

Nelinearna elektronska vezja

4.10.2013

NEV - P - 1

11.10.2013

Delitev po načinu analize: - rezistivna vezja: analitično + grafično
- dinamična vezja: dif. enačbe

- Analitično reševanje rezistivnih vezij: a) eksplicitno $\vec{y} = f(\vec{x})$ (vektor)
- b) implicitno $h(x, y) = 0$

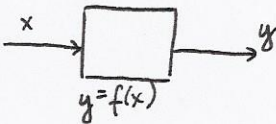
- Grafično reševanje ...: odsekoma linearnizirani elementi
- Analitično reševanje dinamičnih vezij: $\dot{x} = f(x, u)$ enačbe stanja

NEV → neselektivna + selektivna

1. Neselektivna nelinearna vezja za preoblikovanje signalov

1.1 Rezistivna vezja z enim vhodom

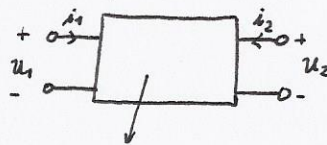
časovno-invariantna



$$u_2 = f(u_1); \quad u_2 = f(i_1)$$

$$i_2 = f(u_1); \quad i_2 = f(i_1)$$

elektronski zapis/model:

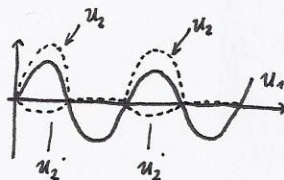
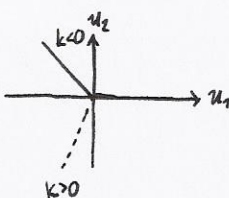
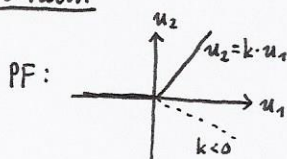


- prenosna funkcija (PF) $i_2(i_1), i_2(u_1)$
- vhodna funkcija (VF) $u_1(i_1), i_1(u_1)$
- izhodna funkcija (IF) $u_2(i_2), i_2(u_2)$

1.1.1 R - Usmerniki

ohmsko breme
signalni usmerniki!

• Polvalni



$$u_2 = k \cdot u_1; \quad u_1 \geq 0 \quad k > 0 \text{ neinvertirajo}$$

$$u_2 = 0; \quad u_1 < 0 \quad k < 0 \text{ invertirajo}$$

$$u_2 = k \cdot u_1; \quad u_1 < 0$$

$$u_2 = 0; \quad u_1 \geq 0$$

Selektivna nelinearna elektronska vezja

I. Vezja za preoblikovanje signalov

A. Krmiljena na enem vhodu

- Množilniki frekvenc
- Ojačevalniki v C-razredu

B. Krmiljena na več vhidih

- Modulatorji
- Demodulatorji

II. Vezja za generiranje signalov

- Harmonični oscilatorji

Literatura pri predmetu NEV:

M. Topič, A. Levstek, M. Jankovec, **Zbirka rešenih nalog iz nelinearnih elektronskih vezij** (3. izdaja), Založba FE in FRI, 2006.

D. A. Bell: *Operational Amplifiers and Linear ICs*, 1997.

T. F. Bogart: *Linear Electronics*, 1994.

T.F. Bogart, J.S. Beasley, and G. Rico: *Electronic Devices and Circuits* (6Ed), 2003.

T. L. Floyd, D. Buchla: *Basic Operational Amplifiers and Linear Integrated Circuits*, 1999.

A.I. Pressman: *Switching Power Supply Design* (3Ed), 2009.

William F. Egan: *Phase-Lock Basics*, 2007.

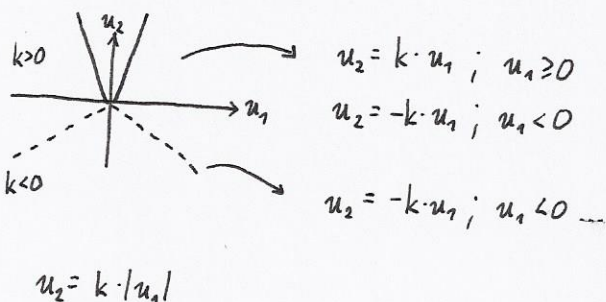
Roland Best: *Phase Locked Loops - Design, Simulation, and Applications* (6Ed), 2007.

D.O. Pederson and K. Mayaram: *Analog Integrated Circuits for Communication: Principles, Simulation and Design* (2Ed), Springer, 2008.

P.R. Gray et al.: *Analysis and Design of Analog Integrated Circuits* (5Ed), Wiley, 2010.

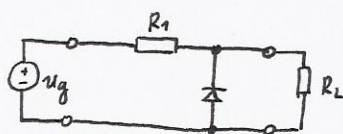
NEV - P - 2

• Polnovalni



• Realizacije

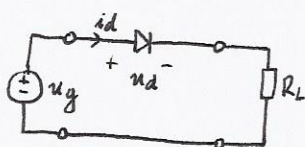
a) paralelna vezava diode:



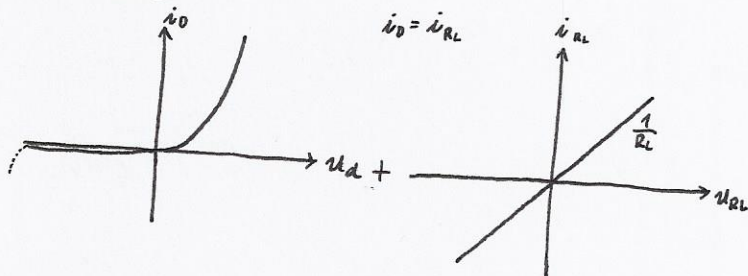
$k = \frac{R_L}{R_1 + R_L} < 1$ poz. perioda

$u_2 = -U_K$ neg. perioda

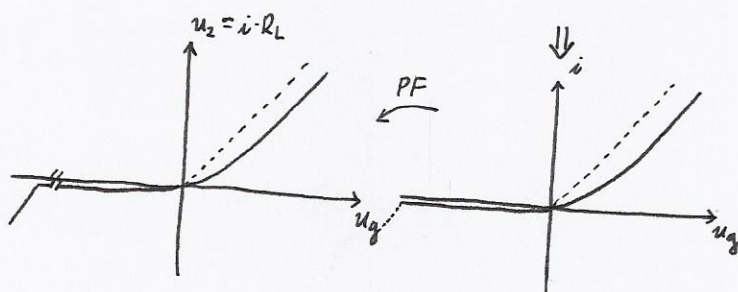
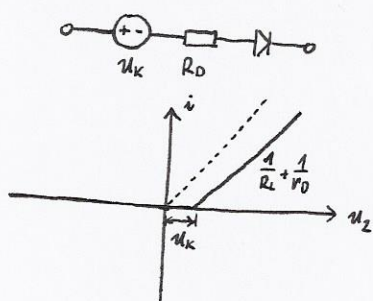
b) serijska vezava diode:



realna dioda:

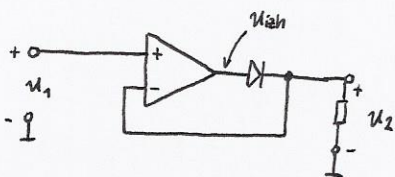


oziroma linearniziran model diode:



• Realizacije z OP-AMP

uporaba NPS: neinvertnajoč polvalni ($k \approx 1$)



analiza za idealni OP-AMP ($A_u \rightarrow \infty$)

$u_{izh} = u_D + u_2$

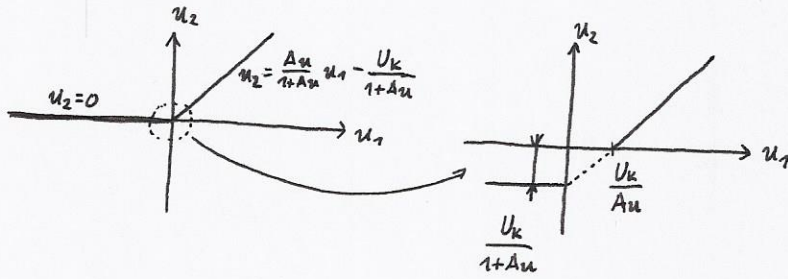
$u_{izh} = A_u \cdot (u_1 - u_2)$ za LIN. področje OP-AMP

$u_D = A_u u_1 - u_2 (1 + A_u)$

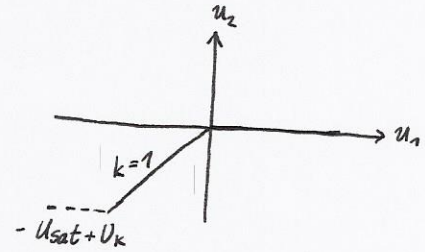
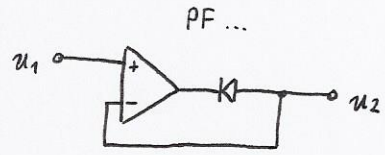
$u_2 = \frac{A_u}{1 + A_u} \cdot u_1 - \frac{u_D}{1 + A_u}$

1) $u_1 > 0V$ u_1 nekoliko večje od u_2
 $u_{izh} = u_D + u_2$, dioda preveža

prevajalna funkcija

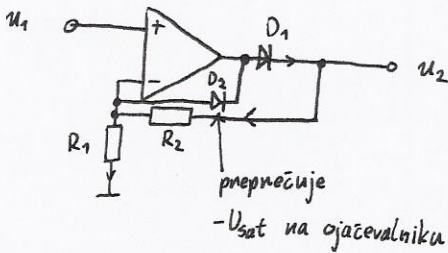


DN:



• neinvertirajoč polvalni R-usm (k > 1)

temelj neinvertirajoč ojač.



analiza:

$u_1 > 0$

D_1 odprta (P_1)
 D_2 zaprta (Z_2)

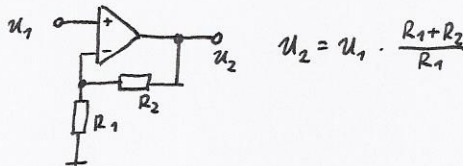
$u_1 < 0$

D_2 odprta (P_2)
 D_1 zaprta (Z_1)

analiza za idealen OP-AMP in diodi:

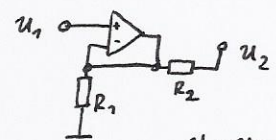
$u_1 > 0$

P_1 in Z_2



$u_1 < 0$

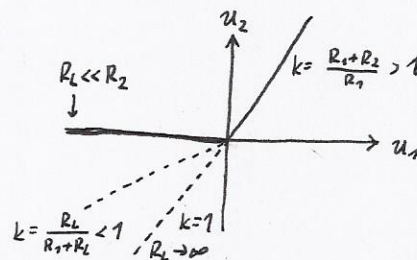
P_2 in Z_1



polvalni usmernik

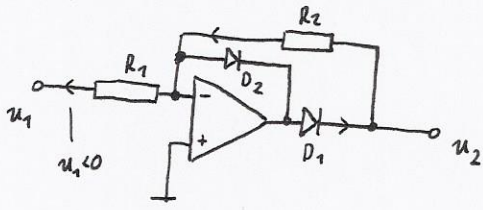
samo pri $R_2 \gg R_L$

PF:



$$u_2 = u_{R2} + u_- = \begin{cases} u_1 & \text{če } R_L = \infty \\ u_1 \frac{R_L}{R_2 + R_L} & \text{če } R_L \neq \infty \end{cases}$$

• inventirajoč polvalni R-VSM

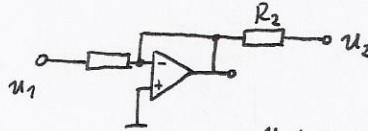


analiza za idealni OP-AMP in diodi

- 1) $u_1 < 0$ D_1 prevaja P_1
 D_2 zapina Z_2

$$u_2 = -\frac{R_2}{R_1} \cdot u_1 \quad u_{izh} = u_{k1} + u_2$$

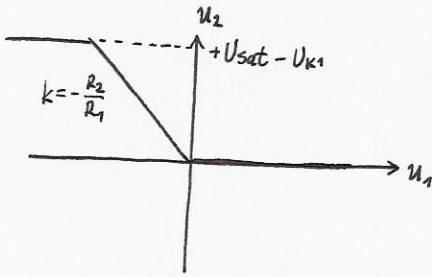
- 2) $u_2 > 0$ Z_1 in P_2



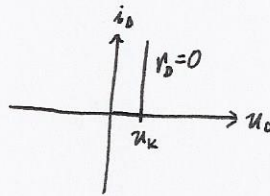
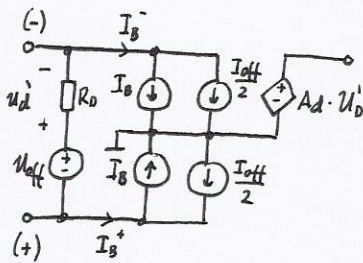
$$u_{izh} = -u_k$$

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

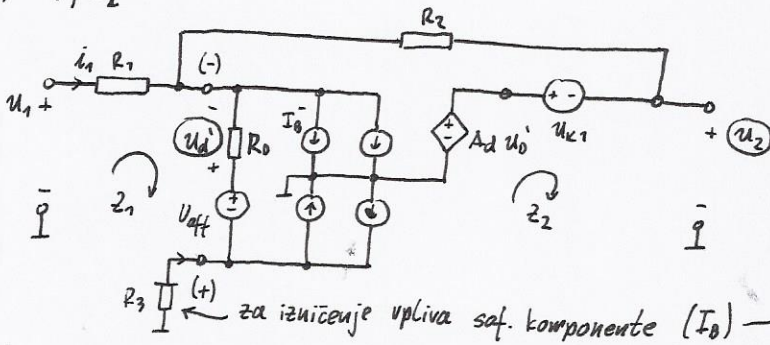
PF:



analiza za realni OP-AMP ($A_u \rightarrow \infty$, U_{off} , I_B , I_{off}) in linearizirani diodi ($U_k, v_D = 0$)
 (tok $R_D = 0$)



- 1) P_1, Z_2 :



$$Z_2: u_2 = -u_{k1} + Ad u_d'$$

$$Z_1: u_0' = U_{off} - u_1 + i_{R1} R_1$$

$$V^-: \frac{u_1 - u^-}{R_1} = \frac{u^- - u_2}{R_2} + I_B^-$$

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

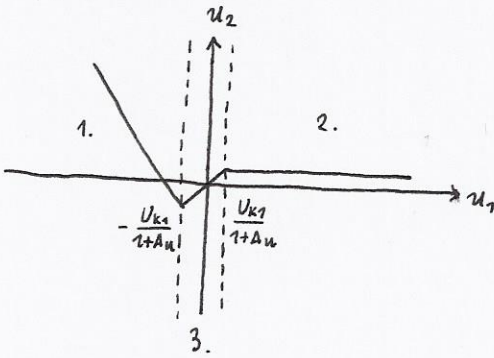
izpeljava... $u_2 = -\frac{R_2}{R_1} u_1 - \frac{U_{k1}}{A_u} \left(1 + \frac{R_2}{R_1}\right) + U_{off} \left(1 + \frac{R_2}{R_1}\right) + \left(1 + \frac{R_2}{R_1}\right) \cdot \left\{ \left[R_1 \parallel R_2 - R_3 \right] I_B + \left[R_1 \parallel R_2 + R_3 \right] \frac{I_{off}}{2} \right\}$

P_1 in Z_1 velja za $u_1 < -\frac{U_{k1}}{1+A_u}$

- 2) P_2, Z_1 : rešitev:

$$u_2 = \frac{r_{D2} \cdot u_1}{A_u \cdot R_1} + \frac{U_{k1}}{A_u} + U_{off} - R_3 I_B^+ - r_{D2} I_B^- ; \quad u_1 > \frac{U_{k1}}{1+A_u}$$

PF :



konkretni zglede

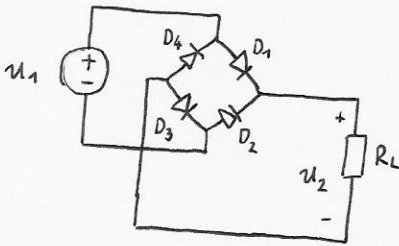
$R_1 = R_2 = 10 \text{ k}\Omega$ $I_{\text{off}} = 50 \text{ nA}$
 $R_3 = 5 \text{ k}\Omega$ $I_B = 250 \text{ nA}$
 $U_{\text{off}} = 3 \text{ mV}$ $U_k = 0.7 \text{ V}$
 $R_{\text{oz2}} = 10 \Omega$ $A_u = 10^5$

$$u_2 = \begin{cases} -1 \cdot u_1 - 2 \cdot 7 \mu\text{V} + 2 \cdot 3 \text{ mV} - \\ -10 \text{ k}\Omega \cdot 50 \text{ nA} ; u_1 < 7 \mu\text{V} \\ 10^{-8} \cdot u_1 + 7 \mu\text{V} + 3 \text{ mV} - 2.5 \text{ mV} - 4.5 \mu\text{V} \\ u_1 - 4.5 \text{ mV} \end{cases}$$

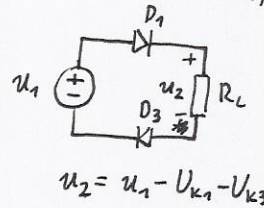
18.10.2013

Realizacije polnovalnega R-usm s plavajočim bremenom

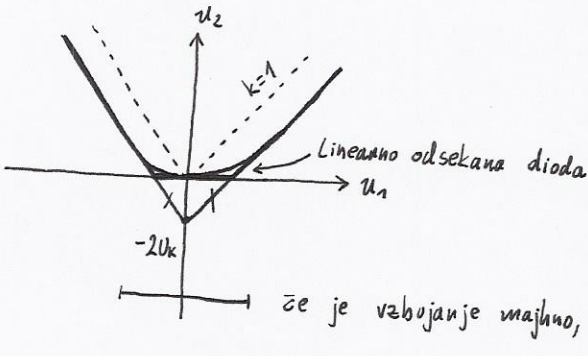
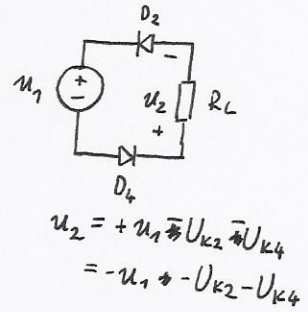
- mostično / Grectzovo vezje



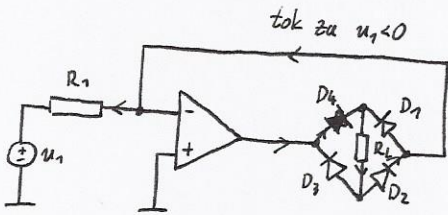
Analiza: $u_1 > 0$ P_1, P_3
 Z_2, Z_4



$u_1 < 0$ P_2, P_4
 Z_1, Z_3



- mostično vezje v neg. povratnim sklopom



tokovno krmiljenje Analiza:

$u_1 > 0$
 P_1, P_3
 Z_2, Z_4

$u_2 = R_L \cdot i_{RL} = R_L \cdot \frac{u_1 - u^-}{R_1} = R_L \frac{u_1}{R_1}$
 $i_{RL} = i_{R1} ; i^- = 0$

$u_1 < 0$
 P_2, P_4
 Z_1, Z_3

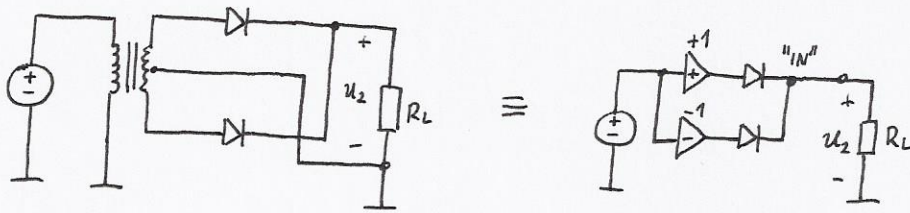
$u_2 = R_L \cdot i_{RL} = R_L \cdot \frac{-u_1}{R_1} =$
 $= R_L \left(-\frac{u_1}{R_1} \right) = \dots$

Lahko dokažeš za $u_1 > 0$ in $u_2 < 0$

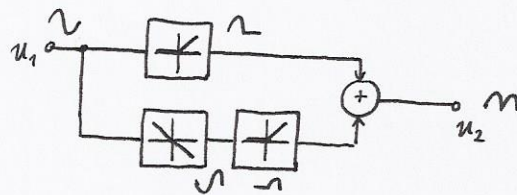
$u = \frac{R_L}{R_1} | \dots |$

Realizacije polnovalnega R-usm z omejenim bremenom

- protitaktna vezava z uporabo transformatorja s srednjim odcepom



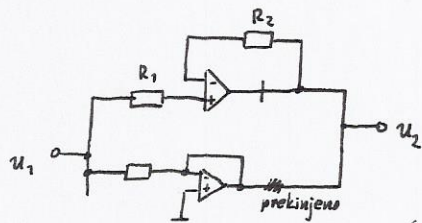
Simbolični prikaz:



- s štirimi OP-AMPi in štirimi diodami dvema (jači!)

