\partial i_2} \quad \text{idealno: } 0 \Omega$$

6. izkoristek regulatorja

$$\eta = \frac{P_{izh}}{P_{vh}} \cdot 100\% = \frac{U_2 \cdot i_2}{U_1 \cdot i_1} \quad \text{idealno: } 100\%$$

Primer analize S in i_{zH} za preprost nap. regulator



nelinearna karkakt.

delovna ~~kur~~ premica

pri $i_z = 0 \rightarrow$ odprta sponka

$$u_2 = \frac{R_L}{R + R_L} \cdot u_1$$

$$A \left(\frac{R_L}{R + R_L} \cdot u_1, 0 \right)$$

pri $u_2 = 0 \rightarrow$ kratek stik

$$i_z = \frac{u_1}{R}$$

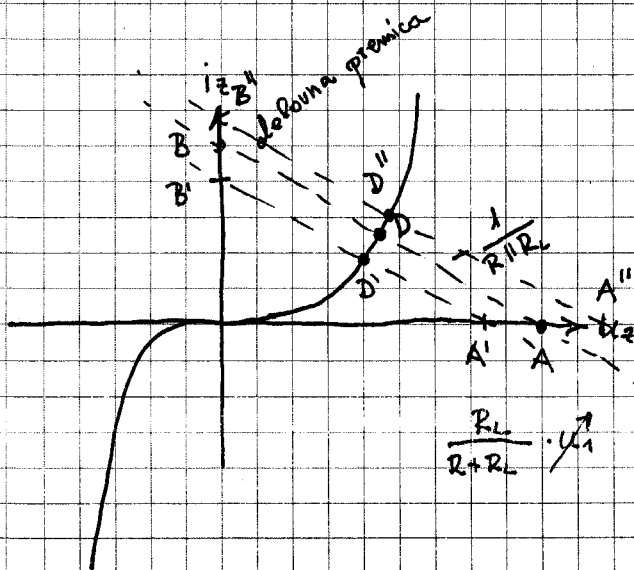
$$B \left(0, \frac{u_1}{R} \right)$$

naklon: $\frac{1}{R \parallel R_L}$

(naklon = nad. upornost)

Naklon določimo tako, da vse vire izklopimo

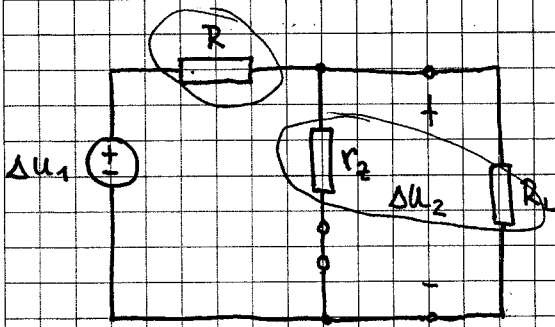
premica



Analiza za odsekoma lin. karakteristiko 2D s pomočjo inkrementalno

nod. vezja:

za $i_2 > I_{2 \min}$



$$S = \frac{1}{\frac{\partial u_2}{\partial u_1}} = \frac{\partial u_1}{\partial u_2}$$

$$S = \frac{\Delta u_1}{\Delta u_2}$$

$$\Delta u_2 = \frac{r_2 \parallel R_2}{R + r_2 \parallel R_2} \cdot \Delta u_1$$

$$S = \frac{R + r_2 \parallel R_2}{r_2 \parallel R_2} = 1 + \frac{R}{r_2 \parallel R_2} \approx 1 + \frac{R}{r_2}$$

$$r_{i2n} = \left. \frac{\partial u_2}{\partial i_2} \right|_{\Delta u_1 = 0} = r_2 \parallel R \Big|_{R \gg r_2} \approx r_2 \quad (\text{reda nekaj } \Omega)$$

slab izkoristek zaradi $i_2 > I_{2 \min}$

DELITEV NAP. REGULATORJEV

A) SERIJSKI A1) BREZ PS

A2) S PS

PS...

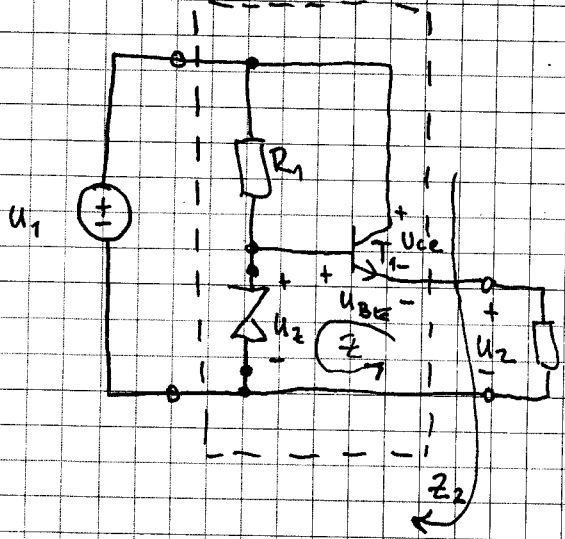
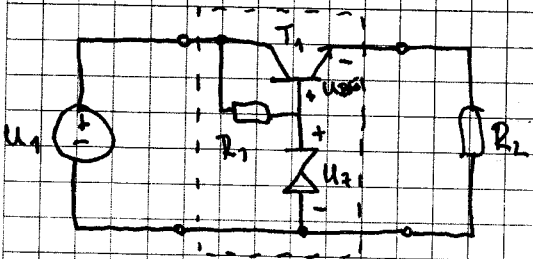
...pomagalni sklop

B) PARALELNI B1) BREZ PS

B2) S PS

A1) serijski nap. regulator brez PS

T_1 ... prepustni transistor



$$I_2: U_2 = U_Z - U_{BE}$$

$I_2 > I_{Z \min} \Rightarrow$ določamo R_1 in U_1

$$I_{Z2}: U_1 = U_{ce} + U_Z \Rightarrow U_1 \geq U_{ce \min} + U_Z$$

T_1 v aktivnem področju delovanja

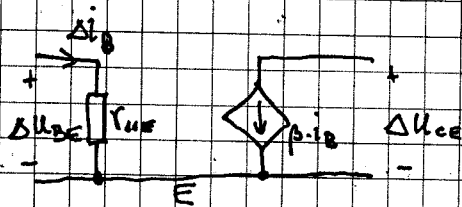
delovna plovica V $I_2(U_2)$

$$\text{pri } I_2 = 0: U_2 = \frac{(1 + \beta_{DC}) \cdot R_L}{R_1 + (1 + \beta_{DC}) \cdot R_L}$$

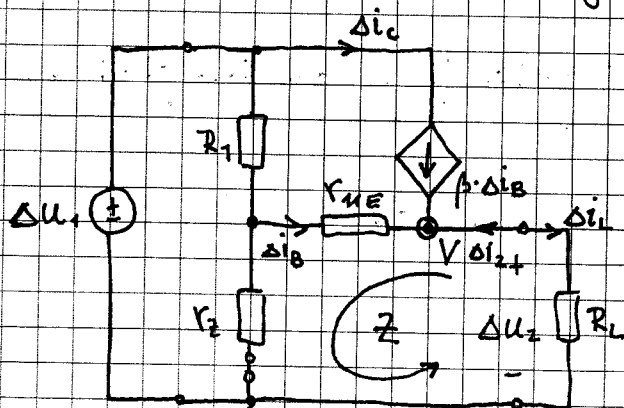
$$\text{pri } U_2 = 0: I_2 = \frac{U_1}{R_1}$$

8.11.2013

- analiza za S in V_{izh} : z modelom bip. tr.



inkrementalno nadomestno vezje:



$$V_{izh} = \left. \frac{\Delta U_2}{\Delta i_2} \right|_{\Delta U_1=0}$$

$$V: \Delta i_L = -\Delta i_2 = \Delta i_B + \Delta i_C = (1+\beta) \cdot \Delta i_B$$

$$Z: \Delta U_2 \Big|_{\Delta U_1=0} = -\Delta i_B \cdot (r_{uE} + r_2 \parallel R_1)$$

$$V_{izh} = \left. \frac{\Delta U_2}{\Delta i_2} \right|_{\Delta U_1=0} = \frac{+\cancel{\Delta i_B} \cdot (r_{uE} + r_2 \parallel R_1)}{+(1+\beta) \cdot \cancel{\Delta i_B}} = \frac{r_{uE} + r_2}{1+\beta} = \frac{1}{g_{21E}} + \frac{r_2}{1+\beta}$$

$$S = \frac{\Delta u_1}{\Delta u_2} = \dots = \frac{R_1 + r_z}{r_z} + \frac{R_1 + \frac{R_1 + r_z}{r_z} \cdot Y_{ME}}{(1 + \beta) \cdot R_L} \approx \frac{R_1 + r_z}{r_z} = 1 + \frac{R_1}{r_z}$$

pri preprostem nosp. reg.:

$$r_{izh} \approx r_z$$

$$S = 1 + \frac{R_1}{r_z}$$

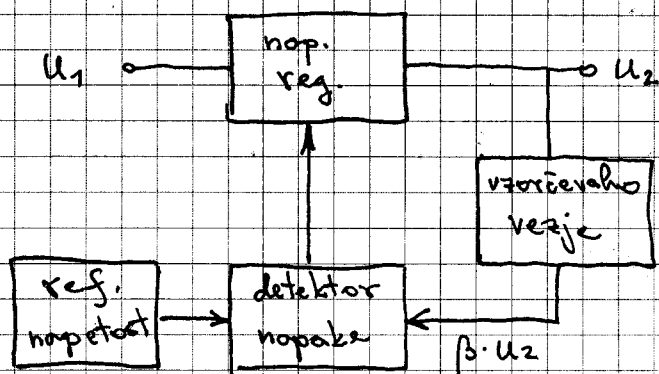
r_{izh} je za β manjša

R_1 je mnogo večji kot R (prej)

s tranzistorjem smo izboljšali zadevo

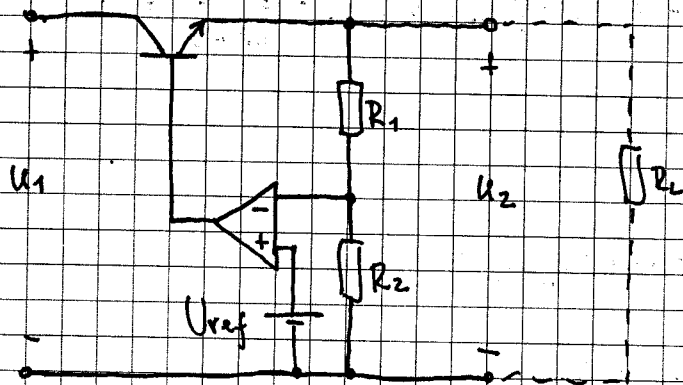
A2. serijski napetostni regulator s PS

- shematsko:



Realizacije napetostnih regulatorjev s PS

a.) O.O. kot oprevalnik napake

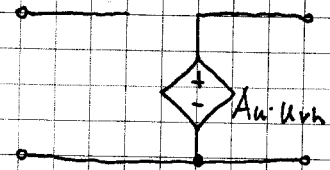
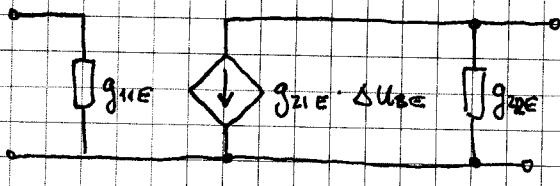


za $i^- = 0$: $u^- = \frac{R_2}{R_1 + R_2} \cdot u_2$

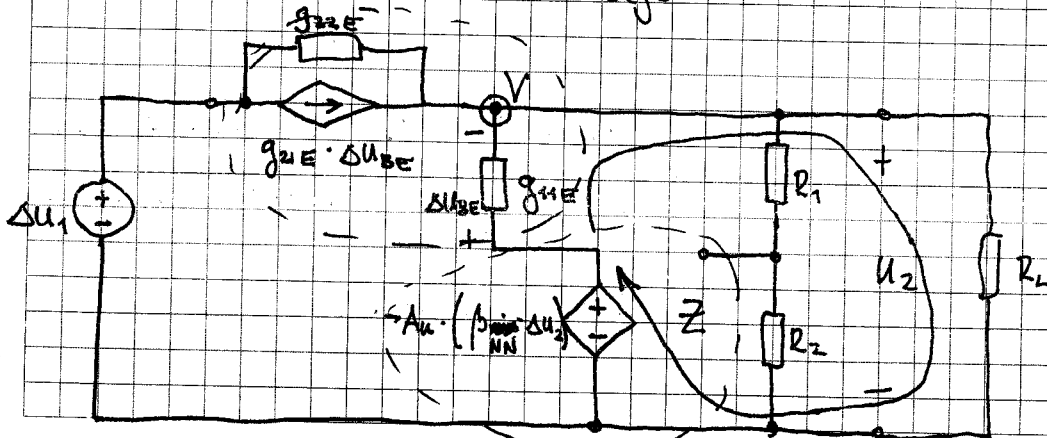
$u^- = u^+$: $U_{ref} = \frac{R_2}{R_1 + R_2} \cdot u_2 \Rightarrow u_2 = \frac{R_1 + R_2}{R_2} \cdot U_{ref}$; $u_2 \approx U_{ref}$

izračun S in r_{izn} :

z modeli :



inkrementalno nadomestno vezje:



$$V: \sum i = 0$$

$$\Delta i g_{22E} + g_{21E} \cdot \underline{\Delta U_{BE}} + g_{11E} \cdot \underline{\Delta U_{BE}} + \underline{\Delta i_2} - \frac{\Delta U_2}{R_1 + R_2} = 0 \quad 3 \text{ neznanke}$$

$$I: \sum u = 0$$

$$\underline{\Delta U_{BE}} + \underline{\Delta U_2} - (-A_u \cdot \beta_{NN} \cdot \underline{\Delta U_2}) = 0$$

$$\Delta i g_{22E} = g_{21E} \cdot (\Delta U_1 - \Delta U_2)$$

$$\Delta U_2 = \frac{g_{22E}}{g_{22E} + (1 + \beta_{NN} \cdot A_u)(g_{11E} + g_{21E}) + \frac{1}{R_1 + R_2}} \cdot \Delta U_1 +$$

$$+ \frac{1}{g_{22E} + (1 + \beta_{NN} \cdot A_u)(g_{11E} + g_{21E}) + \frac{1}{R_1 + R_2}} \cdot \Delta i_2$$

$$Y_{i2H} = \frac{\partial U_2}{\partial i_2} = \left. \frac{\Delta U_2}{\Delta i_2} \right|_{\Delta U_1 = 0} =$$

$$= \frac{1}{g_{22E} + (1 + \beta_{NN} \cdot A_u)(g_{11E} + g_{21E}) + \frac{1}{R_1 + R_2}} \approx \frac{1}{\beta_{NN} \cdot A_u \cdot g_{21E}}$$

↑
 doseđanja Y_{i2H} se nam zmanjša
 še za faktor povratnega sklopa

$$F = 1 + \beta_{NN} \cdot A_u$$

$$S = \frac{\partial u_1}{\partial u_2} = \frac{\Delta u_1}{\Delta u_2} \Big|_{\Delta i_2 = 0} = \frac{g_{z2E} + (1 + \beta_{DMM} \cdot A_{u1})(g_{u1E} + g_{z1E}) + \frac{1}{R_1 + R_2}}{g_{z2E}} \approx$$

$$\approx 1 + (1 + \beta_{DMM} \cdot A_{u1}) \cdot \frac{g_{z1E}}{g_{z2E}}$$

S se od prej še dodatno izboljšuje za faktor

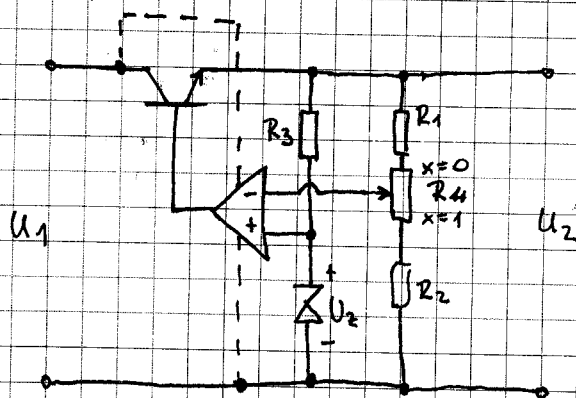
$$F = 1 + \beta_{DMM} \cdot A_{u1}$$

2 NEGATIVNIM POVRATNIM SKLOPOM SMO ŽADEVO DOBRO IZBOLEŠALI

Kako je z napajanjem O.O.?

Glede na PSRR ~ 120 dB, damo O.O. na U_1 napajanje

b.) realizacija U_{ref} in nastavljive U_2 :



$$U_2 = \frac{R_1 + R_2 + R_4}{R_2 + (1-x) \cdot R_1} \cdot U_Z \quad \text{oz.} \quad U_2 \in \left[\frac{R_1 + R_2 + R_4}{R_2 + R_1} \cdot U_Z, \frac{R_1 + R_2 + R_4}{R_2} \cdot U_Z \right]$$

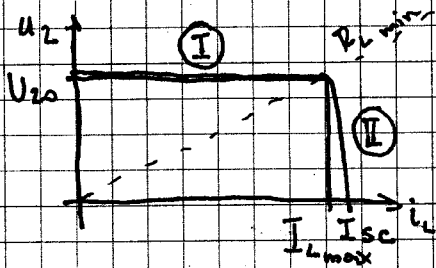
$$R_3 = \frac{U_2 - U_Z}{I_Z} \leq \frac{U_Z^{\min} - U_Z}{I_{Z\min}}$$

$U_{Z\min}$ $U_{Z\max}$

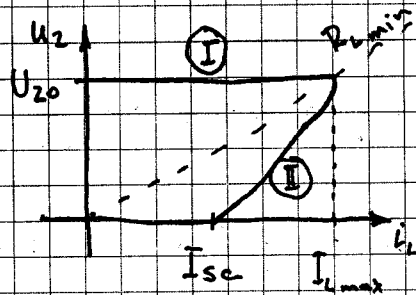
to vezje še nima tokovne zaščite!

OMEJEVANJE TOKA PRI SERIJSKIH NAP. REGULACIJAH

a.) konstantna omejitev toka



b.) prepogojena omejitev toka



za zaščitenje T_1

I... napetostni reg

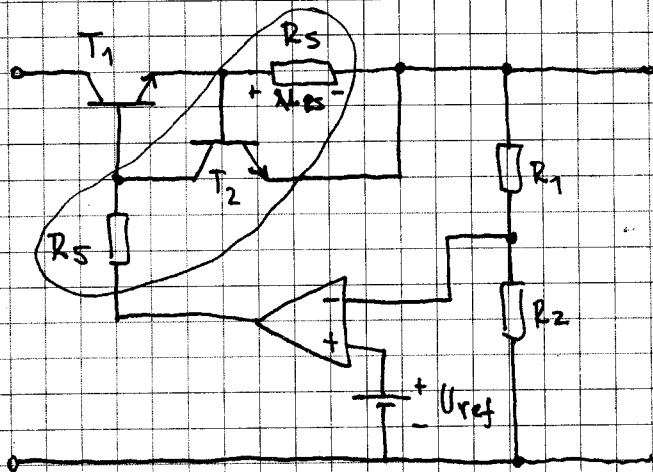
$$R_L \rightarrow R_{L \min}$$

II... tok. generator

$$R_L < R_{L \min}$$

dodatek v prejšnja vezja

a.) KONSTANTNA OMEJITEV TOKA (+ T_2 , R_s , R_5)



točke delovanja



točka A: režim I T_2 zaprt, padec napetosti R_s majhen

točka B: režim I na meji: $U_{R_s} = U_{BE0}$, T_2 začne prevajati

$$I_{L \max} = \frac{U_{BE20}}{R_s}$$

$$I_{sc} = I_{L \max} + I_{C2}$$

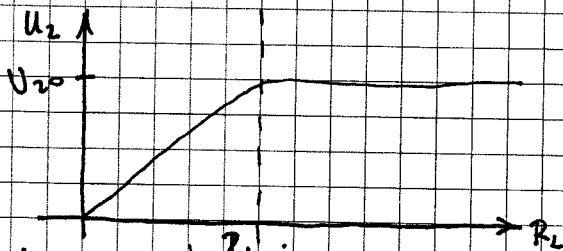
točka C: T_2 odprt

Zakaj R_s ?

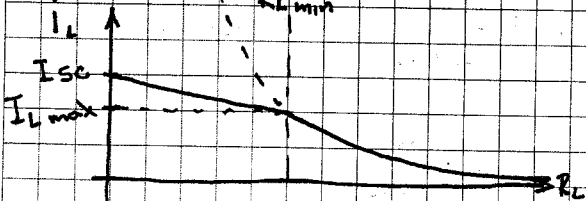
Z R_s omejujemo tok izh. o. za $R_s \cdot I_{R_s} = +U_{sat} = U_1$

$$R_s = \frac{U_1}{I_{C2}} = \frac{U_1}{I_{izh.o. max}}$$

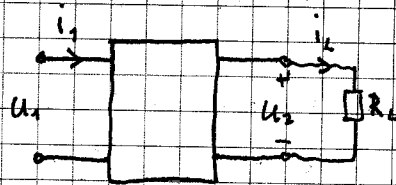
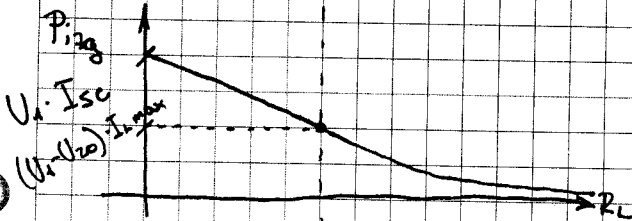
delovanje v odvisnosti od R_L :



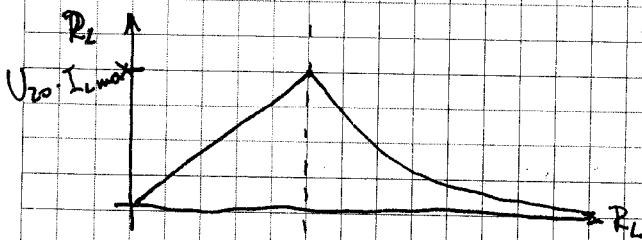
$$R_{Lmin} = \frac{U_{20}}{I_{Lmax}}$$



$$I_L = \begin{cases} \frac{U_{20}}{R_L} & ; R_L > R_{Lmin} \\ I_{Lmax} + I_{sc} & ; R_L < R_{Lmin} \end{cases}$$

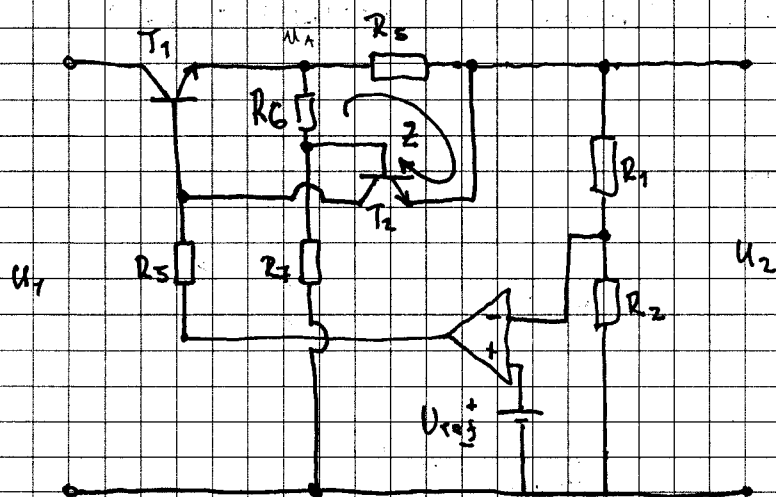


$$P_L = U_2 \cdot I_L = \begin{cases} \frac{U_{20}^2}{R_L} & ; \text{I} \\ R_L \cdot I_L^2 & ; \text{II} \end{cases}$$



$$P_{izg} = \Delta U \cdot I_L = \begin{cases} (U_1 - U_{20}) \cdot \frac{U_{20}}{R_L} & ; \text{I} \\ (U_1 - R_L \cdot I_{Lmax}) \cdot I_{Lmax} & ; \text{II} \end{cases}$$

b.) PREEPOGJNENA OMEJITEV TOKA ($+I_2, R_5, R_5$; $+R_C, R_7$)



$$Z: -U_{RC} + U_{RS} = U_{BE2} \quad u_C = \frac{R_C}{R_C + R_7} \cdot u_1 = k \cdot u_1$$

$$k = \frac{R_C}{R_C + R_7}$$

$$u_1 = R_5 \cdot i_L + u_2$$

$$U_{BE2} = -k \cdot u_1 + U_{RS}$$

$$= -k \cdot (R_5 \cdot i_L + u_2) + R_5 \cdot i_L =$$

$$U_{BE2} = (1-k) \cdot R_5 \cdot i_L - k \cdot u_2$$

Ⓘ T₂ je zaprt, zato $U_{BE2} < U_{BE2k}$; $u_2 = U_{Z0}$

$$U_{BE2} = (1-k) \cdot R_5 \cdot i_L - k \cdot U_{Z0}$$

na meji med Ⓘ in Ⓢ $U_{BE2} = U_{BE2k}$; $i_L = I_{Lmax}$, $u_2 = U_{Z0}$:

$$U_{BE2k} = (1-k) \cdot R_5 \cdot I_{Lmax} - k \cdot U_{Z0}$$

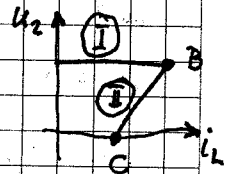
$$R_5 = \frac{k \cdot U_{Z0} + U_{BE2k}}{(1-k) \cdot I_{Lmax}} = \dots = \frac{R_C}{R_7} \cdot \frac{U_{Z0}}{I_{Lmax}} + \left(1 + \frac{R_C}{R_7}\right) \cdot \frac{U_{BE2k}}{I_{Lmax}}$$

① Iz odprt : $U_{BEZ} = U_{BEZK}$:

$$U_{BEZK} = (1-k) \cdot R_S \cdot i_L - k \cdot U_2$$

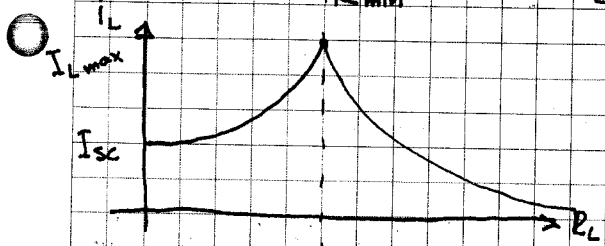
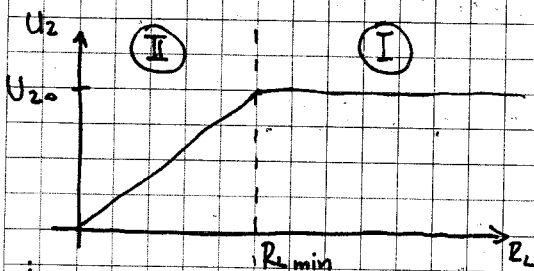
$$i_L = \frac{1}{(1-k) \cdot R_S} \cdot [k \cdot U_2 + U_{BEZK}]$$

↑
potek po premici ; zadostujeta dve točki

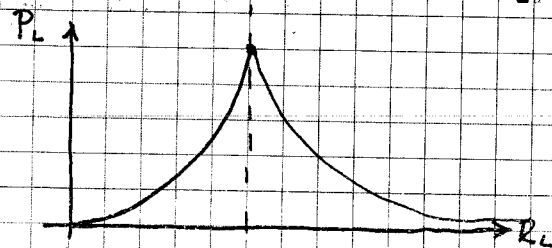


točka B : $U_2 = U_{20}$; $i_L(U_{20}) = \frac{1}{(1-k) \cdot R_S} [k \cdot U_{20} + U_{BEZK}] = I_{Lmax}$

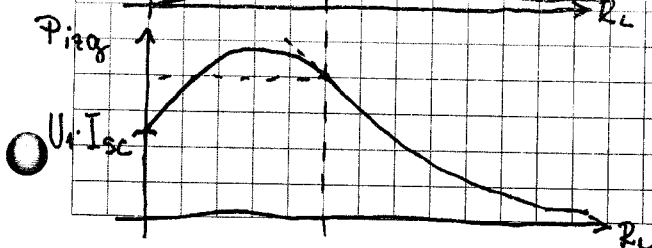
točka C : $U_2 = 0$; $i_L(0) = \frac{1}{(1-k) \cdot R_S} \cdot U_{BEZK} = I_{sc}$



$$i_L = \begin{cases} \frac{U_{20}}{R_L} & ; \textcircled{I} \\ \frac{U_{BEZK}}{(1-k) \cdot R_S + k \cdot R_L} & ; \textcircled{II} \end{cases}$$



$$P_L = \begin{cases} \frac{U_{20}^2}{R_L} & ; \textcircled{I} \\ R_L \cdot I_L^2 & ; \textcircled{II} \end{cases}$$



$$P_{avg} = \begin{cases} \frac{(U_1 - U_{20})^2}{R_L} & ; \textcircled{I} \\ (U_1 - R_L \cdot i_L) \cdot i_L & ; \textcircled{II} \end{cases}$$

ZGLED:

$$U_{20} = 10V$$

$$U_1 = 15V$$

$$I_{Lmax} = 1A$$

$$R_6 = 2k\Omega$$

$$R_7 = 8k\Omega$$

$$U_{BEK} = 0,6V$$

$$k = \frac{R_6}{R_6 + R_7} = \frac{2k\Omega}{(2+8)k\Omega} = 0,2$$

$$R_s = \frac{k \cdot U_{20} + U_{BEK}}{(1-k) \cdot I_{Lmax}} = \frac{0,2 \cdot 10V + 0,6V}{0,8 \cdot 1A} = 3,25k\Omega$$

(več kot pri konst. omejevanju toka $R_s = \frac{U_{BEK}}{I_{Lmax}} = 0,6k\Omega$)

2. prepognjemo kond. $P_{R_s max}$

$$P_{R_s max} = R_s \cdot I_{Lmax}^2 = 3,25W$$

$$R_{Lmin} = \frac{U_{20}}{I_{Lmax}} = \frac{10V}{1A} = 10\Omega$$

$$P_{izg} (R_L = R_{Lmin}) = (U_1 - U_{20}) \cdot I_{Lmax} = (15V - 10V) \cdot 1A = 5W$$

$$P_{izg} (R_L = 0) = U_1 \cdot I_{sc} = 15V \cdot 0,23A = 3,45W$$

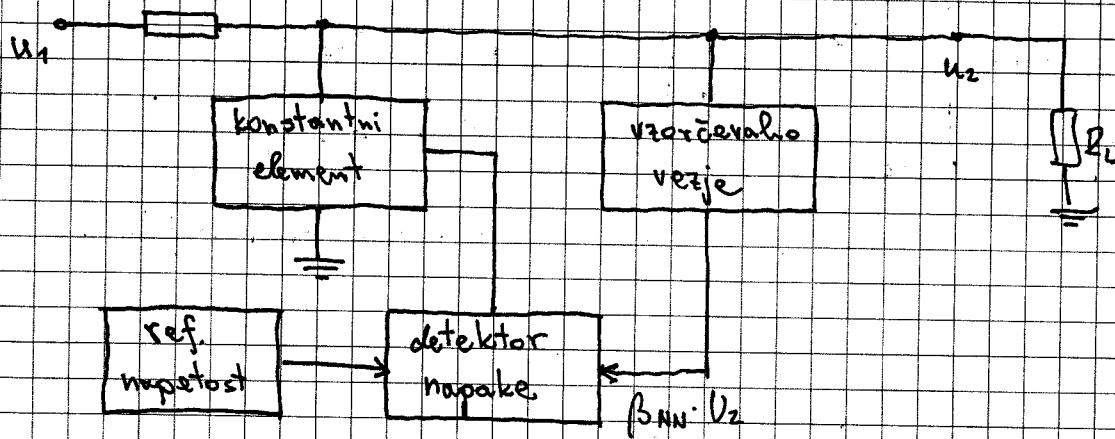
$$I_{sc} = \frac{U_{BEK}}{(1-k) \cdot R_s} = \frac{0,6V}{0,8 \cdot 3,25k\Omega} = 0,23A$$

za ①: $\eta = \frac{P_{izh}}{P_{vh}} = \frac{U_{20}^2 / R_L}{U_1 \cdot \frac{U_{20}}{R_L}} = \frac{U_{20}}{U_1} = 66\%$

