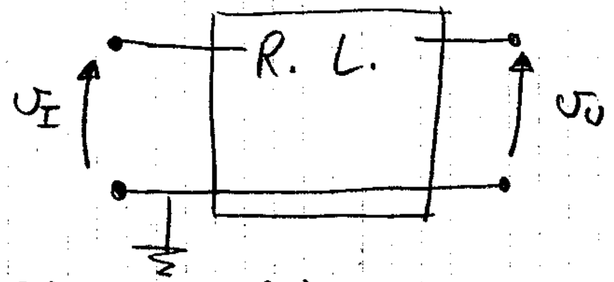
LEZ. 1

- F. d. T
- Diagr. Bode

INTRODUZIONE

- Es. su F. d. T e funz. Risp. in freq. di RETI LINEARI (Tracciam. DIAGR. BODE)

- Rete lineare:



F. d. T: $F(s) = \dfrac{v_U(s)}{v_I(s)}$

si ricava dalla rete

- RISPOSTA IN FREQUENZA:

$s \rightarrow j\omega$ ($\rightarrow$ si suppone v_I SINUSOIDALE ($\rightarrow$ v_U sinus., stessa ω)

$F(j\omega)$

Numero complesso

- DIAGR. di BODE: $|F(j\omega)|_{dB}$ vs. $\log_{10}\left(\frac{\omega}{\omega_0}\right)$

$\measuredangle F(j\omega)$ vs. $\log_{10}\left(\frac{\omega}{\omega_0}\right)$

- POLI e ZERI

$$F(s) = K \cdot s^{\alpha} \cdot \frac{\prod_{1}^{m} i \,(1+s\tau_i)}{\prod_{1}^{n} j \,(1+s\tau_j)}$$

$\rightarrow$ esplicitare

K reale

α intero

$\tau_j > 0$ $\rightarrow$ $(\alpha+n-m)$ ordine di $F(s)$

$z_i = -1/\tau_i \longrightarrow \omega_{zi} = |z_i|$

$p_j = -1/\tau_j \longrightarrow \omega_{pj} = |p_j|$

+ zeri o poli nell'origine

DIAGRAMMI di BODE (APPROX): CONTRIBUTI

! DISEGNARE ASSI !

	VARIAZ. PENDENZA $\|F(j\omega)\|_{dB}$	$\angle F(j\omega)$ per $\omega \to \infty$
POLO	$-20\ dB/dec$	$-90°$
ZERO SX	$+20$	$+90°$
ZERO DX	$+20$	$-90°$

POLI / ZERI NELL'ORIGINE — PARTENZA CON $\omega \to 0$ PEND $= \mp \alpha \cdot 20\ dB/dec$ — $\angle F(j\omega) = \mp \alpha \cdot 90°$ COSTANTE AL VAR. DI ω

x2

- $$\boxed{F(s) = \frac{1-0.1s}{1+0.01s}}$$

$1 - 0.1s = 0 \longrightarrow z = +10\ r/s$ (ZERO DX) $\rightarrow \omega_z = 10\ r/s$

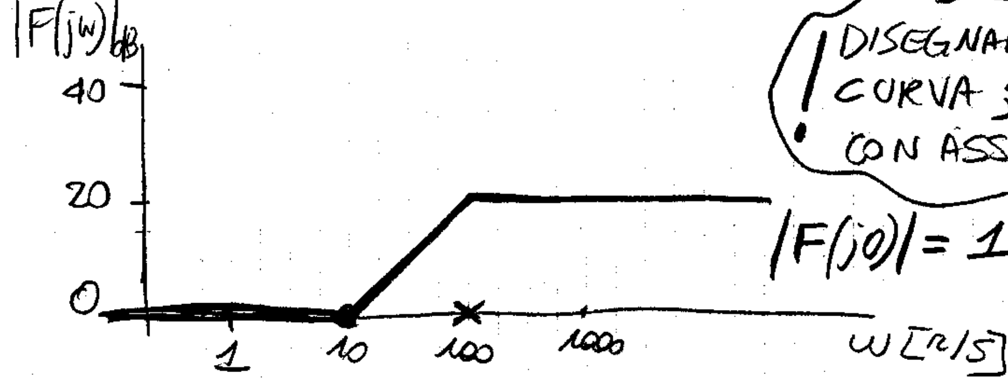
$1 + 0.01s = 0 \longrightarrow p = -10^2\ r/s \quad \rightarrow \omega_p = 10^2\ r/s$

- $|F(j\omega)|$ vs. ω

  - NO zeri/poli nell'orig.