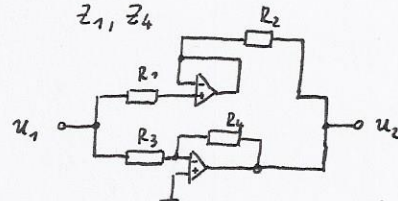
Analiza za idealne diode:

$u_1 > 0$
 P_1, P_4
 Z_2, Z_3

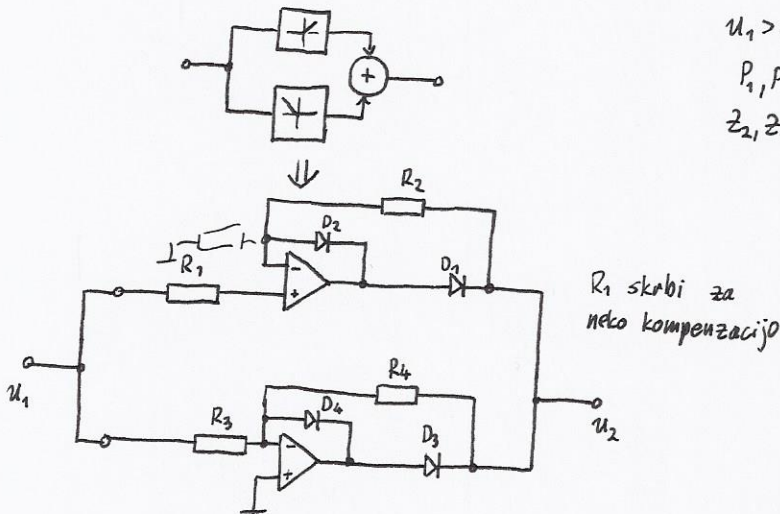


$u_2 = u_1$ (zgonnji sledilnik)
 $i_{zh2} = -U_{k4} - u^- = 0V$

$u_1 < 0$
 P_2, P_3
 Z_1, Z_4



$u_2 = -\frac{R_4}{R_3} u_1$
 $i_{zh1} = -U_{k2} - u^- = u_1$



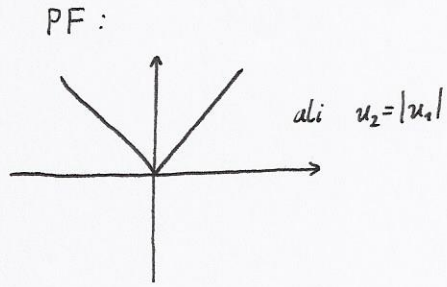
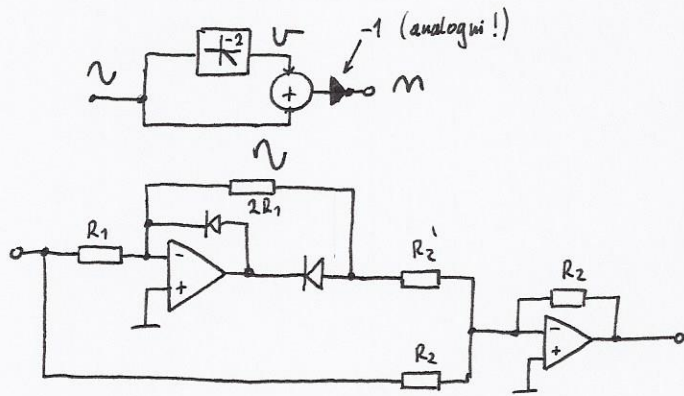
R_2 je obrezen, sicer sta pri $u_1 < 0$ izhod u_2 in \bar{v} vhod zgonnjega OP-AMP zvezana direktno \rightarrow "kratek stik"

$$u_{R2} = u_2 - u_{zh1} = -\frac{R_4}{R_3} u_1 - u_1 = -u_1 \left(1 + \frac{R_4}{R_3}\right)$$

$$i_{R2} < I_{zh2max} \quad \frac{u_{R2}}{R_2} < I_{zh2max}$$

$$R_2 > \frac{u_{R2}}{I_{zh2max}} = \frac{\left(1 + \frac{R_4}{R_3}\right) u_{1max}}{I_{zh2max}}$$

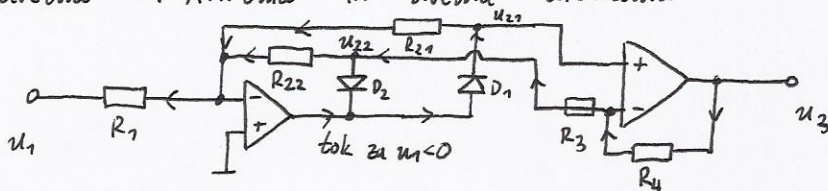
- z dvema OP-AMPoma in dvema diodama



DN: zgornji ojačevalnik ojačanje 1, popravi sestevalnik

R_2' damo na pol

- z dvema OP-AMPoma in dvema diodama



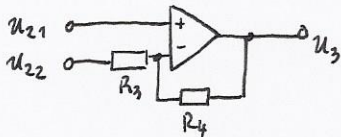
Analiza za idealni diodi:

$u_1 > 0$ Z_1, P_2 $u_{22} = -\frac{R_{22}}{R_1} u_1$

$u_{21} = 0$

$u_3 = -\frac{R_4}{R_3} u_{22} =$

$u_3 = \frac{R_4}{R_3} \frac{R_{22}}{R_1} u_1$



brez OP-AMP2:

u_{21} :

u_{22} :

$u_1 < 0$ P_1, Z_2 $u_{21} = -\frac{R_{21}}{R_1} u_1$

$u_{22} = u_1 + i_{22} R_{22} =$

vozlische minus: $\frac{u_1 - u^-}{R_1} + \frac{u_{21} - u^-}{R_{21}} + \frac{u_3 - u^-}{R_4 + R_3 + R_{22}} = 0$ $u^- = 0 = u^+$

ravimo se eno enačbo

$u_2^- = u_2^+$

$u_{21} = u_2^- = \frac{R_{22} + R_3}{R_{22} + R_3 + R_4} \cdot u_3$... magic ... $u_3 = -\frac{(R_{22} + R_3 + R_4) R_{21}}{(R_{21} + R_{22} + R_3) R_1} \cdot u_1$

želimo seveda $u_3 = |u_1|$

vsi uponi enaki!

za poljuben k: $k = \frac{R_4}{R_3} \frac{R_{22}}{R_1} = \frac{(R_{22} + R_3 + R_4) R_{21}}{(R_{21} + R_{22} + R_3) R_1}$

1.1.2 Rezalniki (angl. Clippers)

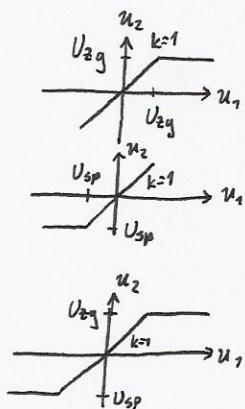
Delitev:

enostranski

- pozitivni (nežejo gor)
- negativni (nežejo dol, a bejž)

dvostranski

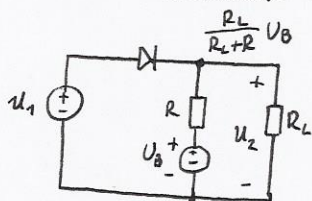
- nežejo gor in dol



k je lahko različen od 1, ampak mora biti zveza linearna

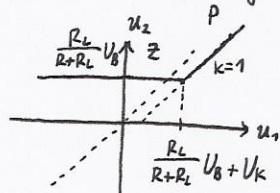
Realizacije diodnih rezalnikov

- enostranski rezalnik s serijsko vezavo diode



Z dioda zaprta

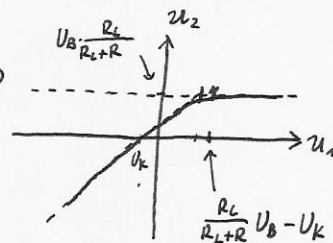
P dioda prevaja



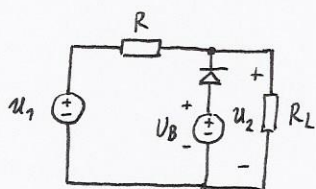
$$u_2 = \frac{R_L}{R+R_L} U_B ; \quad \left. \begin{array}{l} u_d < U_k \\ u_d = u_1 - u_2 \end{array} \right\} \begin{array}{l} u_1 < u_2 + U_k \\ u_1 < \frac{R_L}{R+R_L} U_B + U_k \end{array}$$

$$u_2 = u_1 - u_d = u_1 - U_k ; \quad u_1 > \frac{R_L}{R+R_L} U_B + U_k$$

DN: določi PF za obrnjeno diodo



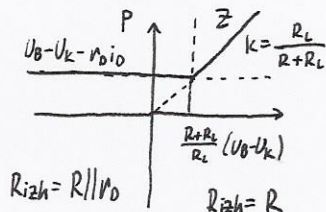
- enostranski rezalnik s paralelno diodo



Z: $u_2 = \frac{R_L}{R+R_L} \cdot u_1 ; \quad u_d < U_k$

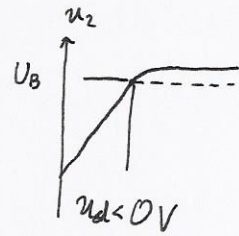
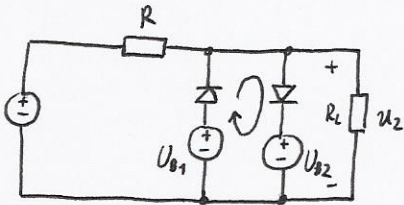
$u_d = U_B - u_2 \rightarrow u_1 > \frac{R+R_L}{R_L} (U_B - U_k)$

P: $u_2 = U_B - u_d = U_B - U_k - u_d \rightarrow u_1 < \frac{R+R_L}{R_L} (U_B - U_k)$



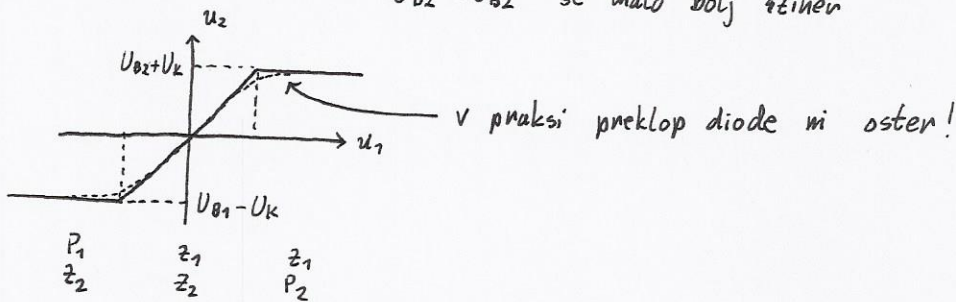
NEV - p - g

- dvostranski vezalnik (s paralelno vezavo diod)

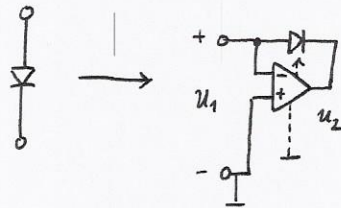


pogoj $U_{B1} - U_{B2} < U_{K1} + U_{K2}$ (sicer prevajata obe diodi)

$U_{B2} < U_{B2}$ še malo bolj fiziken



• Realizacija idealnih diodnih vezalnikov



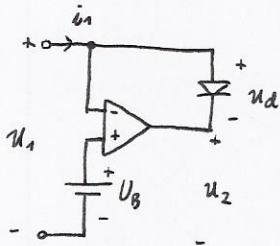
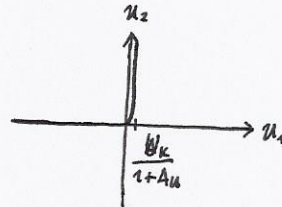
dioda

$$u_1 = u_0 + u_2$$

$$u_2 = -A_u \cdot u_1$$

$$u_1 = u_0 - A_u \cdot u_1$$

$$u_1 = \frac{1}{1+A_u} \cdot u_0$$



$$u_1 = u_d + u_2$$

$$u_2 = -A_u (u^- - u^+) = -A_u (u_1 - U_B)$$

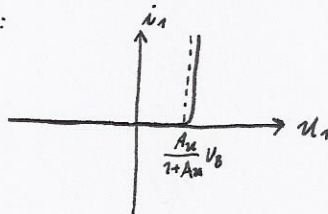
rezitev

~~$$u_1 = \frac{u_0}{1+A_u} + \frac{A_u}{1+A_u} \cdot U_B$$~~

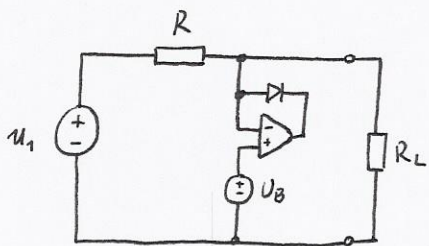
$$u_1 = \frac{u_0}{1+A_u} + \frac{A_u}{1+A_u} \cdot U_B$$

za obrnjeno diodo DN!

VF:

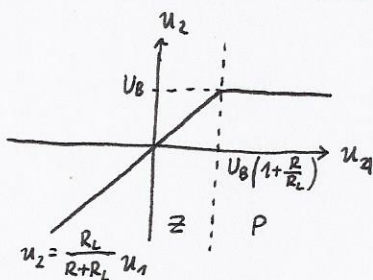


• Enostranski diodni vezalnik z OP-AMP

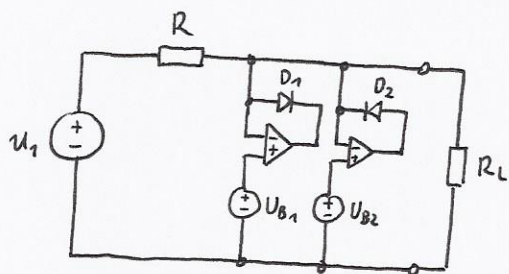


Z: $u_2 = \frac{R_L}{R+R_L} u_1$

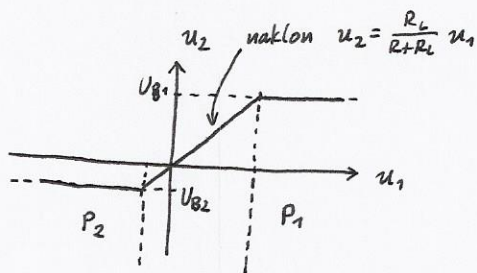
P: $u_2 = U_B \left(= \frac{U_K}{1+A_u} + \frac{A_u}{1+A_u} U_B \right)$



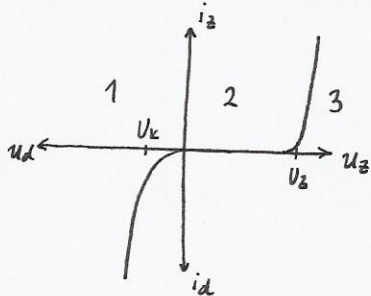
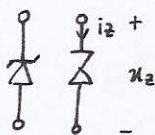
• dvostranski diodni vezalnik z OP-AMP



$U_{B2} < U_{B1}$



• Realizacije prebojno-diodnih vezalnikov

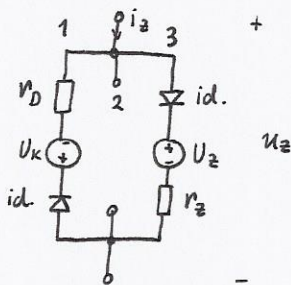


Lahko odsekoma lineariziramo

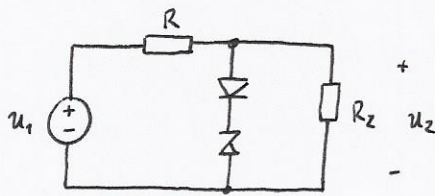
zaporno $\rightarrow U_z, r_z$

prevodno $\rightarrow U_k, r_D$

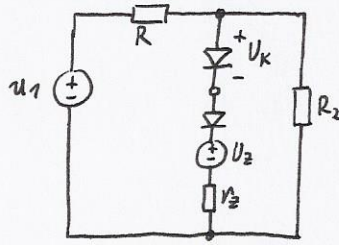
model:



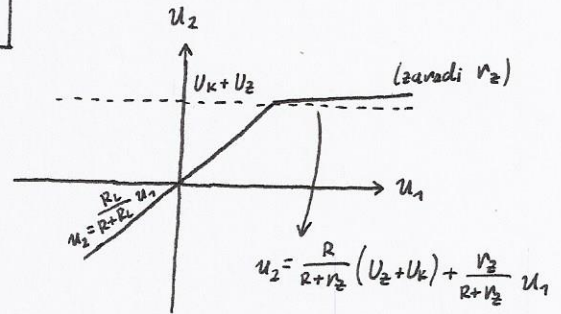
• enostranski nezalnik



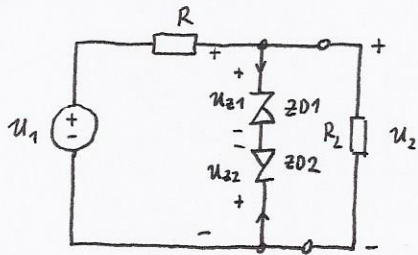
za področje preboja ($i_z > I_{zmin}$)



PF:

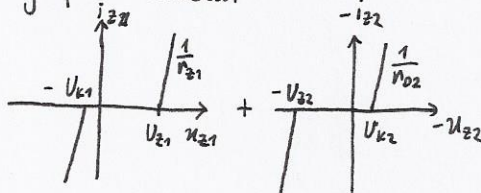


• dvostranski nezalnik

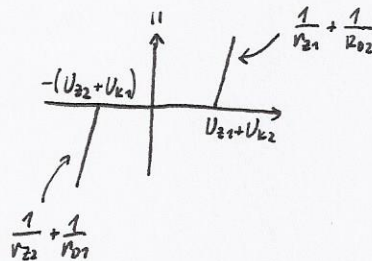
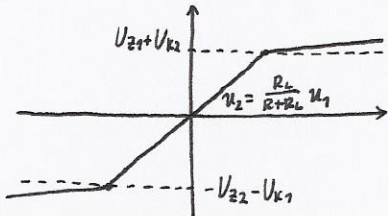


"anti-senijska" vezava

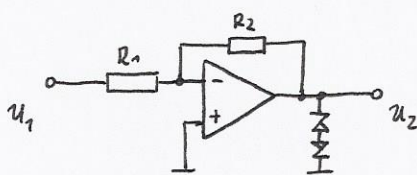
grafični izražaji



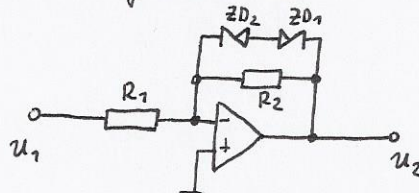
PF:



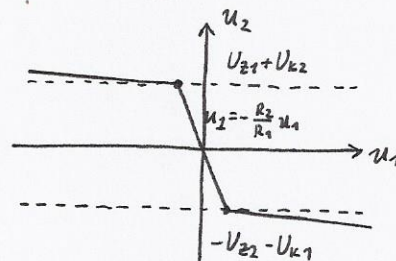
• dvostranski nezalnik v konfiguraciji inv. ojačevalnika:



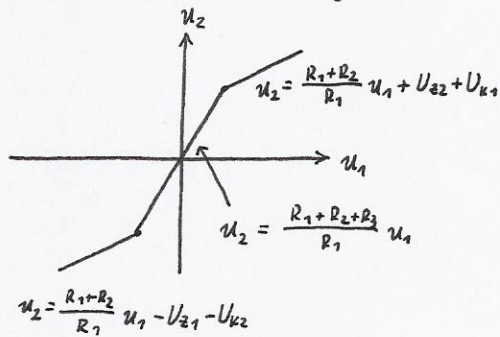
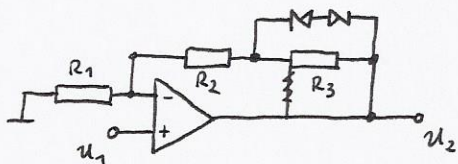
ali



PF:



- uporaba ZD rezalnika za nastavitvev amplitude oscilatorja

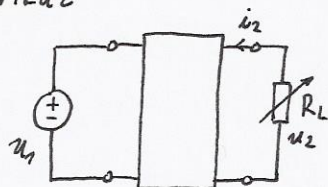


1.1.3 Napetostni regulatorji

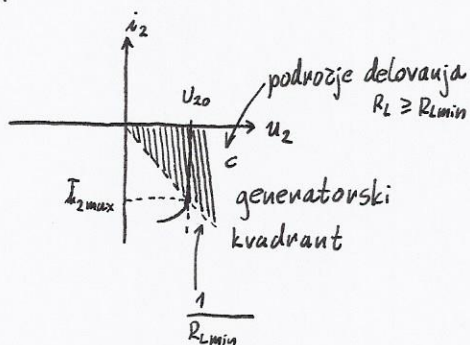
tudi stabilizatorji

- stabilizacija enosmenne napetosti

- shematski prikaz



IF:

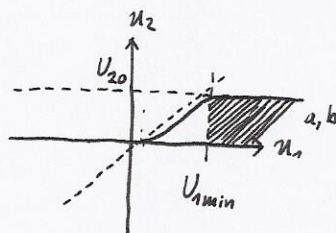


idealni regulator ohranja u_2

konstantno ne glede na spremembe:

- a - vhodne napetosti $u_1(t)$
- b - harmonskih komponent $u_1(t)$
- c - bremenskega toka $i_2(t)$ oziroma $R_L(t)$

PF:



Kriteriji zmogljivosti / kvalitete:

1) "Line regulation"
(regulacija napajanja)

$$LR = \begin{cases} \frac{\Delta u_2}{\Delta u_1 = 10\% U_1} \cdot 100\% & \text{idealno } 0\% \\ \frac{\Delta u_2}{\Delta i_L \cdot U_{20}} \cdot 100\% & \text{idealno } 0\% / V \end{cases}$$

2) faktor stabilizacije

$$S = \frac{1}{\frac{\partial u_2}{\partial u_1}} = \frac{1}{A_u(\omega)} \leftarrow \text{ojačanje} \quad \text{idealno } A_u(\omega) = 0, S \rightarrow \infty$$

3) "ripple rejection"
(rejekcijski faktor)

$$RR = 20 \cdot \log \left[\frac{u_1 \text{ ripple}}{u_2 \text{ ripple}} \right] @ \text{izbrani } \omega \quad \text{idealno } RR \rightarrow \infty \text{ dB}$$