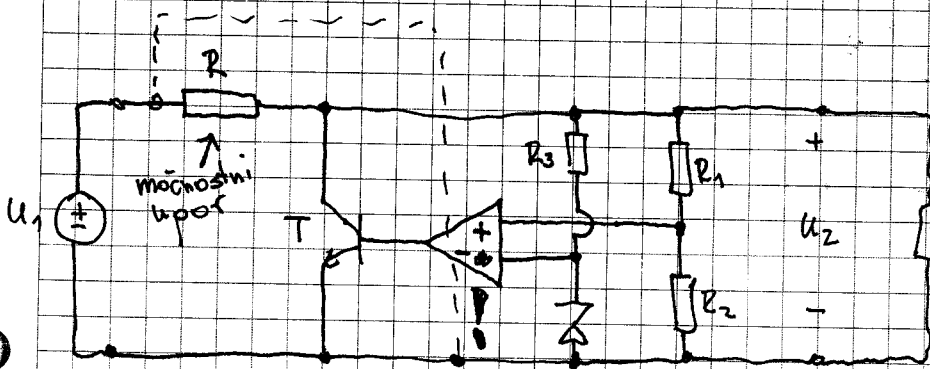
η zmanjšamo tako, da $U_1 \uparrow$ $U_1 \geq (10V + U_{CE1sat} + U_{es})$

PARALELNI NAPETOSTNI REGULATOR

- brez ali s povratnim sklopom



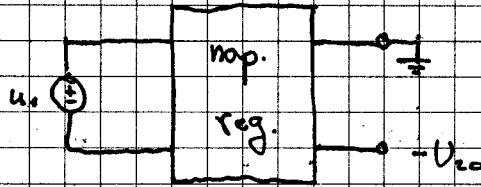
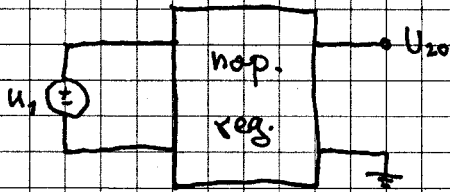
Realizacija s TS:



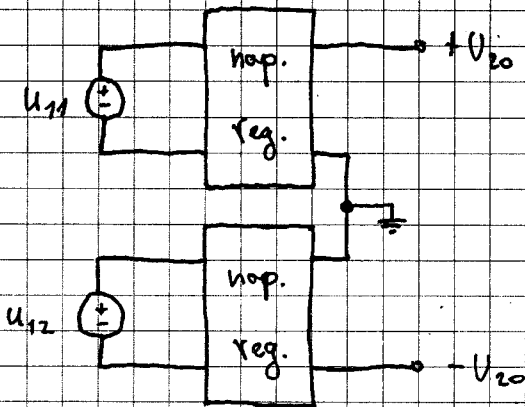
! regulacija

15.11.2013

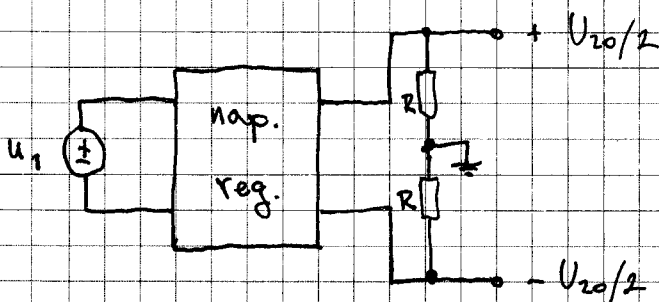
Minus in plus-minus napajanje / nap. regulator



pri čemer mora biti u_1 plavajoč

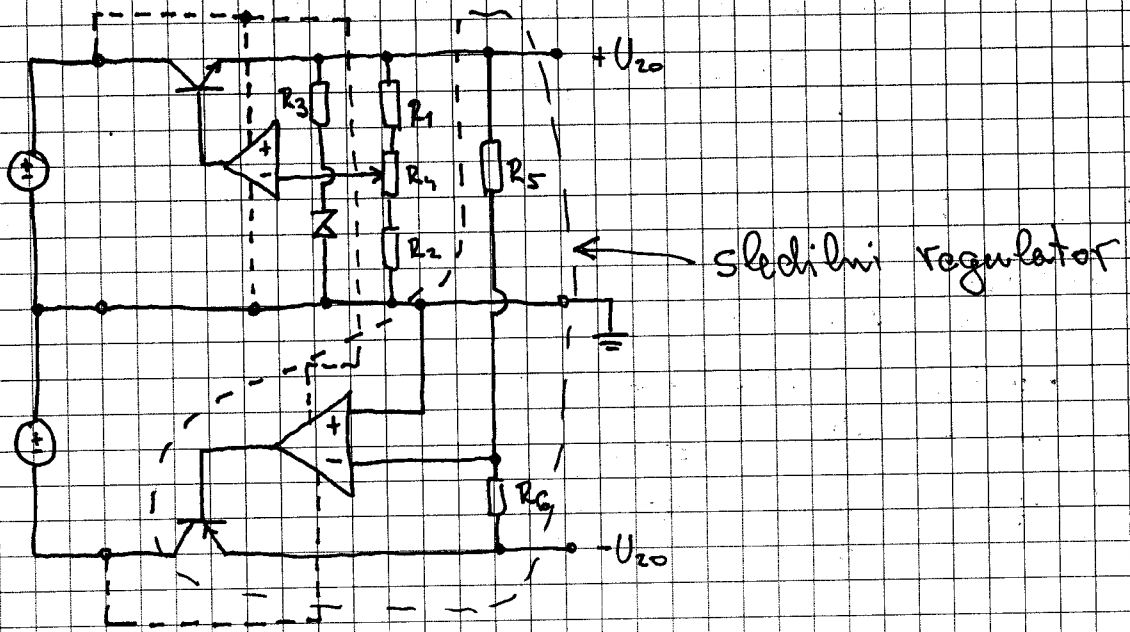


u_{11}, u_{12} - plavajoča



Rizik je problematična
če je obremenitev majhna
potem je to vredn

Realizacija simetričnega plus-minus napajanja z nastarljivo $\pm U_{20}$ s sledilnim regulatorjem



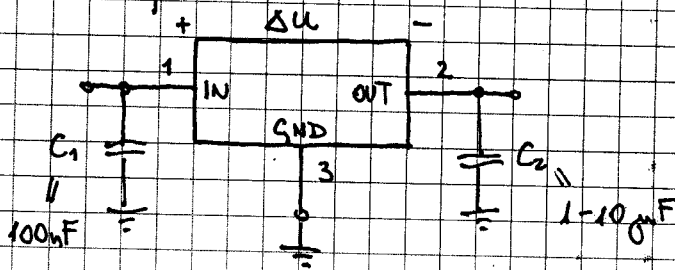
za $R_5 = R_6$: - izhod sledi +izhodu,
 saj $U_{002} = U_{002}^+ = 0$

Integrirani napetostni regulatorji

- Delitev:
- fiksni napetostni regulatorji
 - nastavljivi napetostni regulatorji
 - univerzalni napetostni regulatorji

a.) FIKSNI :

kot tipikal



C_1 za blokiranje motenj

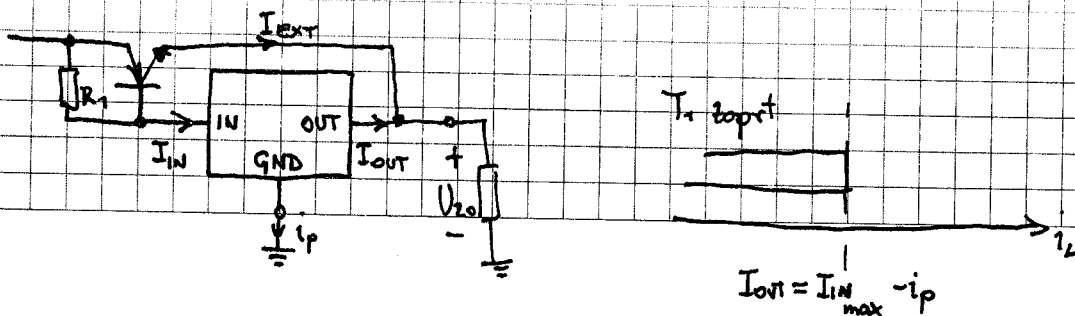
C_2 za zaščito pri trenutnih dinamičnih obremenitvah

za pozitivne napetosti 78xx
7805 (+5V)

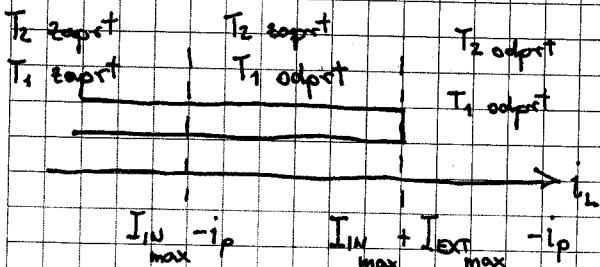
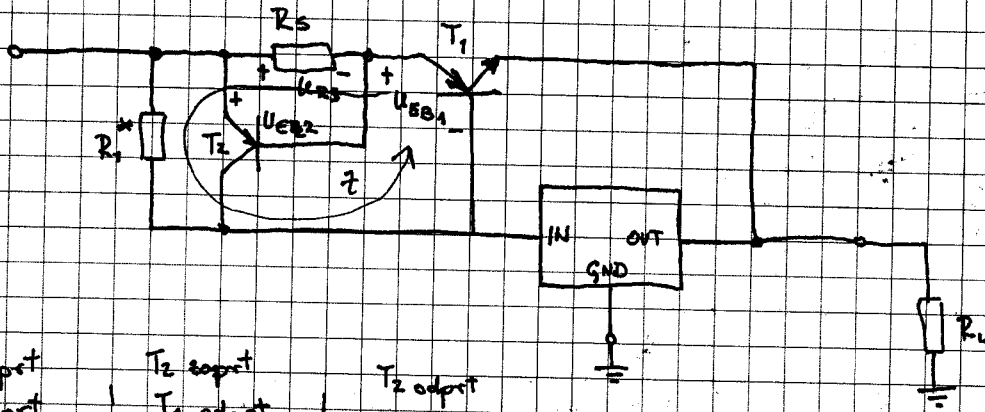
za negativne napetosti 79xx

$\Delta U \geq 3V$ ← da stvar deluje regulator potrebuje veliko moči
 $I_{OUT, max}$ nas omejuje → razširitev tokovnega območja

za večje tokove potrebujemo nadgradnja: (bypass) ($R_1 + T_1$)



naelgradnja za večje tokove z zaščito pred kratkim stikom
 (R_1^* , T_1 , T_2 , R_s)



Z: $U_{BE1} = -U_{RS} + U_{R1}^*$

$$U_{BE1K} = -R_s \cdot I_{RS} + R_1^* \cdot I_{IN_{max}}$$

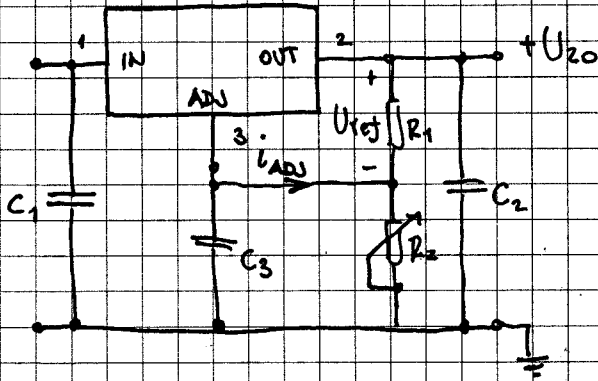
$$U_{BE1} = 0 + R_1^* \cdot I_{IN_{max}}$$

$$U_{BE2} = U_{RS}$$

$$U_{BE2K} = R_s \cdot I_{EXT_{max}}$$

T_2 preusmeri tok I_{EXT} v I_{IN} → dlga temperatura v regulatorju
 → termični shutdown → $I_{IN} = 0$

b.) NASTAVLJIVI :



$$i_{ADJ} \ll i_{R2} \quad (i_{R1} = i_{R2}) \quad U_{R1} = R_1 \cdot i_{R1} = U_{ref} \quad U_{R2} = R_2 \cdot i_{R2}$$

$$U_{20} = U_{R1} + U_{R2} \\ = \frac{R_1 + R_2}{R_1} \cdot U_{ref}$$

pin LM117 : $U_{ref} = 1,25V$ $U_2 \in [1,25V \div 37V]$

LM217 ↗ vojaški

LM317 ↙ komercialni

enako vezje, drugo temperaturno območje

c.) UNIVERZALNI :

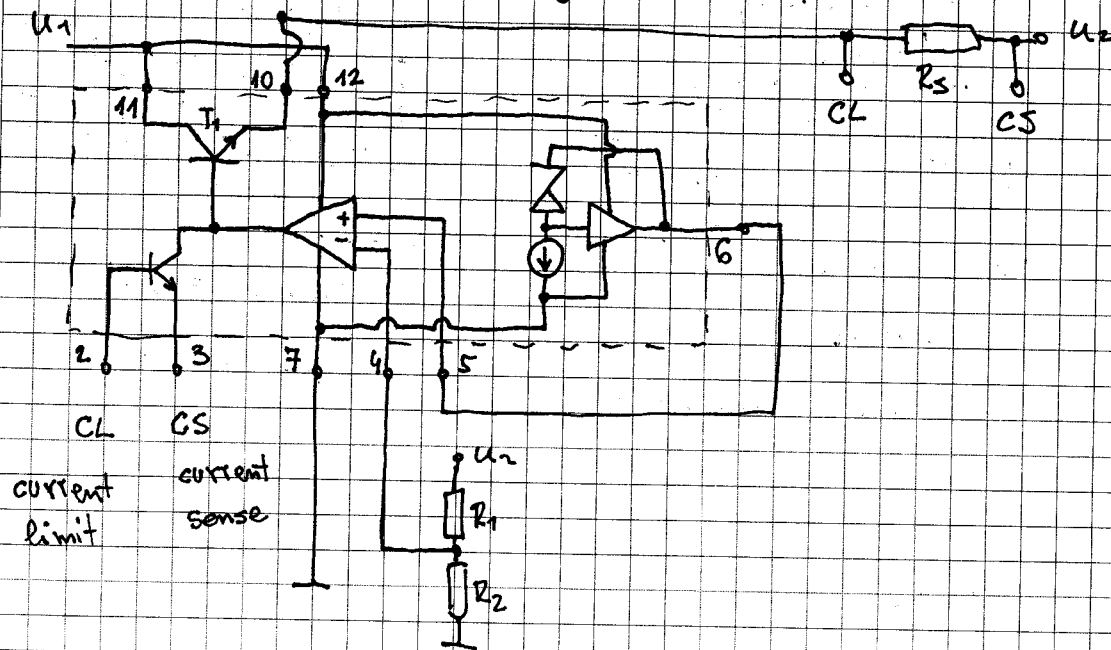
primer: 723

lastnosti: $U_2 \in [+2V \div 37V]$

$I_{Lmax} = 150 mA$

line regulation = 0,01%

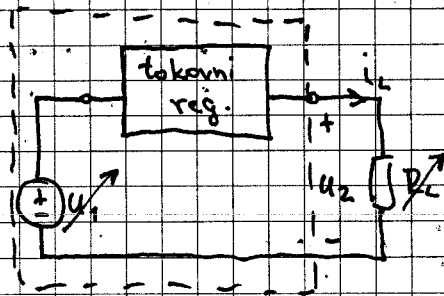
load regulation = 0,03%



1.2.4. TOKOVNI REGULATORSI / STABILIZATORSI / GENERATORSI

- generatorji enosmernega toka

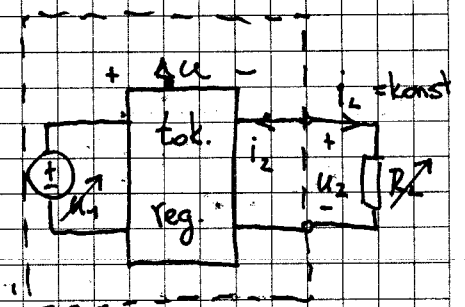
- deliten : A) DVOPOLI



$$u_1 > u_2 = R_L \cdot i_L$$

R_L je navorog omejen

B) ČETVEROPOLI



$$u_1 > u_2 = R_L \cdot i_L$$

R_L navorog omejen

$$i_L = f(u_1, u_2, T)$$

želja : Δi_L čim manjša

$$\Delta i_L = \left. \frac{\partial i_L}{\partial u_1} \right|_D \cdot \Delta u_1 + \left. \frac{\partial i_L}{\partial u_2} \right|_D \cdot \Delta u_2 + \left. \frac{\partial i_L}{\partial T} \right|_D \cdot \Delta T$$

D... izbrana delovna točka

$$i_L = -i_2$$

$$\Delta i_L = - \left. \frac{\partial i_2}{\partial u_1} \right|_D \cdot \Delta u_1 - \left. \frac{\partial i_2}{\partial u_2} \right|_D \cdot \Delta u_2 - \left. \frac{\partial i_2}{\partial T} \right|_D \cdot \Delta T$$

kriteriji kvalitete tokovnih regulatorjev

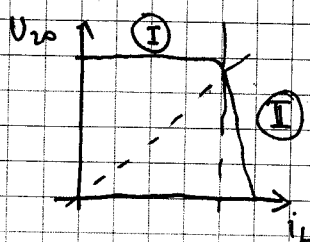
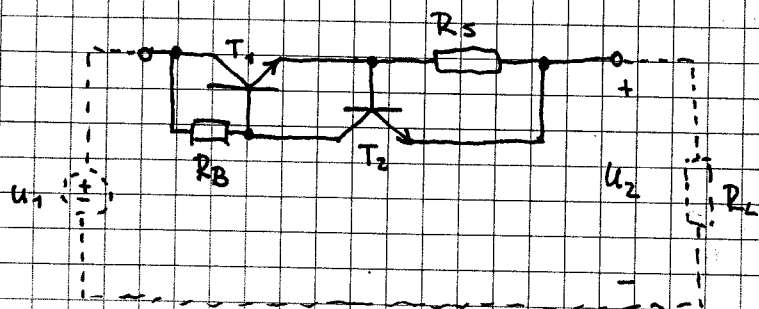
1. transkonduktanca $\frac{\partial i_2}{\partial u_1}$ čim manjša (idealno: 0)

2. izhodna prevodnost $\frac{\partial i_L}{\partial u_2}$ čim manjša (idealno: 0)

izhodna upornost $\frac{\partial u_2}{\partial i_L}$ čim večja (idealno: ∞)

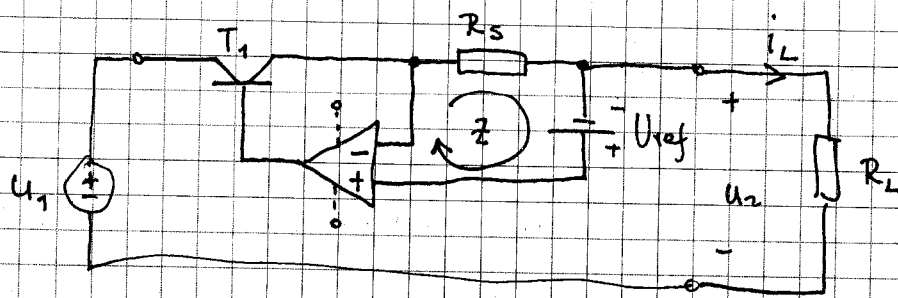
A.) DKO POLNI - realizacije

A1



$R_L \downarrow \Rightarrow i_L \uparrow \Rightarrow u_{RS} \uparrow \Rightarrow T_2$ bolj odpre
 T_1 bolj zapre $\rightarrow i_L \downarrow$

A2



$$Z: U_{ref} = R_S \cdot i_L \Rightarrow i_L = \frac{U_{ref}}{R_S}$$

$$Y_{izh} \approx (1 + A_u) \cdot R_S$$

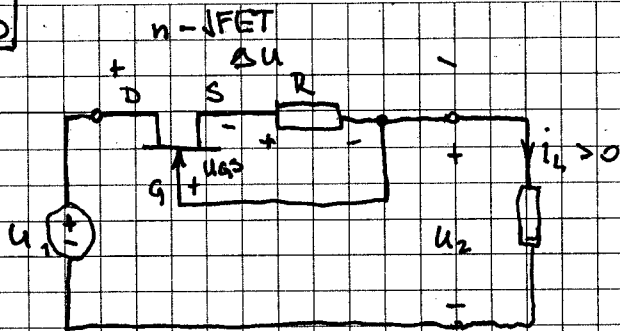
slabost:

- za D.O. potrebno napajanje

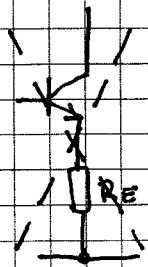
$$-\Delta U \approx U_{CE_{sat}} + U_{ref}$$

↑
slab izkoristek

A3



$$U_{gs} = -R \cdot i_L$$

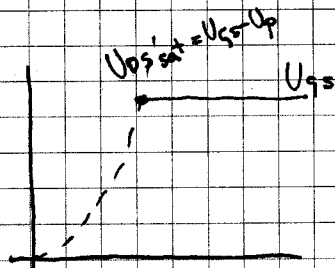


$$i_L = i_D$$

$$i_D = -\frac{U_{gs}}{R}$$

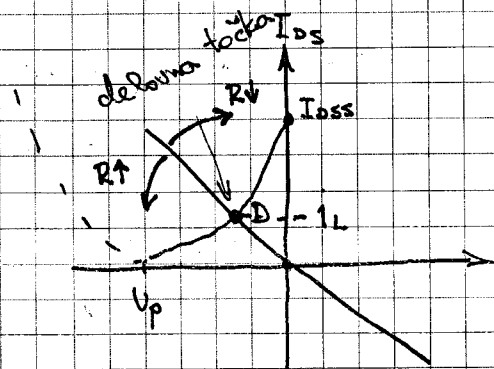
za področje nasičenja: $U_{ds} \geq U_{ds_{sat}} = U_{gs} - U_p$

$$\Delta U = U_{ds} + R \cdot i_L = U_{ds} - U_{gs} > U_{ds_{sat}} - U_{gs}$$



$$\Delta U > -U_p > 0$$

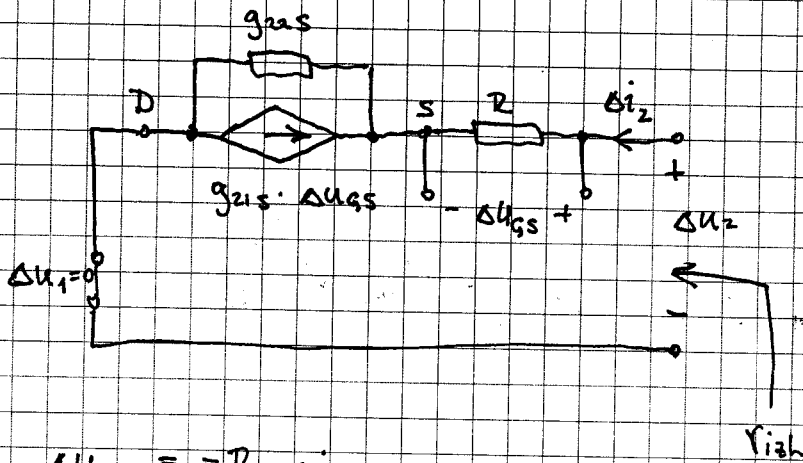
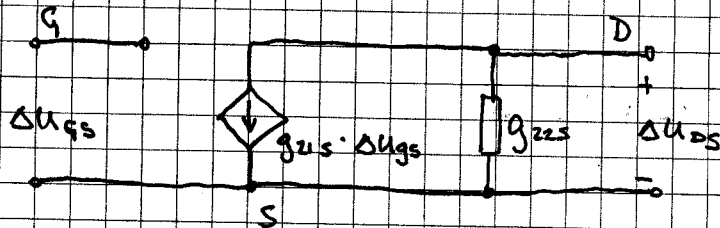
$$i_L = i_D(U_{gs}) = I_{DSS} \left(1 - \frac{U_{gs}}{U_p}\right)^2$$



Ker potrebujemo le 2 elementa je to idealna rešitev za analogni integrirana vezja

- analiza inkrementalnega vezja z dobrotami r_{ih}

NF model JFET:



$$\Delta u_{gs} = -R \cdot \Delta i_2$$

$$\Delta i_D = g_{21s} \cdot \Delta u_{gs} + g_{22s} \cdot \Delta u_{DS}$$

$$= g_{21s} \cdot \Delta u_{gs} + g_{22s} \cdot \Delta u_{DS}$$

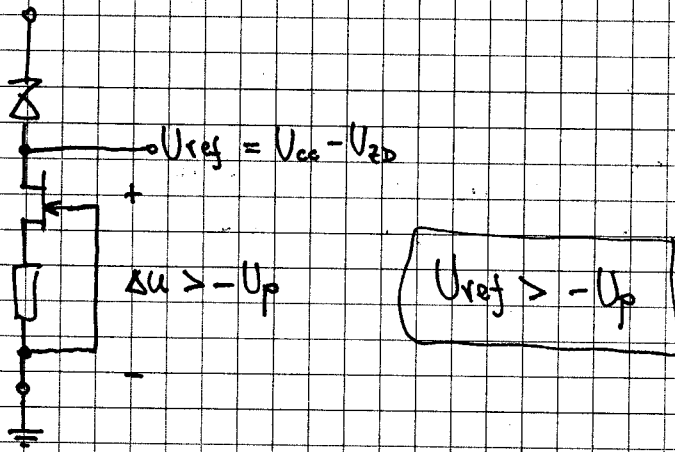
$$= g_{21s} \cdot (-R \cdot \Delta i_D) + g_{22s} \cdot \Delta u_{DS}$$

$$(1 + g_{21s} \cdot R) \cdot \Delta i_D = g_{22s} \cdot \Delta u_{DS}$$

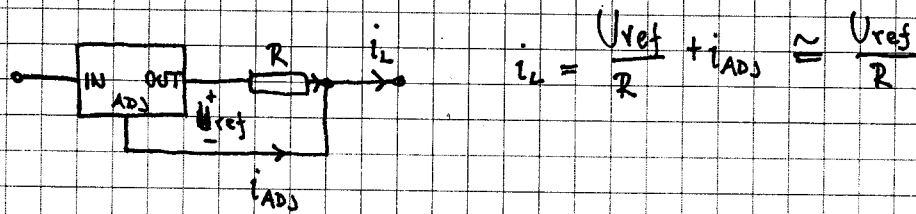
$$r_{ih} = \left. \frac{\Delta u_2}{\Delta i_2} \right|_{\Delta u_1=0} = \frac{\Delta u_{gs} - \Delta u_{DS}}{\Delta i_2} = \frac{-R \cdot \Delta i_D - \frac{1 + g_{21s} \cdot R}{g_{22s}} \cdot \Delta i_D}{\Delta i_2}$$

$$= R + \frac{1 + g_{21s} \cdot R}{g_{22s}} = \left(1 + \frac{g_{21s}}{g_{22s}} \right) R + \frac{1}{g_{22s}}$$

Realizacija v 723 (10) :



A4



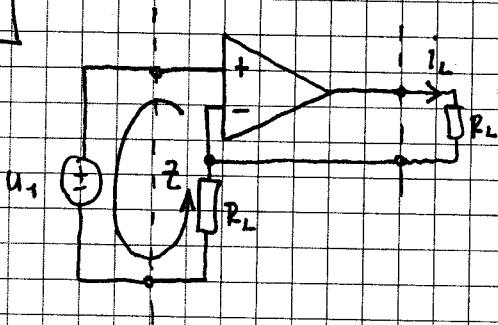
LM317: $i_L \leq 1A$

B.) ČETVERIPOLNI tok. regulatorji

- tokovno krmiljeni tokovni regulatorji (tokovna žrcala 1:1 1:n)

- napetostno krmiljeni tokovni regulatorji

B1



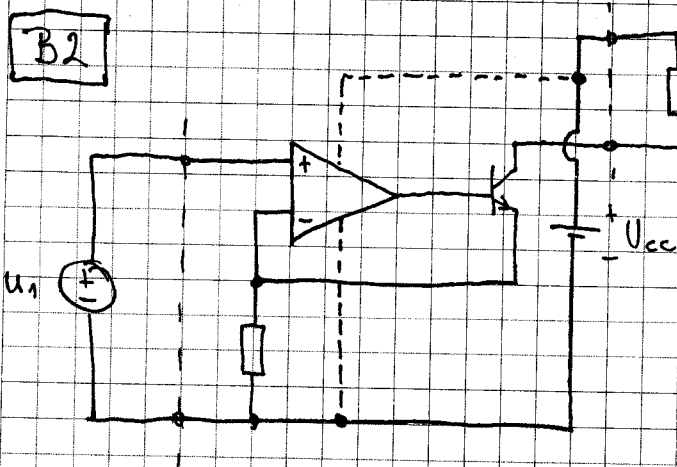
deluje za $+ in - u_1$

slabost:

$$i_L \leq I_{izh_{\infty}}$$

$$\begin{cases} i: & u_R = u_1 \\ & i_R = \frac{u_1}{R} \end{cases} \Rightarrow i_L = i_R = \frac{u_1}{R}$$

B2

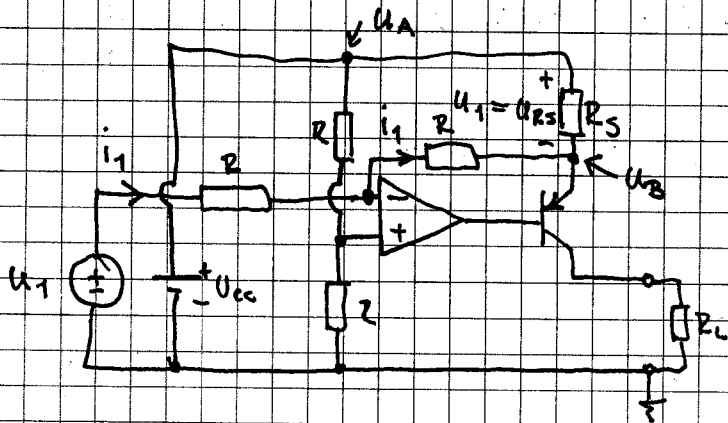


$$i_L \leq \beta \cdot I_{izh_{\infty}}, \text{ vendar } u_1 > 0$$

slabost: 1. samo ena polariteta

2. pravoje breme

B3 rešitev za ozemljeno breme



Analiza za idealni J.O.

$$i^- = i^+ = 0$$

$$u^- = u^+ = \frac{1}{2} U_{cc}$$

$$i_1 = \frac{u_1 - u^-}{R} = \frac{u_1 - \frac{1}{2} U_{cc}}{R}$$

$$u_B = -R \cdot i_1 + u^- = -R \cdot \frac{u_1 - \frac{1}{2} U_{cc}}{R} + \frac{1}{2} U_{cc} = U_{cc} - u_1$$

$$u_{RS} = u_A - u_B = u_1$$

$$\text{za } i_1 \leftarrow i_{RS} = \frac{u_1}{R_S} \Rightarrow \underline{\underline{i_L = \frac{u_1}{R_S}}}$$