  ➡ per $\omega \rightarrow 0$ pend. = 0

! DISEGNARE PRIMA CURVA; POI RIFO CON ASSE TARATO !



$|F(j0)| = 1 = 0\,dB$

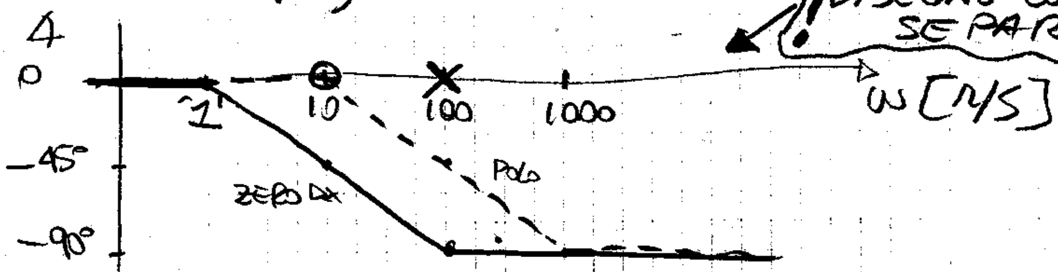
OSSERVAZIONI : - GUAD. UNITARIO × BASSE FREQ

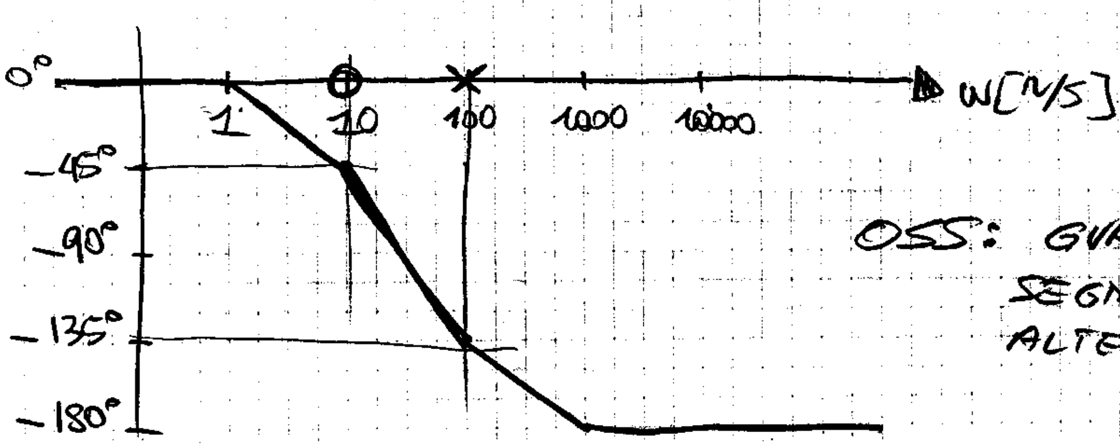
- " |10| " ALTE "

↓ IN REALTÀ È − 10

- $\measuredangle F(j\omega)$ vs. ω

! DISEGNO CONTRIBUTI SEPARATI !