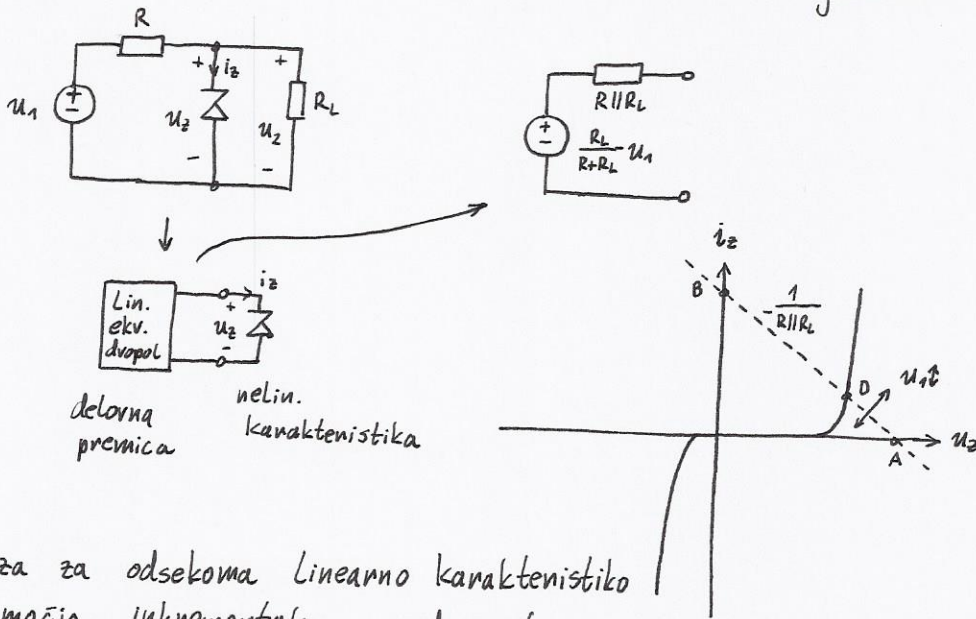
4) "Load regulation"
(regulacija bremena)

$$LR = \begin{cases} \frac{\Delta u_2}{\Delta i_L = I_{Lmax} - 0} \cdot 100\% & \text{idealno } 0\% \\ \frac{\Delta u_2}{\Delta i_L \cdot U_{20}} \cdot 100\% & \text{idealno } 0\% / A \end{cases}$$

5) dinamična izhodna upornost $r_{iZH} = \frac{\partial u_2}{\partial i_2}$ idealno 0Ω

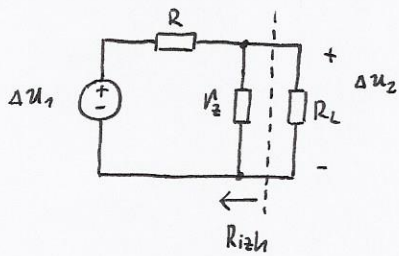
6) izkoristek regulatorja $\eta = \frac{P_{iZH}}{P_{VH}} \cdot 100\% = \frac{u_2 \cdot i_2}{u_1 \cdot i_1} \cdot 100\%$

• Primen analize S in r_{iZH} za preprost napetostni regulator



Analiza za odsekoma linearno karakteristiko s pomočjo inkrementalnega nadomestnega vezja:

za $i_2 > I_{zmin}$



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

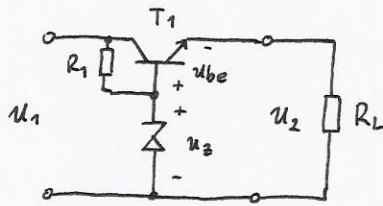
$$r_{iZH} = \left. \frac{\partial u_2}{\partial i_2} \right|_{\Delta u_1 = 0} = r_z \parallel R \doteq r_z$$

$$S = \frac{\Delta u_1}{\Delta u_2} = \frac{R + R_L \parallel r_z}{R_L \parallel r_z} = 1 + \frac{R}{r_z \parallel R_L} \doteq 1 + \frac{R}{r_z}$$

Delitev napetostnih regulatorjev

- A) Serijski
 - A1) brez PS
 - A2) s PS
- B) Paralelni
 - B1) brez PS
 - B) s PS

A1) Serijski nap. regulator brez PS



T_1 - prepustni tranzistor

$u_2 = u_z - u_{be}$ delovanje $i_z > I_{zmin}$
določamo z u_1 in R_1

$u_1 = u_{ce} + u_2$ $u_1 \geq u_{cemin} + u_2$

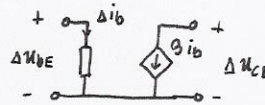
T_1 v aktivnem področju delovanja

delovna premica $i_z(u_z)$

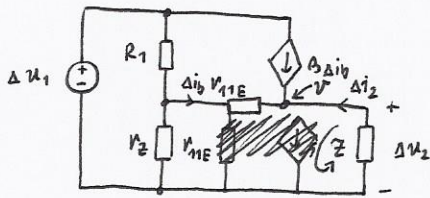
pri $i_z = 0 \rightarrow u_z = \frac{(1 + \beta_{oc}) R_L}{R_1 + (1 + \beta_{oc}) R_L}$

pri $u_z = 0 \rightarrow i_z = \frac{u_1}{R_1}$

analiza za S in V_{izh} , model tranzistorja
inkrementalno nadomestno vezje:



8.11.2013



$V_{izh} = \left. \frac{\Delta u_2}{\Delta i_2} \right|_{\Delta u_1 = 0}$

V : $\Delta i_L = -\Delta i_2 = \beta \Delta i_b + i_b = (1 + \beta) \Delta i_b$

Z : $\Delta u_2 = -\Delta i_b (r_{11E} + r_z || R_1)$

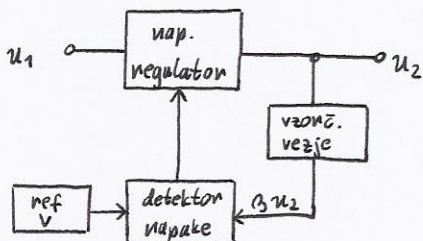
$V_{izh} = \frac{1 + \beta}{1 + \beta} = \frac{r_{11E} + r_z || R_1}{1 + \beta} = \frac{1}{g_{21E}} + \frac{r_z}{1 + \beta}$

$S = \frac{\Delta u_1}{\Delta u_2} = \frac{R_1 + r_z}{r_z} + \frac{R_1 + \frac{R_1 + r_z}{\beta}}{(1 + \beta) R_L}$

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

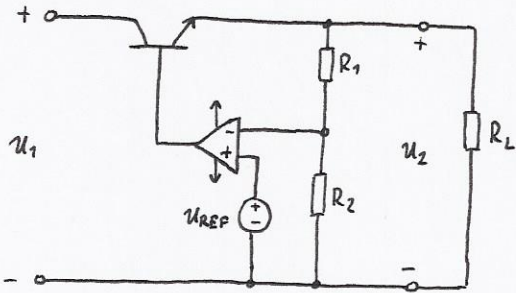
A2) Serijski nap. regulator s PS

shematsko:



• Realizacije serijskih nap. regulatorjev s PS

a) OP-AMP kot ojačevalnik napake



$$u^- = \frac{R_2}{R_1 + R_2} \cdot u_2 \quad (\text{če } i^- = 0)$$

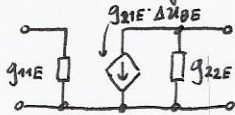
$$u^- = u^+$$

$$U_{REF} = \frac{R_2}{R_1 + R_2} \cdot u_2 \rightarrow u_2 = U_{REF} \frac{R_1 + R_2}{R_2}$$

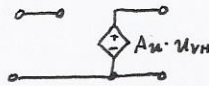
$$u_2 \geq U_{REF}$$

izražun S in r_{izh} :

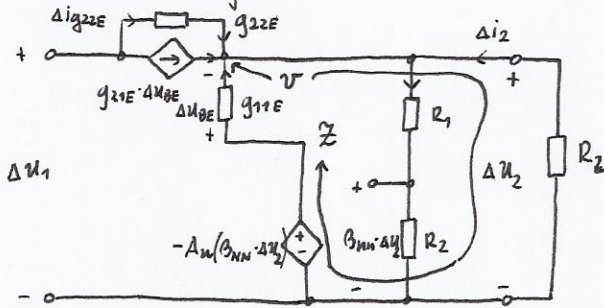
model tranzistorja:



OP-AMP:



nadomestno vezje:



$$v: \sum i = 0$$

$$\Delta i_{g22E} + g_{21E} \cdot \Delta U_{BE} + g_{11E} \Delta U_{BE} + \Delta i_2 - \frac{\Delta u_2}{R_1 + R_2} = 0$$

neznanke

$$z: \sum u = 0$$

$$\Delta U_{BE} + \Delta u_2 + A_u (\beta_{NN} \Delta u_2) = 0$$

$$\Delta i_{g22E} = g_{22E} (\Delta u_1 - \Delta u_2)$$

⋮

$$\Delta u_2 = \frac{g_{22E}}{g_{22E} + (1 + \beta_{NN} A_u) (g_{11E} + g_{21E}) + \frac{1}{R_1 + R_2}} \cdot \Delta u_1 +$$

$$+ \frac{1}{-1} \cdot \Delta i_2$$

← enak imenovalac kot prej

$$r_{izh} = \left. \frac{\partial u_2}{\partial i_2} \right|_{\Delta u_1 = 0} = \frac{1}{g_{22E} + (1 + \beta_{NN} A_u) (g_{11E} + g_{21E}) + \frac{1}{R_1 + R_2}}$$

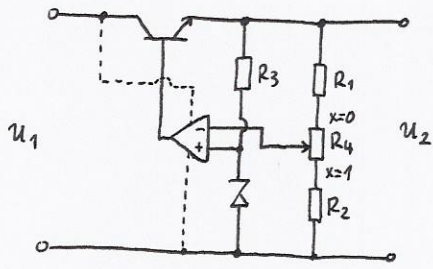
$$r_{izh} \approx \frac{1}{\beta_{NN} \cdot A_u \cdot g_{21E}}$$

se manjša izhodna upornost...

$$S = \frac{\partial u_2}{\partial u_1} = \frac{g_{22E} + (1 + \beta_{NN} A_u) (g_{11E} + g_{21E}) + \frac{1}{R_1 + R_2}}{g_{22E}} \approx 1 + (1 + \beta_{NN} A_u) \cdot \frac{g_{21E}}{g_{22E}}$$

OP-AMP napajamo preko u_1
(PSSR ~ 120 dB)

b) realizacija U_{ref} in nastarljive U_2



kako vezje starta?

$$u_2 = \frac{R_1 + R_2 + R_4}{R_2 + (1-x)R_4} \cdot U_z \quad \text{oz.}$$

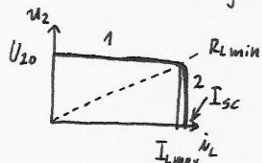
$$u_2 = \begin{cases} \frac{R_1 + R_2 + R_4}{R_2 + R_4} \cdot U_z & x=0 \\ \frac{R_1 + R_2 + R_4}{R_2} \cdot U_z & x=1 \end{cases}$$

$$R_3 = \frac{u_2 - U_z}{I_{z0}} \leq \frac{U_{2min} - U_z}{I_{zmin}}$$

tokovna omejitev ...

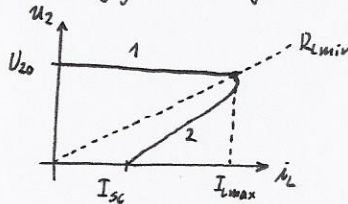
Omejevanje toka pri serijskih nap. regulatorjih

a) konstantna omejitev toka



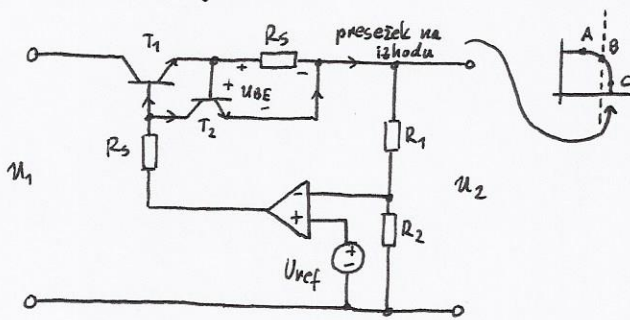
za zaščito T_1

b) prepogojena omejitev toka



maj pregrevanja pri kratkem stiku

• Konstantna omejitev toka (+ T_2, R_s, R_5)



točka A: T_2 zaprt, ker U_{rs} majhna

točka B: na meji, $U_{rs} = U_{BE0}$, T_2 začne prevajati,

$$I_{Lmax} = \frac{U_{BE0}}{R_s}$$

$$I_{sc} = I_{Lmax} + I_{C2}$$

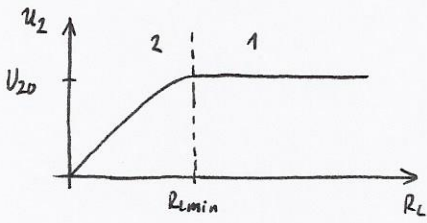
točka C: T_2 odprt

R_5 z namenom omejitve toka izhoda!

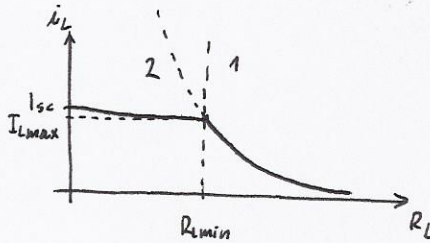
$$\text{za } R_5 \cdot i_{rs} = U_{sat} = U_1$$

$$R_5 = \frac{U_1}{I_{ishmax}}$$

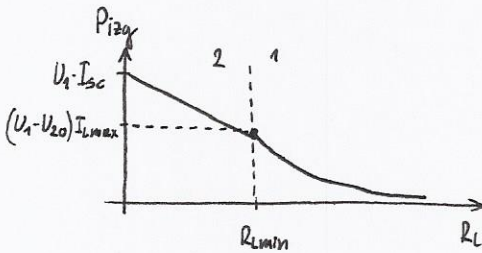
Delovanje v odvisnosti od R_L



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



$$i_L = \frac{U_{20}}{R_L}$$

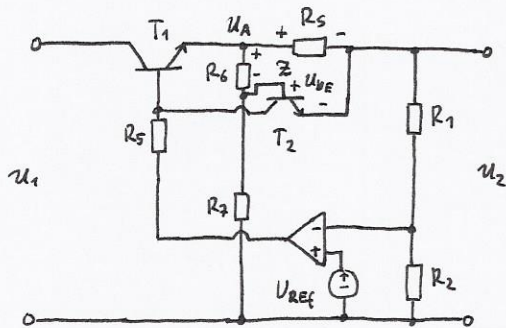


$$P_L = U_2 \cdot I_L = \begin{cases} \frac{U_{20}^2}{R_L}, & 1 \\ R_L I_L^2, & 2 \end{cases}$$

$$P_{izg} = \Delta U \cdot I_L = \begin{cases} (U_1 - U_{20}) \frac{U_{20}}{R_L}, & 1 \\ (U_1 - R_L I_{Lmax}) I_{Lmax}, & 2 \end{cases}$$



• Prepoznajena omejeitev toka (+ T_2, R_5, R_6, R_7)



$$\mathcal{Z} \div -u_{R6} + u_{R5} = u_{BE2}$$

$$u_6 = \frac{R_6}{R_6 + R_7} \cdot u_A = k \cdot u_A$$

$$u_{BE2} = -k \cdot u_A + u_{R5}$$

$$u_A = R_5 i_L + u_2$$

$$u_{BE2} = -k (R_5 i_L + u_2) + R_5 i_L =$$

$$u_{BE2} = (1-k) R_5 i_L - k u_2$$

1) ker $u_{BE2} < U_{BE20}$, je T_2 zaprt

$$u_{BE2} = (1-k) R_5 i_L - k \cdot U_{20}$$

2) meja $u_{BE2} = U_{BE20}$; $i_L = I_{Lmax}$, $u_2 = U_{20}$

$$U_{BE20} = (1-k) R_5 I_{Lmax} - k \cdot U_{20}$$

$$R_5 = \frac{k \cdot U_{20} + U_{BE20}}{(1-k) I_{Lmax}} = \frac{R_6}{R_7} \frac{U_{20}}{I_{Lmax}} + \left(1 + \frac{R_6}{R_7}\right) \frac{U_{BE20}}{I_{Lmax}}$$

3) T_2 odpnt

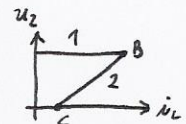
knabek stik

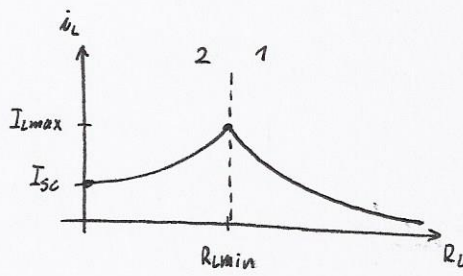
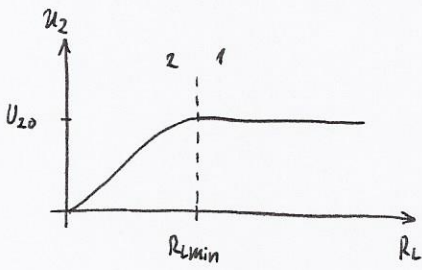
$$u_{BE2} = (1-k) R_5 i_L - k \cdot u_2$$

$$i_L = \frac{1}{(1-k) R_5} [k \cdot u_2 + U_{BE20}] \quad \text{Linearna zveza}$$

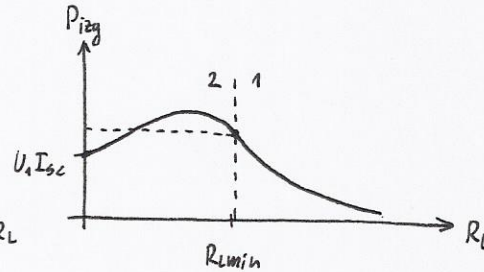
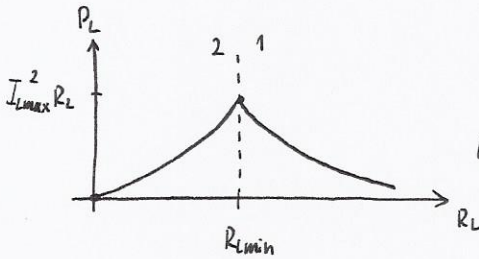
dve značilni točki

$$B: u_2 = U_{20} \rightarrow I_L = \frac{1}{(1-k) R_5} [k \cdot U_{20} + U_{BE20}] = I_{Lmax}$$





$$i_L = \begin{cases} \frac{U_{20}}{R_L} & , 1 \\ \frac{U_{BEK}}{(1-k)R_S + kR_L} & , 2 \end{cases}$$



$$P_L = \begin{cases} \frac{U_{20}^2}{R_L} & , 1 \\ R_L I_L^2 & , 2 \end{cases}$$

$$P_{izg} = \begin{cases} \frac{(U_1 - U_{20})^2}{R_L} & , 1 \\ (U_1 - R_L i_L) \cdot i_L & , 2 \end{cases}$$

Primer:

$U_{20} = 10 \text{ V}$

$U_1 = 15 \text{ V}$

$I_{Lmax} = 1 \text{ A}$

$R_6 = 2 \text{ k}\Omega$

$R_7 = 8 \text{ k}\Omega$

$U_{BE2K} = 0.6 \text{ V}$

$k = \frac{R_6}{R_6 + R_7} = 0.2$

$R_S = \frac{k \cdot U_{20} + U_{BEK}}{(1-k) I_{Lmax}} = 3.25 \Omega$ (več kot pri konst omejitvi $\rightarrow 0.6 \Omega$)

$R_{Smax} = R_S \cdot I_{Lmax}^2 = 3.25 \text{ W}$

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

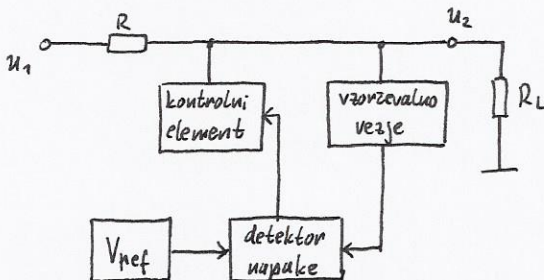
$P_{izg}(R_L = R_{Lmin}) = (U_1 - U_{20}) I_{Lmax} = 5 \text{ W}$

$P_{izg}(R_L = 0) = U_1 \cdot I_{sc} = U_1 \cdot \frac{U_{BEK}}{(1-k) R_S} = 0.23 \text{ A} \cdot 15 \text{ V} = 3.45 \text{ W}$

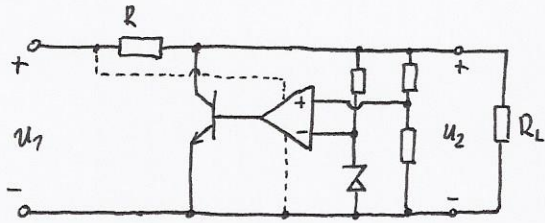
izk: $1 \quad \eta = \frac{P_{izh}}{P_{vh}} = \frac{\frac{U_{20}^2}{R_L}}{U_1 \cdot \frac{U_{20}}{R_L}} = \frac{U_{20}}{U_1} = 67\%$

B1) Paralelni nap. regulator brez PS

shematsko za PS:



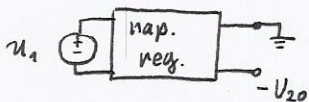
- Realizacija s PS :



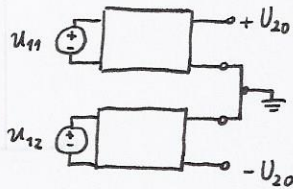
Minus in plus - minus napajanje / nap. regulator

15. 11. 2013

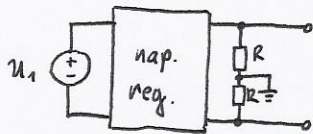
če imamo galvanško ločen izhod, lahko na maso priključimo plus sponko izhoda :



damo skupaj dva vira :

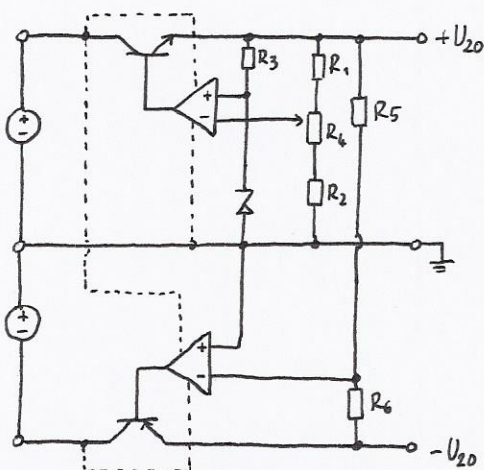


Dvojno napajanje z enim virom :



problematična
Rizh !