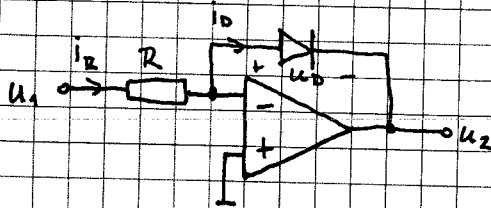
22.11.2013

1.1.5. NELINEARNI OJAČEVALNIKI

A.) LOGARITEMSKI OJAČEVALNIK

$$u_2 = k \cdot \ln \frac{u_1}{U_T}$$

za $u_1 > 0$:



$$u_2 = -u_D + u^- = -u_D$$

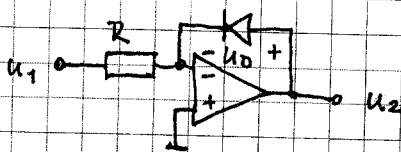
$$i_R = i_D + i^- = i_D$$

$$i_R = \frac{u_1 - u^-}{R} = \frac{u_1}{R}$$

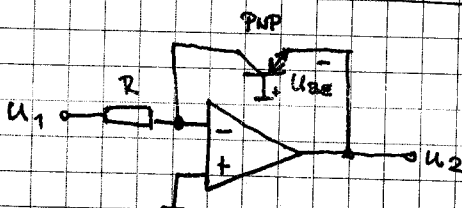
$$u_1 = R \cdot i_R = R \cdot i_D = R \cdot I_S e^{\frac{u_D}{U_T}} = R \cdot I_S \cdot e^{\frac{-u_2}{U_T}}$$

$$u_2 = -U_T \cdot \ln \frac{u_1}{R \cdot I_S} < 0$$

za $u_1 < 0$:

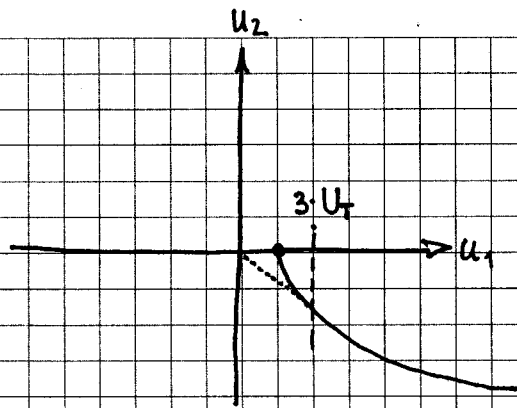


$$u_2 = +U_T \cdot \ln \frac{-u_1}{R \cdot I_S} > 0$$

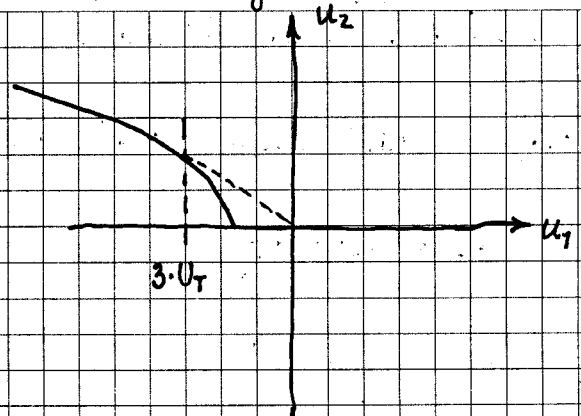


$$u_2 = +U_T \cdot \ln \frac{-u_1}{R \cdot I_{ES}} > 0$$

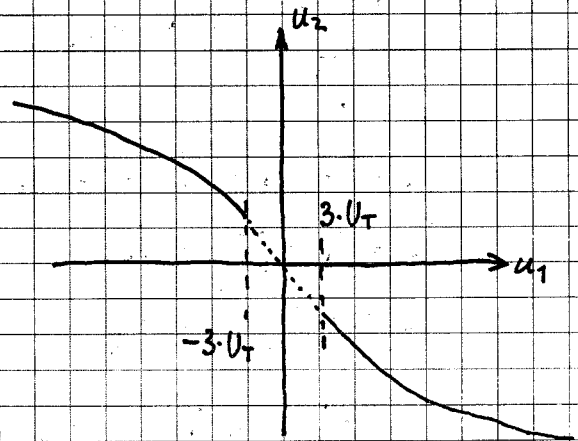
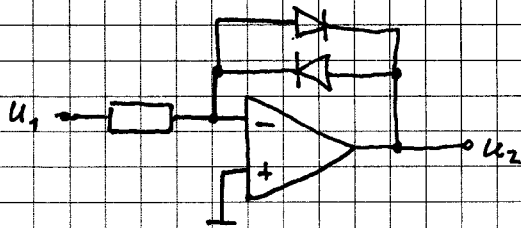
1. vezje



2. vezje



za obe polariteti u_1 :



za logaritemski ojač. poljubne osnove (a):

$$\log_a x = \frac{\ln x}{\ln a} = \frac{1}{\ln a} \cdot \ln x = k \cdot \ln x$$

$$\text{za } \log_{10} x \text{ je } k = \frac{1}{\ln 10} = 0,4343$$

B.) EKSPONENTNI OJAČEVALNIK

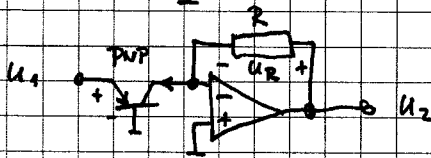
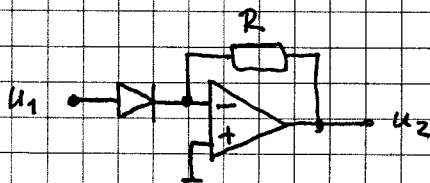
$$u_2 = k \cdot e^{\frac{u_1}{U_T}}$$

za $u_1 > 0$:

$$u_1 = U_{EB}$$

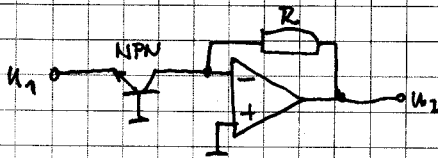
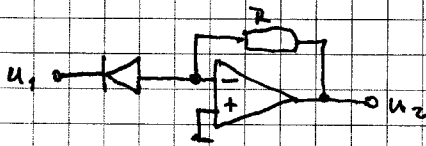
$$i_c \approx -i_E = -I_{ES} \cdot e^{\frac{U_{EB}}{U_T}} = -I_{ES} e^{\frac{u_1}{U_T}}$$

$$u_2 = U_R = R \cdot i_c = -R \cdot I_{ES} \cdot e^{\frac{u_1}{U_T}} < 0$$

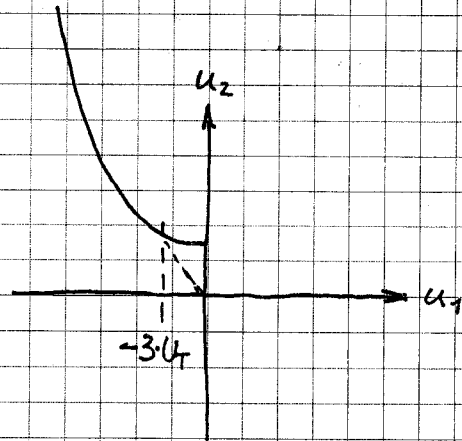
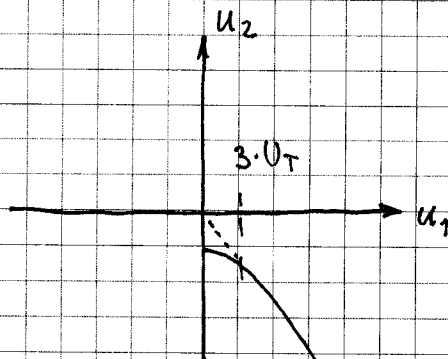


za $u_1 < 0$:

$$u_2 = R \cdot I_{ES} \cdot e^{\frac{-u_1}{U_T}} > 0$$



PF:



slabost log in antilog ojačevalnikov je prevelika temperaturna odvisnost [$I_{ES}(T)$, $U_T(T)$]

C.) ANALOGNI MNOŽILNIKI IN DELILNIKI :

vezja krmiljena z DUEMA vhodoma!

a1) MNOŽILNIKI

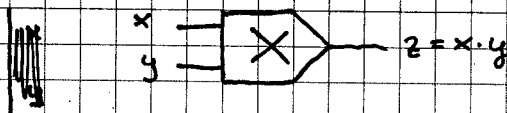
izkoriščajo lastnosti:

$$\ln(a \cdot b) = \ln a + \ln b$$

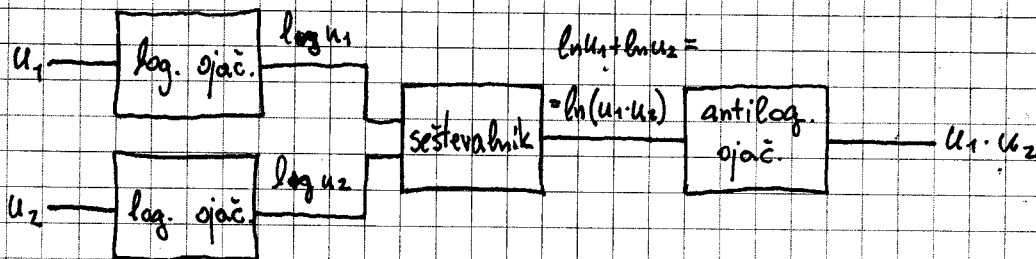
$$e^{\ln x} = x$$

$$u_1 \cdot u_2 = e^{\ln(u_1 \cdot u_2)} = e^{(\ln u_1 + \ln u_2)}$$

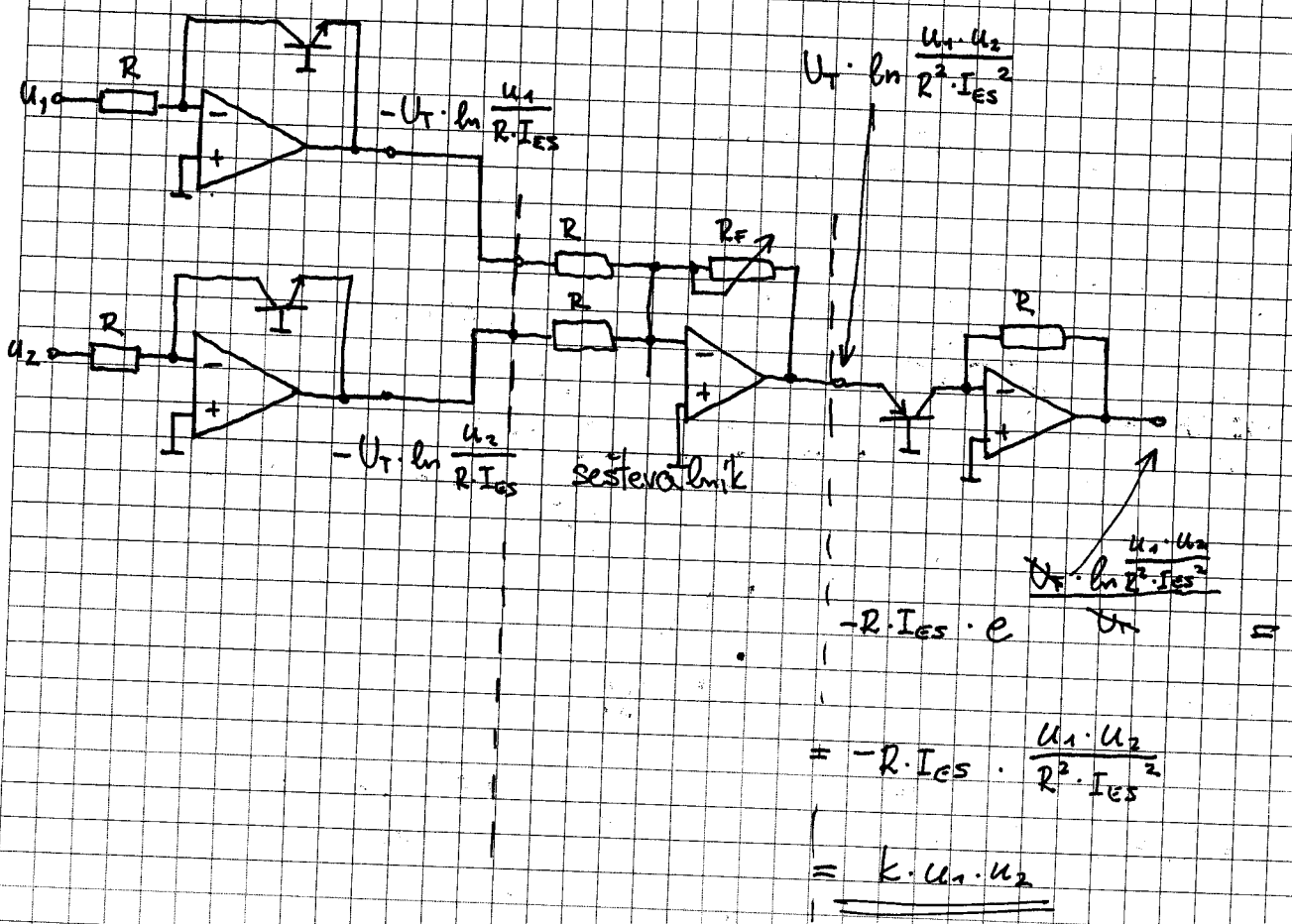
Simbol:



shematski prikaz vezja:



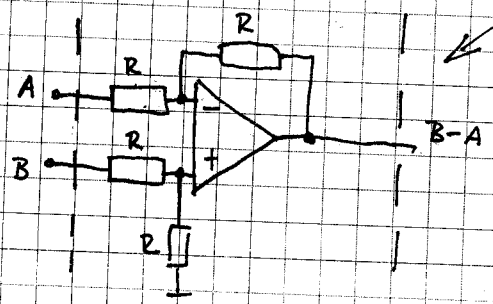
Realizacija za $u_1 > 0, u_2 > 0$:



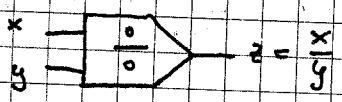
c2) DELILNIKI

velja: $\frac{u_1}{u_2} = e^{\ln \frac{u_1}{u_2}} = e^{(\ln u_1 - \ln u_2)}$

odštevalnik
(diferenčni oprevalnik)



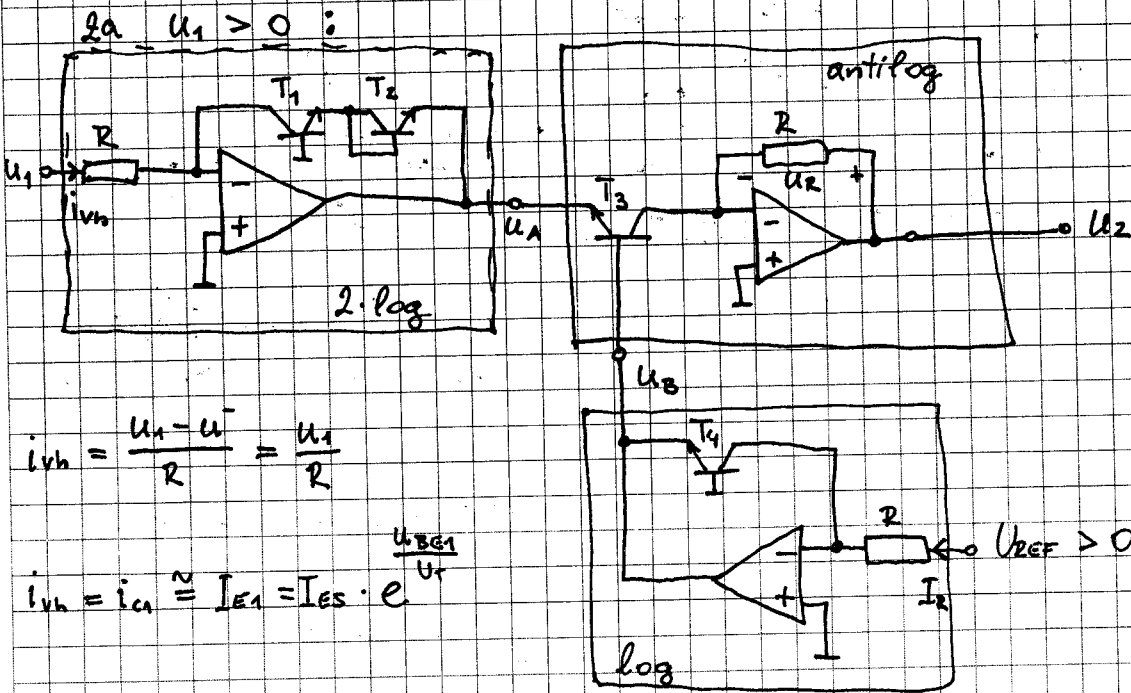
simbol:



D.) KVADRIRNI OJACEVALNIK

$$u_2 = k \cdot u_1^2$$

$$u_1^2 = e^{\ln u_1^2} = e^{2 \cdot \ln u_1}$$



$$i_{vh} = \frac{u_1 - u^-}{R} = \frac{u_1}{R}$$

$$i_{vh} = i_{c1} \approx I_{E1} = I_{ES} \cdot e^{\frac{u_{BE1}}{U_T}}$$

$$u_A = -u_{BE2} - u_{BE1} - u^- \Big|_{T_1 \approx T_2} =$$

$$= -2 \cdot u_{BE} = -2 \cdot U_T \cdot \ln \frac{i_{vh}}{I_{ES1,2}}$$

$$I_R = \frac{u_{REF}}{R} = i_{c4} \approx i_{E4} = I_{ES4} \cdot e^{\frac{u_{BE4}}{U_T}} = I_{ES4} \cdot e^{\frac{-u_B}{U_T}}$$

$$u_B = -u_{BE4} = -U_T \cdot \ln \frac{I_R}{I_{ES4}}$$

$$u_{BE3} = u_B - u_A = 2 \cdot U_T \ln \frac{i_{vh}}{I_{ES1,2}} - U_T \cdot \ln \frac{I_R}{I_{ES4}} = U_T \cdot \ln \left[\frac{i_{vh}^2}{I_{ES1,2}^2} \cdot \frac{I_{ES4}}{I_R} \right] =$$

$$= U_T \cdot \ln \frac{i_{vh}^2}{I_{ES} \cdot I_R}$$

antilog o'ac :

$$i_{c3} \approx -i_{e3} = I_{ess} \cdot e^{-\frac{U_{REF}}{U_T}} = I_{ess} \cdot e^{-\frac{U_T \cdot \ln \frac{i_{vh}^2}{I_{ES} \cdot I_R}}{U_T}} = I_{ess} \cdot \frac{i_{vh}^2}{I_{ES} \cdot I_R}$$

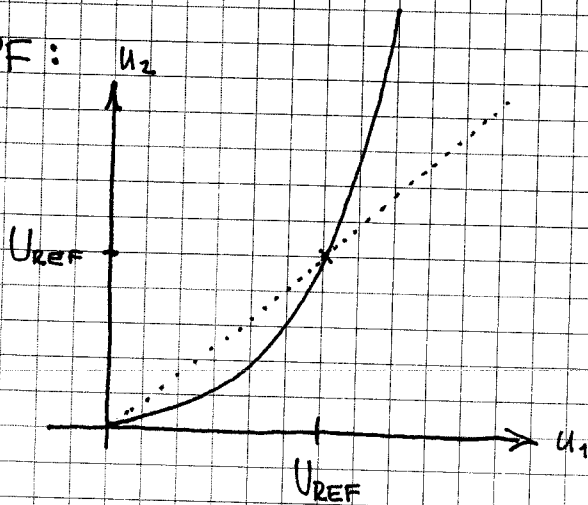
$$= \frac{i_{vh}^2}{I_R}$$

$$U_2 = U_z = R \cdot i_{c3} = R \cdot \frac{i_{vh}^2}{I_R} = R \cdot \frac{\frac{U_1^2}{R^2}}{I_R} = \frac{U_1^2}{R \cdot I_R} = \frac{U_1^2}{R \cdot \frac{U_{REF}}{R}} =$$

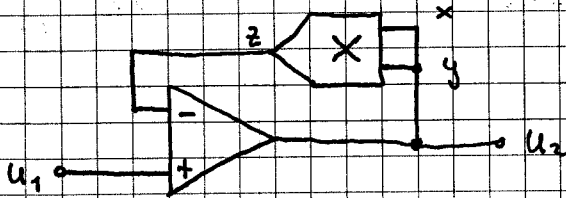
$$U_2 = \frac{U_1^2}{U_{REF}}$$

$$\frac{U_2}{U_{REF}} = \left(\frac{U_1}{U_{REF}} \right)^2$$

PF:



E.) KVADRATNO KORENSKI OJAČEVALNIK:



$$u_1 = z \quad (\text{zlato pravilo O.D.})$$

$$u_2 = x = y$$

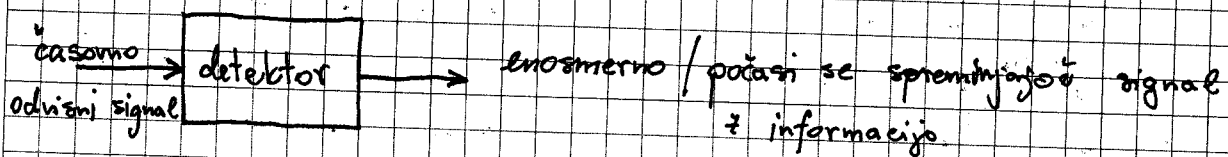
$$z = x \cdot y = x^2 = k \cdot u_2^2 = u_1$$

$$u_2 = \sqrt{\frac{u_1}{k}} = k^* \cdot \sqrt{u_1}$$

namesto množilnika lahko uporabimo
tudi kvadrirnik

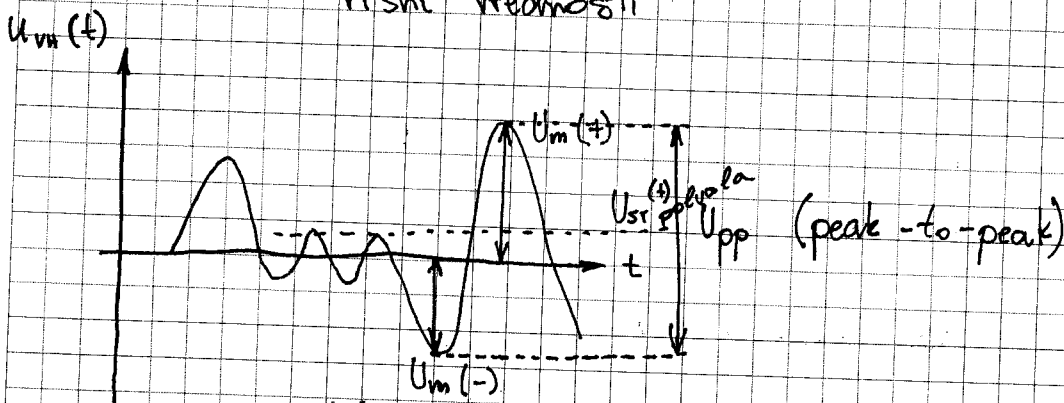
1.2. DINAMIČNA VEZJA (z enim vhodom) ZA PREOBLIKOVANJE SIGNALOV

1.2.1. DETEKTORJI



Izkodna veličina je premo sorazmerno merjeni veličini / informaciji (idealno $k = 1:1$)

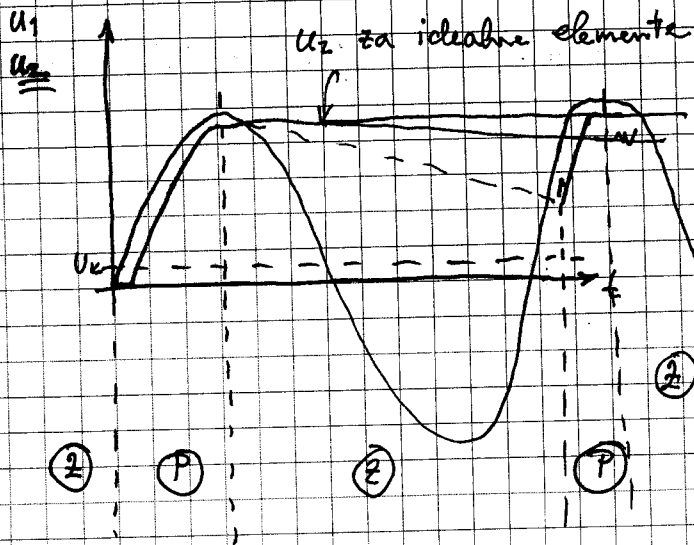
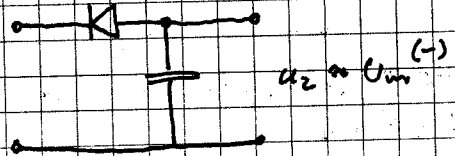
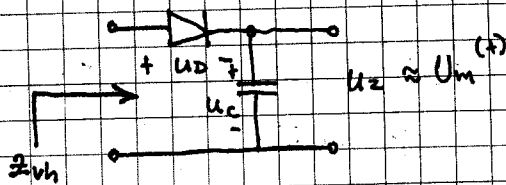
- amplitudi
- srednji vrednosti polvala
- efektivni vrednosti
- torenski vrednosti
- vršni vrednosti



1.2.1.1. DETEKTOR TEMENNE VREDNOSTI

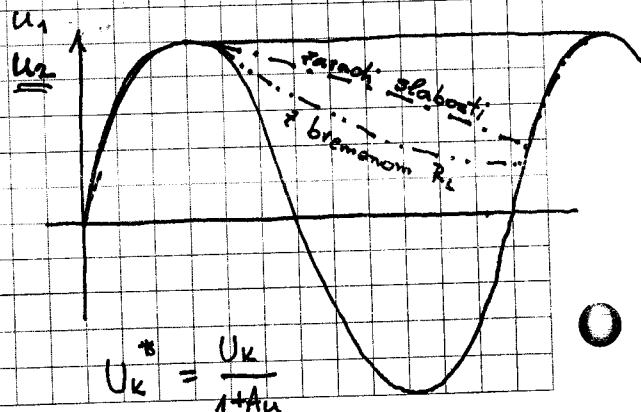
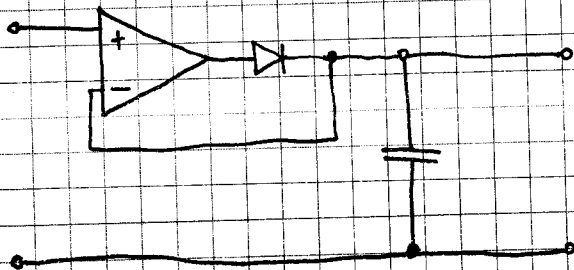
- bodisi za $U_m^{(+)}$ ali $U_m^{(-)}$

- preprost detektor



- slabosti :
1. napaka v u_2 zaradi U_k : $U_2 = U_1 - U_k$
 2. problem spremenljive Z_{uh}

NADGRADNJA Z NAP. SLEDNIKOM :



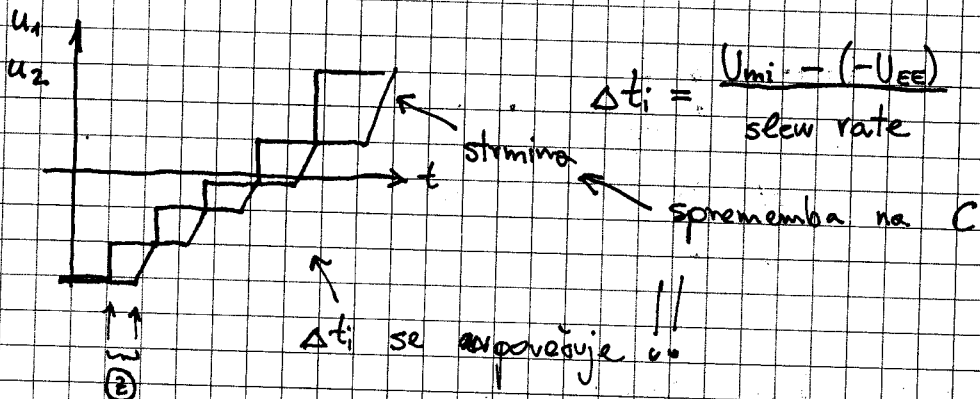
$$U_k^* = \frac{U_k}{1+A_u}$$

$$U_2 = U_1 = U_m^{(+)}$$

~~slabosti v. zmanjšane spremembe iz napetosti~~

slabosti:

1. zakasnitev spremembe izh. napetosti Δt_i



2. omejena hitrost spremembe $u_c(t)$

$$\frac{du_2}{dt} = \frac{du_c}{dt} = \frac{I_{\text{zh. o.o. max}}}{C}$$

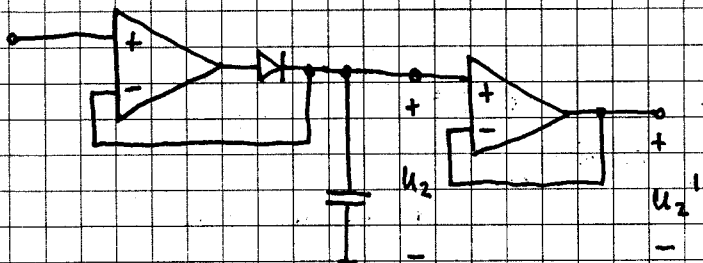
želja: čim manjši C,
čim večji $I_{\text{zh. o.o. max}}$

3. praznjenje kondenzatorja

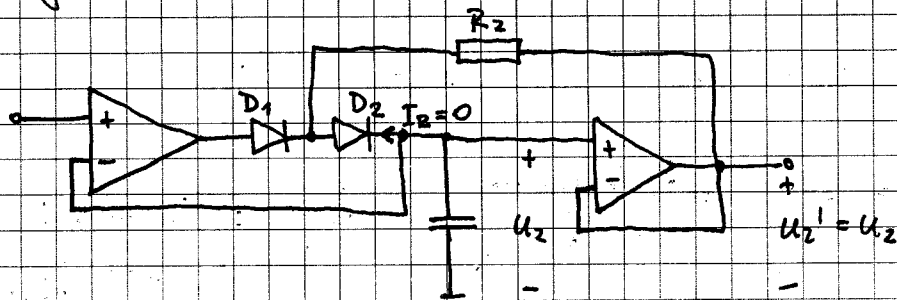
$$\frac{du_c}{dt} = - \frac{I_B + I_Z + I_n}{C}$$

želja: čim večji C,
čim manjši tokovi

+ izničenje vpliva R_L : (+ buffer na izhodu)

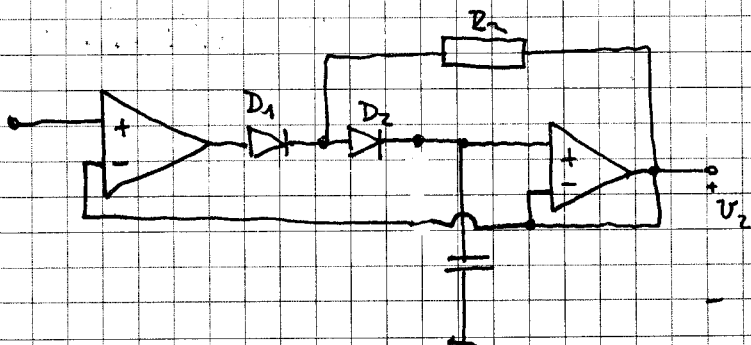


- izničenje vpliva I_R : (+ D_2, R_2)



pri $U_D = 0$: $I_D = 0$

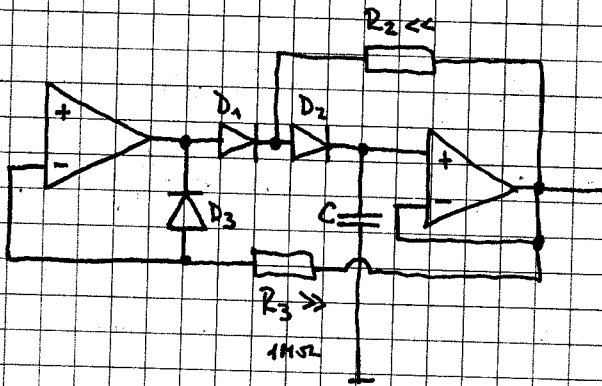
- izničenje vpliva I_B^- :