OSS: GUAD. HA SEGNO "−" PER ALTE FREQ.

$$\boxed{F(s) = \frac{10}{s} \cdot \frac{1+s}{1+0.1s}}$$

$z = -1\ r/s \rightarrow \omega_z = 1\ r/s$

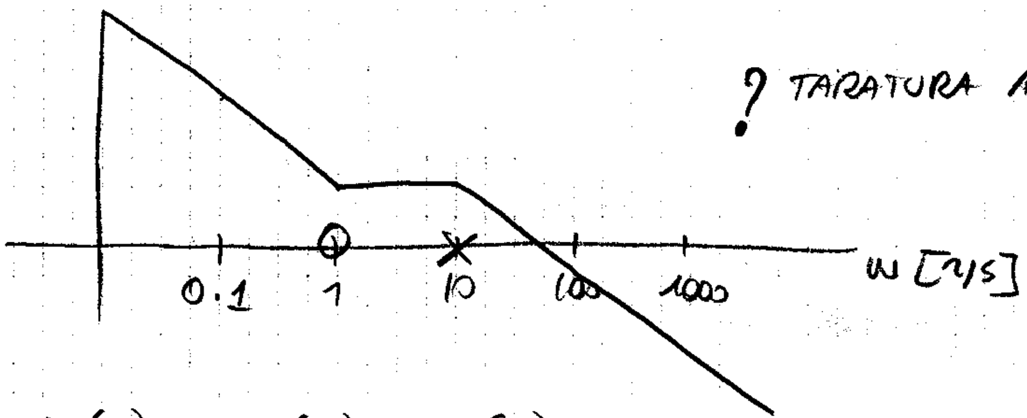
$p_1 = 0\ r/s \rightarrow \omega_{p1} = 0\ r/s$ (POLO NELL'ORIG.)

$p_2 = -10\ r/s \rightarrow \omega_{p2} = 10\ r/s$

- $|F(j\omega)|$ vs. ω

POLO NELL'ORIG: PER $\omega \rightarrow 0$ PEND. $= -20\,dB/dec$

? TARATURA ASSE ORD ?