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



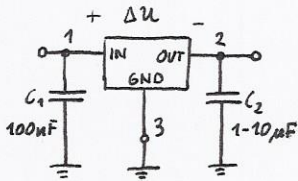
za $R_5 = R_6$: - izhod sledi + izhodu
 $u_{op2}^- = u_{op2}^+ = 0$

Integrirani napetostni regulatorji

- Delitev:
- a) fiksni
 - b) nastavljivi
 - c) univerzalni

a) Fiksni

kot tnapol

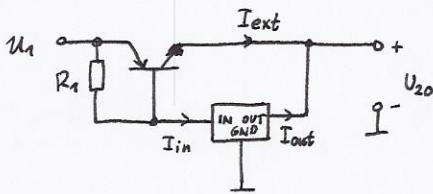


C_1 blokirni kondenzator

C_2 "zaloga" naboja za dinamične obremenitve

78XX
79XX $\rightarrow \Delta u \approx 3V \text{ min}$

za večje tokove lahko dodamo zunanji tranzistor:

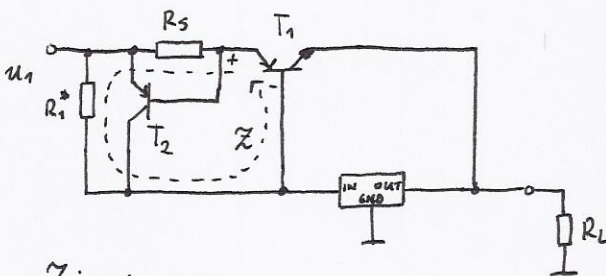


brez kratkostične omejitve!

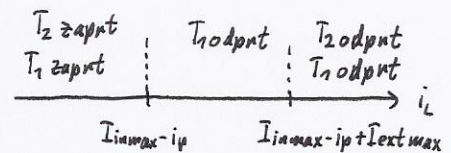
$$U_{be1} = R_1 \cdot I_{in}$$

$$U_{be0} = R_1 \cdot I_{inmax}$$

nadgradnja za večje tokove in tokovno zaščito:



tak se dvigne od $I_{inmax-ip}$
do $I_{inmax-ip} + I_{extmax}$



$$Z: U_{be1} = -U_{RS} + U_{R1^*}$$

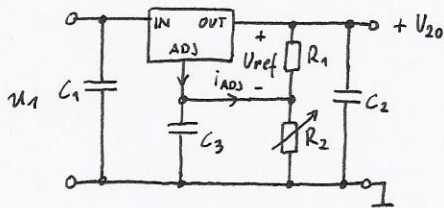
$$U_{be1} = -R_S I_{RS} + R_1^* I_{inmax}$$

$$U_{be1} = 0 + R_1^* I_{inmax} \text{ (pred/vkop } T_1 \text{) meja}$$

$$U_{be1} = U_{RS} = R_S I_{extmax}$$

T_2 preusmeri tok I_{ext} v $I_{in} \Rightarrow$
dvig temperature v regulatorju \rightarrow thermal shut-down

b) Nastavljivi



če je i_{ADJ} zanemarljiv ($i_{ADJ} \ll i_{R2}$)

$$U_{R1} = U_{REF} = \frac{R_1}{R_1 + R_2} U_{20}$$

$$U_{20} = \frac{R_1 + R_2}{R_1} U_{REF}$$

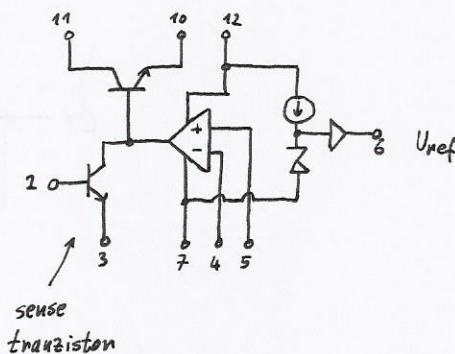
c) Univerzalni

primer: 723

Lastnosti: $u_2 \in [2V, 37V]$

Line regulation = 0.01%

Load regulation = 0.03%

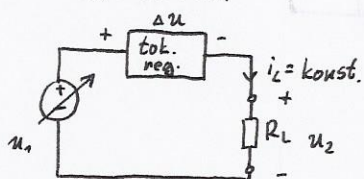


1.2.4. Tokovni generatorji / regulatorji / stabilizatorji

generatorji enosmernega toka

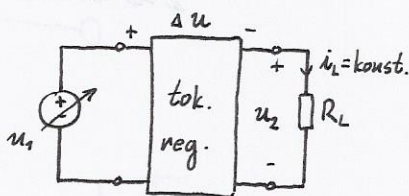
Delitev:

a) DVOPOLI



$u_1 > u_2$
bremenska upornost dovolj majhna

b) ČETVEROPOLI



$u_1 > u_2$, R_L omejena
navzgor

Izhodni tok: $i_2 = f(u_1, u_2, T)$

želje Δi_2 čim manjša

$$\Delta i_2 = \frac{\partial i_2}{\partial u_1} \Delta u_1 + \frac{\partial i_2}{\partial u_2} \Delta u_2 + \frac{\partial i_2}{\partial T} \Delta T$$

$i_2 = -i_L$ (i_2 tok v izhod četverpola)

$$\Delta i_2 = -\frac{\partial i_2}{\partial u_1} \Delta u_1 - \frac{\partial i_2}{\partial u_2} \Delta u_2 - \frac{\partial i_2}{\partial T} \Delta T$$

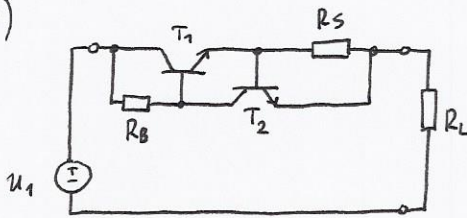
kriteriji kvalitete
regulatorja

za majhne
spremembe

- 1) transkonduktanca $\frac{\partial i_2}{\partial u_1} (\rightarrow 0)$
- 2) izhodna prevodnost $\frac{\partial i_2}{\partial u_2} (\rightarrow 0)$ $R_{i2} \rightarrow \infty$
- 3) temperaturni koeficient $\frac{\partial i_2}{\partial T} (\rightarrow 0)$

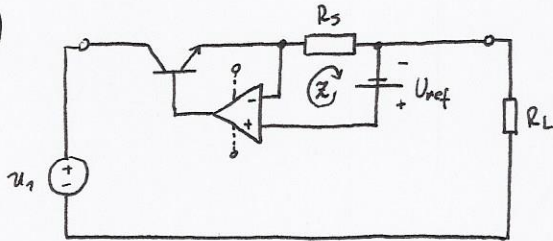
A) DVOPOLNI :

A1)



vezje tokovne omejitve iz napajalnika

A2)



\approx : $U_{ref} = R_S i_L$

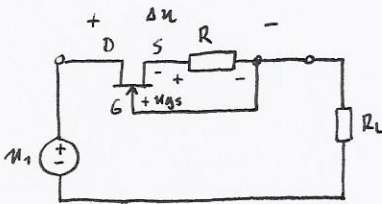
$i_L = \frac{U_{ref}}{R_S}$

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

slabost: napajanje OP-AMP

$\Delta u \geq U_{ref} + U_{cesat}$

A3)



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

JFET vedno v področju nasičenja

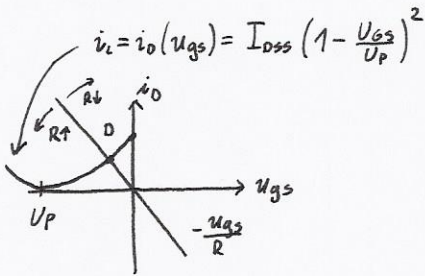
$i_L = i_d$

$u_{ds} = u_{gs} - U_p \geq U_{dsat} = U_{gs} - U_p$

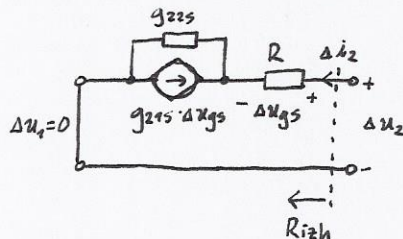
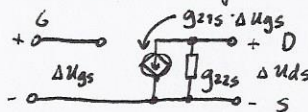
$i_D = -\frac{u_{gs}}{R}$

$\Delta u = u_{ds} + R i_L = \dots \geq -U_p$

$\Delta u > -U_p > 0$



inkrementalno vezje za določitev R_{izh} :



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

$i_D = g_{215} \Delta u_{gs} + g_{225} \Delta u_{ds}$

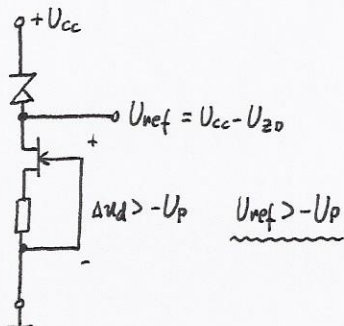
$= g_{215} (-R \Delta i_D) + g_{225} \Delta u_{ds}$

$R_{izh} = \frac{\Delta u_{ds}}{\Delta i_2} = \frac{\Delta u_{gs} - \Delta u_{ds}}{\Delta i_2} =$
 $= \frac{-R \Delta i_D - \frac{1 + g_{225} R}{g_{225}} \Delta i_D}{\Delta i_2} = \dots$

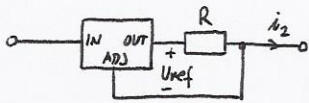
$R_{izh} = \left(1 + \frac{g_{215}}{g_{225}}\right) \cdot R + \frac{1}{g_{225}}$

to je lahko veliko

realizacija v 723 :



A4)

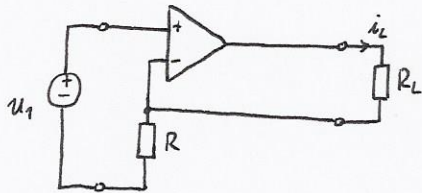


$$i_2 = \frac{U_{ref}}{R} + i_{adj} \approx \frac{U_{ref}}{R}$$

B) ČETVEROPOLNI:

- tokovno krmiljeni tokovni regulatorji (tokovna zrcala 1:1, 1:n) že obdelali!
- napetostno krmiljeni tokovni regulatorji

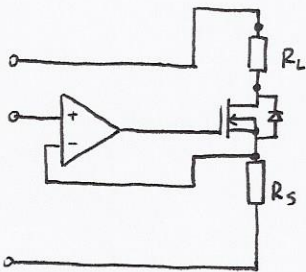
B1)



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

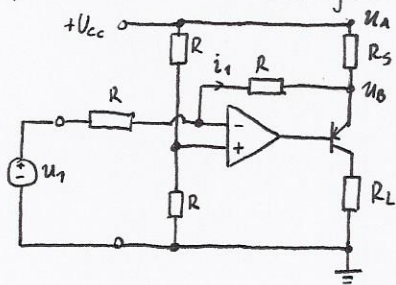
$$i_L = \frac{u_1}{R} = i_R$$

B2)



samo ena polariteta
breme ni ozemljeno

B3) rešitev za ozemljeno breme



analiza za idealni OP-AMP

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

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

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

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

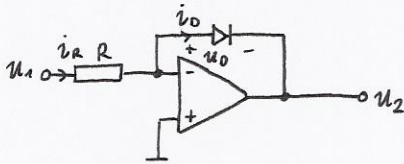
$$u_{RS} = u_A - u_B = u_1 \quad i_L = \frac{u_1}{R_S} \quad \text{za } i_1 < i_{RS}$$

1.1.5 Nelinearni ojačevalniki

22.11.2013

A) Logaritemski ojač: $u_2 = k \cdot \ln \frac{u_1}{U_R}$

za $u_1 > 0$



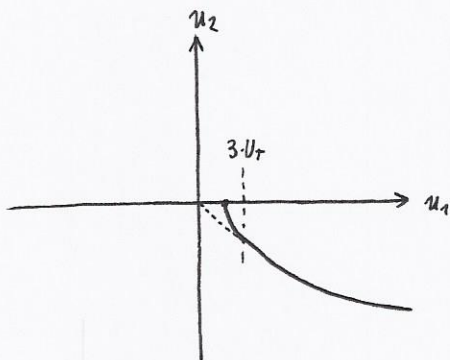
$$u_2 = -u_0 + u^+ = -u_0$$

$$i_R = i_0 + i^- = i_0$$

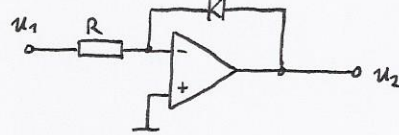
$$i_R = \frac{u_1 - u^-}{R} = \frac{u_1}{R}$$

$$u_1 = R \cdot i_R = R \cdot i_0 = R \cdot I_s e^{\frac{u_0}{U_T}} = R \cdot I_s e^{\frac{u_2}{U_T}} \quad | \ln$$

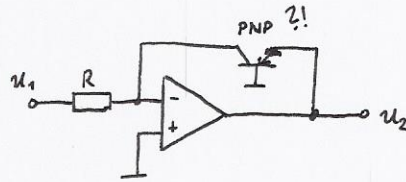
$$u_2 = -U_T \cdot \ln \frac{u_1}{R \cdot I_s}$$



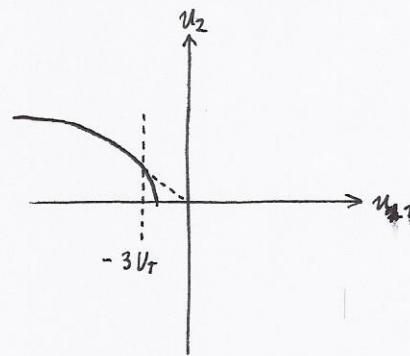
za $u_1 < 0$



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

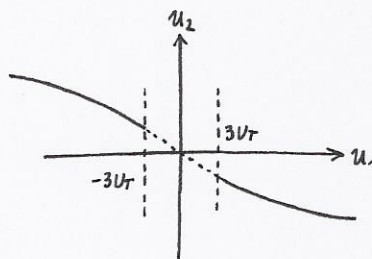
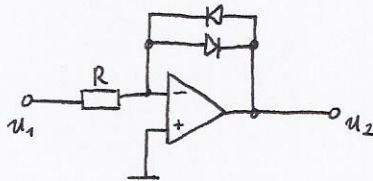


$$u_2 = U_T \cdot \ln \frac{-u_1}{R \cdot I_{Es}}$$



• za obe smeri u_1 :

anti-paralelni diodi v NPS



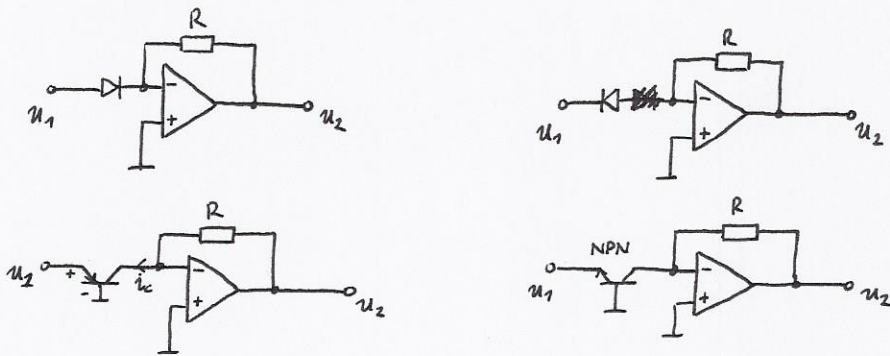
• za logaritem poljubne osnove:

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

za desetiškega:

$$\log_{10} x = 0.4343 \cdot \ln x$$

B) eksponentni ojač: $u_2 = k \cdot e^{\frac{u_1}{U_T}}$

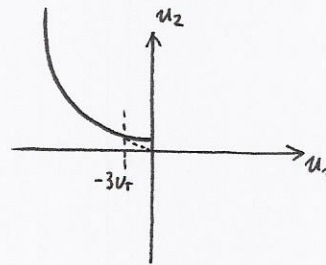
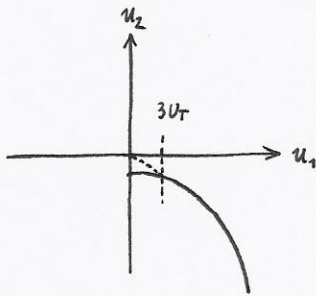


$u_1 = u_{EB}$

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

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

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



slabost: velika temperaturna odvisnost!
 dioda in tok nasičenja I_{ES}
 $I_{ES}(T), U_T(T)$

C) Analogni množilniki in delilniki
 dva vhoda!

C1) Množilniki

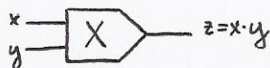
izkoriščajo lastnost logaritmov

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

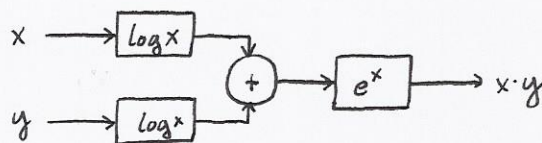
$e^{\ln x} = x$

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

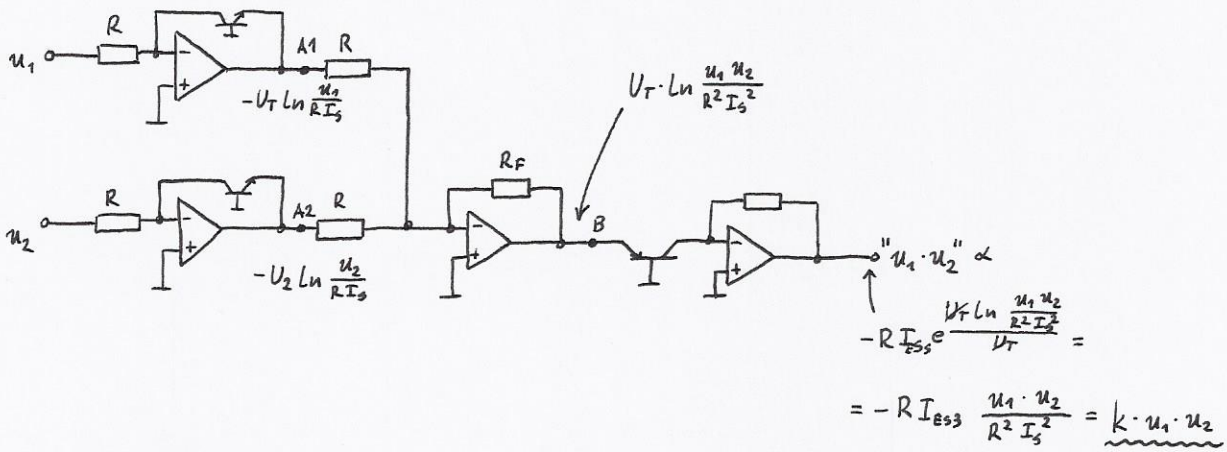
• simbol:



• shematsko:

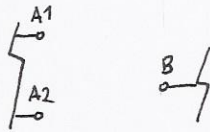


realizacija za $u_1, u_2 > 0$



C2) Delilniki

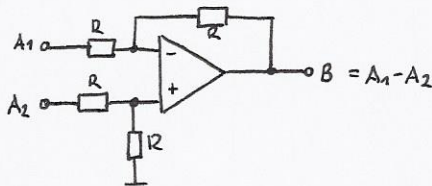
namesto sestevalnika damo odstevalnik



simbol:



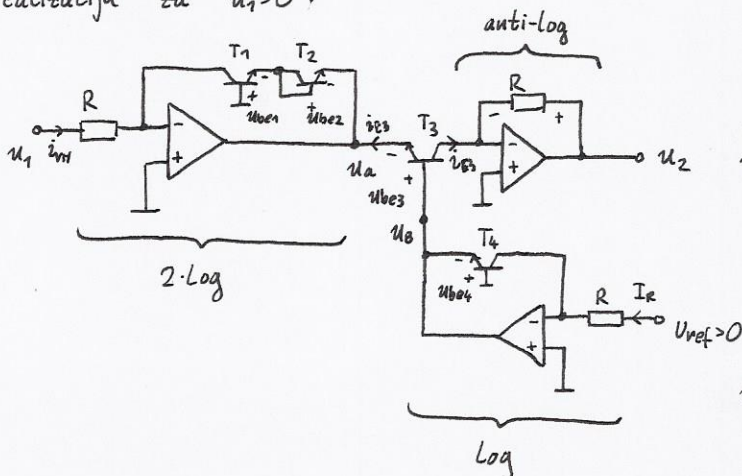
diferencialni ojačevalnik:



D) Kvadrirni ojačevalnik: $u_2 = k \cdot u_1^2$

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

realizacija za $u_1 > 0$:



$i_{vH} = \frac{u_1}{R}$

$i_{vH} = i_{c1} = i_{E1} = I_{ES} e^{\frac{u_{be1}}{U_T}}$

$u_a = -u_{be2} - u_{be1} = -2 u_{ba} = -2 U_T \cdot \ln \frac{i_{vH}}{I_{ES^{1/2}}}$

$I_R = \frac{U_{ref}}{R} = i_{c4} = i_{E4} = I_{ES4} e^{\frac{u_{be4}}{U_T}} = I_{ES4} e^{-\frac{u_B}{U_T}}$

$u_B = -U_T \cdot \ln \frac{I_R}{I_{ES4}} = -U_T \cdot \ln \frac{U_{ref}}{R \cdot I_{ES4}}$

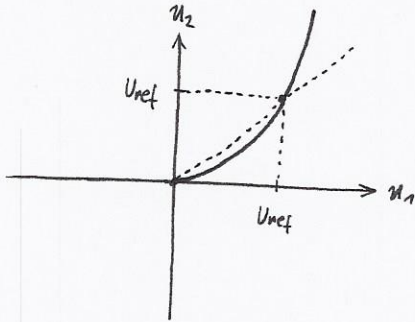
$u_{be3} = u_B - u_a = 2 U_T \ln \frac{i_{vH}}{I_{ES^{1/2}}} - U_T \ln \frac{I_R}{I_{ES4}} =$
 $= U_T \ln \left[\frac{i_{vH}^2}{I_{ES^{1/2}}^2} \frac{I_{ES4}}{I_R} \right] = \text{identični tranzistorji}$

$u_{be3} = U_T \ln \left[\frac{i_{vH}^2}{I_{ES} \cdot I_R} \right]$

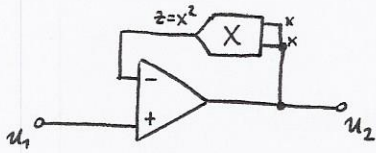
anti-log ojač:

$$i_{c3} = -i_{E3} = I_{E33} e^{\frac{u_{be3}}{U_T}} = I_{E33} e^{\frac{U_T \ln \frac{i_{v1}^2}{I_{E3} I_R}}{U_T}} = I_{E33} \frac{i_{v1}^2}{I_{E3} I_R} = \frac{i_{v1}^2}{I_R}$$

$$u_2 = u_R = i_{c3} \cdot R = R \cdot \frac{i_{v1}^2}{I_R} = R \cdot \frac{u_1^2}{R^2} = \frac{u_1^2}{R I_R} = \frac{u_1^2}{R \cdot \frac{U_{ref}}{R}} = \frac{u_1^2}{U_{ref}} \quad \frac{u_2}{U_{ref}} = \left(\frac{u_1}{U_{ref}} \right)^2$$



E) Kvadratno - korenski ojačevalnik:



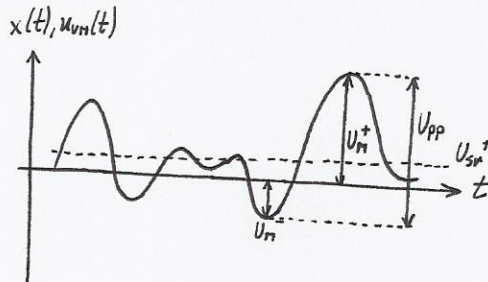
$$\begin{aligned} u_1 &= z \\ u_2 &= x \\ z &= x^2 = u_2^2 \cdot k \\ \underline{u_2} &= \sqrt{u_1} = \sqrt{\frac{u_1}{k}} = \underline{k^* \sqrt{u_1}} \end{aligned}$$

1.2 Dinamična vezja (z enim vhodom) za preoblikovanje signalov

1.2.1 Detektorji



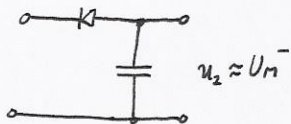
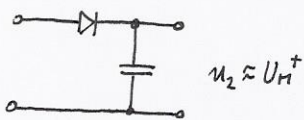
y d informaciji (x) idealno k=1
 ↓
 amplituda,
 sn. vrednost,
 RMS, temenska vr.