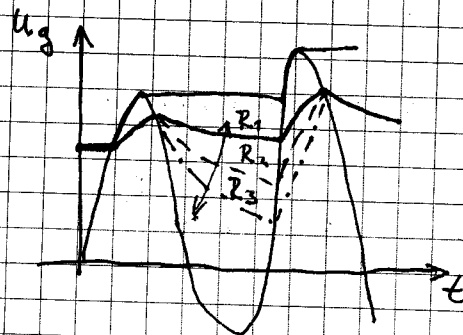
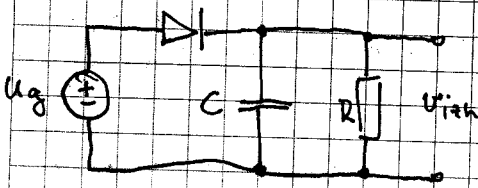
povezava PS namesto na U_C damo na U_2'

- minimizacija vpliva I_B^+ o.o.z: MOSFET vhodni dif. pojačevalnik

- izračunje Δt_i : $(+D_3, R_3)$



1.2. DETEKTOR AMPLITUDE

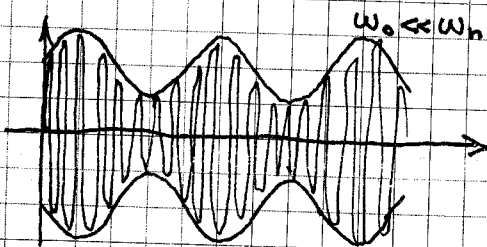


brez R (detektor temenske vred)
z R (detektor amplitude)

- vse nadgradnje detektorja temenske vrednosti lahko uporabimo tudi pri detektorju amplitude

- izziv je dimenzioniranje R in C (glede polnjenja in praznjenja)

- zgled : $u_g = U_m \sin \omega t$ $U_m(t) = U_n \cdot (1 + m \cdot \cos \omega_m t) \cdot \cos \omega_c t$



faktor modlacije $\in [0, 1]$

informacija
nosilni signal

1. zahteva - polnjenje C: polnjenje preko diode je hitrejše kot naraščanje ovjnice $\tau_0 \ll R$

2. zahteva - prenosenje C: prenosenje preko upora R ($\tau = RC$),
saj je dioda zaprta

mora biti počasnejše kot perioda nosilnega signala:

$$\tau > T_n = \frac{1}{f_n} = \frac{2\pi}{\omega_n} \quad RC > \frac{2\pi}{\omega_n}$$

3. zahteva - prenosenje C: prenosenje preko upora R ($\tau = RC$)
mora biti hitrejša kot upadanje ovojnice

napetost ovojnice: $u_o(t) = U_n \cdot (1 + m \cdot \cos \omega_o t)$

$$\frac{du_o}{dt} = -U_n \cdot m \cdot \omega_o \sin \omega_o t \quad \text{gradient ovojnice (naraščanje ali upadanje)}$$

napetost $u_c(t) = U_{c0} e^{-\frac{t}{\tau}}$ če ne upoštevamo samopoznenja
(I_n, I_B, \dots)

$$\frac{du_c}{dt} = \frac{U_{c0}}{\tau} e^{-\frac{t}{\tau}} = -\frac{u_c(t)}{\tau} = -\frac{u_c(t)}{RC}$$

$$\frac{du_c}{dt} \leq \frac{du_o}{dt} < 0 \quad ; \quad u_c(t) = u_o(t)$$

$$-\frac{u_o(t)}{RC} \leq -U_n \cdot m \cdot \omega_o \sin \omega_o t \quad | \cdot (-1)$$

$$\frac{1}{RC} \geq \frac{U_n \cdot m \cdot \omega_o \cdot \sin \omega_o t}{U_n \cdot (1 + m \cdot \cos \omega_o t)} = f(\omega_o t) \quad \omega_o t \in [0, 2\pi]$$

iščemo maksimum za $f(\omega_o t)$: $\frac{df(\omega_o t)}{d\omega_o t}$

$$= \frac{df(\omega_0 t)}{d\omega_0 t} = \frac{m \cdot \omega_0 \cdot \cos \omega_0 t \cdot (1 + m \cdot \cos \omega_0 t) - m \cdot \omega_0 \cdot \sin \omega_0 t \cdot m \cdot (-\sin \omega_0 t)}{(1 + m \cdot \cos \omega_0 t)^2} = 0$$

$$m \cdot \omega_0 \cdot \cos \omega_0 t + m^2 \cdot \omega_0 \cdot \cos^2 \omega_0 t + m^2 \cdot \omega_0 \cdot \sin^2 \omega_0 t = 0 \quad | : (m \cdot \omega_0)$$

$$\cos \omega_0 t + m = 0$$

$$\cos \omega_0 t = -m$$

$$\sin \omega_0 t = \sqrt{1 - \cos^2 \omega_0 t} = \sqrt{1 - m^2}$$

$$\frac{1}{RC} \geq \frac{m \cdot \omega_0 \cdot \sqrt{1 - m^2}}{1 + m \cdot (-m)}$$

$$\frac{1}{RC} \geq \frac{m \cdot \omega_0 \sqrt{1 - m^2}}{1 - m^2} = \frac{m \cdot \omega_0}{\sqrt{1 - m^2}}$$

$$RC = \frac{\sqrt{1 - m^2}}{m \cdot \omega_0}$$

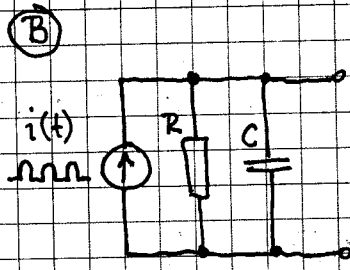
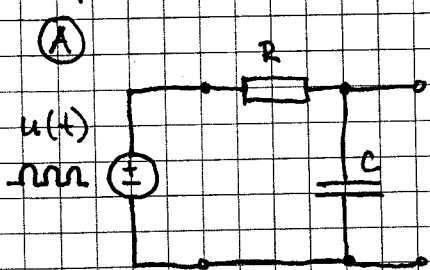
Združitven kriterij pri 2. in 3. zahtevi:

$$\frac{2\pi}{\omega_n} < RC < \frac{\sqrt{1 - m^2}}{m \cdot \omega_0}$$

za večje m (bližje vrednosti 1) je potrebno RC zmanjšati:

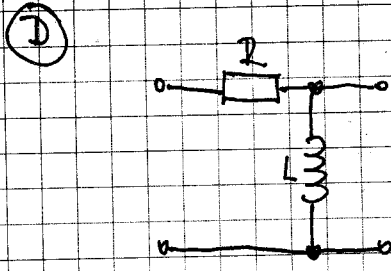
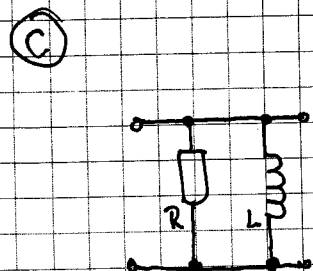
1.2.1.3. DETEKTOR SREDNJE VREDNOSTI

- povprečenje pozitivnega ali negativnega polvala ali povprečenje obeh polvalov
- pristopi: na osnovi povprečenja s C ali L
- koncepti s C:

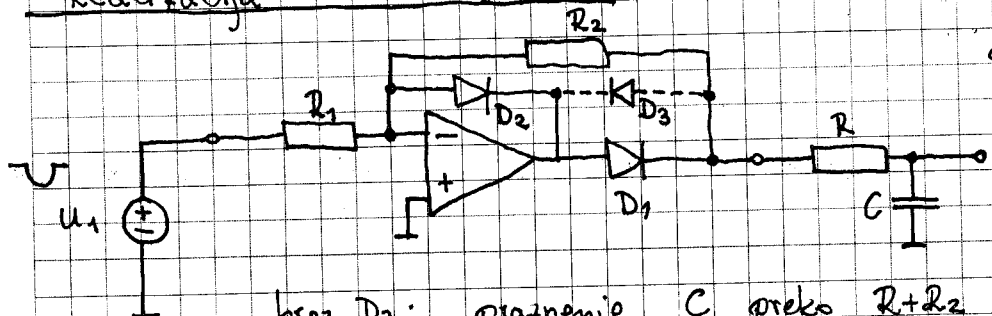


perioda
 $RC \gg T$

- dualni koncepti z induktivnostjo:



Realizacija 1: KONCEPT (A)



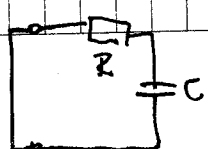
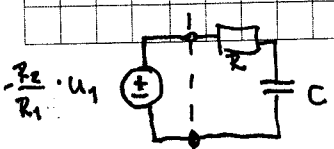
povprečimo negativni polval $u_1(t)$

brez D_2 : praznjenje C preko $R+R_2$

z D_3 : pri $D_2 \equiv D_3$ in obe prevodno polarizirani: praznjenje C preko R

za $u_1 < 0$:

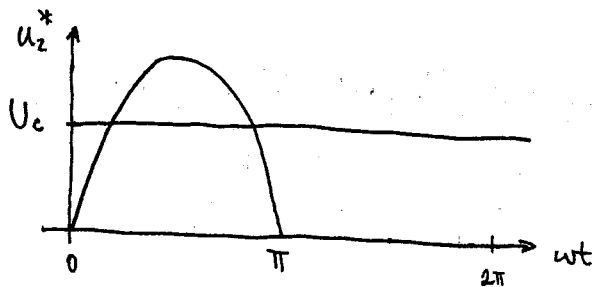
za $u_1 > 0$:



za stacionarne razmere:

$$\Delta Q \propto \int_0^T i_c(t) dt = 0 \quad \text{oz} \quad \int_0^{2\pi} i_c(\omega t) \cdot d\omega t = 0$$

$$\int_0^{\pi} i_{c \text{ polnjenje}} d\omega t + \int_{\pi}^{2\pi} i_{c \text{ praznjenje}} d\omega t = 0$$



$$\int_0^{\pi} \frac{U_m \cdot \sin \omega t - U_c}{R} d\omega t + \int_{\pi}^{2\pi} \frac{0 - U_c}{R} d\omega t = 0$$

$$\frac{U_m}{R} (-\cos \omega t) \Big|_0^{\pi} - \frac{U_c}{R} (\pi - 0) - \frac{U_c}{R} (2\pi - \pi) = 0$$

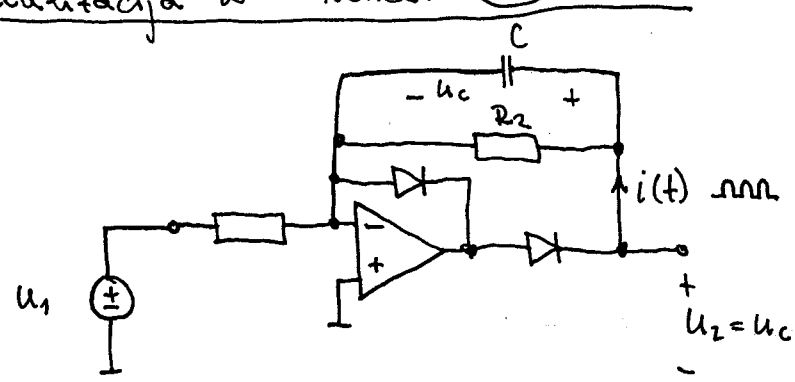
$$\frac{2U_m}{R} - 2 \frac{U_c}{R} \cdot \pi = 0$$

$$U_m = U_c \cdot \pi$$

$$\underline{\underline{U_c = \frac{1}{\pi} U_m = \frac{1}{\pi} \frac{R_2}{R_1} \cdot U_1}}$$

napetost U_c je res srednja vrednost negativnega polvala $u_2(t)$

Realizacija 2: KONCEPT (B)



$RC \gg T$

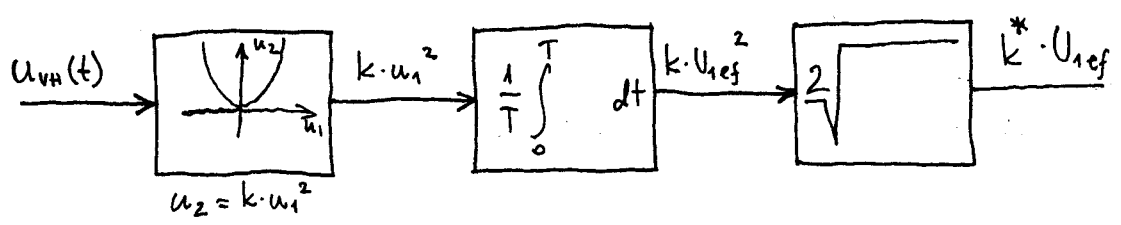
$$U_c = \frac{1}{\pi} \cdot \frac{R_2}{R_1} \cdot U_i$$

za negativni polval $u_1(t)$

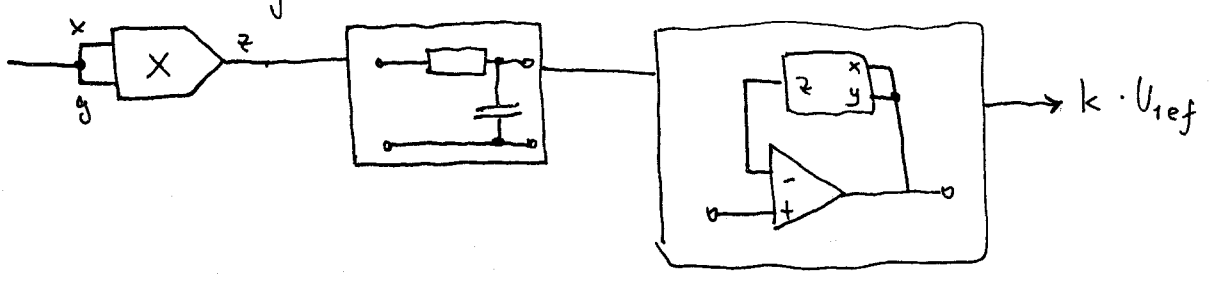
1.2.1.4. DETEKTOR PRAVE EFEKTIVNE VREDNOSTI (RMS)

$$U_{ef}^2 = \frac{1}{T} \int_0^T u^2(t) dt \quad \text{ali} \quad U_{rms} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} u_1^2(\omega t) d\omega t}$$

- simbolični prikaz:

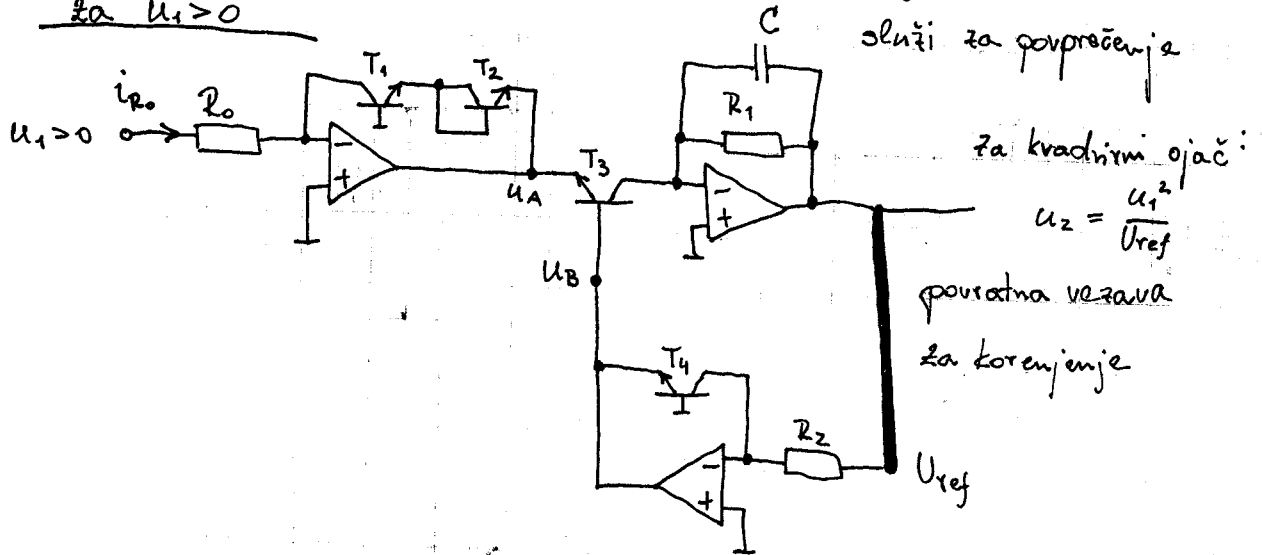


- načelna realizacija z analognim množilnikom (ali kvadrirnik)



- realizacija RMS detektorja s kodirnim vezjem

za $u_1 > 0$



analize za idealne O.O.:

$$i_{R0} = \frac{u_1}{R_0}$$

$$i_{R0} = i_{c1} \approx i_{e1} = i_{c2} \approx i_{e2} = I_{ES} \cdot e^{\frac{U_{BE}}{U_T}}$$

$$U_A = -U_{BE2} - U_{BE1} \Big|_{T_1 \approx T_2} = -2 \cdot U_{BE} = -2 \cdot U_T \cdot \ln \frac{u_1}{R_0 \cdot I_{ES}}$$

$$U_B = -U_{BE4} = -U_T \cdot \ln \frac{I_{R2}}{I_{ES4}} = -U_T \cdot \ln \frac{U_2}{R_2 \cdot I_{ES4}}$$

$$U_{BE3} = U_B - U_A = U_T \cdot \ln \left[\left(\frac{u_1}{R_0 \cdot I_{ES1}} \right)^2 \cdot \frac{R_2 \cdot I_{ES4}}{U_2} \right]$$

$$I_{c3} = I_{ES3} \cdot e^{\frac{U_{BE3}}{U_T}} = I_{ES} \cdot \left[\left(\frac{u_1}{R_0 \cdot I_{ES1}} \right)^2 \cdot \frac{R_2 \cdot I_{ES4}}{U_2} \right]$$

$$U_2 = U_c = \overline{U_c} = R_1 \cdot i_{c3} = R_1 \cdot I_{ES3} \left(\frac{u_1}{R_0 \cdot I_{ES1}} \right)^2 \cdot \frac{R_2 \cdot I_{ES4}}{U_2} = \frac{R_1 \cdot R_2 \cdot I_{ES3} \cdot I_{ES4}}{R_0^2 \cdot I_{ES1} \cdot I_{ES2}} \cdot \overline{u_1^2} \cdot \frac{1}{U_2}$$

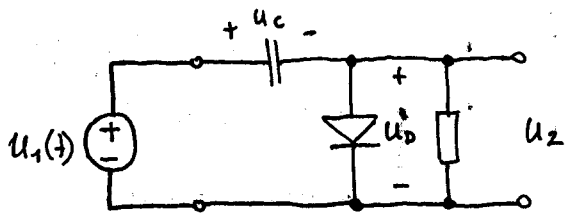
$$T_1 \approx T_2 \approx T_3 \approx T_4: U_2^2 = \frac{R_1 \cdot R_2}{R_0^2} \cdot \overline{u_1^2}$$

$$U_2 = \sqrt{\frac{R_1 \cdot R_2}{R_0^2} \cdot \frac{1}{T} \int_0^T u_1^2 dt}$$

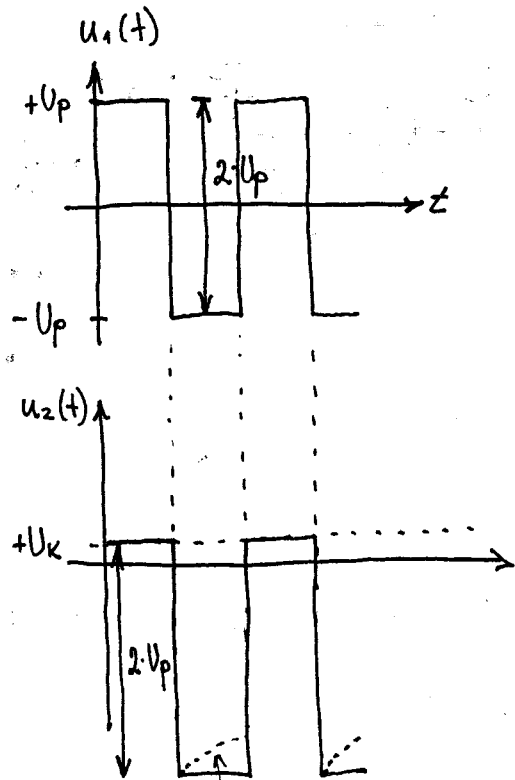
za $R_1 = R_2 = R_0$ dobimo RMS detektor

1.2.2.1. PRIPENJALNIK ("CLAMPER")

- preprosta realizacija :



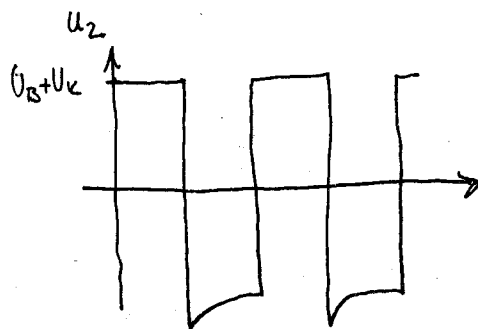
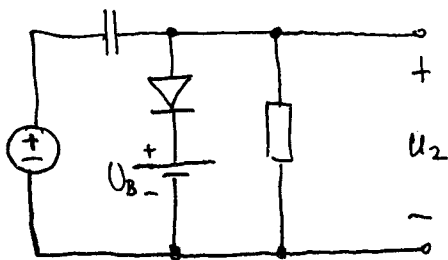
$$U_c = U_p - U_k$$



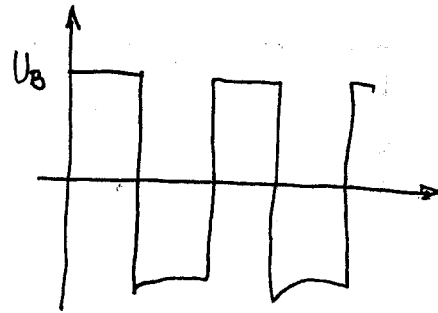
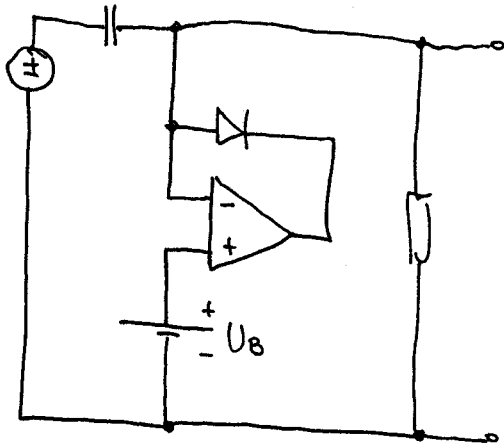
omejitev prostiranja :

$$\tau = RC \gg T$$

praznjenje zaradi R

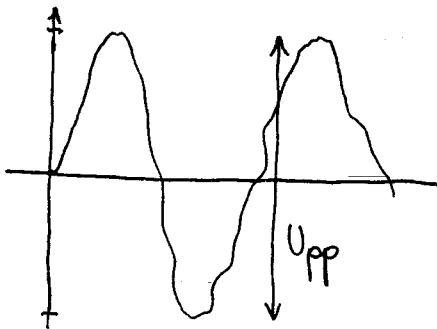


- z idealizirano diodo:

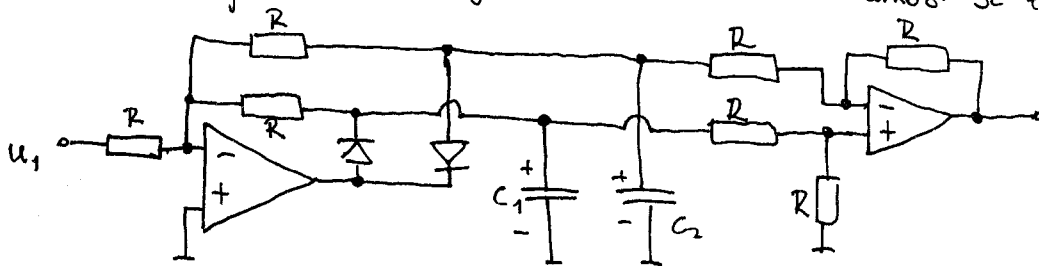


mešnjava z ciframi

1.2.1.5 DETEKTOR MEDTEMENJSKE VREDNOSTI (peak-to-peak)



Realizacija 1: (omejitev za max in min vrednost se zahteva različna polariteta)

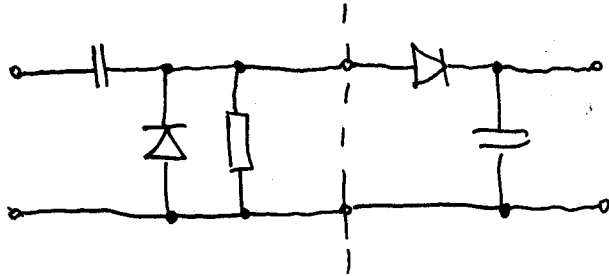


za $U_{min} < 0$ in $U_{max} > 0$:

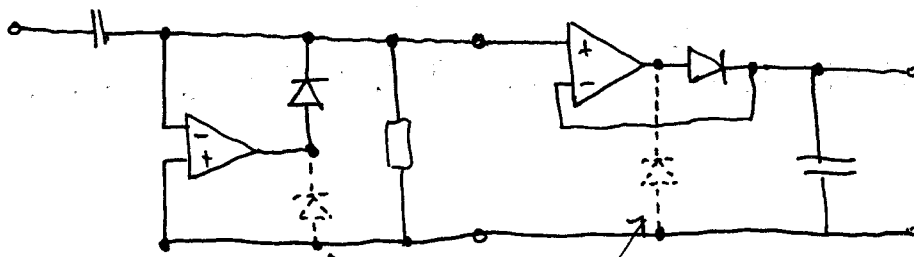
$$U_z = U_{c1} - U_{c2}$$

$$= +U_{min} - (+U_{max}) = \underline{\underline{U_{pp}}}$$

Realizacija 2 (pripenjalnik + detektor temenske vrednosti):



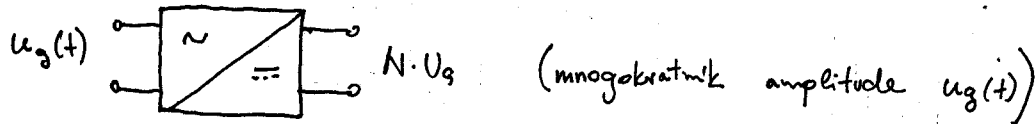
2 0.0.



diodi za prepacitev da gre $v - U_{sat}$

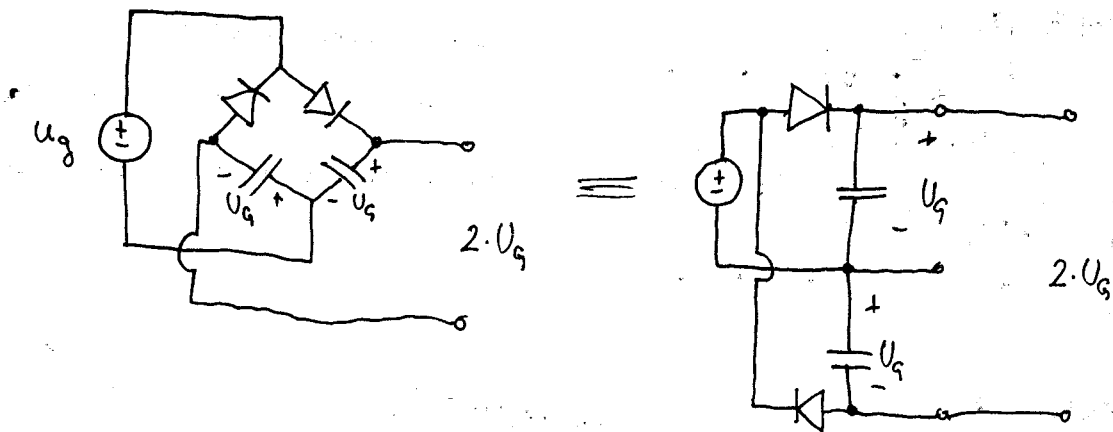
6.12.2013

1.2.3. MNOŽILNIKI NAPETOSTI



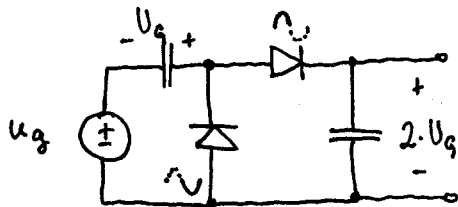
1. PODVOJILNO VEZJE

A) iz mostičnega vezja (dve diodi nadomestimo z C) (x2)



V primeru realnih diod: $2 \cdot (U_g - U_k)$

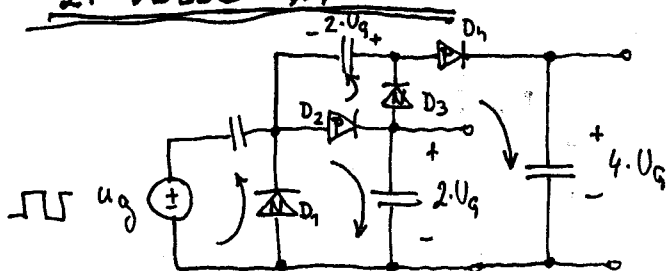
B) polvalni napetostni množilnik (x2)



v primeru realnih diod :
 $2 \cdot (U_g - U_k)$

rešitev je boljša od prve zato, ker se iz te da narediti vezje (x4)

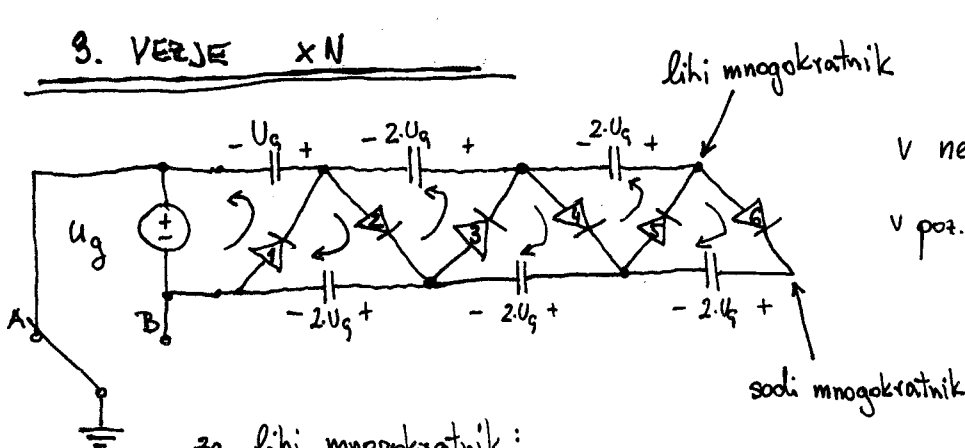
2. VEZJE x4



STACIONARNO STANJE :

neg. polval prevajata D_1, D_3 ; polnenje ↑
 poz. polval prevajata D_2, D_4 ; polnenje ↓

3. VEZJE xN



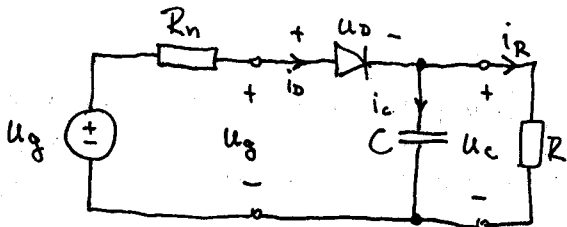
polnenje ↗
 v neg. polvalni prevajoji lihe diode
 v poz. polvalni prevajoji sode diode
 polnenje ↘

za lihi mnogokratnik:
 stikalo v A (masa)

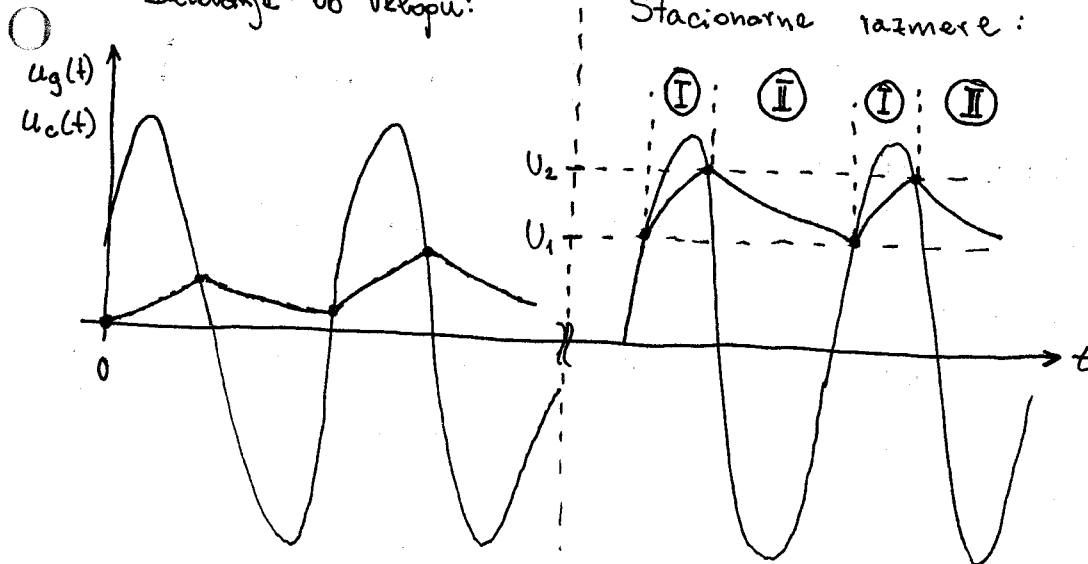
za sodi mnogokratnik:
 stikalo v B (masa)

1.2.4. RC USMERNIKI

1.2.4.1. POLVALNI RC-USM



Delovanje ob vklopu:



FAZE:

I ... polnjenje
II ... praznjenje

Za prehodni pojav: LT Spice

Za stacionarne razmere:

$$\bar{i}_D = \bar{i}_R \quad \text{zaradi} \quad \Delta Q_{\text{polnjenje}} = \Delta Q_{\text{praznjenje}}$$

oziroma $I_D = I_R$... komponenti DC tokov

$$u_o(t) = u_g(t) - u_c(t) \quad ; \quad u_g = U_g \cdot \cos(\omega t)$$

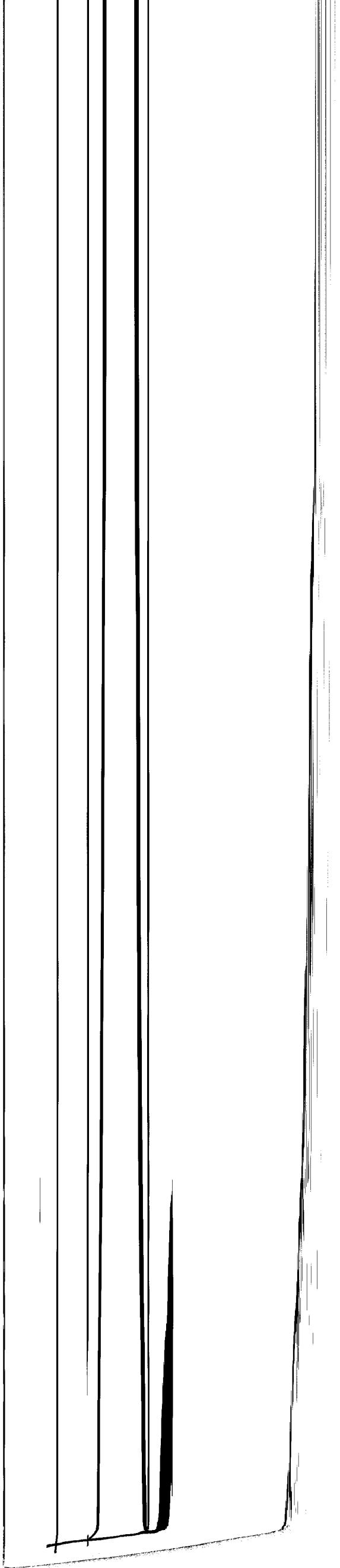
$$i_R = \frac{u_c(t)}{R}$$

$$i_D = i_c(t) + i_R(t)$$

$$i_c = C \cdot \dot{u}_c$$

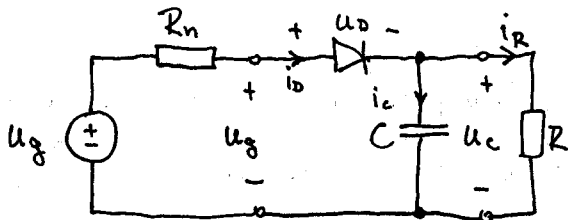
$$i_D = i_D(u_o) = i_D(u_g(t) - u_c(t))$$

Alta



1.2.4. RC USMERNIKI

1.2.4.1. POLVALNI RC-USM

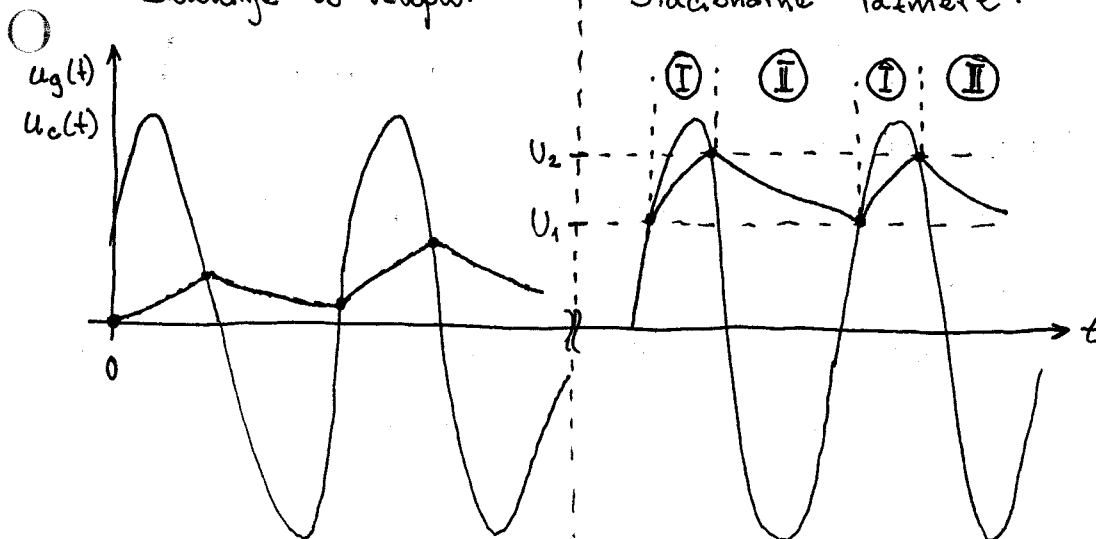


Delovanje ob vklopu:

Stacionarne razmere:

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I ... polnjenje
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Za stacionarne razmere:

$$\bar{i}_o = \bar{i}_R \quad \text{zaradi} \quad \Delta Q_{\text{polnjenje}} = \Delta Q_{\text{praznjenje}}$$

oziroma $I_o = I_R$... komponenti DC tokov

$$u_o(t) = u_g(t) - u_c(t) \quad ; \quad u_g = U_g \cdot \cos(\omega t)$$

$$i_R = \frac{u_c(t)}{R}$$

$$i_o = i_c(t) + i_R(t)$$

$$i_c = C \cdot \dot{u}_c$$

$$i_o = i_o(u_o) = i_o(u_g(t) - u_c(t))$$

Abeta

$$C \cdot \dot{u}_c + \frac{u_c}{R} = f(u_g(t) - u_c(t))$$

$$\dot{u}_c = g(u_c) \quad \leftarrow \text{nehomogena diferencialna enačba 1. reda}$$

- (I) $u_g > u_c$: D prevoja, polnjenje C \Rightarrow nehomogena nelin. dif. en. } ne poznamo
 (II) $u_g < u_c$: D zaprta, praznjenje C \Rightarrow homogena dif. en. } robnih pogojev
U₁ in U₂

analitična rešitev ni možna
brez premostavitel!

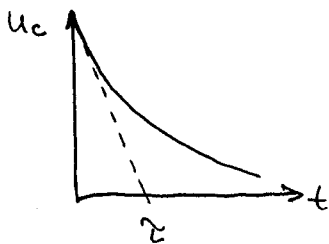
KAMMERLOCHERJEVA METODA:

- aproksimativna metoda s. trikotno napetostjo na kondenzatorju

- za oba segmenta:

I. potek u_c aproksimiramo z linearnim potekom & odsokoma linearizirana dioda

II. potek u_c aproksimiramo z linearnim potekom



$$t \ll \tau = RC$$

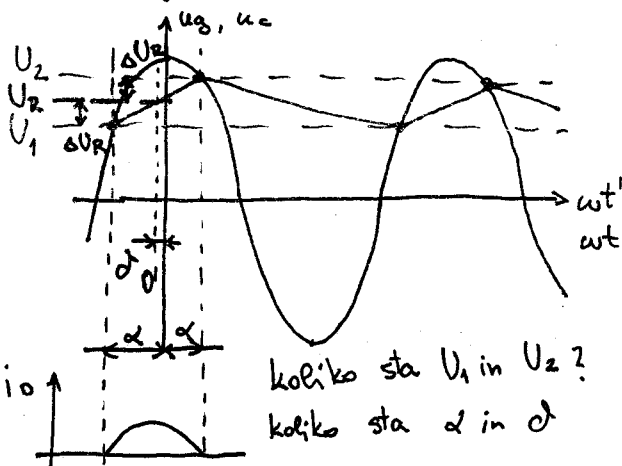
$$t_I \text{ in } t_{II}, \quad t_I + t_{II} = T \Rightarrow T \ll \tau = RC$$

$$\text{v EU: } T = 20 \text{ ms} \quad (50 \text{ Hz})$$

izpolnitev
pogoja

metoda:

$$u_g = U_g \cdot \cos \omega t' = U_g \cdot \cos(\omega t' - \varphi)$$



$$U_1 = U_g \cdot \cos(-\alpha - \varphi)$$

$$U_2 = U_g \cdot \cos(\alpha - \varphi)$$

$$U_R = \frac{1}{2}(U_1 + U_2) = \frac{1}{2}(u_g|_{\omega t' = -\alpha} + u_g|_{\omega t' = +\alpha})$$

$$= \frac{1}{2} U_g \cdot [\cos(\alpha + \varphi) + \cos(\alpha - \varphi)]$$

$$\cos(\alpha \pm \beta) = \cos \alpha \cdot \cos \beta \mp \sin \alpha \cdot \sin \beta$$

koliko sta U₁ in U₂?

koliko sta α in φ

$$\dots \Rightarrow U_R = \frac{1}{2} \cdot U_g \cdot [\cos \alpha \cdot \cos \alpha - \cancel{\sin \alpha \cdot \sin \alpha} + \cos \alpha \cdot \cos \alpha + \cancel{\sin \alpha \cdot \sin \alpha}]$$

$$U_R = U_g \cdot \cos \alpha \cdot \cos \alpha$$

$$\Delta U_R = \frac{1}{2} (U_2 - U_1) = \dots$$

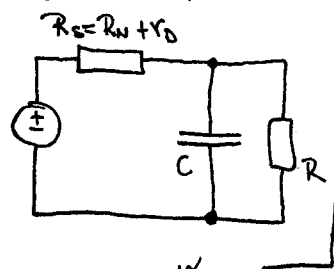
$$\Delta U_R = U_g \cdot \sin \alpha \cdot \sin \alpha$$

○ Valovitost y :

$$y = \frac{\text{izmenična amplituda}}{\text{enosmerna amplituda}} = \frac{\Delta U_R}{U_R} = \text{tg } \alpha \cdot \text{tg } \alpha$$

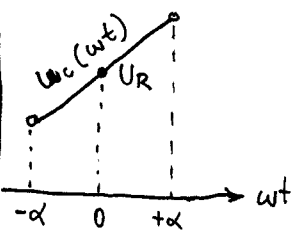
poiščimo α iz (I):

$U_g > U_c$, dioda prevaja (r_D), $-\alpha \leq \omega t \leq +\alpha$



v stacionarnih razmerah velja:

$$I_D = \frac{1}{2\pi} \int_{-\alpha}^{+\alpha} \frac{u_g(\omega t) - u_c(\omega t)}{R_s} d\omega t$$



$$\dots I_D = \frac{1}{2\pi \cdot R_s} \int_{-\alpha}^{+\alpha} \left[U_g \cdot \cos(\omega t - \alpha) - \frac{\Delta U_R}{\alpha} \cdot \omega t - U_R \right] d\omega t$$

$$u_c(\omega t) = \frac{\Delta U_R}{\alpha} \cdot \omega t + U_R$$

$$y = k \cdot x + n$$

$$= \frac{U_g}{\pi \cdot R_s} \cos \alpha (\sin \alpha - \alpha \cdot \cos \alpha) =$$

$$= \frac{U_g \cdot \cos \alpha \cdot \cos \alpha}{\pi \cdot R_s} (\text{tg } \alpha - \alpha) = \frac{U_R}{\pi \cdot R_s} (\text{tg } \alpha - \alpha)$$

$$I_D = I_R = \frac{U_R}{R}$$

○ $\frac{1}{\pi \cdot R_s} (\text{tg } \alpha - \alpha) = \frac{1}{R}$

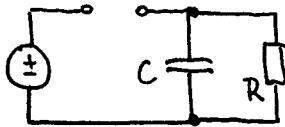
$$\alpha_{i+1} = \arctg \left(\alpha_i + \pi \frac{R_s}{R} \right)$$

$\text{tg } \alpha - \alpha = \pi \cdot \frac{R_s}{R}$
 iterativna rešitev

Albeta

poiščimo δ iz **I** ob poznavanju α :

$$U_g < U_c ; \quad +\alpha \leq \omega t \leq 2\pi - \alpha \quad ; \quad \text{dioda zaprta}$$



praznjenje C = odtokanje naboja

če opazujemo R :

$$\begin{aligned} \Delta Q_R &= I_R \cdot \Delta t = \frac{U_R}{R} \left(\frac{2\pi - \alpha}{\omega} - \alpha \right) = \\ &= \frac{U_R}{R} \cdot \frac{2(\pi - \alpha)}{\omega} \end{aligned}$$

če opazujemo C :

$$\Delta Q_c = C \cdot \Delta U_c = C (U_2 - U_1) = C \cdot 2\Delta \cdot U_R$$

$$\Delta Q_R = \Delta Q_c$$

$$\frac{U_R}{R} \cdot \frac{2 \cdot (\pi - \alpha)}{\omega} = C \cdot 2 \cdot \Delta \cdot U_R$$

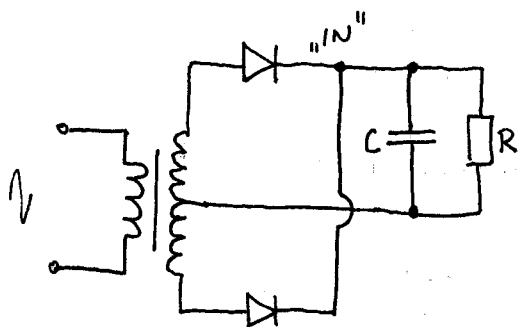
$$\frac{\Delta U_R}{U_R} = \frac{\pi - \alpha}{\omega R C}$$

$$\operatorname{tg} \alpha \cdot \operatorname{tg} \delta = \frac{\pi - \alpha}{\omega R C} \Rightarrow$$

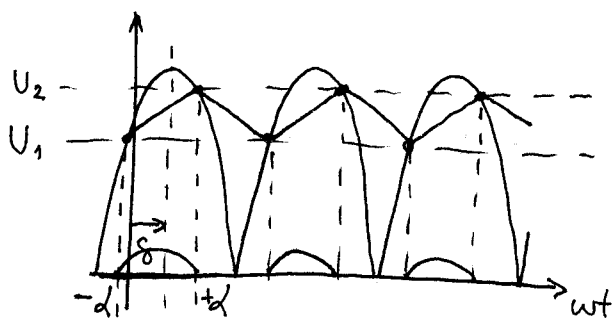
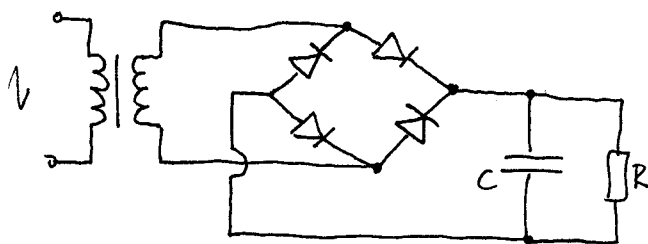
$$\delta = \operatorname{arctg} \left(\frac{1}{\omega R C} \cdot \frac{\pi - \alpha}{\operatorname{tg} \alpha} \right)$$

1.2.4.2. POLNOVALNI RC-USM - rešitev s KAMMERLOCHERJEVO METODO

Ⓐ z dvema diodama iz s trafo s srednjim ožepom



Ⓑ s štirimi diodami in navadni trafo



Rešitev za α in δ po Kammerlocherjevi metodi:

$$\alpha_{i+1} = \arctg \left(\alpha_i + \frac{\pi}{p} \cdot \frac{R_s}{R} \right) ; \quad p = \begin{cases} 1 & \text{; polvalno} \\ 2 & \text{; polnovalno} \\ 3 & \text{; trifazno} \end{cases}$$

$$\operatorname{tg} \delta = \frac{1}{\omega RC} \cdot \frac{\frac{\pi}{p} - \alpha}{\operatorname{tg} \alpha}$$

$$U_G = U_{2m} - n \cdot U_k$$

$$n = \begin{cases} 1 & \text{; za 1 diodo} \\ 2 & \text{; za 2 diodi} \end{cases}$$

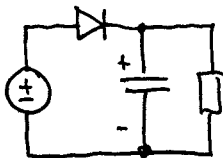
Metar

$$U_R = U_G \cdot \cos \alpha \cdot \cos \beta = (U_{2m} - n \cdot U_K) \cdot \cos \alpha \cdot \cos \beta$$

$$\gamma = \tan \alpha \cdot \tan \beta = \frac{\frac{\pi}{\rho} - \alpha}{\omega RC}$$

Razmere na usmerniških diodah:

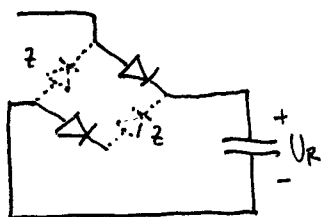
- v področju zapore: • dioda pri polvalnem RC-USM:



$$U_G + U_R < 2 \cdot U_G < U_{RRM}$$

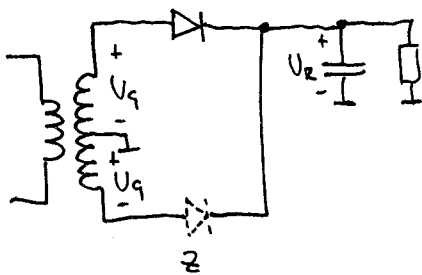
(Repetitive Reverse Magnitude) ← kataloški podatek

- dioda pri polvalnem RC-USM z mostičem / 4 diode:



$$|-U_R - U_K| < U_G + U_K < U_{RRM}$$

- dioda pri polvalnem RC-USM s trafu sred. odcep / 2 diodi:



$$2 \cdot U_G - U_K < 2 \cdot U_G < U_{RRM}$$

• V področju prevajanja:

- enosmerni tok $I_D = \frac{P}{T} \cdot \frac{U_R}{(R_n + n \cdot r_D)} \cdot (\text{tg } \alpha - \alpha)$

iz kataloga

$< I_{F(AV)}$

average forward current

- temenski tok

$I_{D_{\text{temenski}}} = i_D(\omega t = 0) = \frac{U_S}{R_n + n \cdot r_D} \cdot \cos \alpha \cdot (1 - \cos \alpha) < I_{F(RM)}$

repetitive maximum current

- kratkostični tok:

$I_{D_{\text{kratkostični}}} \approx \frac{U_S - 0}{R_n + n \cdot r_D} < I_{F(SM)}$

single maximum current

- faktor obremenitve:

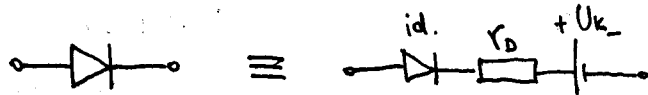
$\int i_D^2 dt \approx \frac{U_S^2 \cdot C}{R_n \cdot n \cdot r_D} < \int i^2 dt = I^2 \Delta t$ tipično $\Delta t = 10 \text{ ms}$

- efektivni tok:

$I_{D_{\text{ef}}} = \frac{\pi}{2\sqrt{2}} \sqrt{\frac{\pi}{\alpha}} \cdot I_D < I_{F(RMS)}$

RMS forward current

Disipacija moči na diodi :



za čas prevajanja diode : $-\alpha < \omega t < +\alpha$

$$u_D = r_D \cdot i_D + U_k$$

trenutna moč :

$$P(t) = i_D(t) \cdot u_D(t) = i_D \cdot (r_D \cdot i_D + U_k) = r_D \cdot i_D^2 + i_D \cdot U_k$$

poprečna moč preko diode:

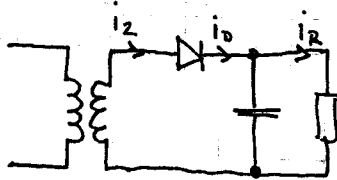
$$P_D = \frac{1}{2\pi} \int_0^{2\pi} P(\omega t) d\omega t = r_D \cdot I_{D\text{ef}}^2 + I_D \cdot U_k$$

za vse 3 RC usmeritve

13.12.2013

1.4. RAZMERE NA TRANSFORMATORJU :

a.) polvalni RC USM:



$$I_D = I_R$$

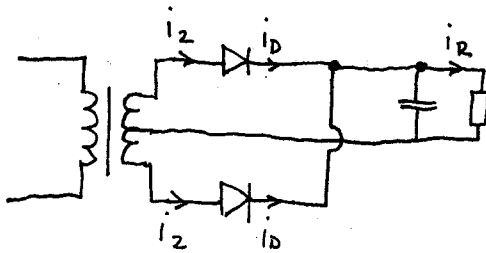
$$I_{Def} = \frac{\pi}{2\sqrt{2}} \sqrt{\frac{\pi}{\alpha}} \cdot I_D$$

$$I_{2ef} = I_{Def}$$

$$P_{ef} = I_{2ef} \cdot U_{2ef} \text{ [VA]}$$

$$U_{2ef} = \frac{U_{2m}}{\sqrt{2}} = \frac{U_G + U_K}{\sqrt{2}} = \frac{\frac{U_2}{\cos\alpha} + U_K}{\sqrt{2}}$$

b.) polnvalni RC USM s trafo s srednjim odcepom:



$$I_D = \frac{1}{2} I_2$$

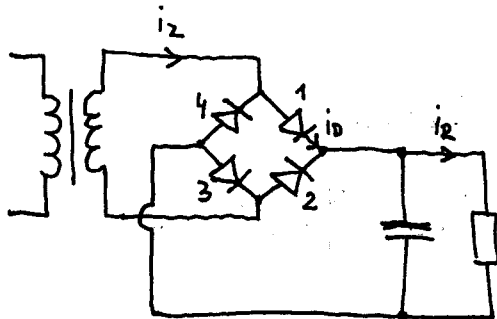
$$I_{Def} = \frac{\pi}{2\sqrt{2}} \sqrt{\frac{\pi}{\alpha}} \left(\frac{1}{2} I_2 \right)$$

$$I_{2ef} = I_{Def}$$

$$U_{2ef} = \frac{U_{2m}}{\sqrt{2}} = \frac{U_G + U_K}{\sqrt{2}}$$

$$P_{2ef} = I_{2ef} \cdot U_{2ef}$$

c.) polnvalni RC USM z Graetzovim mostičnim vezjem

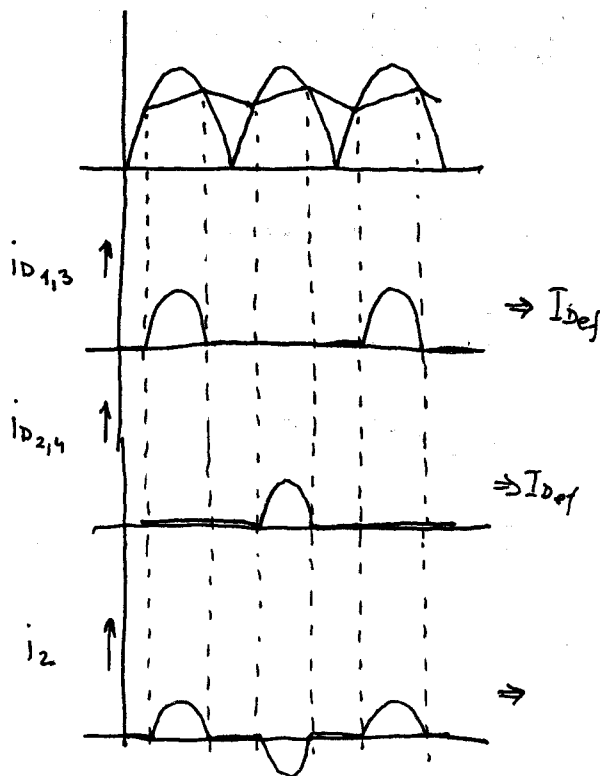


$$I_D = \frac{1}{2} I_R$$

$$I_{Def} = \frac{\pi}{2\sqrt{2}} \sqrt{\frac{\pi}{2}} \cdot I_D$$

$$I_{2ef} = ?$$

$$I_{2ef}^2 = \frac{1}{2\pi} \int_0^{2\pi} i_2^2 d\omega t = I_{Def,1,3}^2 + I_{Def,2,4}^2 = 2 I_{Def}^2$$



$$I_{2ef} = \sqrt{2} I_{Def}$$

$$U_{2ef} = \frac{U_{2m}}{\sqrt{2}} = \frac{U_g + 2U_k}{\sqrt{2}}$$

$$P_{ef} = I_{2ef} \cdot U_{2ef}$$

Potek načrtovanja RC USM:

ne glede na tip RC USM

zahtave: $U_R, (I_R \text{ oz. } R), \gamma, f, ? \text{ tip RC USM}$

št. polvalov

št. diod

$$p = \begin{cases} 1 \\ 2 \\ 3 \end{cases} \quad n = \begin{cases} 1 \\ 2 \end{cases}$$

↑
dopustna
valovitost

ocena vrednosti trafo in diod:

R_w (upornost navitja trafota) $\div (< 1 \Omega)$

r_D, U_k (dioda) $\div (0,1 \dots 1,2 \Omega ; 0,7 \dots 1,0 V)$

postopek izračuna:

① $\alpha = ?$ (kot odprtja)

$$\alpha_{i+1} = \arctg \left(\alpha_i + \frac{\pi \cdot R_s}{p \cdot R} \right)$$

iterativno! $\alpha = 30^\circ \div 40^\circ$

② $\delta = ?$

$$\delta = \arctg \left(\frac{\gamma}{\tan \alpha} \right)$$

$$\delta \leq 10^\circ$$

③ $C = ?$

$$C = \frac{1}{\omega R} \frac{\frac{\pi}{p} - \alpha}{\gamma}$$

④ parametri diod = ?