U_m ... magnitude
 U_{pp} ... vršna (peak to peak)
 U_{sr+} ... srednja vr. polvala + ?
 U_{rms}, U_{ef} ... RMS vrednost

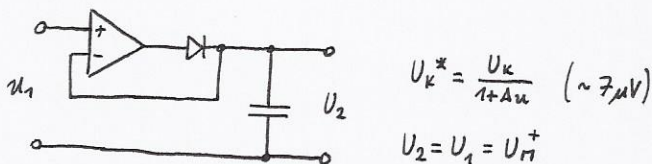
• Detektor temenske vrednosti

- bodisi za U_m^+ ali U_m^-



slabosti: - napaka pri u_2 zaradi U_k
- spremenljiva Z_{vh}

nadgradnja z napetostnim sledilnikom:

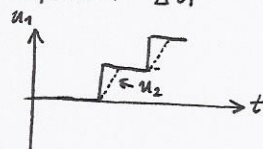


$$U_k^* = \frac{U_k}{1+A_u} \quad (\sim 7\mu V)$$

$$U_2 = U_1 = U_m^+$$

slabosti:

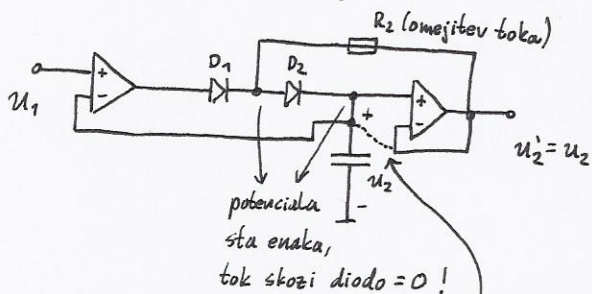
- zakasnitev spremembe izhodne napetosti Δt_i



$$\Delta t_i = \frac{U_{mi} - (-U_{EE})}{\text{slew-rate}}$$

vpliv bremenskega upora na izhodu izničimo:
lahko dodamo še en sledilnik napetosti

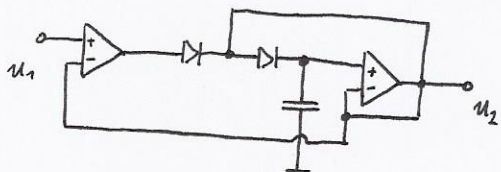
- izničenje vpliva reverznega toka diode:



potenciala sta enaka, tok skozi diodo = 0!

Lahko premaknemo

- izničenje vpliva I_B^-



- minimizacija vhodnega toka I_{B002}^+ :

MOSFET vhodna stopnja!

izhod OP-AMP je v minus nasitjenju če $u_1 < u_2$

- omejena hitrost spremembe na kondenzatorju $u_c(t)$

$$\frac{du_2}{dt} = \frac{du_c}{dt} = \frac{I_{\text{izhoptop max}}}{C}$$

- čim manjši C

- čim večji izhodni tok

- praznjenje kondenzatorja

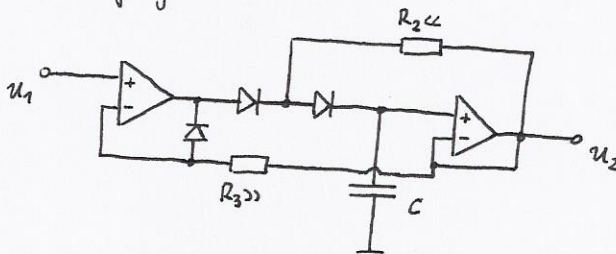
vhodni tok OP-AMPa

puščanje diode

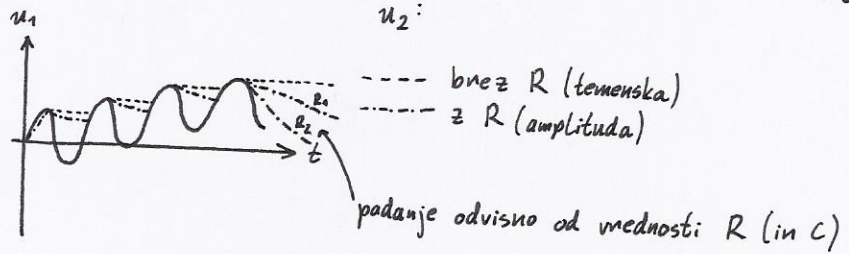
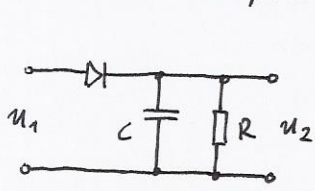
izolacijska upornost C

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

- zmanjšanje Δt_i :



• Detektor amplitude



Vse nadgradnje temenske vrednosti
lahko uporabimo tudi pri detektorju amplitude

Izziv: dimenzioniranje R in C (pri polnjenju in praznjenju)

Zgled: amplitudna modulacija:

$u_g = u_{am}$
 $u_{am} = U_n (1 + m \cdot \cos \omega_0 t) \cdot \cos \omega_n t$

modulacija (informacija) \uparrow
 faktor modulacije $0 < m < 1$ \uparrow
 nosilni signal \uparrow

1. zahteva - polnjenje C: polnjenje preko diode je hitrejše kot nanaščanje ovojnice $\tau_0 \ll R$
2. zahteva - praznjenje C: praznjenje preko upora R mora biti počasnejše od nosilnega signala

3. zahteva - praznjenje C: praznjenje mora biti hitrejše od frekv. m informacije
 $RC = \tau > \frac{2\pi}{\omega_n} = T_n$

napetost ovojnice: $U_n \cdot (1 + m \cos \omega_0 t) = u_g$
 $\frac{du_g}{dt} = -U_n \cdot m \cdot \omega_0 \cdot \sin \omega_0 t$ gradient ovojnice

praznjenje kondenzatorja: $u_c(t) = U_{c0} e^{-\frac{t}{\tau}}$ $\tau = RC$
 $\frac{du_c}{dt} = -U_{c0} \frac{1}{\tau} e^{-\frac{t}{\tau}} = -\frac{u_c(t)}{\tau} = -\frac{u_c(t)}{RC}$

oba negativna!
 nap. ovojnice \downarrow
 $\frac{du_c}{dt} < \frac{du_g}{dt} < 0$ $u_c(t) = u_g(t)$
 $-\frac{u_g(t)}{RC} \leq -U_n \cdot m \cdot \omega_0 \cdot \sin \omega_0 t$

$\frac{1}{RC} \geq \frac{U_n \cdot m \cdot \omega_0 \cdot \sin \omega_0 t}{U_n (1 + m \cdot \cos \omega_0 t)} = f(\omega_0)$

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

pogledamo kdaj je desna stran maksimalna

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

$m \omega_0 \cos \omega_0 t + \frac{m^2 \omega_0 \cos^2 \omega_0 t + m^2 \omega_0 \sin^2 \omega_0 t}{1} = 0$
 $\cos \omega_0 t + m = 0$

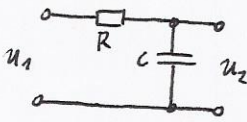
Združitev zahtev 2. in 3. :

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

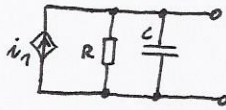
• Detektor srednje vrednosti

popravnice pozitivnega, negativnega polvala ali poprečje obeh polvalov
 principi - gladilniki (C, L)

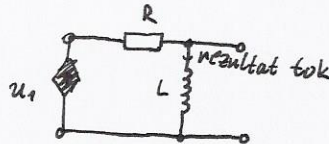
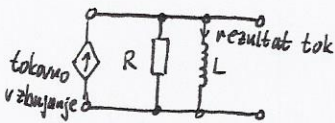
način s C:



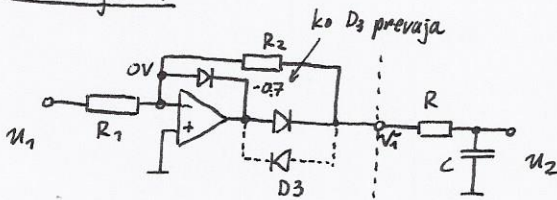
način s C:



način z L:



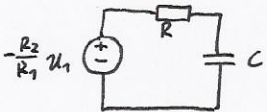
Realizacija 1:



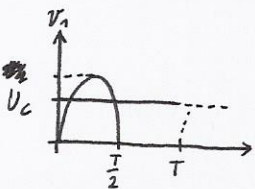
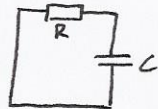
prepuščamo negativni polval $u_1 < 0$

- brez D_3 praznenje C preko R in R_2
- z D_3 je napetost na v_1 pri praznjenju na 0V zato polnimo in praznimo preko R

za $u_1 < 0$:



za $u_1 > 0$



Za stacionarne razmere:

$$\int_0^T i_c(t) dt = 0, \quad \langle i_c(t) \rangle = 0$$

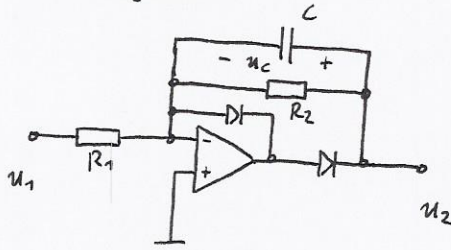
$$\int_0^{T/2} i_{cpol.}(t) dt + \int_{T/2}^T i_{cpraz.}(t) dt = 0$$

$$\int_0^{T/2} \frac{U_m \sin(\omega t) - U_c}{R} dt + \int_{T/2}^T -\frac{U_c}{R} dt = 0$$

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

2U_m = U_c

Realizacija 2:



za negativni polval sin:

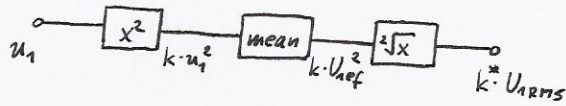
$$U_C = \frac{1}{T} \frac{R_2}{R_1} U_1$$

• Detektor prave efektivne vrednosti:

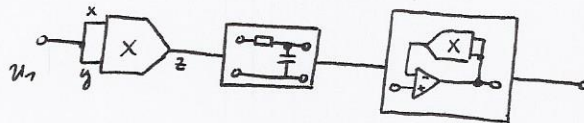
koren povprečja kvadrata
RMS - root mean square

$$U_{RMS} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} u_1^2(t) dt}$$

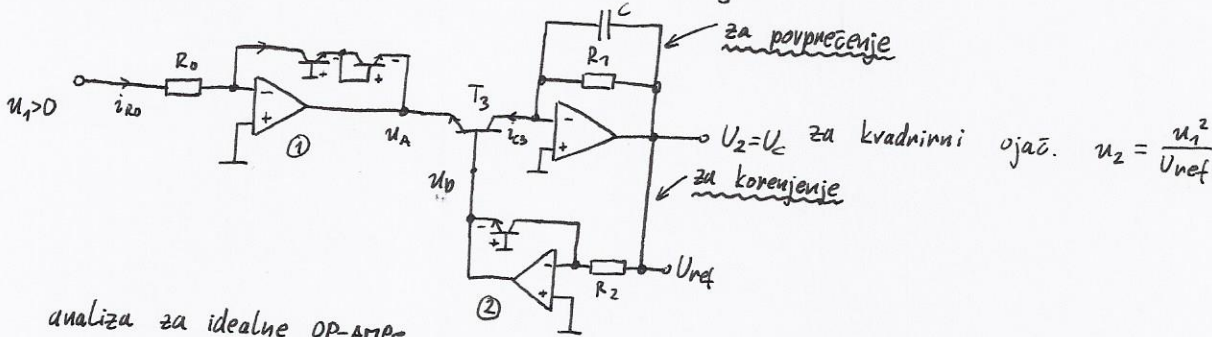
simbolični prikaz:



načelna realizacija:



Realizacija RMS detektonja s kvadrirnim vezjem



analiza za idealne OP-AMPE

① $i_{R0} = \frac{u_1}{R_0} = i_{c1} = i_{E1} = i_{c2} = i_{E2} = I_{ES} \cdot e^{\frac{u_{be}}{U_T}}$
 $u_A = -u_{be2} - u_{be1} = -2 u_{be} = -2 \cdot U_T \cdot \ln \frac{u_1}{R_0 I_{ES}}$

② $u_B = -u_{be4} = -U_T \cdot \ln \frac{I_{R2}}{I_{ES4}} = -U_T \ln \frac{U_2}{R_2 \cdot I_{ES4}}$

$T_3: u_{be3} = u_B - u_A = U_T \cdot \ln \left[\left(\frac{u_1}{R_0 I_{ES}} \right)^2 \cdot \frac{R_2 I_{ES4}}{U_2} \right]$

$i_{c3} = I_{ES3} \cdot e^{\frac{u_{be3}}{U_T}} = I_{ES3} \cdot \left[\left(\frac{u_1}{R_0 I_{ES}} \right)^2 \cdot \frac{R_2 I_{ES4}}{U_2} \right]$

$U_2 = U_C = \bar{u}_C = R_1 \cdot i_{c3} = R_1 \cdot I_{ES3} \cdot \left[\left(\frac{u_1}{R_0 I_{ES}} \right)^2 \cdot \frac{R_2 I_{ES4}}{U_2} \right] =$

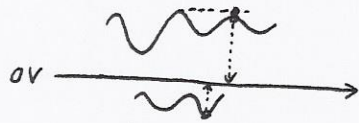
$U_2 = \frac{R_1 R_2}{R_0^2} \cdot \frac{I_{ES3} \cdot I_{ES4}}{I_{ES1} \cdot I_{ES2}} \cdot \frac{\bar{u}_1^2}{U_2}$

rezultat:

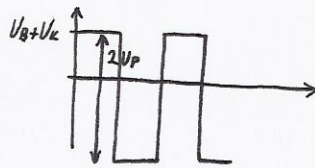
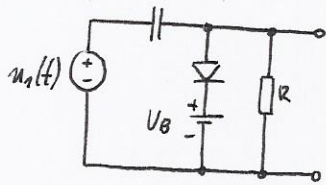
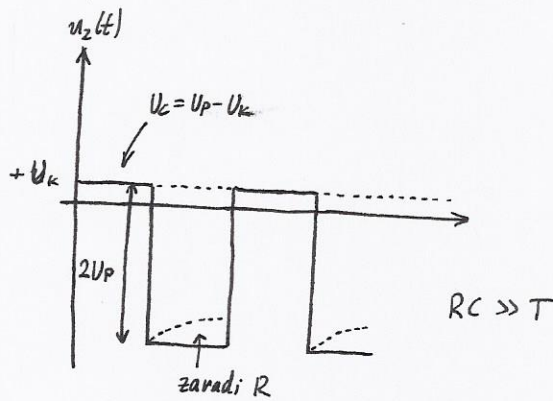
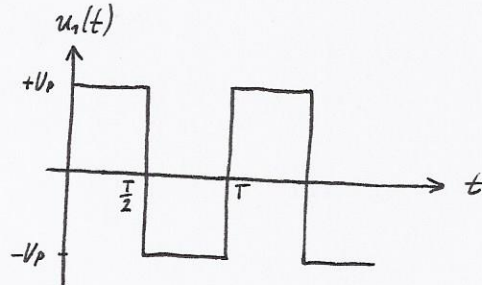
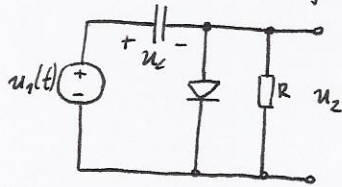
$U_2^2 = \sqrt{\frac{R_1 \cdot R_2}{R_0^2} \cdot \frac{1}{T} \int_0^T u_1^2 dt}$

za $I_{ESx} = konst$
za $R_1 = R_2 = R_0$ dobimo
RMS detektor

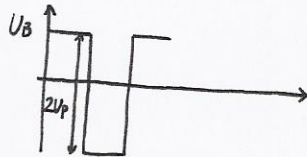
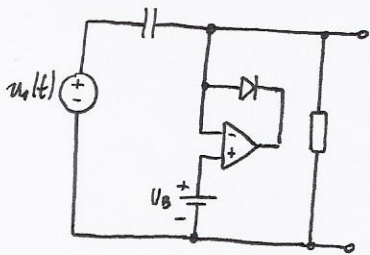
- Pripenjalnik (clampen oz. level shifter?)



preprosta realizacija:

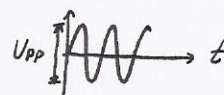
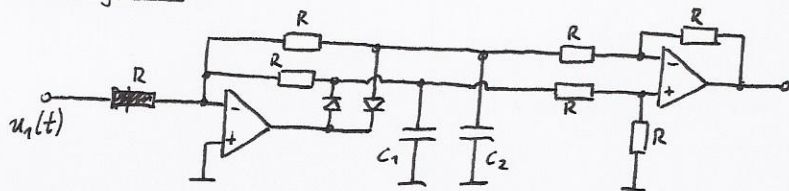


z idealno diodo:



- Detektor medtemenske vrednosti (peak-to-peak)

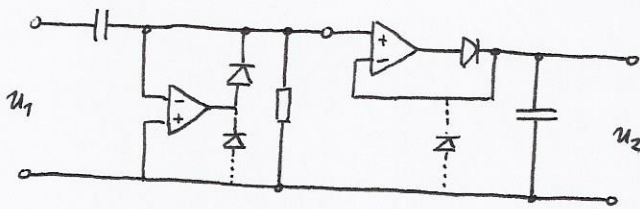
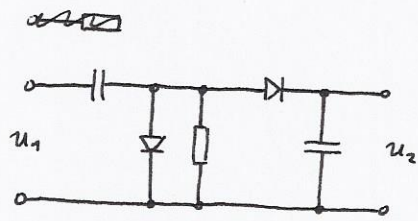
Realizacija 1:



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

$$u_2 = U_{C1} - U_{C2} = +U_{min} - (+U_{max}) = U_{pp}$$

Realizacija 2: pripenjalnik + detektor temenske vr.