I_D, I_{Df}, P_{Df} glede na ohišje (1, 2, 4 diode v ohišju)

zaradi hlajenja

↓
izbrati tip diode

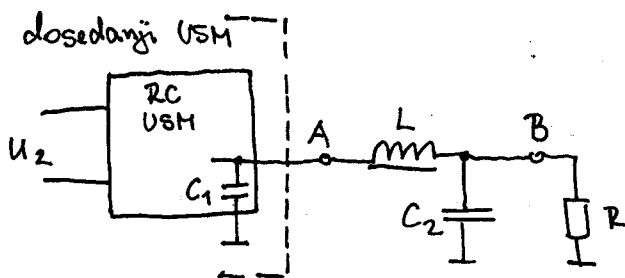
⑤ parametri trafo:

$I_{ef}, U_{ef} \Rightarrow n_1 : n_2, P_{ef} [VA]$ ← trafo nesme biti v nasičenju

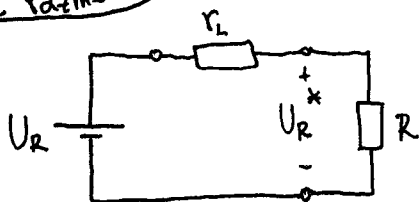
1.5. DODATNO GLAJENJE

LC filter: služi namesto povečanja C

$$\gamma = \frac{1}{\omega RC} \left(\frac{\pi}{P} - \alpha \right) \leftarrow \text{brez LC filtra}$$

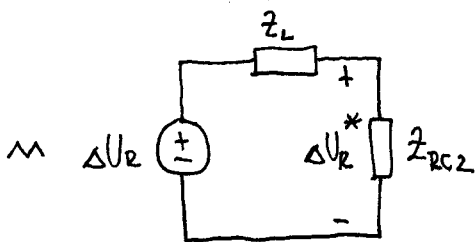


DC razmere:



$$U_R^* = \frac{R}{r_L + R} \cdot U_R$$

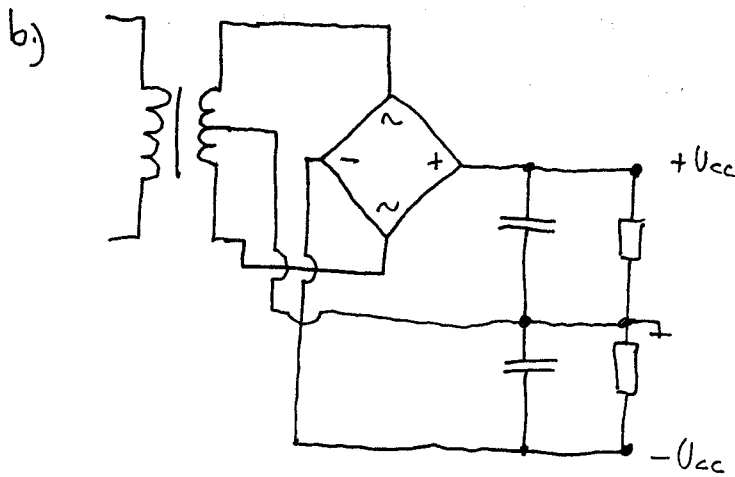
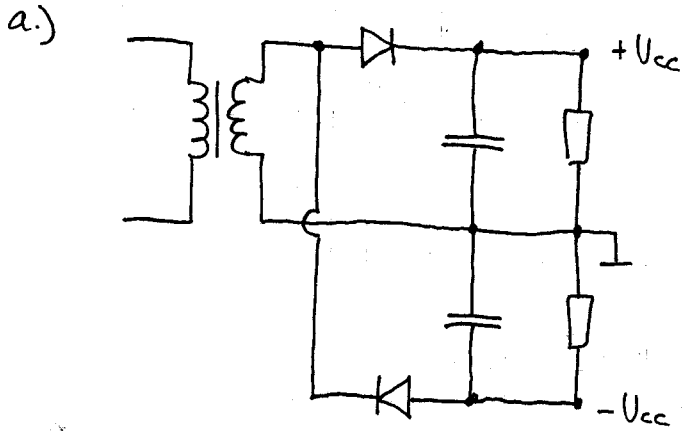
AC razmere (valovitost):



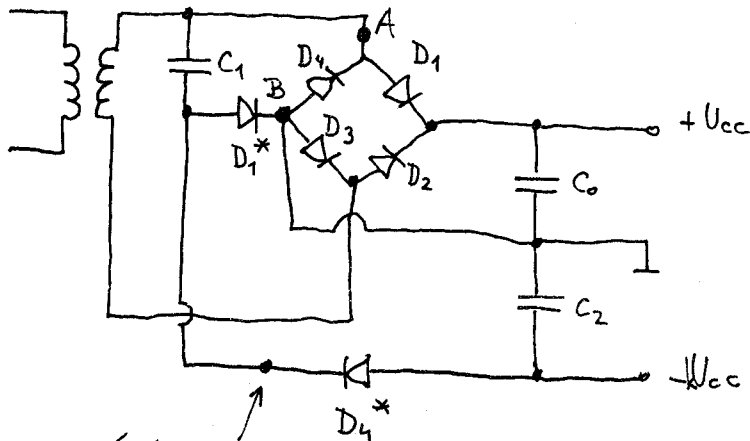
$$\Delta U_R^* = \frac{Z_{RC2}}{Z_L + Z_{RC2}} \cdot \Delta U_2 \quad ; \quad |Z_L| = |j\omega L| \gg |Z_{RC2}| = \left| \frac{1}{1 + j\omega RC_2} \right|$$

$$\Delta U_R^* \approx \frac{Z_{RC2}}{Z_L} \cdot \Delta U_2 \approx \frac{1}{\omega^2 LC_2} \cdot \Delta U_2 \quad (\text{velike atenuacije valovitost})$$

1.6. RC USM Z DVOJNIM NAPAJANJEM



c.) $+U_{cc}$ in šibko $-k \cdot U_{cc}$, $k < 1$



$(-U_{cc} - U_{D4})$
ob neg. polvaletu

pozitivni polval: D_1, D_3 prevajata in polnita C_0

$$\begin{aligned}U_{AB} &= U_{D1} + U_{C0} = U_{C1} + U_{D1}^* \\ &= U_{K1} + U_{C0} = U_{K1}^* + U_{C1} \Rightarrow D_1^* \text{ prevaja in polni } C_1\end{aligned}$$

negativni polval: D_2, D_4 prevajata in polnita C_0

$$U_{AB} = -U_{K4} = -U_{D4} \Rightarrow D_1^* \text{ zaprta}$$

dioda D_4^* prevaja, zato se preko D_4 in D_4^* naboji iz C_1 preoporedi med C_1 in C_2 !
in na C_2 dobimo $-k \cdot U_{CC}$

2. STIKALNI DC NAPETOSTNI REGULATORJI (DC/DC) IN USMERNIKI (AC/DC)

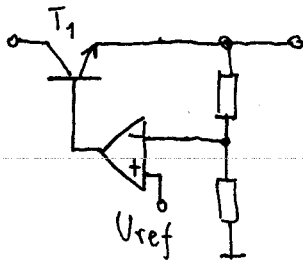
slabost RC USM : nizek izkoristek

za serijski nap. regulator : $\eta = \frac{U_2 \cdot I_2}{U_1 \cdot I_1}$ $= \frac{U_2}{U_1}$; $\Delta U = U_2 - U_1 \geq 2V$

| prečni tok
zanemajmo
 $I_1 = I_2$

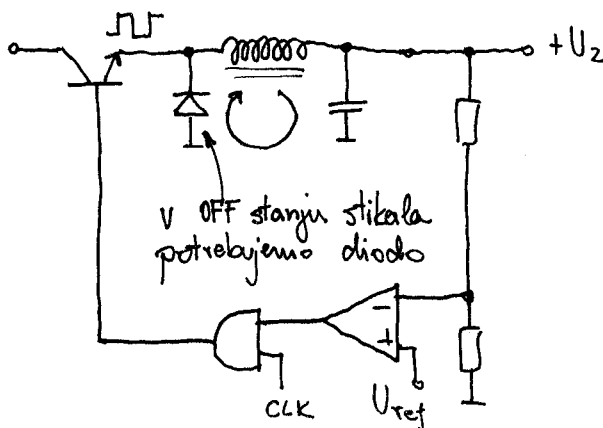
$\eta \in [30 \div 70\%]$

linearni regulator :



T_1 deluje v aktivnem področju \Rightarrow
 \Rightarrow velika poraba moči

stikalni regulator :



T_1 deluje v ON/OFF režimu
 \Rightarrow manjša disipacija moči na T_1
 \Rightarrow višji izkoristek

Dodatna prednost:

1. možnost $+U_2 > +U_1$
2. možnost $-U_2$ pri $+U_1$

DELITEV STIKALNIH DC/DC REGULATORJEV:

1. regulator navzdol ("step-down", "buck"): $|U_2| < |U_1|$

2. regulator navzgor ("step-up", "boost"): $|U_2| > |U_1|$

3. invertirajoč regulator ("inverting regulator"): $U_2 = -k \cdot U_1$ $k > 1$
 $k < 1$

Slabosti:

- število komponent je večje kot pri linearnih
- šum in motnje (zaradi stikalnega delovanja)
- dodatni gladilni elementi (na izhodu in na vходу)

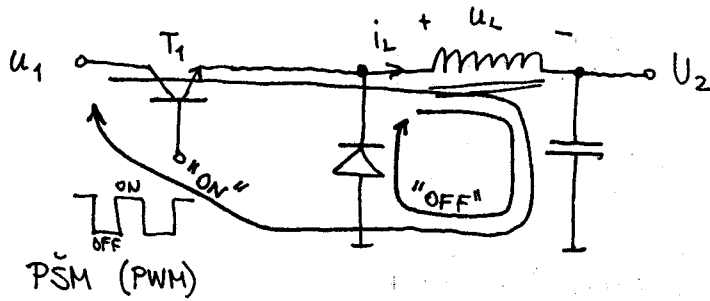
Prednost:

- miniaturnost

- izkoristek: $\eta = \frac{P_{izh}}{P_{vh}} = \frac{P_{izh}}{P_{izh} + P_{reg}}$; $P_{reg} = konst$, zato $\eta \uparrow$ pri $P_{izh} \uparrow$

2.1. REGULATOR NAVZDOL

tučkava $L \gg$ (čim višji)



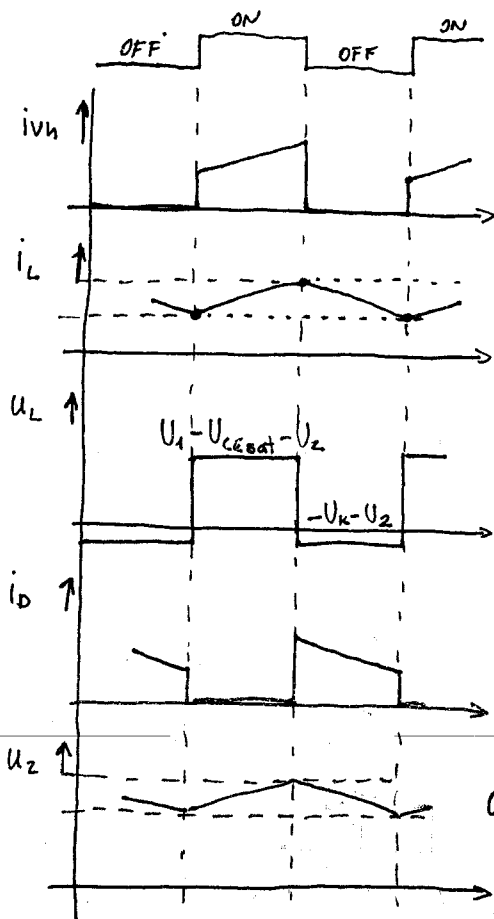
Princip delovanja:

T_1 v ON: T_1 v nasičenju, $u_L = U_1 - U_{CE\text{ sat}} - U_2 > 0$

$$\frac{di_L}{dt} = \frac{U_{L\text{ on}}}{L} > 0 \Rightarrow \text{tok } i_L \text{ linearno narašča}$$

T_1 v OFF: T_1 v zapori, $u_L = -u_D - u_C = -U_k - U_2 < 0$

$$\frac{di_L}{dt} = \frac{U_{L\text{ off}}}{L} < 0 \Rightarrow \text{tok } i_L \text{ linearno upada}$$



$$0 < U_2 < U_1 - U_{CE\text{ sat}}$$

Analiza za idealne elemente: (idealno stikalo, idealna dioda)

"ON": $u_1 = u_L + u_2 = L \cdot \frac{di_L}{dt_{ON}} + u_2$

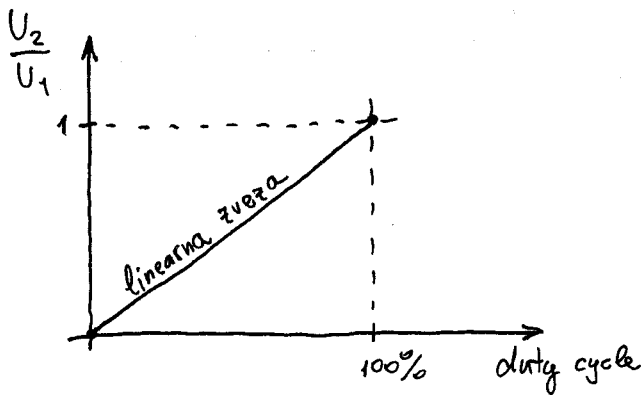
"OFF": $u_2 = -u_L = -L \cdot \frac{di_L}{dt_{OFF}}$

za stacionarne razmere: $|\Delta I_{L ON}| = |\Delta I_{L OFF}|$

$$\frac{U_1 - U_2}{L} \cdot t_{ON} = \frac{U_2}{L} \cdot t_{OFF}$$

$$U_1 \cdot t_{ON} = U_2 (t_{ON} + t_{OFF})$$

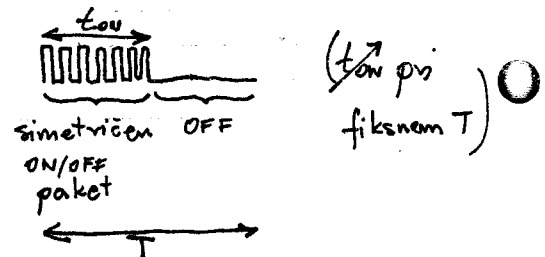
$$U_2 = \frac{t_{ON}}{t_{ON} + t_{OFF}} \cdot U_1 = \frac{t_{ON}}{T} \cdot U_1 = \frac{\text{"duty cycle"}}{100\%} \cdot U_1$$



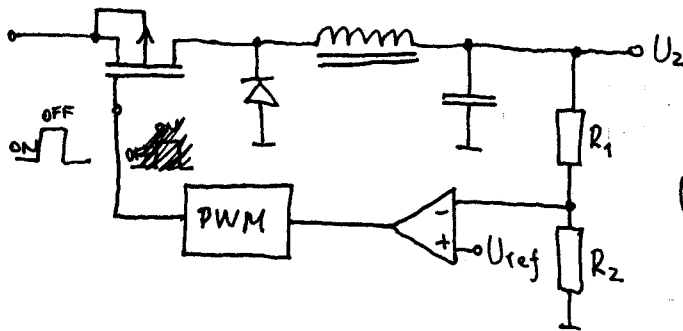
Da dobimo regulator, potrebujemo povratni sklop z krmilnim vezjem.

Trije koncepti:

- PWM - pulse width modulation (t_{ON} pri fiksnem T)
- PFM - pulse frequency modulation ($f_{oz.}$ pri fiksnem t_{ON})
- interval PWM - paketno intervalna PŠM



Realizacija regulatorja navzgor: (PMOS tranzistor)



$$U_2 = \frac{t_{ON}}{T} \cdot U_1$$

$$U_2 = \frac{R_1 + R_2}{R_2} \cdot U_{ref}$$

○ zgled: MAX638

$$U_1 \in [5 \div 16V] \quad f_{osc} = 65kHz$$

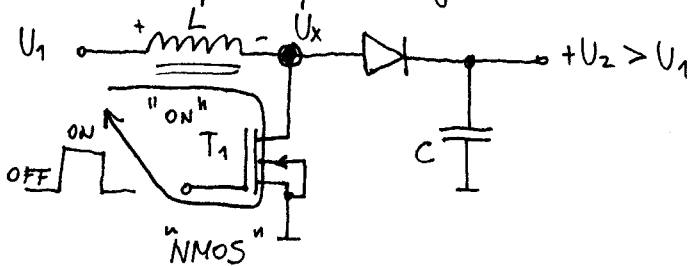
$$U_2 = +5V$$

$$\eta = 85\%$$

$$T = \frac{1}{f_{osc}}$$

2.2. REGULATOR NAVZGOR

- osnovno preklopno vezje:



- princip delovanja:

T_1 v "ON": T_1 v nasičenju, $u_L = U_1 - U_{osat}$

$$\frac{di_L}{dt} = \frac{U_L}{L} > 0 \Rightarrow \text{linearno naraščanje } i_L$$

T_1 v "OFF": T_1 zaprt, nakopičena energija $\frac{1}{2} Li_L^2$ se prenaša na C

$U_x = U_1 - u_L > U_1$, dioda in C v vlogi detektorja temenske

vednosti: $U_c = U_x - U_k$

Analiza delovanja za idealne elemente:

$$\text{"ON"}: u_1 = u_L = L \cdot \frac{di_L}{dt_{\text{ON}}}$$

$$\text{"OFF"}: u_1 = u_L + u_2 = L \cdot \frac{di_L}{dt_{\text{OFF}}} + u_2$$

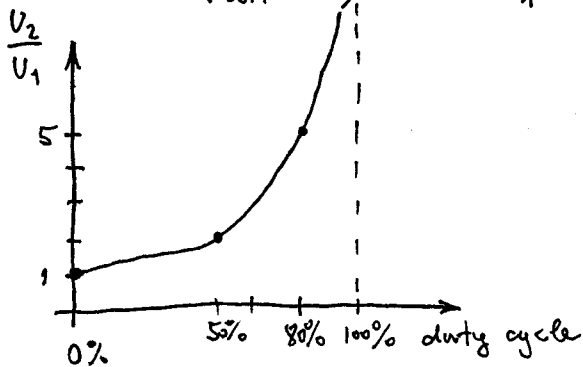
za stacionarne razmere:

$$|\Delta I_{L\text{ON}}| = |\Delta I_{L\text{OFF}}|$$

$$\frac{U_1}{L} \cdot t_{\text{ON}} = \frac{|U_1 - U_2|}{L} \cdot t_{\text{OFF}}$$

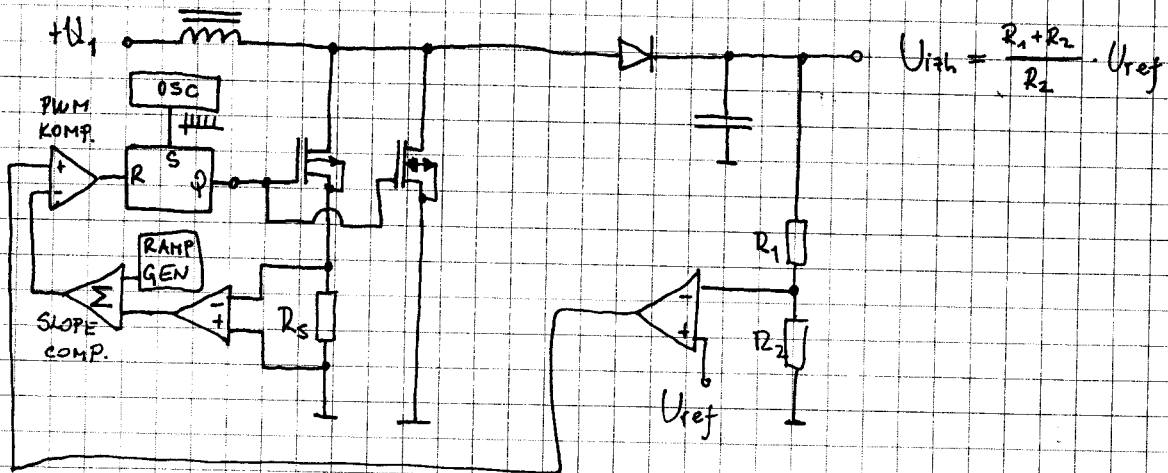
$$U_1 (t_{\text{ON}} + t_{\text{OFF}}) = U_2 \cdot t_{\text{OFF}}$$

$$U_2 = \left(\frac{t_{\text{ON}}}{t_{\text{OFF}}} + 1 \right) \cdot U_1 = \frac{1}{1 - \frac{\text{duty cycle}}{100\%}} \cdot U_1$$



20.12.2013

pozreto po MAX752: regulator navedor



1. povratna zanka: $U_{rs} = R_s \cdot i_L$
2. povratna zanka: ojač. napake preko R_1, R_2

MAX752:

$$U_{vh} \geq 1.8V$$

$$f_{osc} = 170kHz$$

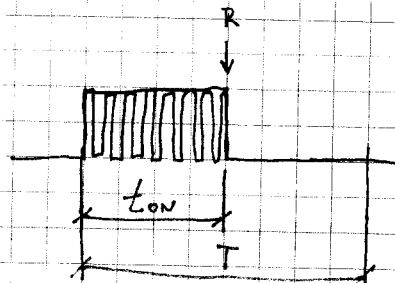
$$U_{izh} \leq 15V$$

$$I_{izh} \leq 200mA$$

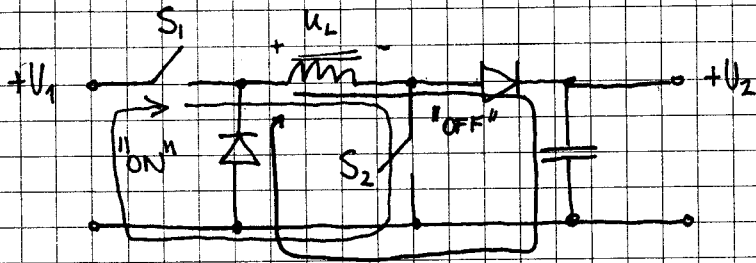
prečni tok : 2mA

$$\eta_{FULLLOAD} = 85 \div 95 \%$$

realizacija paketno simetrični PWM:



2.3. REGULATOR NAVEZDOL / NAVEGOR (2 stikali, 2 diodi)



- sinhrono krmiljenje S_1 in S_2

- princip delovanja:

"ON": i_L narašča linearno, $u_L = +U_1$, diodi zaprti

"OFF": i_L vrtaja, polariteta u_L se obrne, diodi prevajata in C se polni

Analiza za idealne elemente:

$$\text{"ON": } u_L = u_L = L \cdot \frac{di_L}{dt_{\text{on}}}$$

$$\text{"OFF": } -u_L = u_2$$

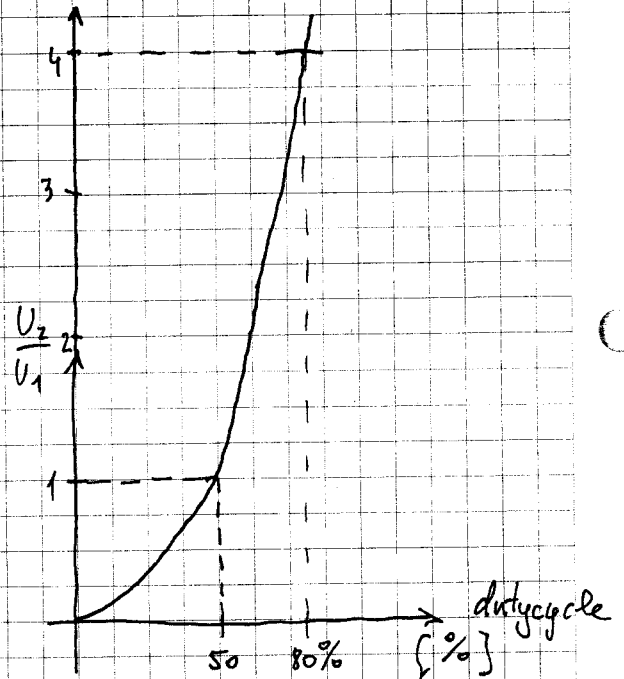
$$-L \frac{di_L}{dt_{\text{off}}} = u_2$$

za stacionarne razmere:

$$|\Delta I_{L \text{ ON}}| = |\Delta I_{L \text{ OFF}}|$$

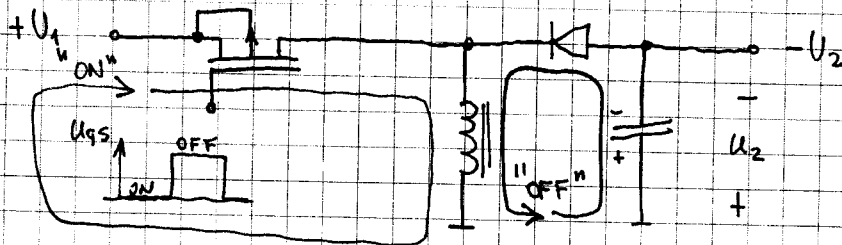
$$\frac{U_1}{L} \cdot t_{\text{on}} = \frac{U_2}{L} \cdot t_{\text{off}}$$

$$U_2 = \frac{t_{\text{on}}}{t_{\text{off}}} \cdot U_1 = \frac{\text{duty cycle}}{100\% - \text{duty cycle}} \cdot U_1$$



2.4. INVERTIRAJOO REGULATOR

- Osnovna shema: (izgrajeni PMOS)



- princip delovanja:

"ON": $u_L = U_1$, i_L linearno narašča

"OFF": i_L upada, dioda postane prevodna polarizirana

Analiza za idealne elemente:

"ON": $u_1 = u_L = L \cdot \frac{di_L}{dt_{ON}}$

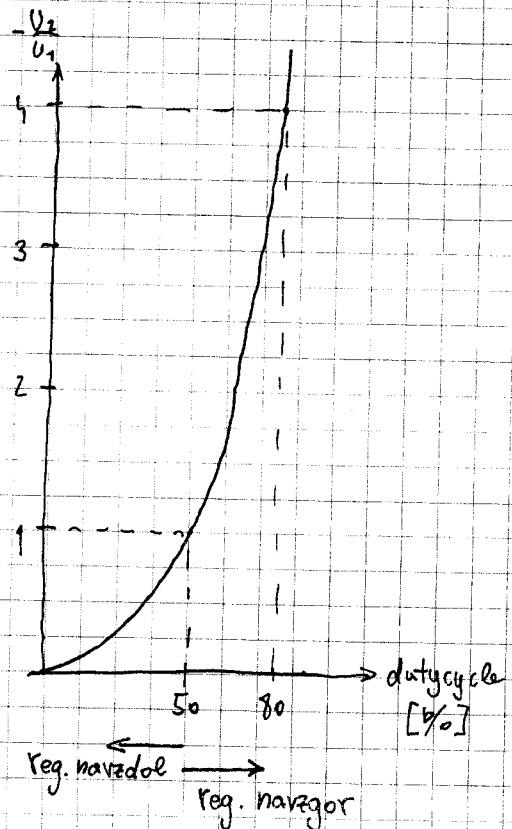
"OFF": $u_2 = -u_L = -L \cdot \frac{di_L}{dt_{OFF}}$

za stacionarne razmere:

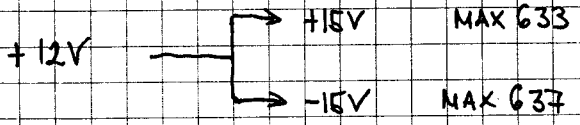
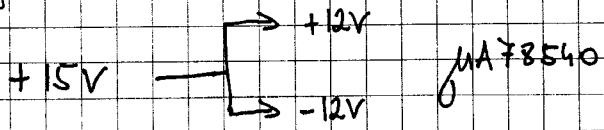
$$|\Delta I_{L ON}| = |\Delta I_{L OFF}|$$

$$\frac{U_1}{L} \cdot t_{ON} = \frac{-U_2}{L} \cdot t_{OFF}$$

$$-U_2 = \frac{t_{ON}}{t_{OFF}} \cdot U_1 = \frac{\text{duty cycle}}{100\% - \text{duty cycle}} \cdot U_1$$



Zgledni:

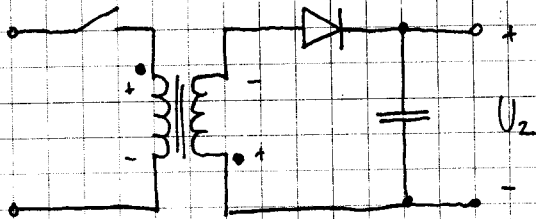


IC: DC-DC regulator : MC34063

2.5. STIKALNI NAPAJALNIK

Galvansko ločena stikalna regulatorja navzdol!

① "FLYBACK" oz. zaporni stikalni regulator navzdol, z galvansko ločitvijo:
(do 100 W)

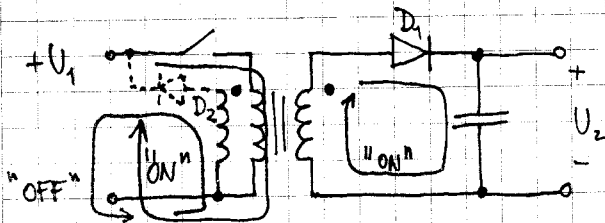


Princip delovanja:

"ON": $u_p = u_1$, i_p linearno narašča, na sekundarju je napetost obrnjena in dioda zaprta

"OFF": nakopičena ^{mag.} energija mora odteči, na sekundarju obrat napetosti in dioda

② "FORWARD" oz. prevodni stikalni regulator navzdol z galvansko ločitvijo:
(nad 100 W)

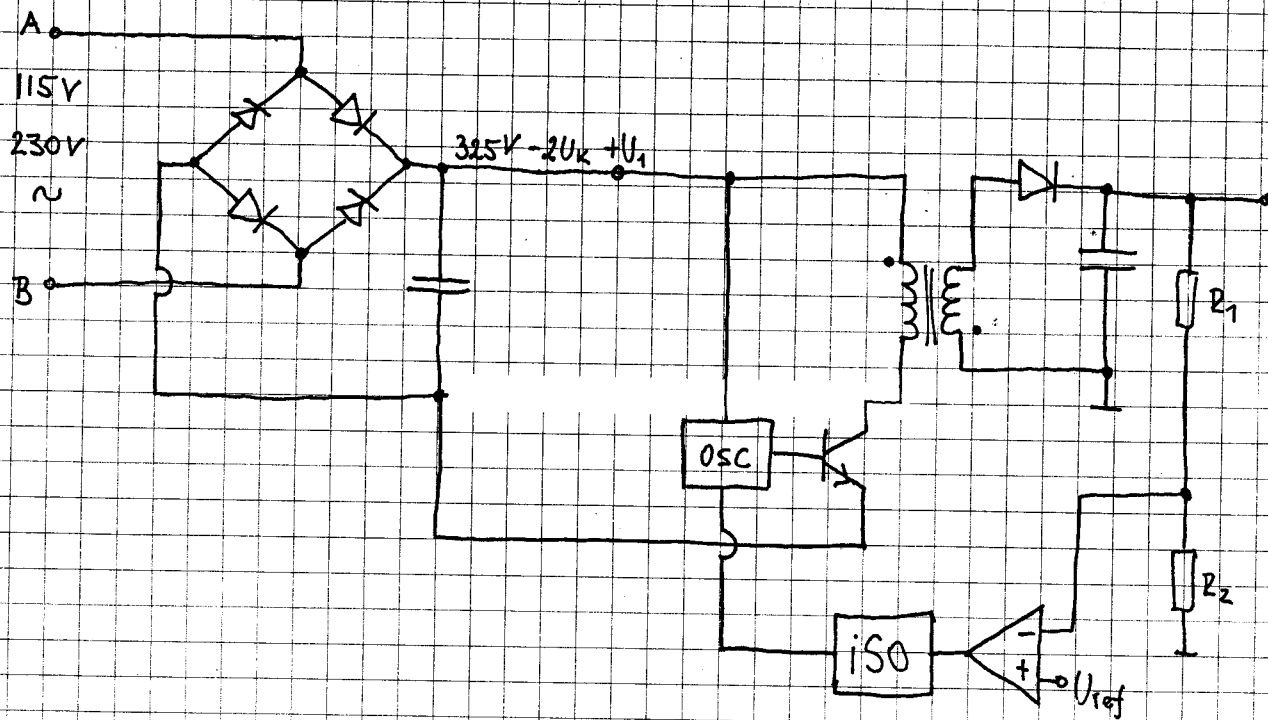


Princip delovanja:

"ON": inducirana napetost na sekundarju diodo prevodno polarizira in polni C

"OFF": dioda se zaporno polarizira, stikalo je OFF, zato mag. energija mora odteči, zato damo L_3 in diodo D_2 , ki vračata energijo na vhod.

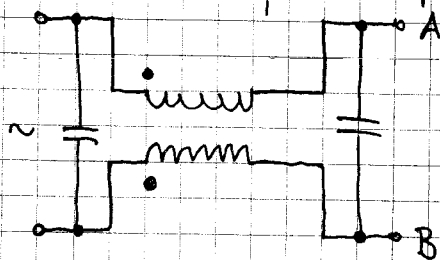
Celotni FLYBACK napajalnik:



Small pulse trafo
optical isolation

filter na vходу:

ni trafo ampak 2 sklopjeni tuljavi



	linearen RC-USM	stikalni napajalnik
	5V, 25A	5V, 26A
	3,5kg	1,2kg
volumen	4	1
temp delovanja	vroče (75W)	hladen (<5W)

3. NESELEKTIVNA VEZJA ZA GENERIRANJE SIGNALOV

Delitev: v dve skupine:

1. KRMILJENI GENERATORJI

2. SAMOVBUSJANI GENERATORJI

1. a.) ENOFAZNO KRMILJENI - monostabilni multivibrator (MMV)

eno stabilno stanje, s pomočjo krmilnega impulza ga vržemo iz S kamor se vrača v limitnem ciklu

b.) VEČFAZNO KRMILJENI - bistabilni multivibrator (BMV) S_1, S_2

- multistabilni multivibrator (MULTIMV) S_1, S_2, \dots, S_n

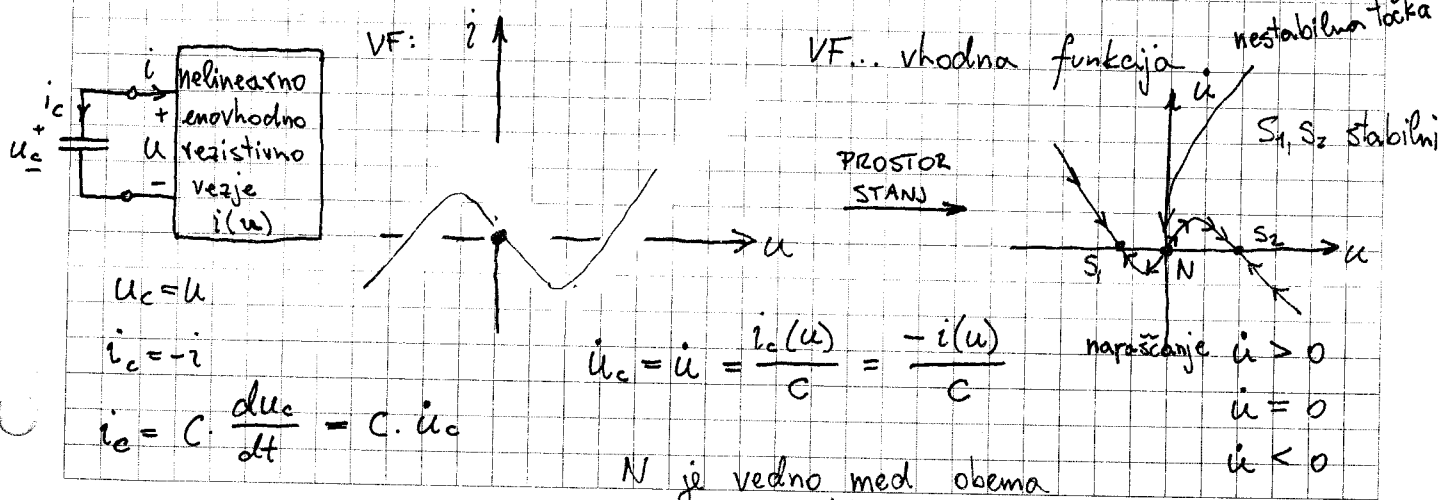
2. - astabilni multivibratorji (relaksacijski oscilatorji)

ena nestabilna singularna točka (N) z neskončnim limitnim ciklom

realizacija: nelin. rezistivno vezje in en reaktiven element (C ali L)

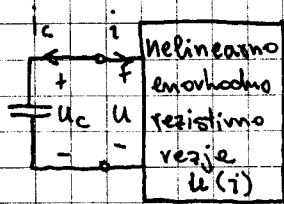
↑
po teoremu dualnosti

* BISTABILNOST:

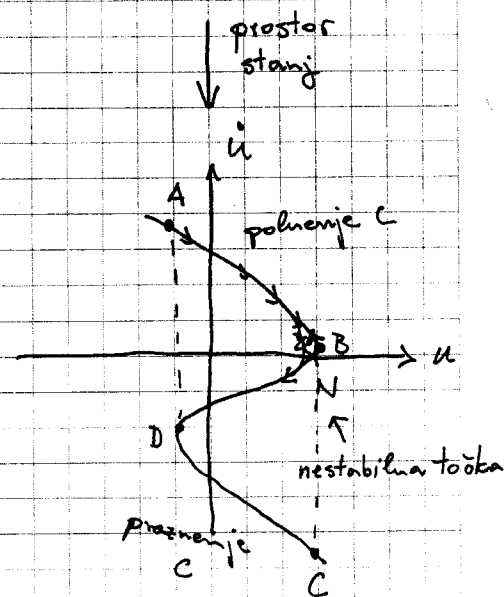
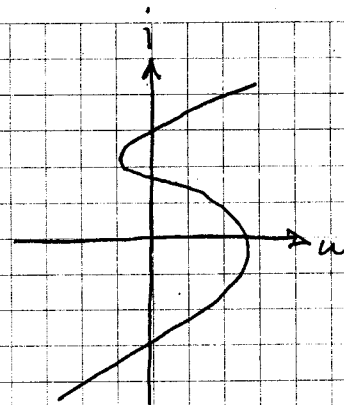
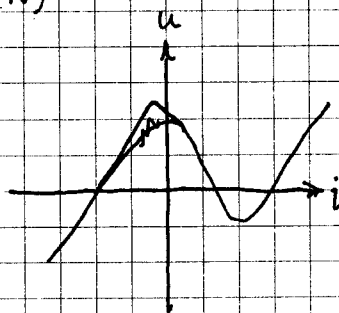


Alta

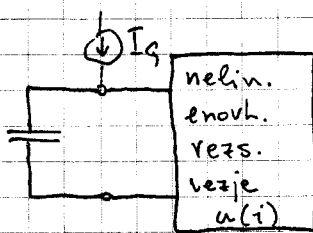
* ASTABILNOST (N)



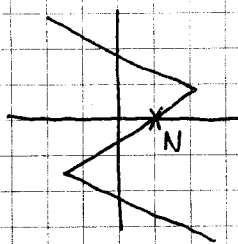
$$i = i_c = -\frac{u}{C}$$



* MONOSTABILNOST

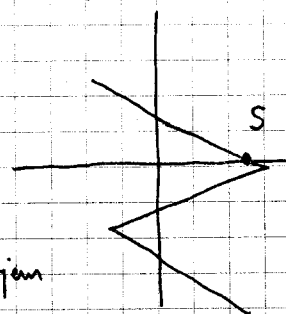


$i \approx$ AMV



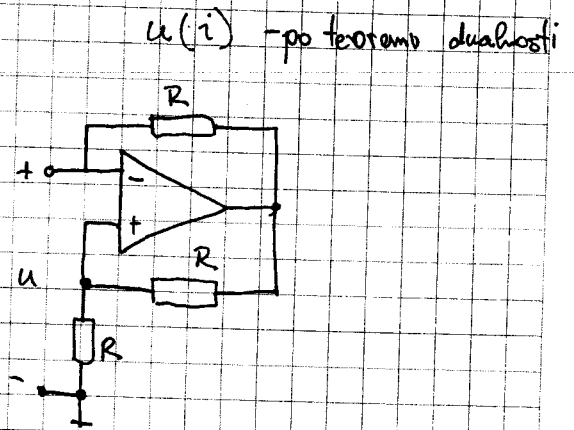
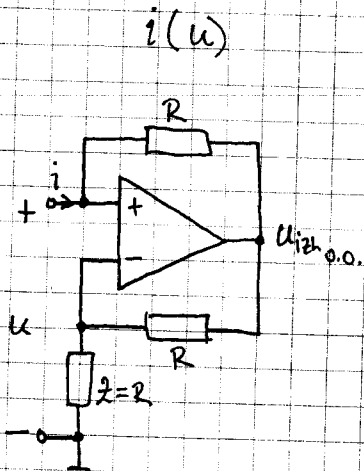
premik po i
2 DC tokovim regulatorjem

v MMV



REALIZACIJE Z O.O.

1. Realizacija enovhodnih nelinearnih rezistivnih vezij



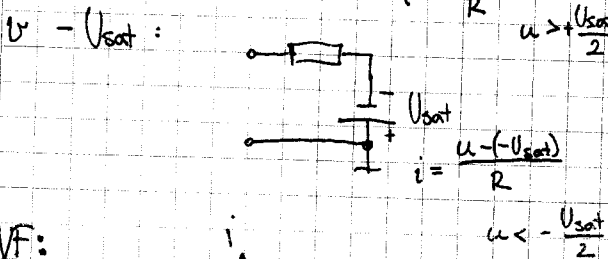
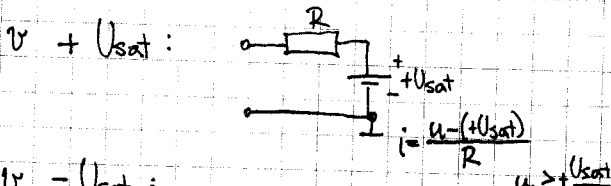
negativni impedančni pretvornik

$Z_{vh} = -z$ (za lin. območje delovanja)

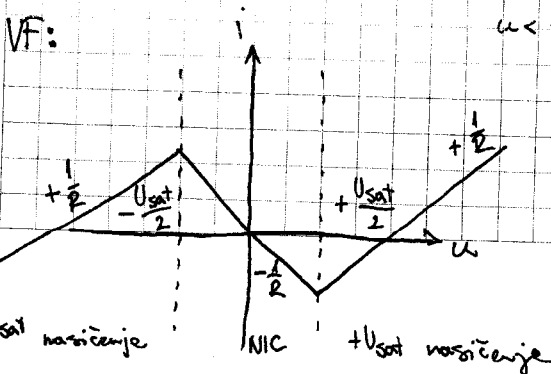
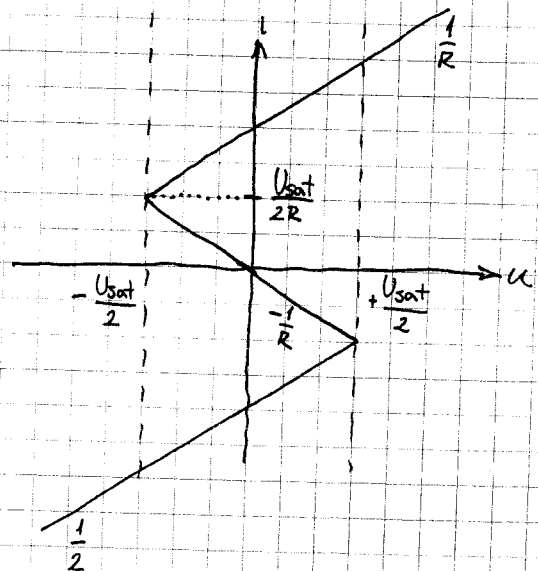
v lin. delovanju: $U_{izh.o.o.} = 2 \cdot u$

$$i = \frac{u - U_{izh.o.o.}}{R} = \frac{-u}{R}$$

velja za: $-\frac{U_{sat}}{2} < u < +\frac{U_{sat}}{2}$

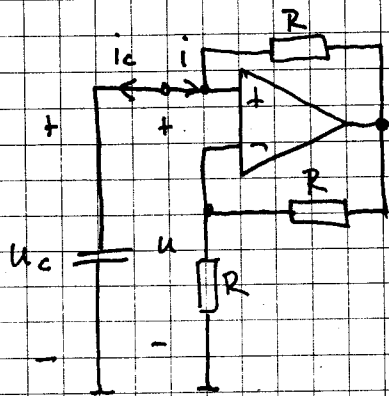


VF: (zrcaljenje preko diagonale likih kvadrantov)



2. BMV (S₁ N S₂)

Bi-stabilni multivibrator

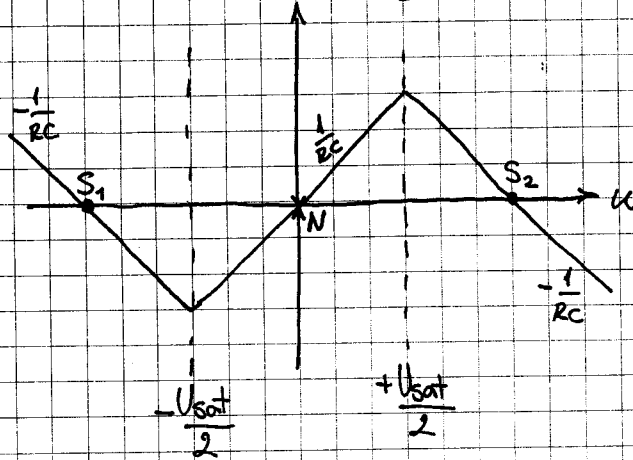


$$u_c = u$$

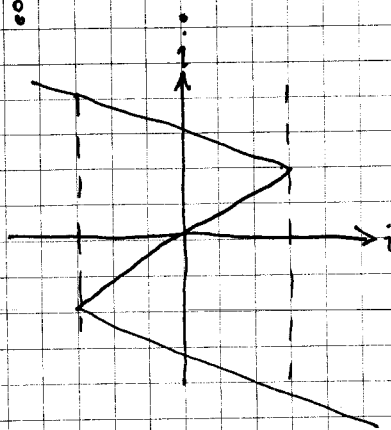
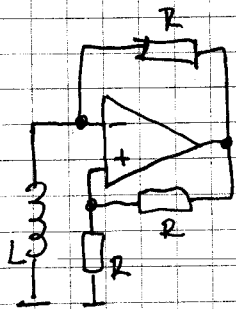
$$i_c = -i$$

$$i_c = C \cdot \dot{u}_c \Rightarrow \dot{u} = \dot{u}_c = \frac{i_c}{C} = \frac{-i(u)}{C}$$

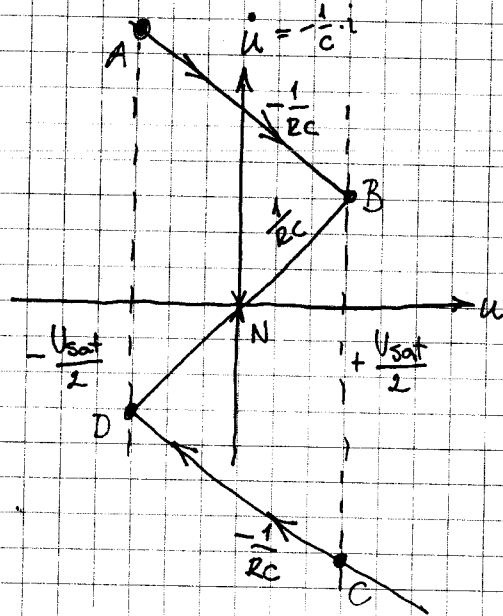
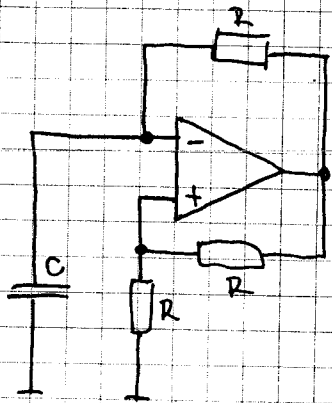
$$\dot{u} = -\frac{1}{RC} \cdot i$$



po teoremu dualnosti :

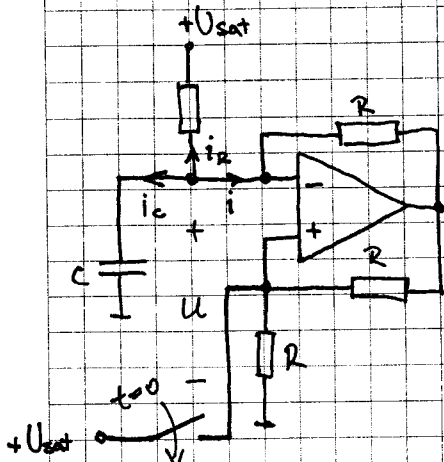


3. AMV (N) astabilni multivibrator



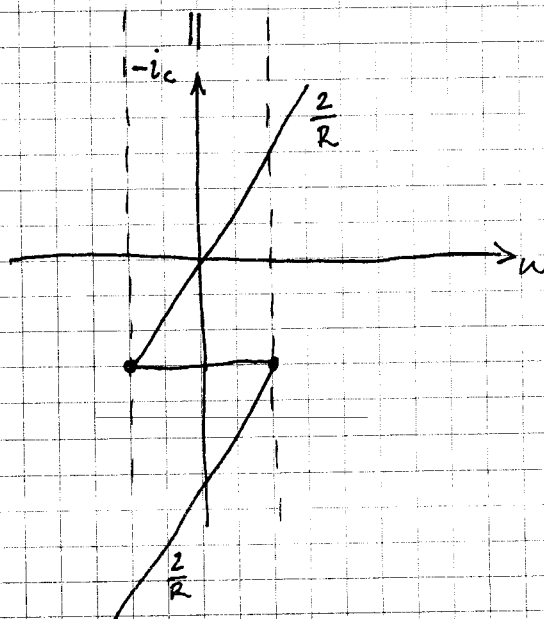
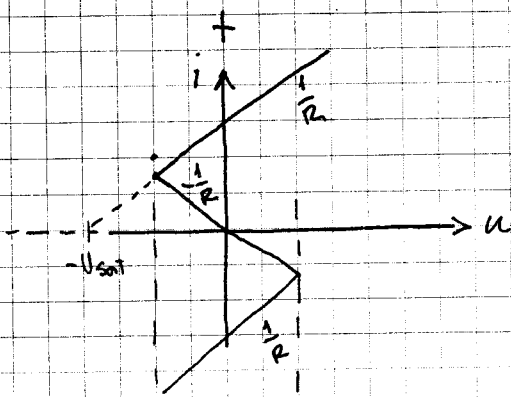
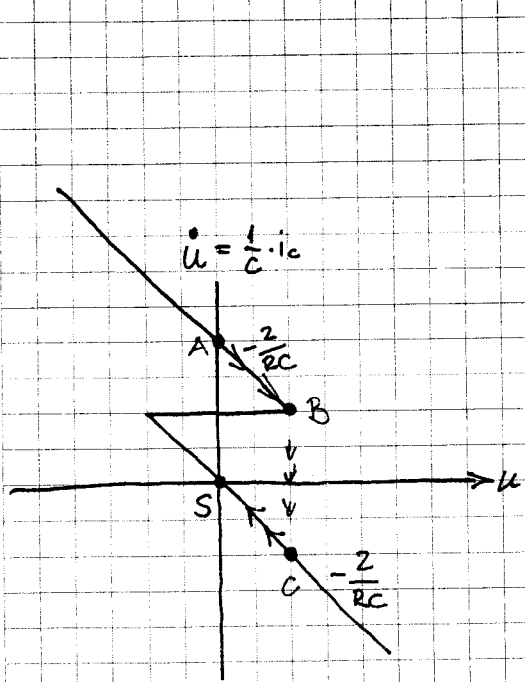
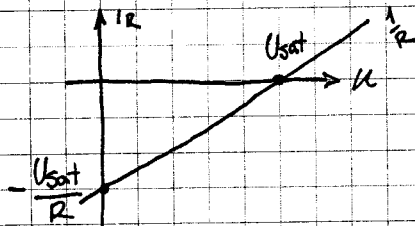
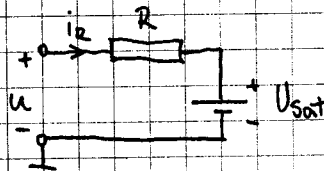
perioda: $T = t_{as} + t_{ca}$
 $= 2 \cdot RC \cdot \ln 3$

4. MMV (S) monostabilni multivibrator



$$i_c = -i - i_R = -(i + i_R)$$

dodan dvopol:



$$\text{ob } t=0^+ : u^+ = +U_{sat}$$

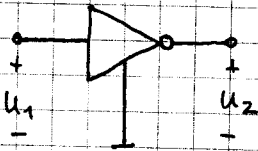
$$u_{izh_{0.0.}} = +U_{sat}$$

$$i(t=0^+) = \frac{0 - U_{sat}}{R} < 0$$

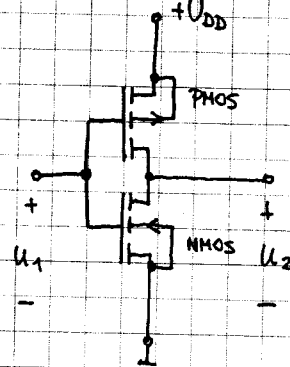
$$i_c = -i_R - i = -\frac{2U_{sat}}{R}$$

REALIZACIJE Z LOGIČNIMI VEZJI

inverter - osnovni logični gradnik



realizacija v CMOS:

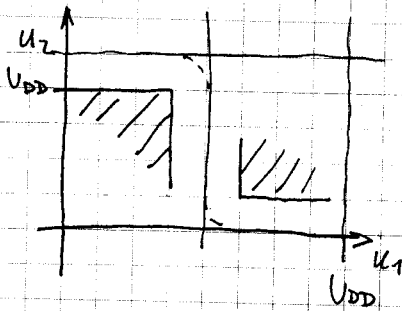


idealni CMOS parametri:

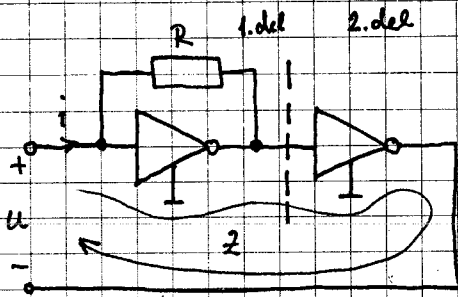
$$R_{ih} \rightarrow \infty \quad \text{oz.} \quad i_{ih} = 0$$

$$R_{izh} = 0 \quad \text{oz.} \quad i_{izh} \leq I_{izh \max} \rightarrow \infty$$

PF:



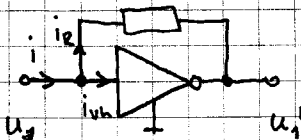
1. AMV (N) ob uporabi C in enosmernega nlin. rezist. vezja



VF: $u(i) = ?$

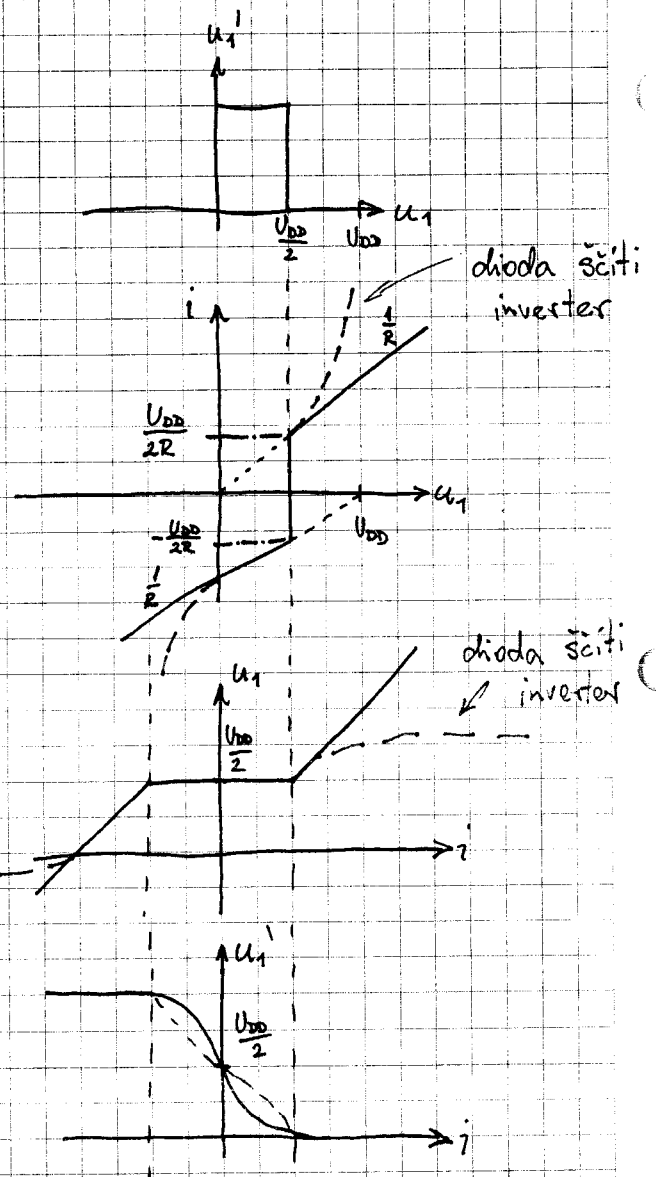
z: $u(i) = u_1(i) - u_2(i)$

1. del vezja:

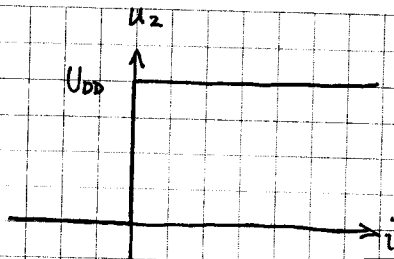
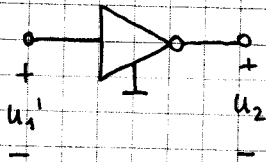


$i = i_{in} + i_R = i_R$

$$i = \frac{u_1 - u_1'}{R} = \begin{cases} \frac{u_1 - 0}{R} & ; u_1 > \frac{U_{DD}}{2} \\ \frac{u_1 - U_{DD}}{R} & ; u_1 < \frac{U_{DD}}{2} \end{cases}$$



2. del vezja:

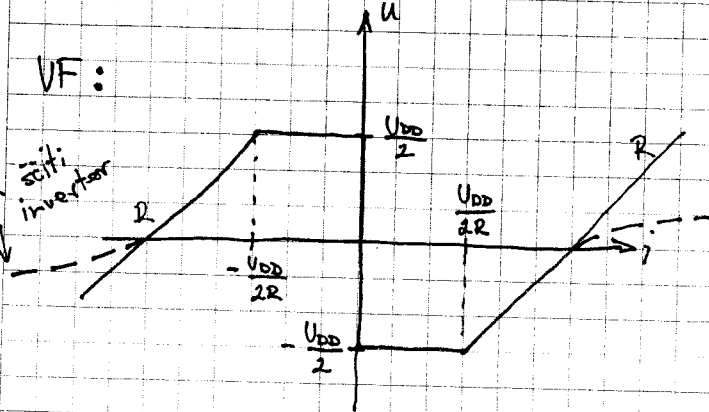


celotna vezja:

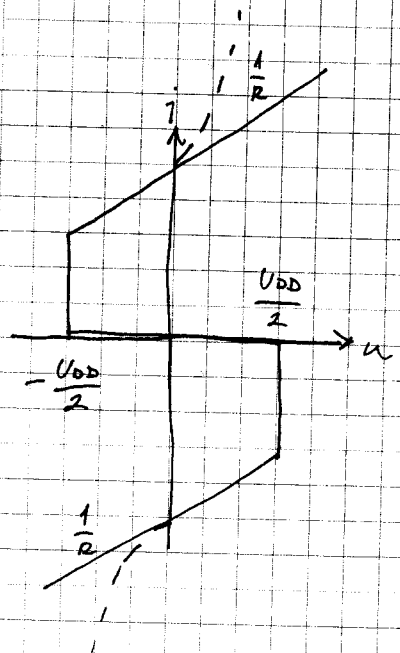
$$u(i) = u_1(i) - u_2(i)$$

VF:

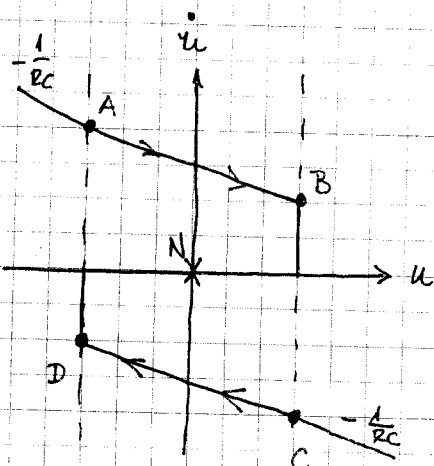
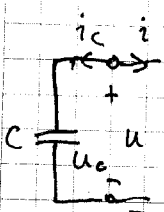
dioda
zašiti
inverter



VF:

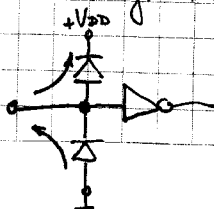


ob dodanem C:

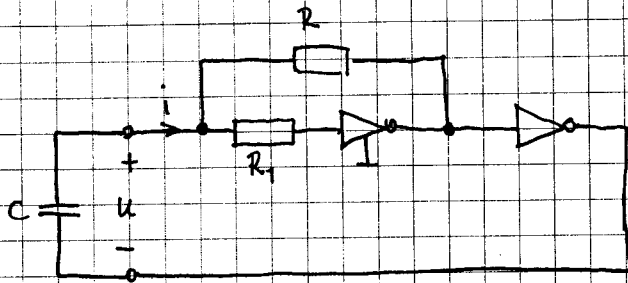


Rešitev za nedelujočo vezja je omejitelj toka prek zaščitnih diod (upor pred inverter)

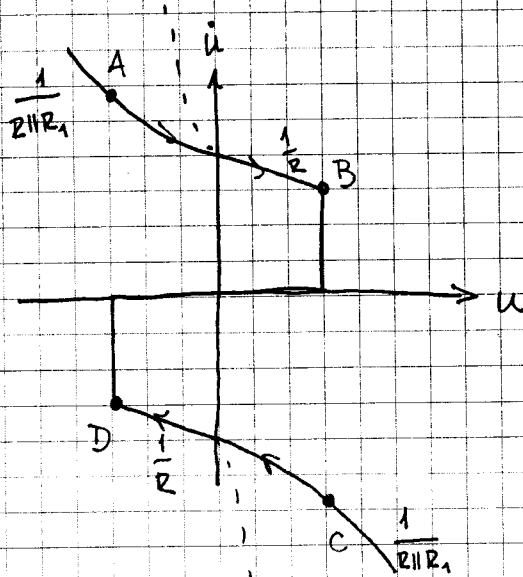
CMOS invertorji imajo zaščitni diodi na vpadu



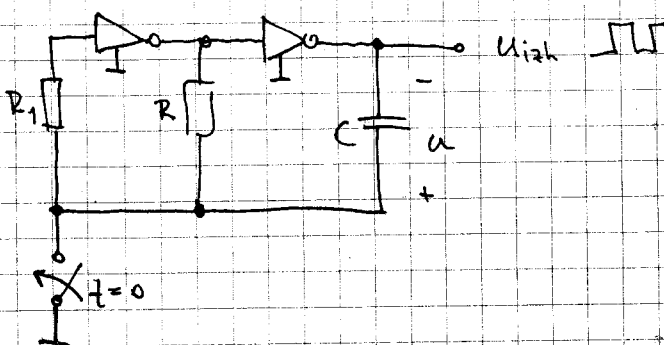
Realizacija z R_1 :



običajno $R_1 \gg R$



naríšemo vezje nekoliko drugače:



za $t < 0$: (L, H, L) in preko R teče tok proti masi

za $t = 0^+$: preko R teče tok v C in polni kondenzator, u narasča dokler INV1 ne preklopi

(pri $u = \frac{U_{DD}}{2}$)

(B)

4. FAZNO SKLENJENE ZANKE (PLL - phase locked loop)

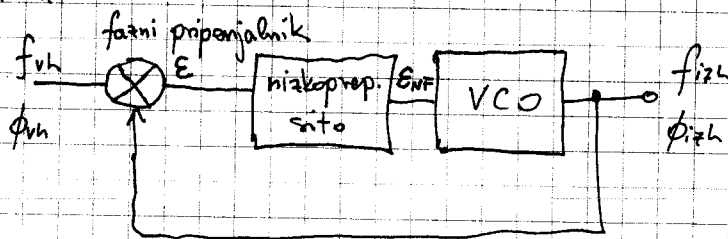
- sistem s PS, kjer je povratna informacija in regulirano veličina faza signala

- ideja leta 1930

- dan danes: FM dekoderji / tunerji, regulatorji hitrosti, lokalne oscilatorske frekvence v TV/RADIO

- princip delovanja:

• shematski prikaz:

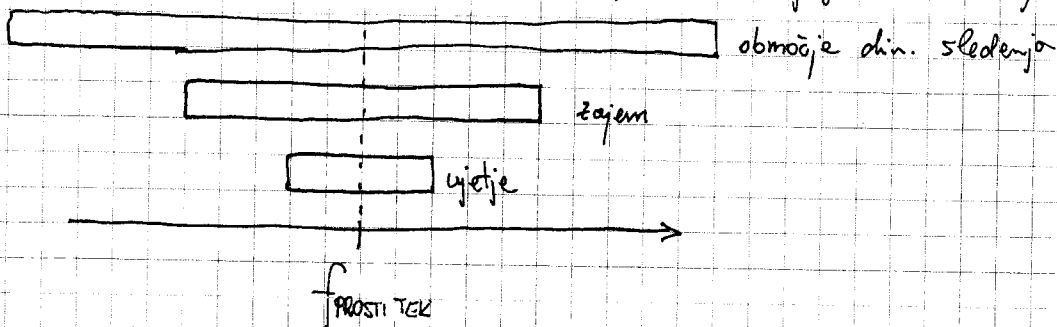


PLL ima tri stanja delovanja:

a) PROSTI TEK: (ko ni signala na vhodu ($f_{vh} = 0$), $f_{vzh} = f_{prosti\ tek}$)

b) ZAJEM: ($f_{vh} \neq 0$, Δf znotraj intervala zajema)

c) UJETJE: ($f_{vh} \uparrow$, Δf znotraj intervala ujetja, sinhronizacija znotraj periode)