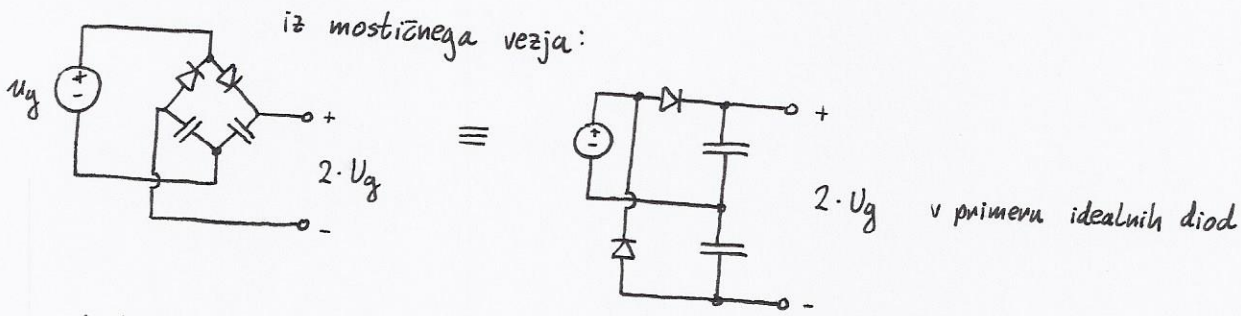


• Množilniki napetosti

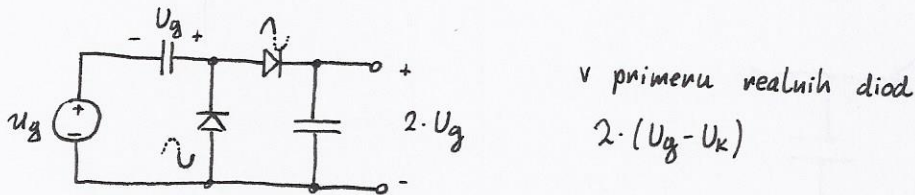
6.12.2013



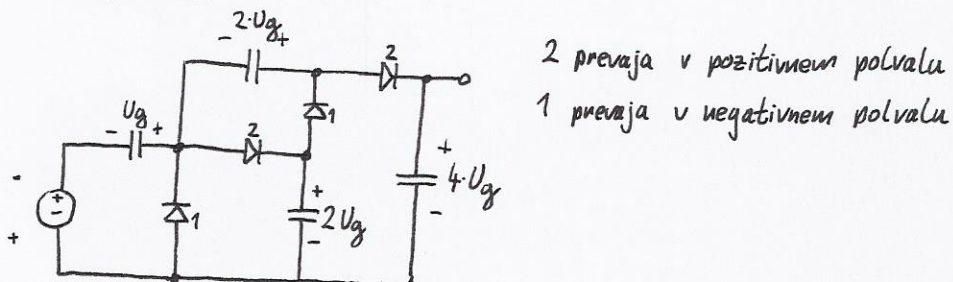
1) Podvojlno vezje



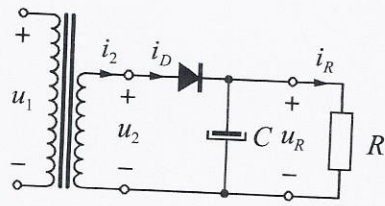
polvalni napetostni množilnik:



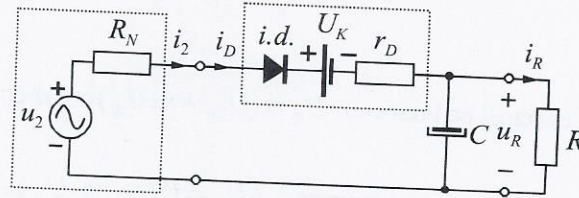
2) Vezje x4



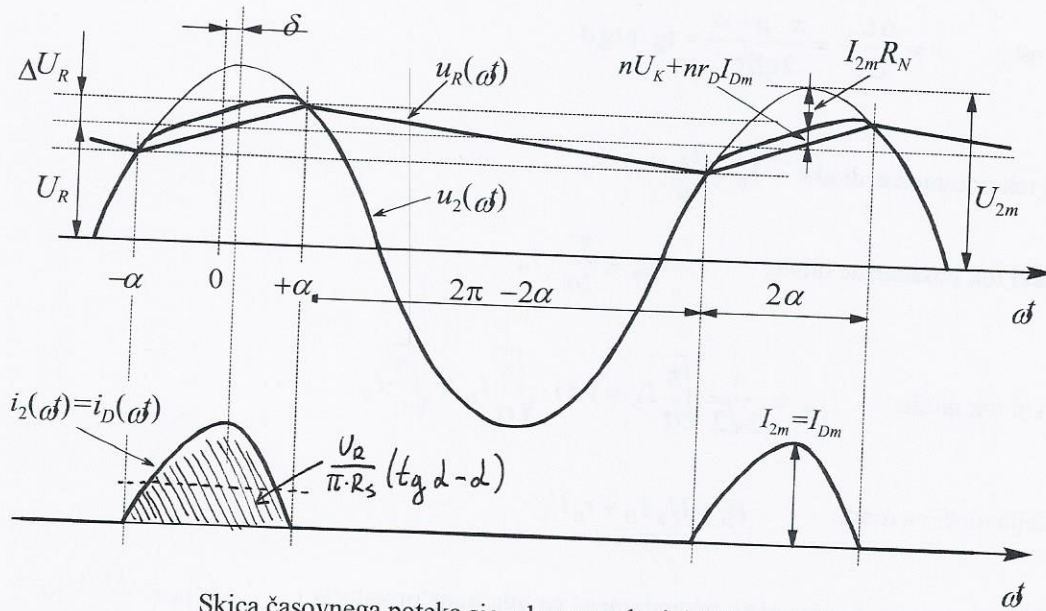
Polvalni RC usmernik:



Vezje polvalnega RC usmernika



Nadomestno vezje polvalnega RC usmernika



Skica časovnega poteka signalov za polvalni RC usmernik

Enačbe za polvalni ali polnovalna (s srednjim odcepom tr. ali z mostičem) RC usmernika:

Tip usmernika:
$$p = \begin{cases} 1, & \text{polvalni} \\ 2, & \text{polnovalni} \end{cases}$$

Število diod, ki prevaja v enem polvalu:

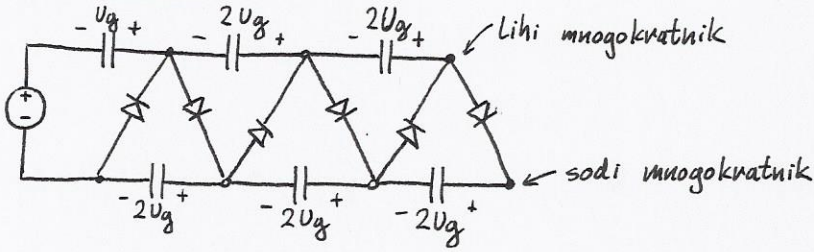
$$n = \begin{cases} 1, & \text{polvalni ali polnovalni s transformatorjem s srednjim odcepom} \\ 2, & \text{polnovalni z mostičem} \end{cases}$$

Nadomestna serijska upornost na vходу usmernika:
$$R_S = R_N + n \cdot r_D$$

Kot odprtja α rešimo iterativno:
$$\alpha_{i+1} = \arctg\left(\frac{\pi \cdot R_S}{p \cdot R} + \alpha_i\right)$$

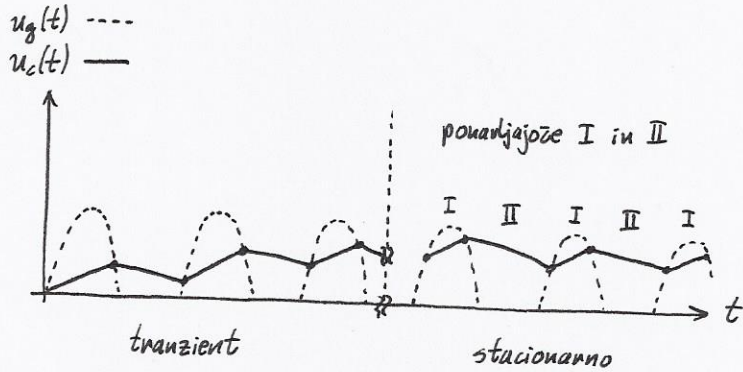
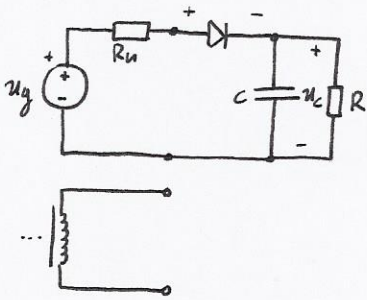
Kot δ izračunamo iz znanega kota odprtja α :
$$\delta = \arctg\left(\frac{\pi/p - \alpha}{2\pi f \cdot RC \cdot \tg \alpha}\right)$$

3) Vežje x N



1.2.4. RC usmerniki

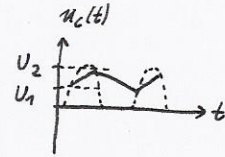
• Polvalni RC-usm



Za prehodni pojav → Spice
za stacionarne razmere

$\langle i_o \rangle = \langle i_R \rangle$
 $I_D = I_R$ (DC)

$i_c = C \cdot \frac{du_c}{dt}$ stacionarno u_c ni več ne raste,
zato $\langle i_c \rangle = 0$



$$\left. \begin{aligned} u_o(t) &= u_g(t) - u_c(t) \\ i_R(t) &= \frac{u_o(t)}{R} \\ i_o(t) &= i_c(t) + i_R(t) \\ i_c(t) &= C \cdot \frac{du_c(t)}{dt} \end{aligned} \right\} \text{SPLOŠNO}$$

- Ⓘ $u_g > u_c$: D prevaja
- Ⓢ $u_g < u_c$: D zaprta

→ ne poznamo robnih pogojev (U_1 in U_2), analitična rešitev ni možna brez preprostitev

$i_o(t) = C \frac{du_c(t)}{dt} + \frac{u_c(t)}{R}$

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

Kammenlochenjeva metoda

-aproximacija s trikotno obliko napetosti na kondenzatorju
glej list...

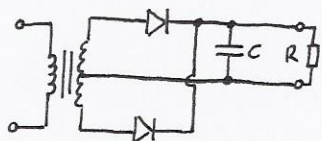
$U_1 = U_g \cdot \cos(-\alpha - \delta)$
 $U_2 = U_g \cdot \cos(\alpha - \delta)$ → $U_R = U_g \cdot \cos \alpha \cdot \cos \delta$ (srednja vrednost)

valovitost $\gamma = \text{tg} \alpha \cdot \text{tg} \delta$

še vedno rabimo α in δ

● Polnovalni RC-usm

A) z dvema diodama in srednjim odcepom na sekundarju



Rezitev po Kammerlochenju:

$$d_{im} = \arctg \left(d_i + \frac{\pi}{p} \cdot \frac{R_s}{R} \right)$$

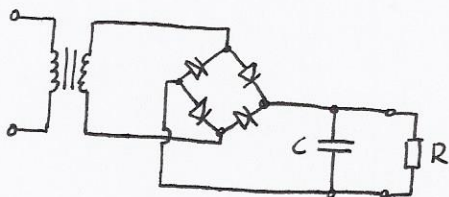
$$\operatorname{tg} \delta = \frac{1}{\omega RC} \cdot \frac{\frac{\pi}{p} - d}{\operatorname{tg} d}$$

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

↑
število diod

polvalni
↓
p = 1, 2, 3 ← trifazni
↑
polnovalni

B) s štirimi diodami (graetz)



Razmere na usmerniških diodah:

zapora: • pri polvalnem usmerniku čuti maks. $2 \cdot U_g$

U_{RRM} (reverse repetitive magnitude) dovolj visoka

• pri polnovalnem RC usmerniku z mostičem maks $U_g + U_k < U_{RRM}$

• pri polnovalnem RC usmerniku z odcepom maks $2 \cdot U_g$

prevajanje: enosmerni tok $I_D = \frac{p}{\pi} \cdot \frac{U_g}{(R_N + n \cdot r_D)} (\operatorname{tg} d - d) < I_{F(av)}$

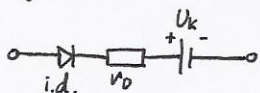
temenski tok $I_{Dmax} = \frac{U_g}{R_N + n \cdot r_D} \cos \delta (1 - \cos d) < I_{F(RM)}$

kratkostični tok $I_{Dkratkostični} = \frac{U_g}{R_N + n \cdot r_D} < I_{F(sm)}$

faktor obnemenitve $\int i_D^2 dt = \frac{U_g^2 \cdot C}{R_N + n \cdot r_D} < \int i_D^2 dt = I^2 \cdot \Delta t$ tipično $\Delta t = 10 \mu s$

efektivni tok $I_{Def} = \frac{\pi}{2\sqrt{2}} \sqrt{\frac{\pi}{d}} \cdot I_D < I_{F(RMS)}$

Disipacija moči na diodi:



za čas prevajanja diode $-d < \omega t < d$

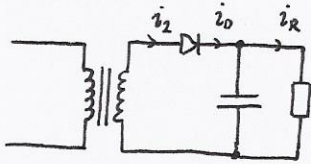
$$u_d = r_D \cdot i_D + U_k$$

trenutna moč $p(t) = i_D(t) \cdot u_D(t) = i_D (r_D \cdot i_D + U_k) = i_D^2 r_D + i_D U_k$

povprečna moč $P_D = \frac{1}{2\pi} \int_0^{2\pi} p(\omega t) d\omega t = r_D I_{Def}^2 + I_D \cdot U_k$

Razmene na transformatorju:

a) polvalni USM



$$I_D = I_R$$

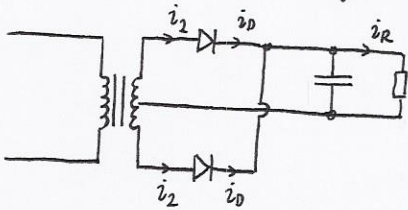
$$I_{D\text{ef}} = \frac{\pi}{2\sqrt{2}} \sqrt{\frac{\pi}{\alpha}} \cdot I_D$$

$$I_{2\text{ef}} = I_{D\text{ef}}$$

$$U_{2\text{ef}} = \frac{U_{2m}}{\sqrt{2}} = \frac{U_G + U_K}{\sqrt{2}} = \frac{U_R}{\cos\alpha \cdot \cos\delta} + U_K$$

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

b) polnovalni USM s srednjim odcepom



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

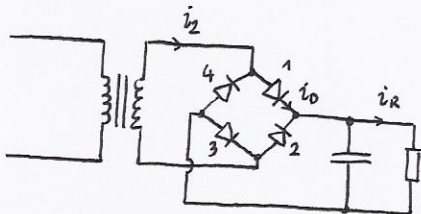
$$I_{D\text{ef}} = \frac{\pi}{2\sqrt{2}} \sqrt{\frac{\pi}{\alpha}} \cdot \frac{1}{2} I_R$$

$$I_{2\text{ef}} = I_{D\text{ef}}$$

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

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

c) polnovalni USM z Graetzovim vezjem



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

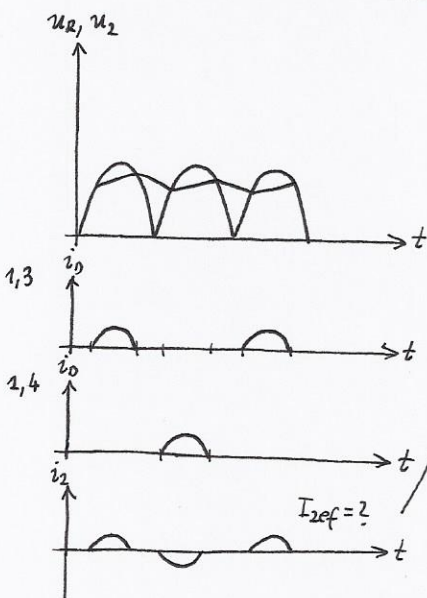
$$I_{D\text{ef}} = \frac{\pi}{2\sqrt{2}} \sqrt{\frac{\pi}{\alpha}} \cdot \frac{1}{2} I_R$$

$$I_{2\text{ef}} = ?$$

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

$$I_{2\text{ef}} = \sqrt{2} I_{D\text{ef}}$$

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



Potek načrtovanja RC USM

ne glede na tip RC usm

Zahteve: U_R , valovitost γ , f , tip usmunnika

ocena vrednosti trafo in diod: $R_N (< 1 \Omega)$

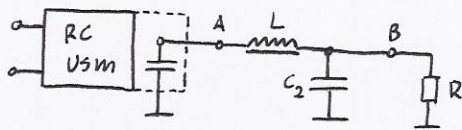
$r_o, U_k (0.1 \div 1.2 \Omega) (0.3 \div 1.0 V)$

• Postopek:

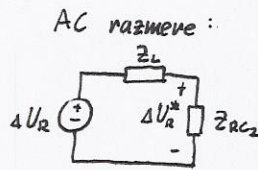
- ① kot odprtja $d = ?$ $d_{i+1} = \arctg(d_i + \frac{U_R}{P} \cdot \frac{R_s}{R})$ $p \dots$ št. polvalov $d = 30 \dots 40^\circ$
- ② parameter δ $\delta = \arctg(\frac{\gamma}{\tan d})$ $\delta \leq 10^\circ$
- ③ kapacitivnost C $C = \frac{1}{\omega R} \cdot \frac{\frac{\pi}{\delta} - d}{\gamma}$
- ④ parametri diod I_o, I_{def}, P_{def} (glede na ohlajenje)
- ⑤ parametri trafo $I_{zef}, U_{zef} \rightarrow n_1:n_2, P_{ef} [VA]$

Dodatno glajenje

LC-filten (namesto povezovanja C)



zaradi upornosti tuljave se izhodna napetost nekoliko zmanjša: $U_B = U_A \cdot \frac{R}{n_2 + R} = U_R^*$
 tudi U_R



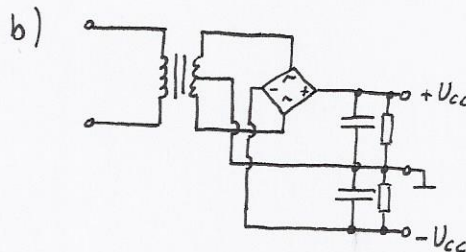
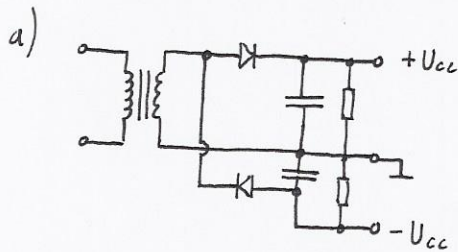
$$\Delta U_R^* = \frac{Z_{RC2}}{Z_L + Z_{RC2}} \cdot \Delta U_R$$

$$\Delta U_R^* \approx \frac{Z_{RC2}}{Z_L} \cdot \Delta U_R$$

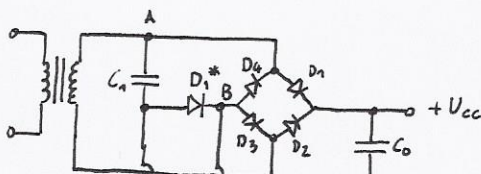
$$\Delta U_R^* \approx \frac{1}{\omega^2 L C_2} \cdot \Delta U_R \quad (\text{velika atenuacija valovitosti})$$

$$|Z_L| = |\omega L| \gg |Z_{RC2}| = \left| \frac{1}{1 + j\omega R C_2} \right|$$

1.6. RC USM z dvojnim napajanjem



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



Analiza c) po polvalih:

- poz-polval: D_1, D_3 prevajata in polnita C_0

$$u_{AB} = u_{01} + u_{C0} = u_{C1} + u_{01}^* = U_{K1} + u_{C0} = u_{C1} + U_{K1}^* \Rightarrow D_1^* \text{ prevaja in polni } C_1 \quad (C_1 \text{ se napolni na } \sim U_{CC})$$

- neg-polval: D_2, D_4 prevajata in polnita C_0

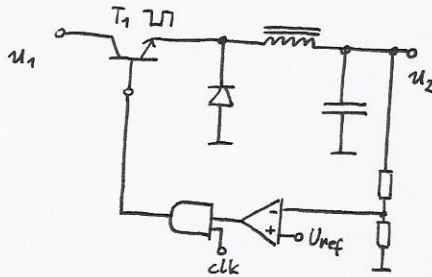
$$u_{AB} = -u_{04} = -U_{K4} \Rightarrow D_1^* \text{ zaprta}$$

dioda D_4^* prevaja, zato se naboj iz C_1 prerazporedi preko D_4 in D_4^* na C_2

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

slabost RC USM: nizek izkoristek [30 ÷ 70 %]
(regulatorjev)

stikalni regulator:



- Dodatna prednost (poleg izkoristka):

- možnost $U_2 > U_1$
- možnost $-U_2$ pri $+U_1$

Delitev:

- 1) regulator navzdol (step-down) $|U_2| < |U_1|$ buck
- 2) regulator navzgor (step-up) $|U_2| > |U_1|$ boost
- 3) invertirajoč regulator (inverting, buck-boost) $U_2 = -kU_1$ $k > 1$ ali $k < 1$

- Slabosti:

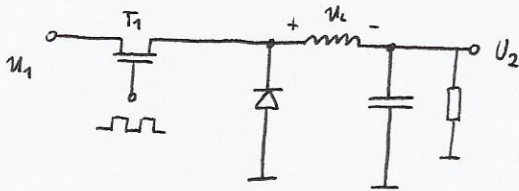
- število komponent
- sum in motnje zaradi preklapljanje
- dodatni gladilni elementi (vhod in izhod)

- Prednosti:

- miniaturnost
- izkoristek

$$\eta = \frac{P_{izh}}{P_{izh} + P_{preg}} \quad P_{preg} = \text{koust.}$$

2.1. Regulator navzdol



• princip delovanja:

T₁ ON: polnjenje L in C

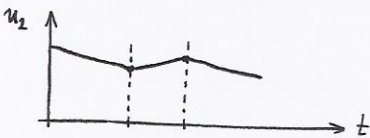
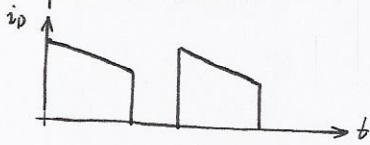
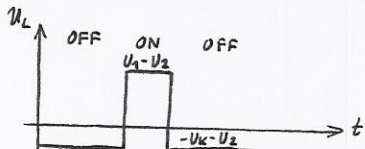
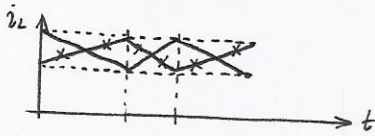
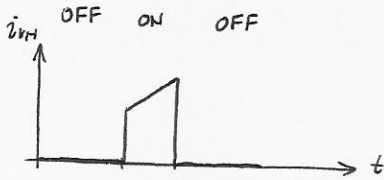
$$u_L = u_1 - R_{on} \cdot i_L - U_2 > 0$$

$$\frac{di_L}{dt} = \frac{U_L}{L} \quad (\text{tok narašča})$$

T₂ OFF: praznjenje L in C

$$u_L = -u_0 - u_C = -U_k - U_2 < 0$$

$$\frac{di_L}{dt} = \frac{U_L}{L} \quad (\text{tok linearno upada})$$



• Analiza za idealne elemente:
(R_L, R_{ESR} = 0, R_{on} = 0, U_k = 0)

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

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

za stacionarne razmere $|\Delta I_{Lon}| = |\Delta I_{Loff}|$

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

$$U_2 (t_{off} + t_{on}) = U_1 \cdot t_{on}$$

$$\frac{U_2}{U_1} = \frac{t_{on}}{t_{on} + t_{off}} = D$$

$$U_2 = D \cdot U_1$$

D... duty cycle (0=1)

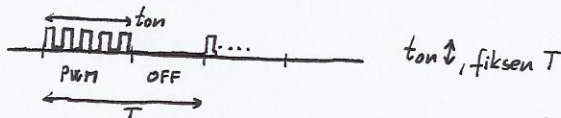
Da dobimo regulator, potrebujemo povratni sklop s krmilnim vezjem:

Trije koncepti:

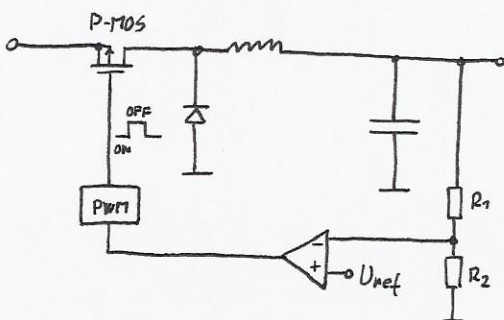
- PWM $t_{on} \uparrow$, fiksni T

- PFM (pulse-frequency modulation) T \downarrow , fiksni ton

- interval PWM, paketni intervali



• Realizacija regulatorja navzdol:



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

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

primer MAX 638

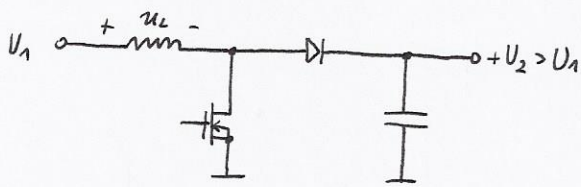
$$U_1 = 5 \dots 16 \text{ V}$$

$$U_2 = +5 \text{ V}$$

$$\eta \approx 85 \%$$

$$f_{osc} = 65 \text{ kHz}$$

2.2 Regulator navzgor



"ON" $u_L = U_1 - R_L i_L$

$\frac{di_L}{dt} = \frac{u_L}{L} > 0$ tok linearno narašča

"OFF" nakopičena energija $W_L = \frac{1}{2} L i_{pk}^2$

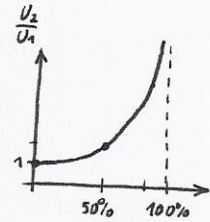
$u_L = U_1 - U_2 - U_k < 0$

$\rightarrow t_{on} U_1 + t_{off} (U_1 - U_2) = 0$

$U_1 (t_{on} + t_{off}) - t_{off} U_2 = 0$

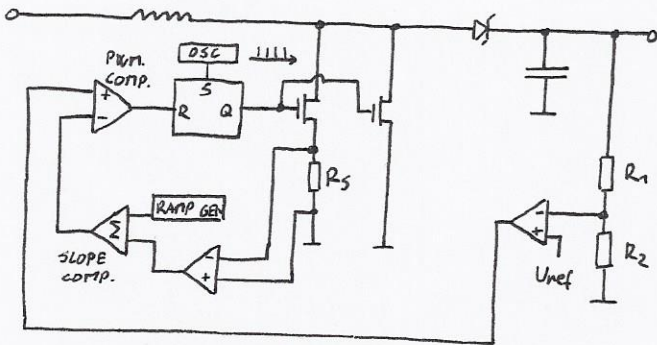
$U_2 = \left(\frac{t_{on}}{t_{off}} + 1\right) \cdot U_1$

$U_2 = \frac{1}{1-D} U_1$

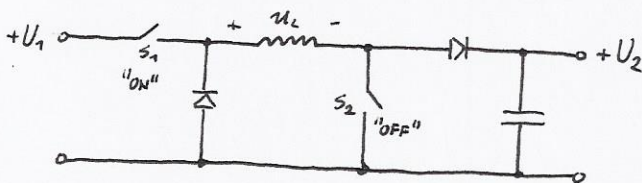


MAX 752:

20.12.2013



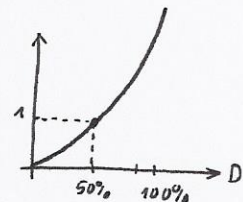
Regulator navzdol in navzgor (neinvertirajoč) 2.3



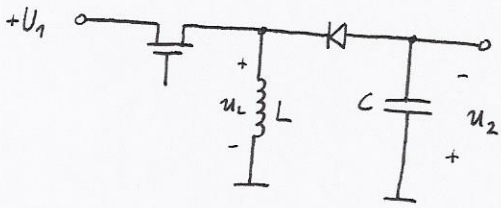
sinhrono krmiljenje S_1 in S_2

Analiza za idealne elemente:

$U_2 = \frac{t_{on}}{t_{off}} \cdot U_1 = \frac{D}{1-D} U_1$



2.4 Invertirajoč regulator



"ON" $u_L = U_1$ i_L narašča

"OFF" $u_L = -u_2 - U_k$ i_L pada

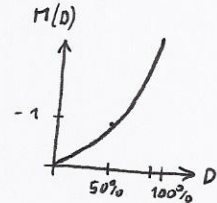
Analiza:

$$D U_1 + D'(-u_2) = 0$$

$$U_1 = -\frac{D'}{D} u_2$$

$$U_1 = -\frac{1-D}{D} u_2$$

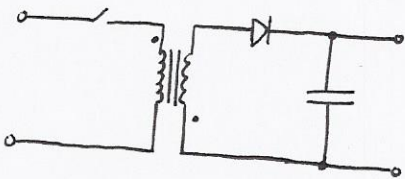
$$u_2 = -\frac{D}{1-D} U_1$$



2.5 Stikalni napajalniki

galvansko ločeni stikalni regulatorji:

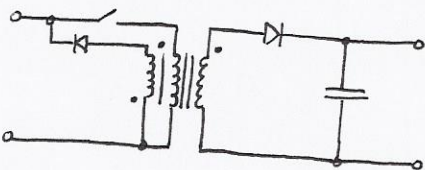
1) "FLYBACK" oz zaporni regulator navzdol niže moži (?)



"ON" tok v primaru narašča, dioda zaprta

"OFF" kondenzator se napolni, inducirana napetost "resetira" tuljavo

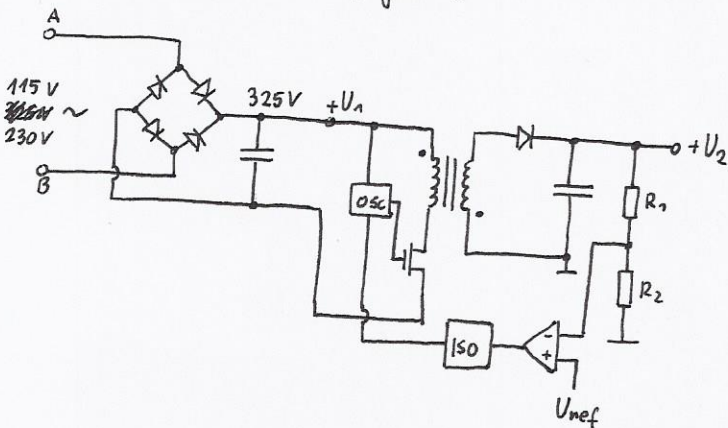
2) "FORWARD" oz prevodni regulator navzdol večje moži (?)



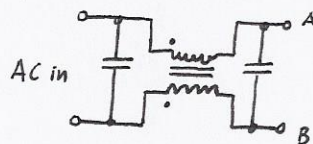
"ON" inducirana napetost na sekundanju polni kondenzator

"OFF" dioda zaporno pol., stikalo zaprto (energija ne more odteči)

Celotni FLYBACK napajalnik:



filter na vrodu:



prednosti / slabosti:

Linearni	stikalni
5V, 25A	5V, 26A
9.5 kg	1.2 kg
4	1 volumen
25 W	<5 W izlobo

3. Neselektivna vezja za generiranje signalov

Delitev v 2. skupini:

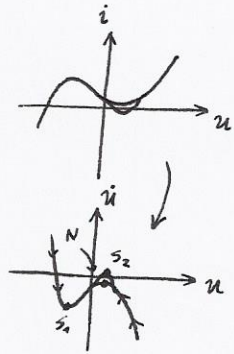
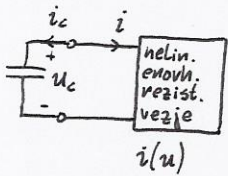
- 1) Krmiljeni generatorji:
- a) enofazno krmiljeni
 - monostabilni multivibrator
 - eno stabilno stanje - s pulzom ga vržemo iz stanja, kamor se vrne
 - b) večfazno krmiljeni
 - bistabilni multivibrator
 - dve stabilni stanji
 - multistabilni multivibrator
 - več stabilnih stanj

- 2) Samovzbujani generatorji:
- astabilni multivibrator (relaksacijski oscilator)

realizacija:

nelinearno rezistivno vezje in en neaktiven element (C ali L)

* BISTABILNOST



$$u_c = u$$

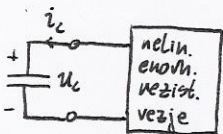
$$i_c = -i \quad i_c = C \frac{du_c}{dt} = C \cdot \dot{u}_c$$

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

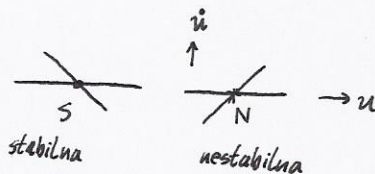
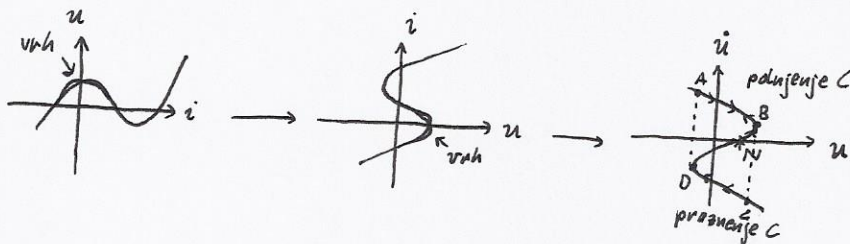
$\dot{u} > 0$ naraščanje
 $\dot{u} = 0$
 $\dot{u} < 0$

S_1, N, S_2
 meja med stabilnima stanjema (nestabilna točka)

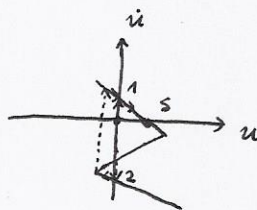
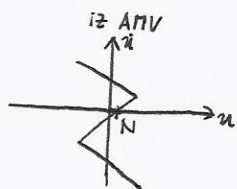
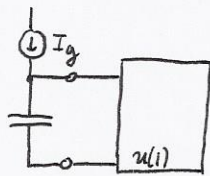
* ASTABILNOST



$$\dot{u} = -\frac{i(u)}{C}$$



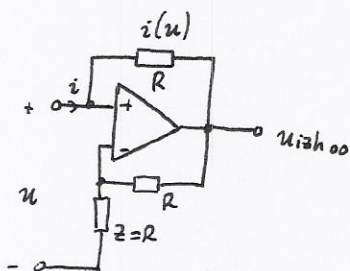
* MONOSTA BILNOST



Realizacije z OP-AMPI

3.1.2014

1) realizacija enovhodnih nelin. rezistivnih vezij

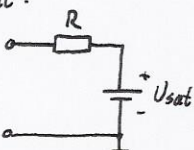


negativni impedančni pretvornik: $Z_{vh} = -Z$ (za lin. območje)

v lin. področju delovanja $u_{izhoo} = 2 \cdot u$

$$i = \frac{u - u_{izhoo}}{R} = \frac{-u}{R} \text{ ; znotraj nasičenja}$$

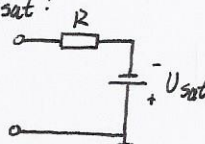
v + Usat:



$$i = \frac{u - (+Usat)}{R}$$

za $u > \frac{+Usat}{2}$

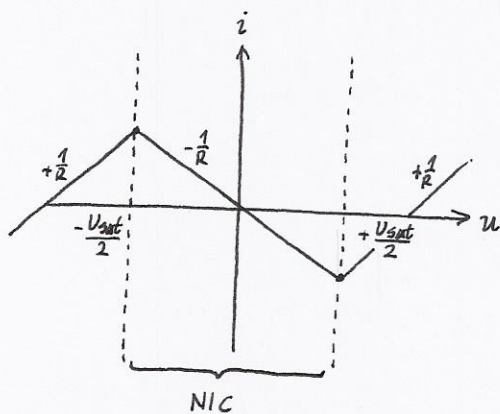
v - Usat:



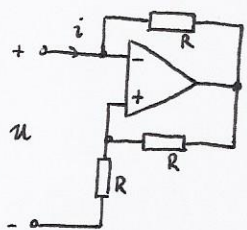
$$i = \frac{u - (-Usat)}{R}$$

za $u < \frac{-Usat}{2}$

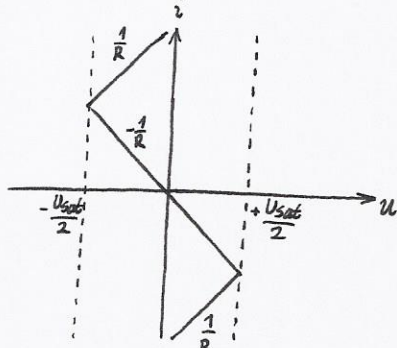
VF:



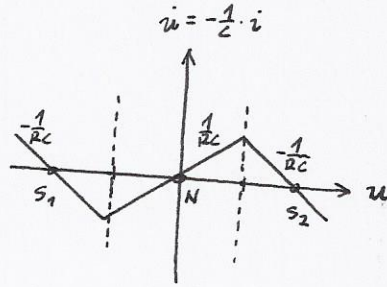
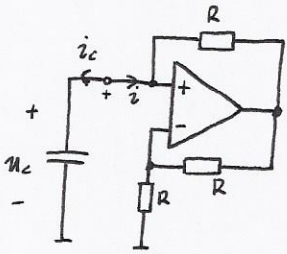
po teoremu dualnosti $\rightarrow u(i)$



VF:



2) Bistabilni multivibrator (s_1 N s_2)

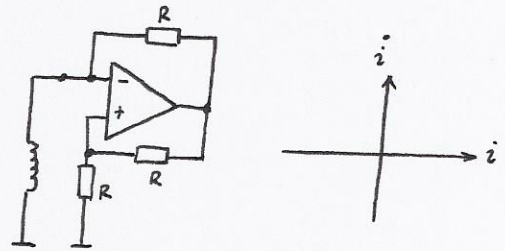


$u_c = u$

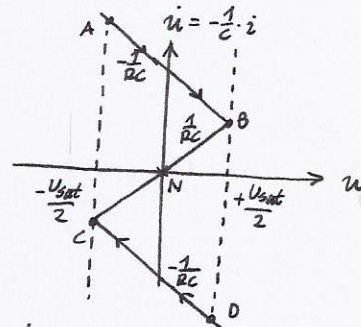
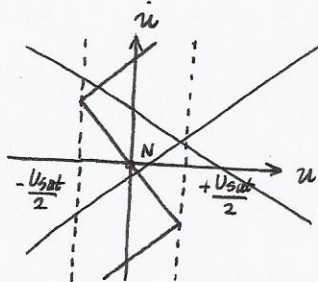
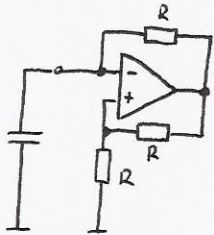
$i_c = -i$

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

po teoremu dualnosti:



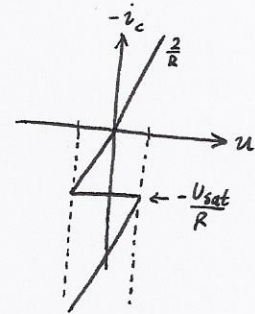
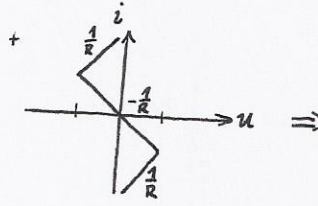
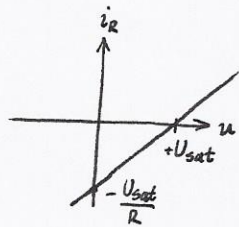
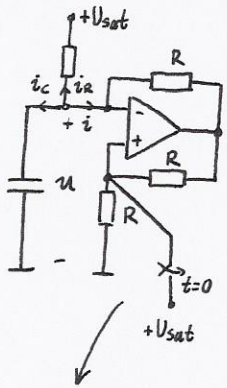
3) Astabilni multivibrator (N)



$T = t_{ao} + t_{co}$

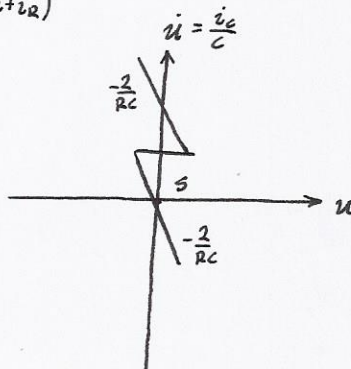
$T = 2 \cdot RC \cdot \ln 3$

4) Monostabilni multivibrator (s)



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

proston stanj:



$u^+ = U_{sat}$

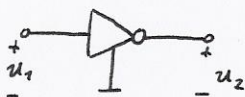
$u_{ishoo} = +U_{sat}$

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

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

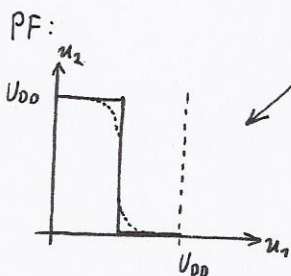
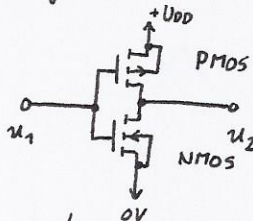
Realizacije z logičnimi vezji

osnovni gradnik → inverter

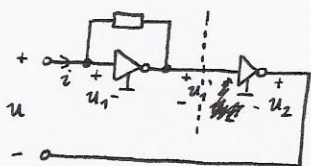


idealni: $R_{vh} \rightarrow \infty$
 $R_{izh} \rightarrow 0$

realizacija s CMOS:



1) AMV (N) ob uporabi C in enovhodnega neline. rezist. vezja



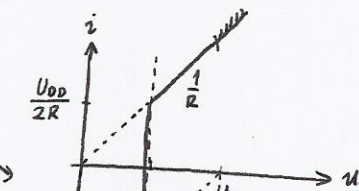
VF: $u(i) = ?$
 za idealne invertenje

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

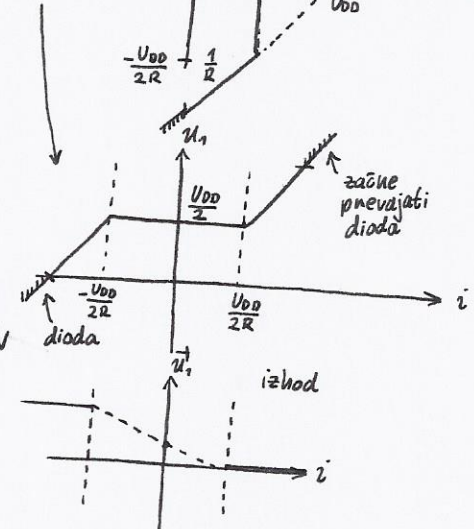
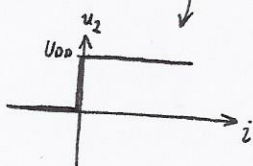
1. del vezja:



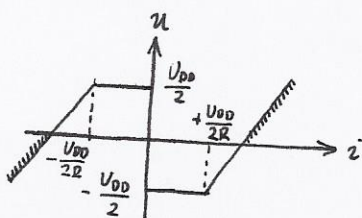
$i = i_R$
 $i = \frac{u_1 - u_1'}{R} = \begin{cases} \frac{u_1 - 0}{R} & ; u_1 > \frac{U_{DD}}{2} \\ \frac{u_1 - U_{DD}}{R} & ; u_1 < \frac{U_{DD}}{2} \end{cases}$



2. del vezja:

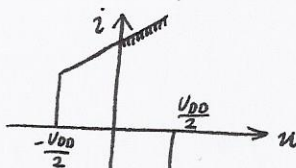


celotno vezje:

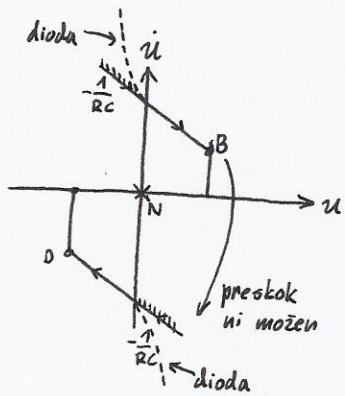
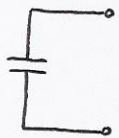


VF

zrcaljena



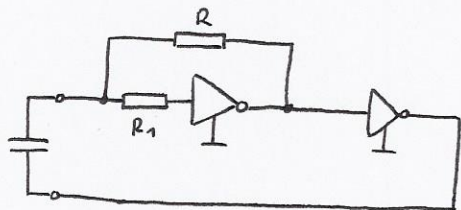
ob dodanem C:



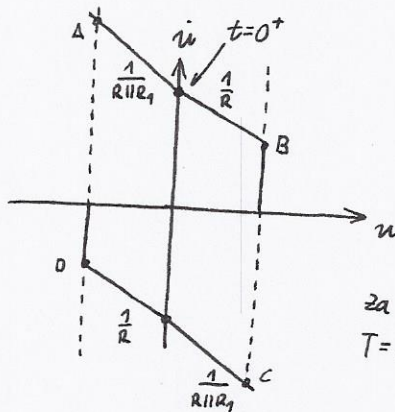
vezje v praksi ne deluje zaradi vgrajenih varnostnih diodah na vходу invertiranja (glej prejšnjo stran)

moramo omejiti tok (ena opcija na vходу invertiranja)

Realizacija z R1:

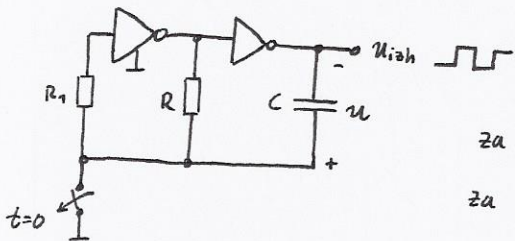


običajno $R_1 \gg R$



za $R_1 \gg R$
 $T = 2RC \ln 3$

naríšemo vezje nekoliko drugače:



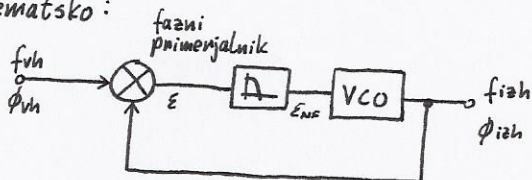
za $t < 0$: (L, H, L) in preko R_1 teče proti masi
za $t = 0^+$: preko R teče tok v C in ga polni, u narašča, dokler INV1 ne prekloni (pri $u = \frac{U_{DD}}{2}$)

4. FAZNO SKLENJENE ZANKE

(PLL)

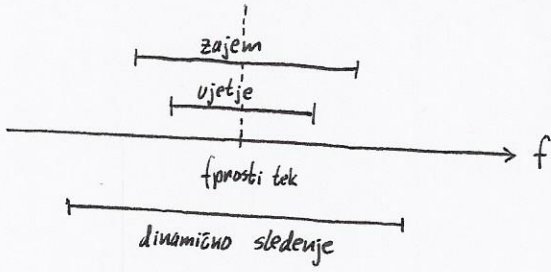
- povratni sklop je faza signala!
- danes: FM dekodernji, ...

shematsko:



• PLL ima tri stanja delovanja:

- prosti tek (vhodnega signala ni, $f_{vh} = 0$, $f_{ish} = f_{prostitek}$)
- zajem ($f_{vh} \neq 0$, Δf znotraj ujetja)
- ujetje (zanka se ujeme v eni periodi f_{vh} , sinhronizacija)

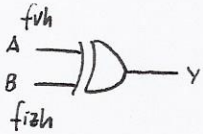


v področju sledenja je frekvenčno območje še širše

Fazni primerjalniki:

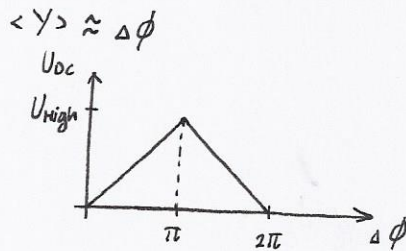
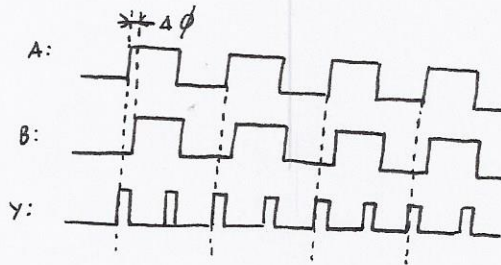
- analogni → analog PLL
- digitalni → digital PLL

1. fazni primerjalnik EXOR

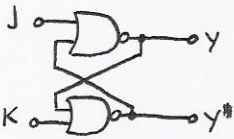


A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

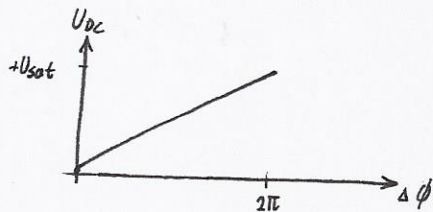
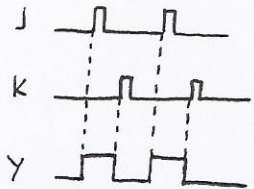
delovanje: za signal 50% DT deluje XOR kot fazni primerjalnik



2. fazni primerjalnik JK-flipflop

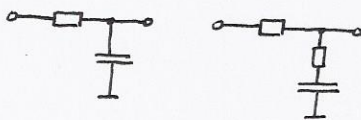


proženje na prehod (edge-trigger)

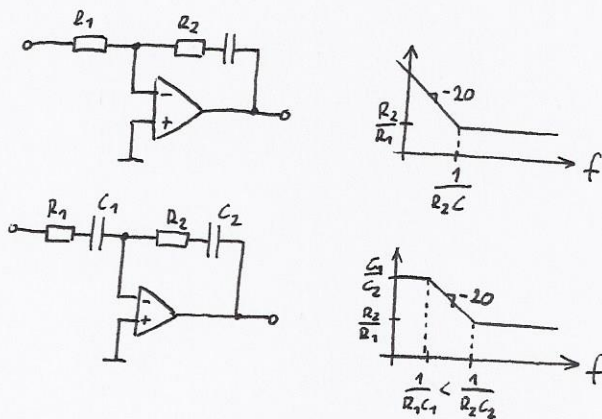


3. nizko-prepustni filter

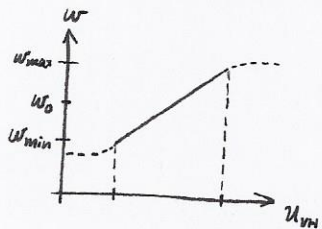
- pasivna izvedba low-pass:



- aktivna izvedba z OP-AMP:



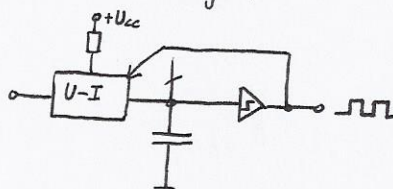
4. VCO - napetostno krmiljen oscilator



• realizacija z varicap diodo \rightarrow

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

• realizacije s tokovno krmiljenim relaksacijskim oscilatorjem

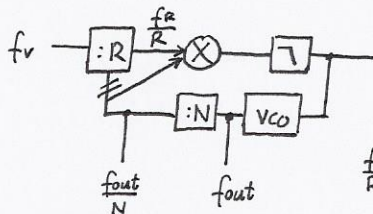


5. monolitske izvedbe PLL: glej liste...

6. uporaba PLL:

- frekvenčni množilniki
- FM modulatorji / demodulatorji
- FSK modulatorji / demodulatorji
- krmiljenje motorjev
- ...

• digitalni frekvenčni sintetizator s celostevilskim deliteljem



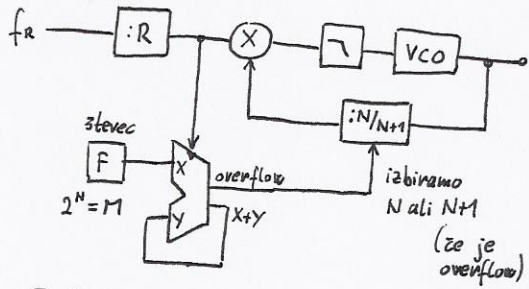
$$\frac{f_R}{R} = \frac{f_{out}}{N}, \quad f_{out} = f_R \cdot \frac{N}{R}$$

GSM 900 s 124-kanali po 200 kHz

$$N \in [4450 - 4575]$$

fazni sum nanašča z N
nedkeje detektiramo fu30

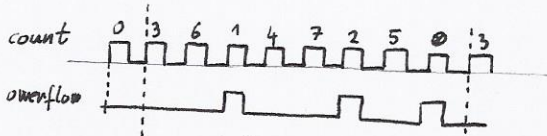
- digitalni frekvenčni sintetizator z racionalnim deliteljem



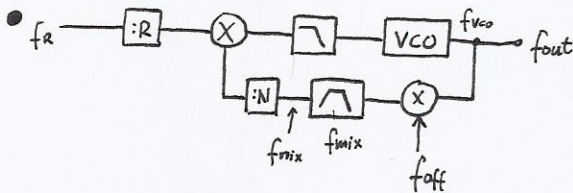
za GSM 900

$$N \in \left[139 \frac{2}{32} - 142 \frac{31}{32} \right]$$

F = 3
M = 8



$$\frac{5 \cdot N + 3(N+1)}{8} = \frac{8N+3}{8} = N + \frac{3}{8} \quad \text{splošno } N + \frac{F}{M}$$



digitalni frekvenčni sintetizator z mešalno stopnjo

npr. $f_{min} = f_{VCO} - f_{off}$

$$\frac{f_R}{R} = \frac{f_{mix}}{N} \rightarrow f_{VCO} = \frac{N}{R} f_R + f_{off}$$

FM tuner:

88.7 - 108.7 MHz

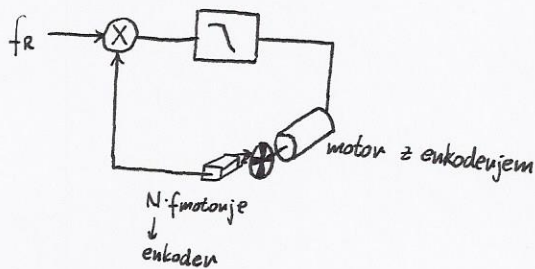
$f_R = 1 \text{ MHz}$

$R = 10$

$f_{off} = 88 \text{ MHz}$

$N \in [7, 207]$

- regulator hitrosti motonja

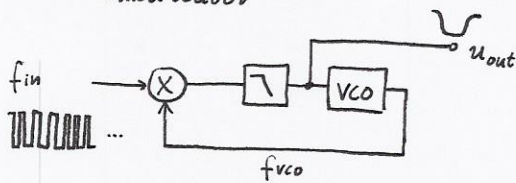


$$f_{motonja} = \frac{f_R}{N}$$

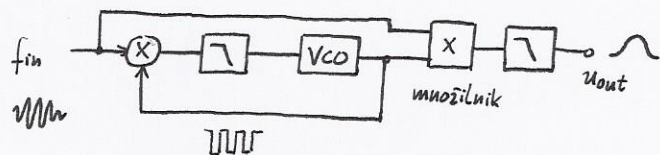
P(ID) regulacija

odvisno od sata!

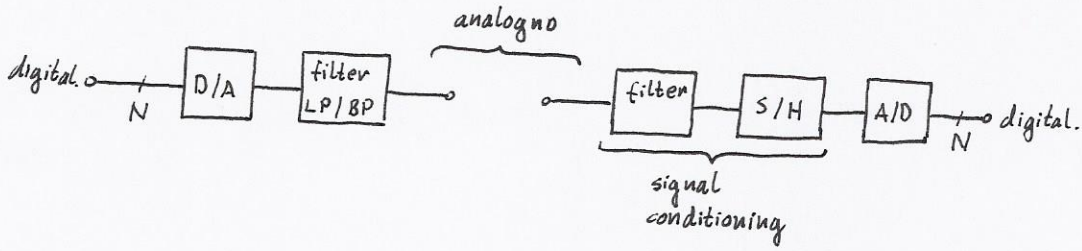
- FM demodulator



- AM demodulator po homodinskem principu

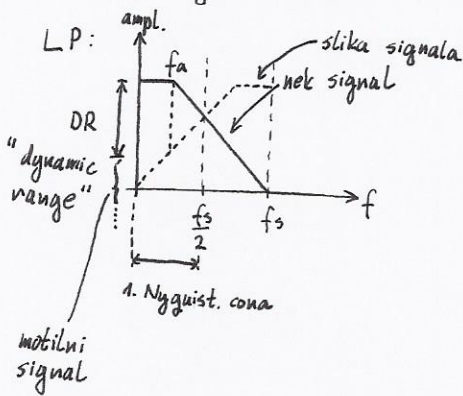


5. D/A in A/D PRETVORNIKI



digitalizacija: časovna in amplitudna kvantizacija / diskretizacija

"Anti-aliasing" filtri (proti prekrivanju?)

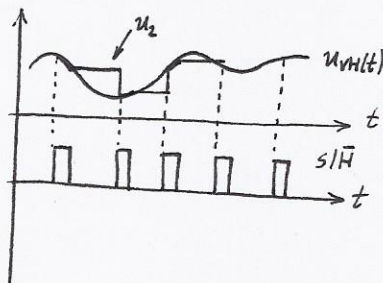
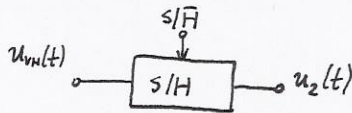


$$DR = [(f_s - f_a) - f_a] \cdot \text{strmina filtra}$$

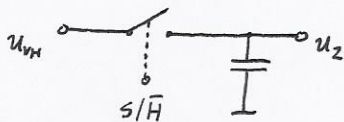
rešujemo z dobrimi siti ali nadzorovanjem in preprostimi siti

S/H vezja - vezja za vzorčenje in zadrževanje

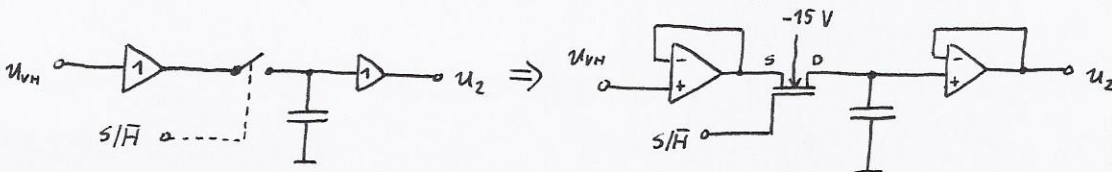
-dvo-vhodno dinamično vezje



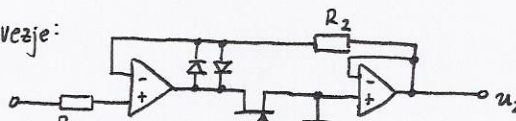
osnovni princip:



nadgradnja z operacijskim sledilnikom



podobno vezje:

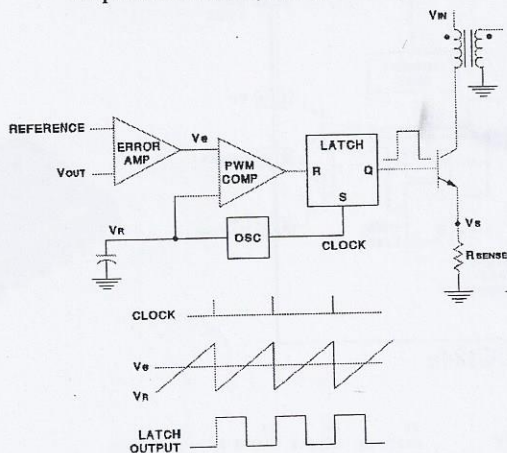


ne vem zakaj je ta boljši...

Omrežni (offline) stikalni napajalniki

1. Način krmiljenja izhodne napetosti:

Napetostni način (voltage mode)



- Starejši način krmiljenja
- Primerja vrednost napake V_e z žagastim signalom oscilatorja

Prednosti:

- Lažji za analizo
- Visoka amplituda žagastega signala predstavlja majhno šumno občutljivost krmiljenja

Slabosti:

- Počasnejši odziv: Vsako spremembo v stanju vezja zaznamo šele v spremembi izhodne napetosti in šele nato sledi odziv.
- Tokovna zaščita primarne induktivnosti in tranzistorja mora biti dodatno izvedena.

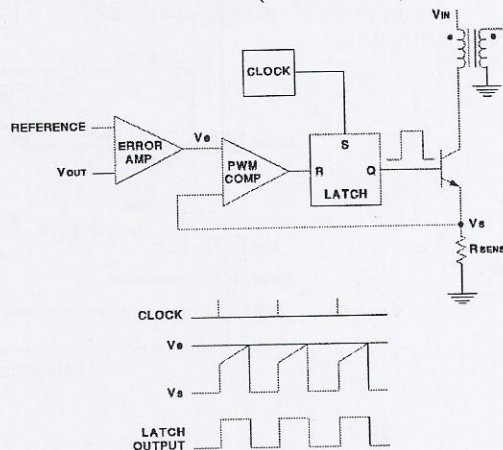
Izboljšava:

- »Voltage feed forward«, kjer krmilno vezje spreminja strmino žagastega signala glede na vhodno napetost in s tem simulira tokovni način delovanja.

Področje uporabe:

- Pri nizkih pričakovanih obremenitvah, ko je pričakovan tok primarne tuljave premajhen za uporabo tokovnega načina (občutljivost na šum)
- Pri aplikacijah visokih moči oz. tam, kjer so pričakovani zelo šumni signali in s tem nestabilnost pri uporabi tokovnega načina

Tokovni način (current mode)



- Novejši način krmiljenja, uporabljen v večini sodobnih stikalnih napajalnikov
- Primerja vrednost napake V_e s tokom primarne induktivnosti trikotne oblike, katere strmina je neposredno odvisna od vhodne napetosti.

Prednosti:

- Ojačevalnik napake neposredno kontrolira tok primarne induktivnosti.
- Hiter odziv na spremembo vhodne napetosti, ki se odraža v spremembi toka primarne induktivnosti.

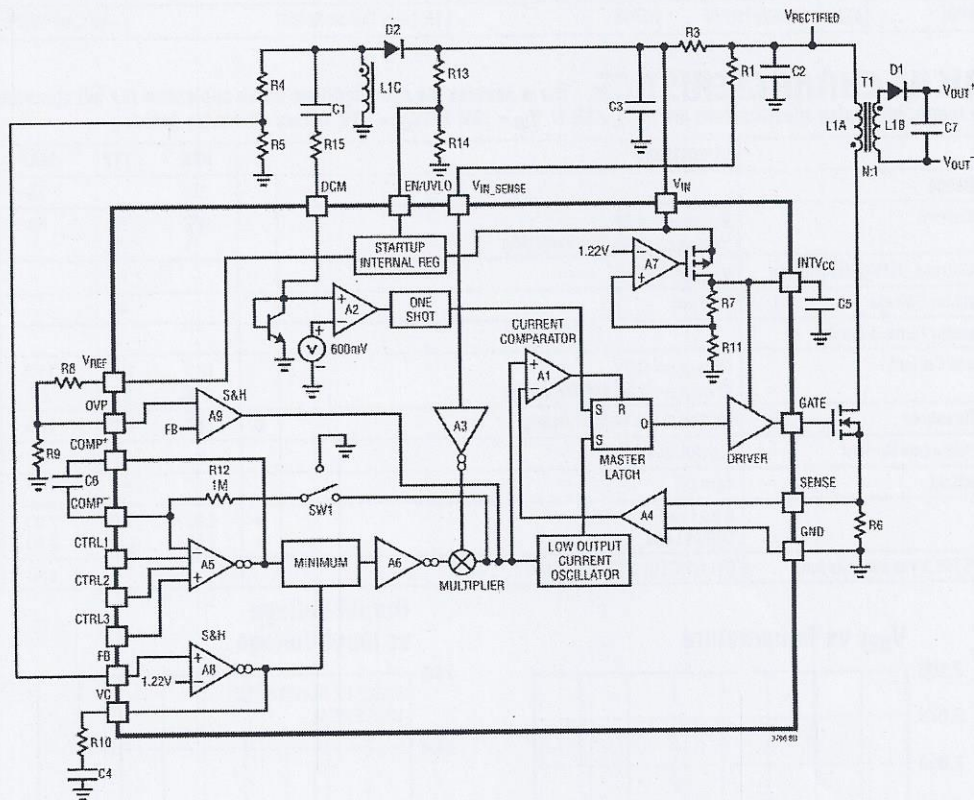
Slabosti:

- Dve regulacijski zanki – težja analiza vezja.
- Nizka amplituda signala na senzorskem uporu R_{SENSE} in s tem povezana občutljivost na šum
- Motnje v tokovnem signalu primarnega navitja vplivajo na regulacijo (problem začetne tokovne konice zaradi medvojnje kapacitivnosti)
- Problemi z nestabilnostjo pri »duty-cycle« krmilnega signala nad 50 %.

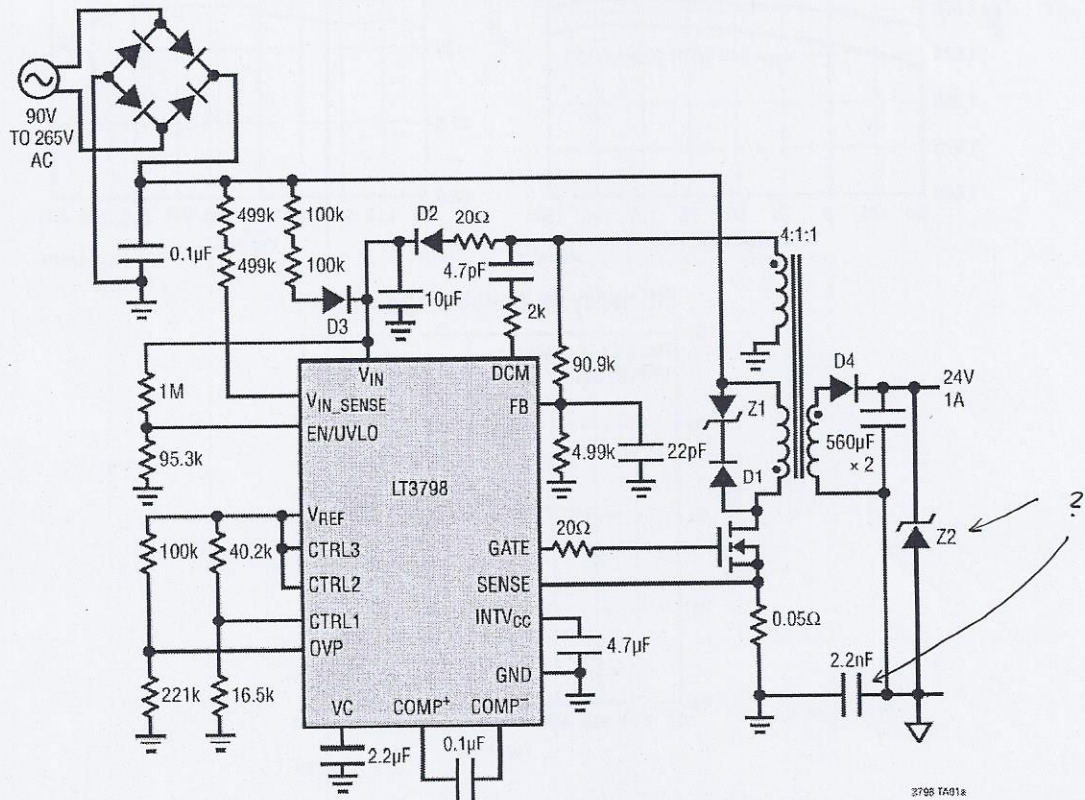
Področja uporabe:

- Pri visokih vhodnih napetostih ali če je vir energije tokovni vir
- Če je zahtevan zelo hiter odziv regulacije
- Pri modularnih aplikacijah, kjer vezemo več enakih napajalnikov vzporedno.
- Nizkocenovne aplikacije, kjer je zahtevano minimalno število komponent

3. Primer »flyback« napajalnika s krmiljem na tokovni način z uporabo LT3798 krmilnega vezja:
 (<http://www.linear.com/product/LT3798>)



Integrirano vezje LT3798 z zunanjimi gradniki



Primer »offline flyback« napajalnika z LT3798