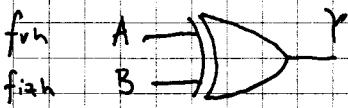


v procesu sledenja je frekvenčno območje še večje

1. FAZNI PRIMERJALNIKI :

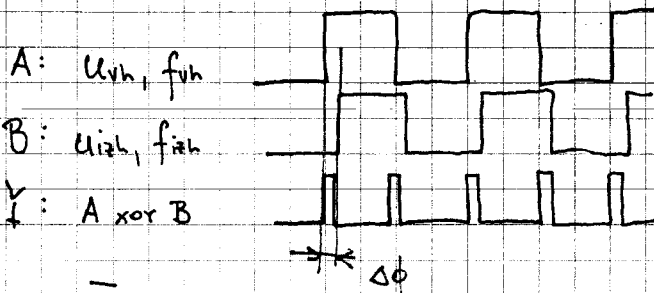
- Delitev: - analogni → analog PLL
 - digitalni → digital PLL

1. Fazni primerjalnik EXOR :

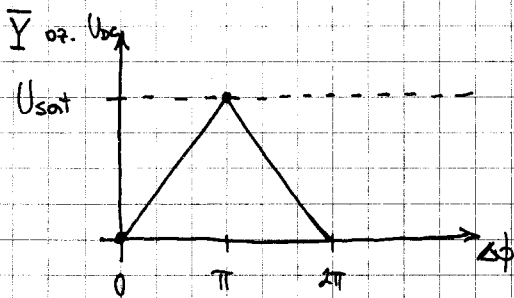


A	B	Y
L	L	L
L	H	H
H	L	H
H	H	L

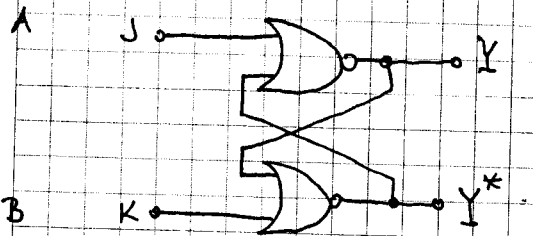
za signal z 50% duty cycle deluje EXOR kot fazni primerjalnik



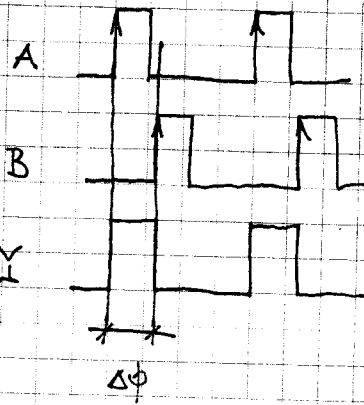
$$\bar{Y} \propto \Delta\phi$$



2. Fazni primerjalnik iz JK flipflopa :

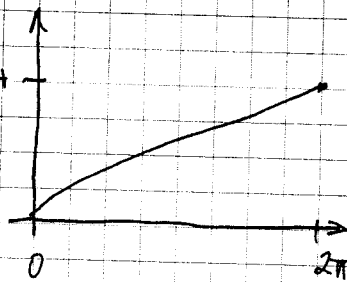


proženje na prehod ("edge-triggered")



\bar{Y} oz U_{bc}

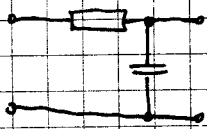
+ U_{sat}



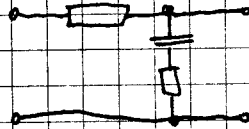
10.1. 2014

2. NIZKOPROSTNI FILTER :

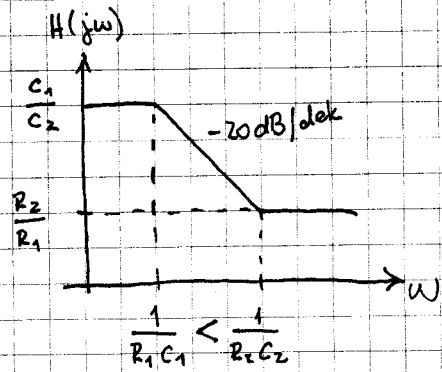
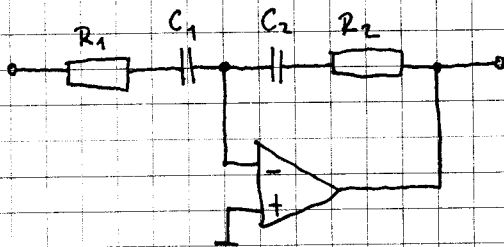
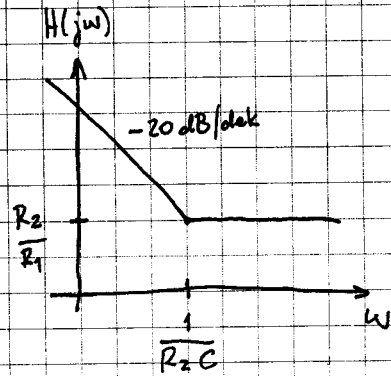
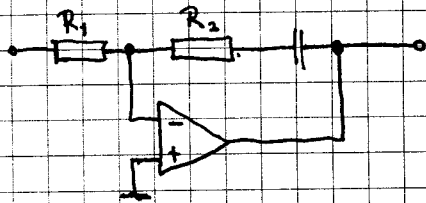
- pasivna izvedba low-pass filtra:



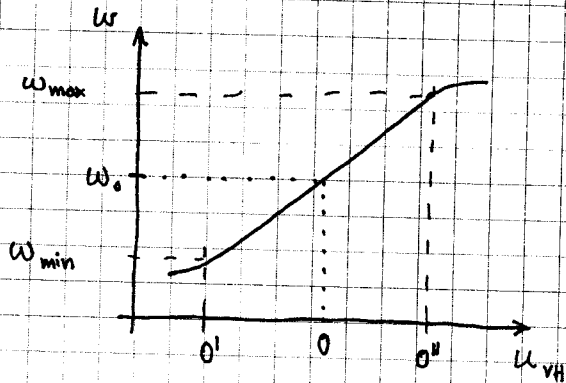
ali



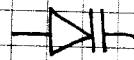
- aktivna izvedba ob uporabi O.O.



3. VCO - NAPETOSTNO KEMILJEN OSCILATOR :



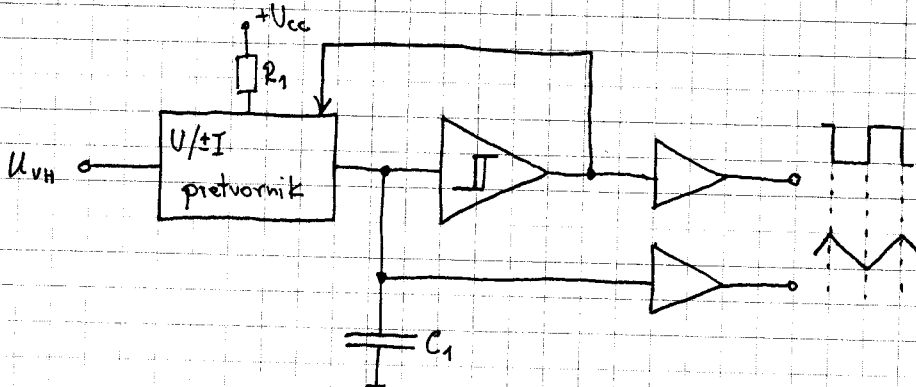
- realizacije z varicap diodo



$$C_T(U_R) = \frac{C_{T0}}{\sqrt{1 + \frac{U_R}{U_0}}}$$

- realizacije z tokovno krmiljenim relaksacijskim oscilatorjem

- princip delovanja :



pri NE566 :
$$f_{izh} = \frac{2 \cdot (+U_{cc} - U_{VH})}{R_1 C_1 \cdot (+U_{cc})}$$

$f_{izh} < 1 \text{ MHz}$

pri CD4046 : glej fotokopijo

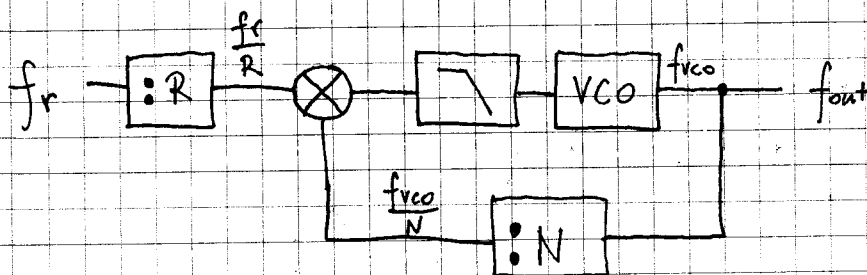
4. MONOLITSKE IZVEDBE PLL:

glj list

5. UPORABA PLL

- frekvenčni množilniki
- FM modulatorji / demodulatorji
- FSK modulatorji / demodulatorji
- digitalni frekvenčni sintetizatorji
- krmiljenje motorjev

5.1. Digitalni frekvenčni sintetizator s celštevilskim deliteljem

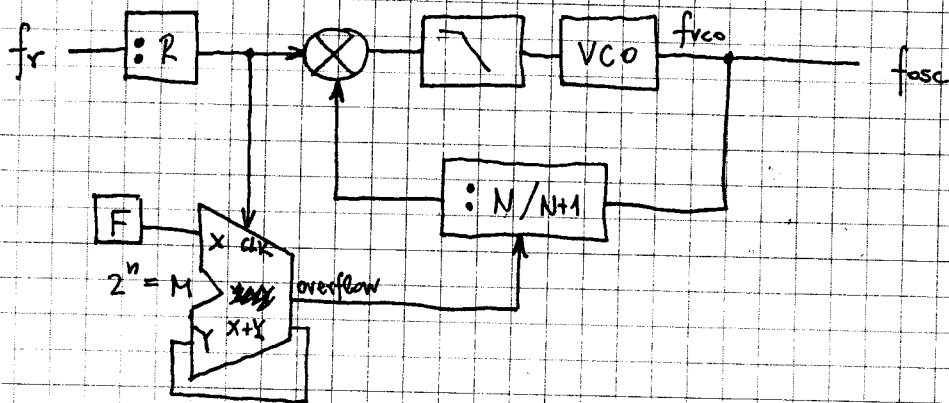


$$\frac{f_r}{R} = \frac{f_{vco}}{N} \rightarrow f_{vco} = \frac{N}{R} \cdot f_r$$

GSM900 \approx 124 kanali \uparrow , po 200 Hz : $N \in [4450, 4575]$

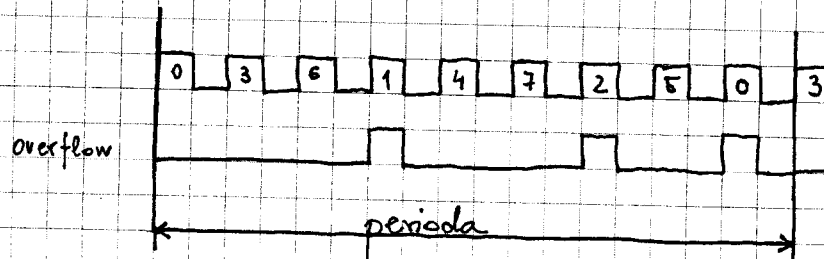
fazni šum narašča z N

5.2. Digit. frekv. sintetizator z iracionalnim deliteljiem



$$F=3$$

$$M=8$$



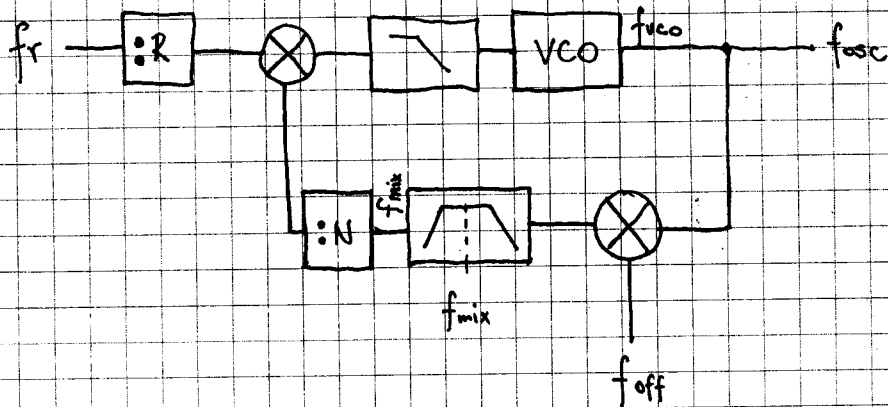
$$\frac{5 \cdot N + 3(N+1)}{8} = \frac{8N+3}{8} = N + \frac{3}{8}$$

splošno: delitelj = $N + \frac{F}{N}$

za GSM 900: $N \in \left[139 \frac{2}{32}, 142 \frac{31}{32} \right]$

N/N+1	8/9
P/P+1	16/17
	32/33
	64/65

5.3. Digitalni frekvenčni sintelizer z mešalno stopnjo



$$f_{mix} = f_{vco} - f_{off} \quad (\text{frekvenčno prestavljanje navzdol})$$

$$\frac{f_r}{R} = \frac{f_{mix}}{N}$$

$$f_{vco} = \frac{N}{R} \cdot f_r + f_{off}$$

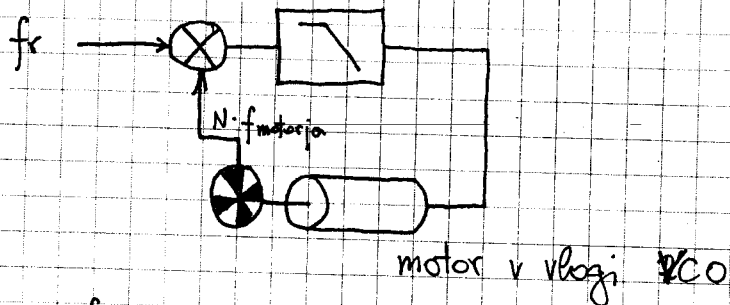
FM tuner : 88,7 ... 108,7 MHz

$$f_r = 1 \text{ MHz}$$

$$R = 10$$

$$f_{off} = 88 \text{ MHz} , N \in [7, 207]$$

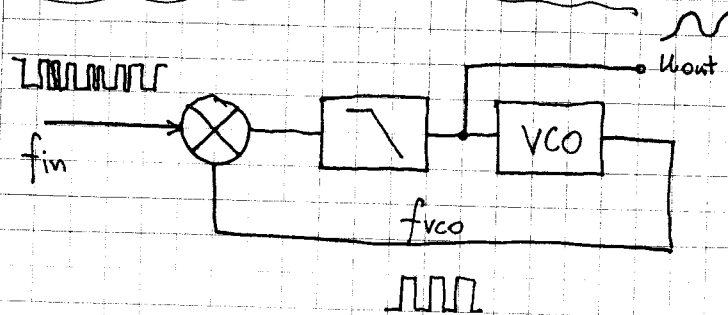
5.4. Regulator hitrosti motorja



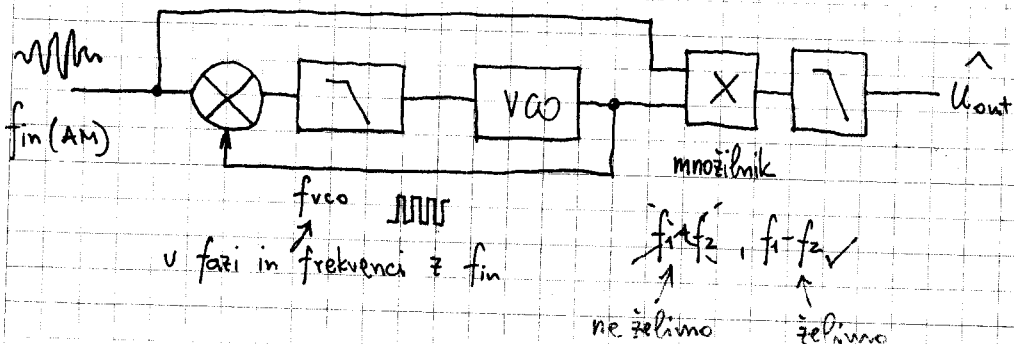
$$f_r = N \cdot f_{\text{motorja}}$$

$$f_{\text{motorja}} = \frac{f_r}{N}$$

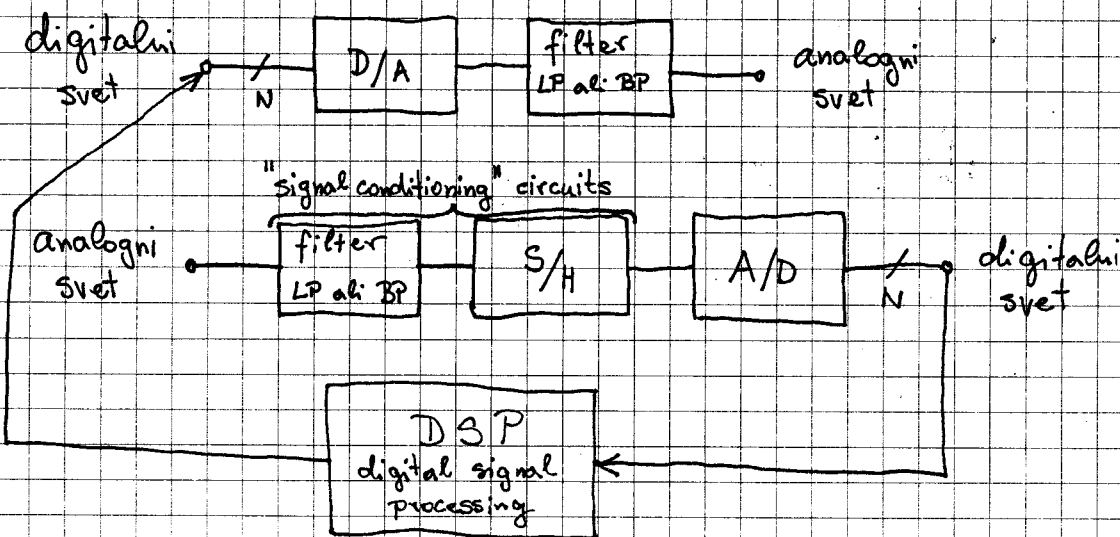
5.5. FM demodulator



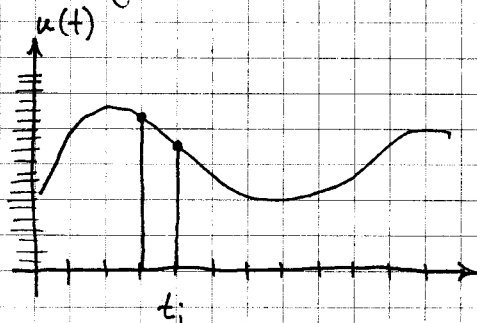
5.6. AM demodulator po homodinamskem principu



5. D/A IN A/D PRETVORNIKI

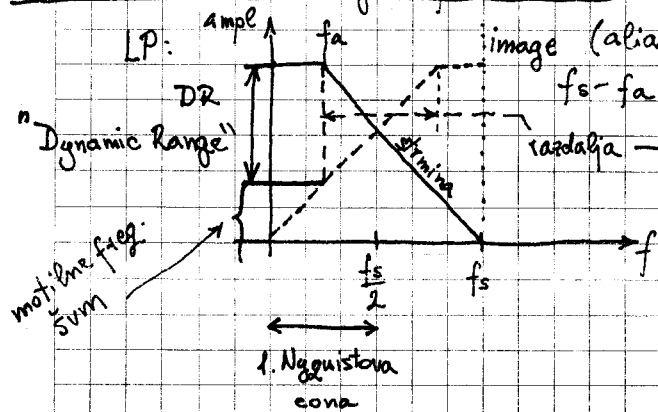


digitalizacija: časovna diskretizacija + amplitudna kvantizacija



$$T_s = \frac{1}{f_s} \quad f_s \dots \text{Sampling frequency}$$

5.1. "Anti-aliasing" filtri



problem je da se slika pojavi v 1. Nyquistovi coni

$$DR = [(f_s - f_a) - f_a] \cdot \text{strmina filtra}$$

eliptični filtri: flat in-band, linearno spreminjanje faze

LE1182: 11-polni eliptični filter

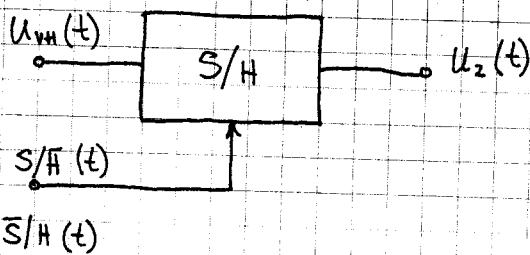
Za povečanje DR:

- Spremeniti filter s povečano strmino
- oversampling $K \cdot f_s$

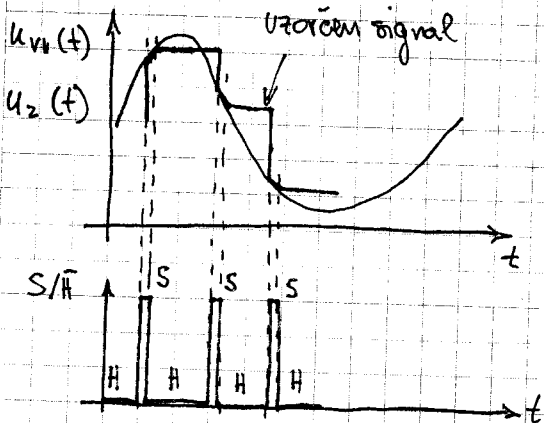
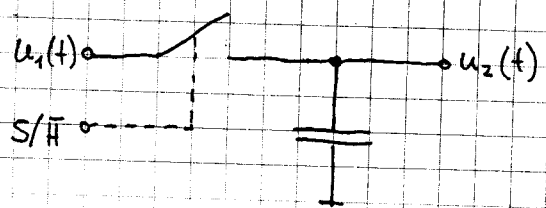
$$DR = [(K \cdot f_s - f_a) - f_a] \cdot \text{strmina}$$

5.2. S/H VEZJA - vezja za vzorčenje in zadrževanje

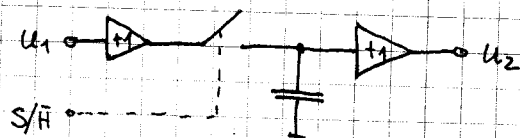
- dvohodno dinamično vezje:

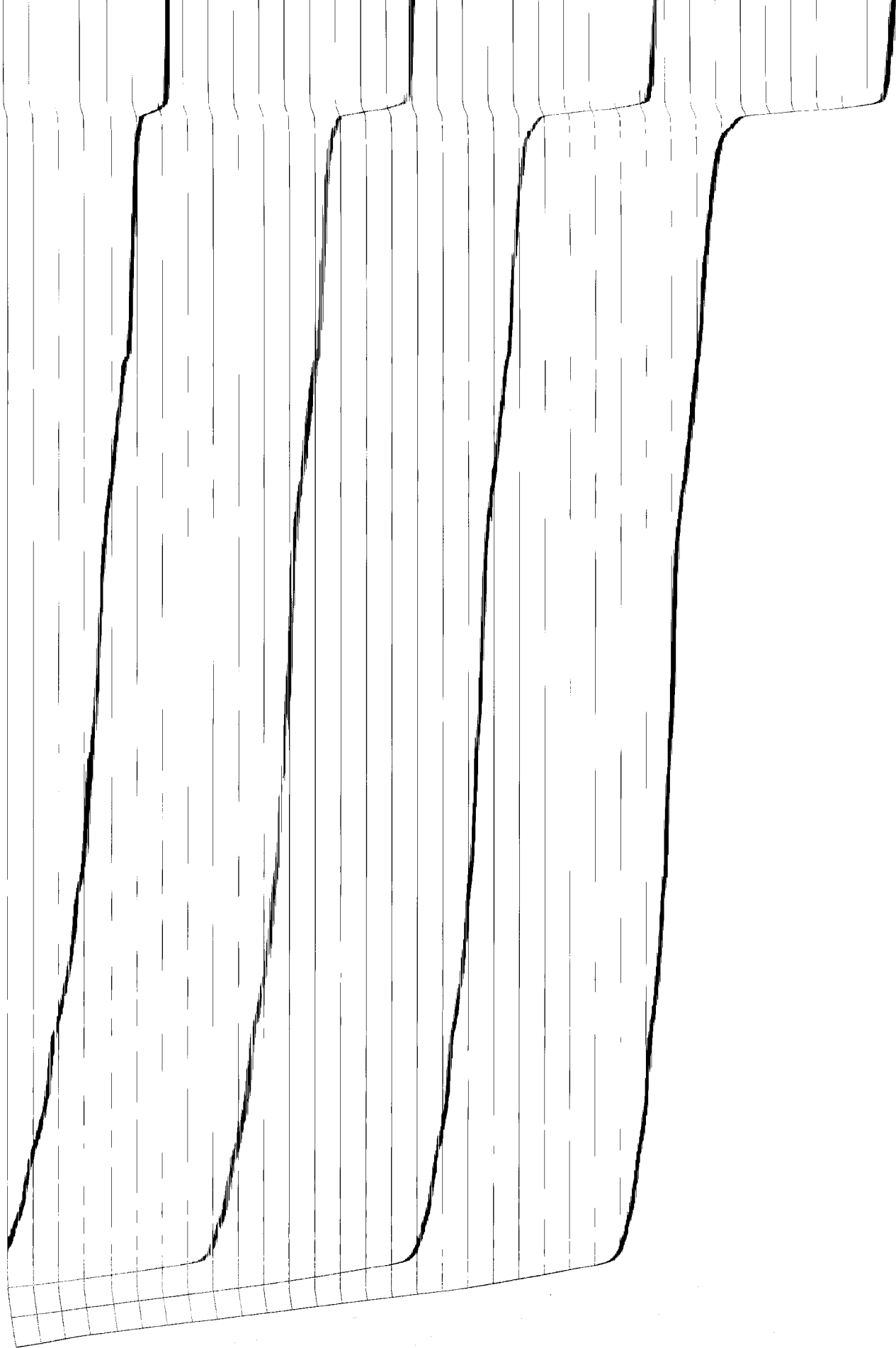


- osnovni princip vezja:



- nadgradnja z bufferjem na vnosu in izhodu





Za povečanje DR:

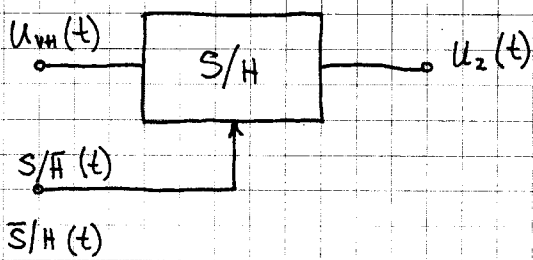
- Sprememiti filter s povečano strmino
- oversampling $K \cdot f_s$



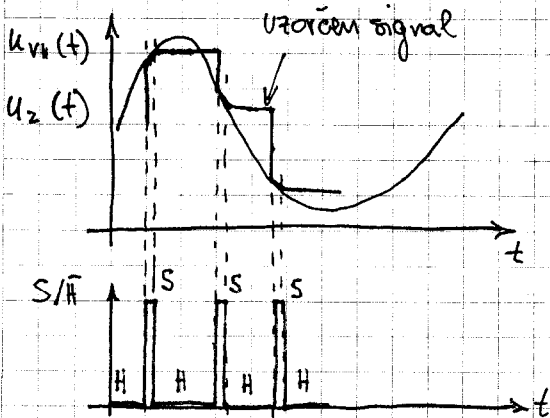
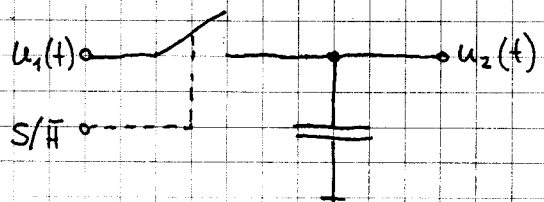
$$DR = [(K \cdot f_s - f_a) - f_a] \cdot \text{strmina}$$

5.2. S/H VEZJA - vezja za vzorčenje in zadrževanje

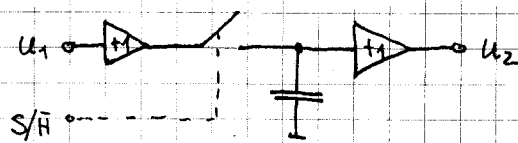
- dvohodno dinamično vezje:



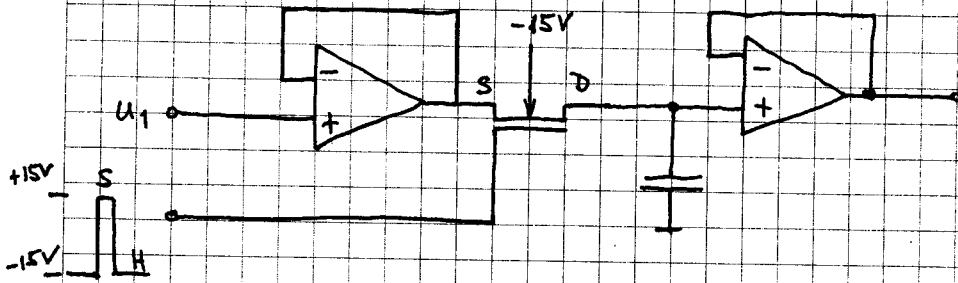
- osnovni princip vezja:



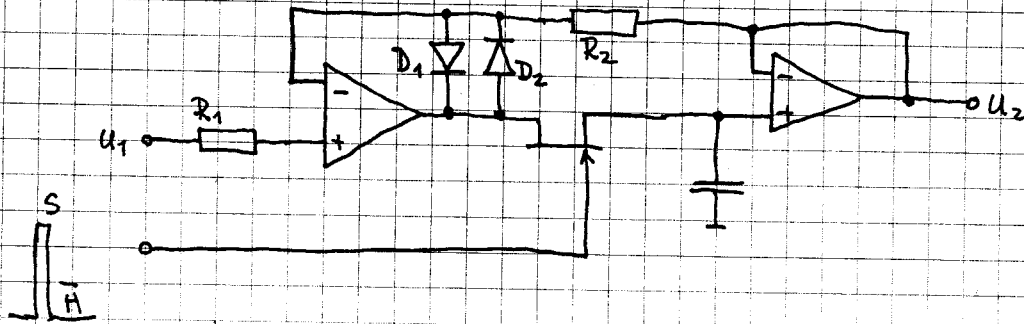
- nadgradnja z bufferjem na vnosu in izhodu



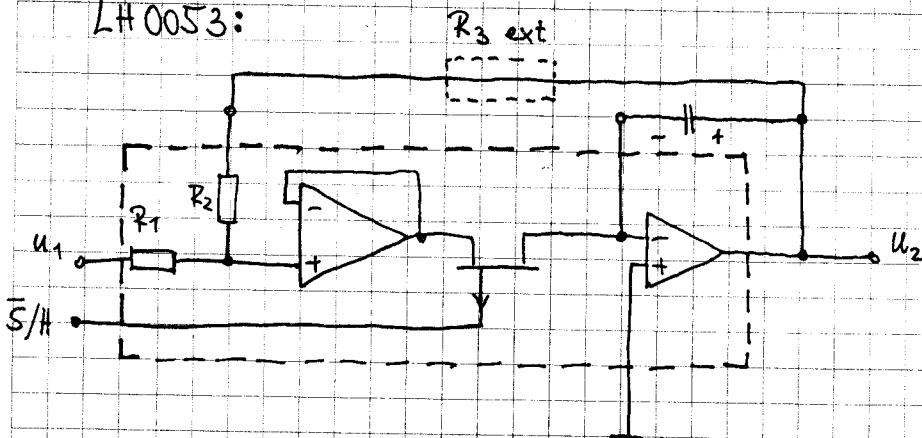
realizacija z nap. sledilniki ≈ 0.0 :



Izboljšava v izogib nasičenja 0.0.1 dodamo D_1, D_2



LH0053:



ojačanje $u_c = u_2 = -\frac{R_2 + R_{3\text{ext}}}{R_1} \cdot u_1$

↑ S/H ojačevalnik ↑