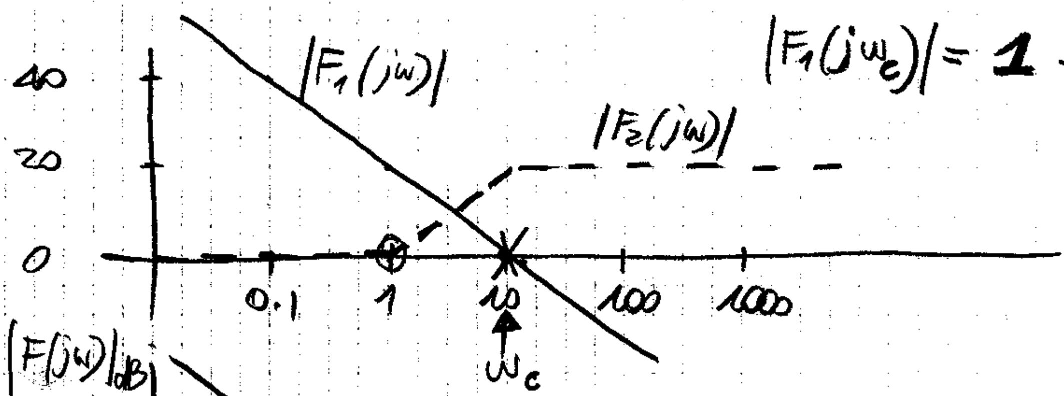


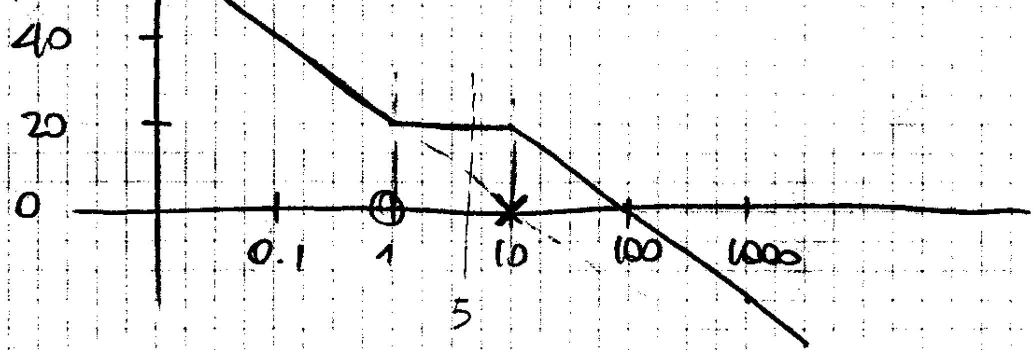
$F(s) = F_1(s) \cdot F_2(s)$

$F_1(s) = \frac{10}{s}$; $F_2(s) = \frac{1+s}{1+0.1s}$

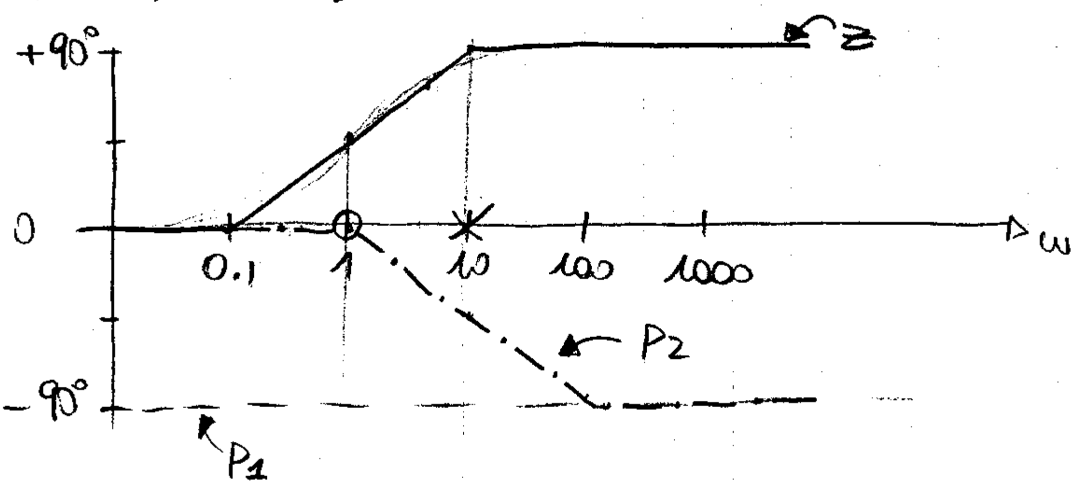
SU DIAGR. BODE : SI SOMMANO :

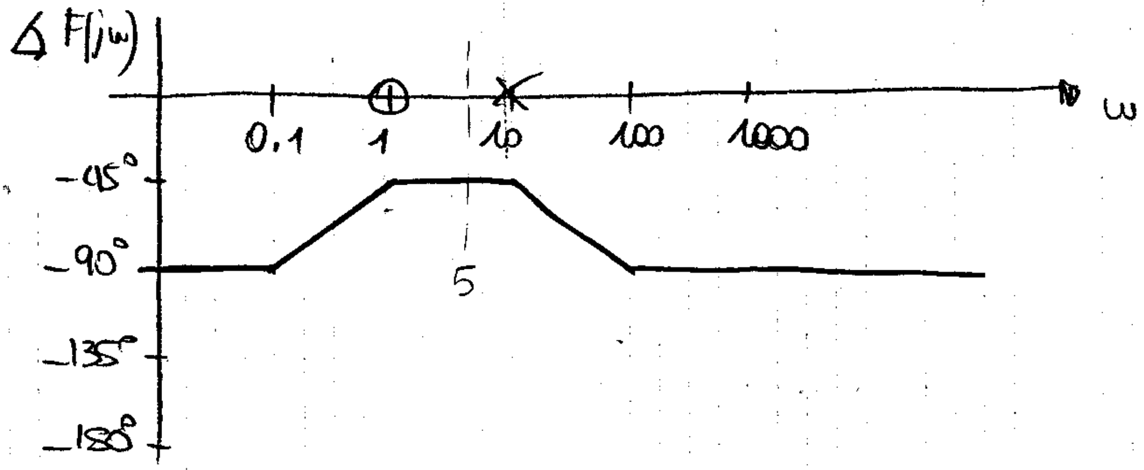
$|F_1(j\omega_c)| = 1 \rightarrow \omega_c = 10\ r/s$

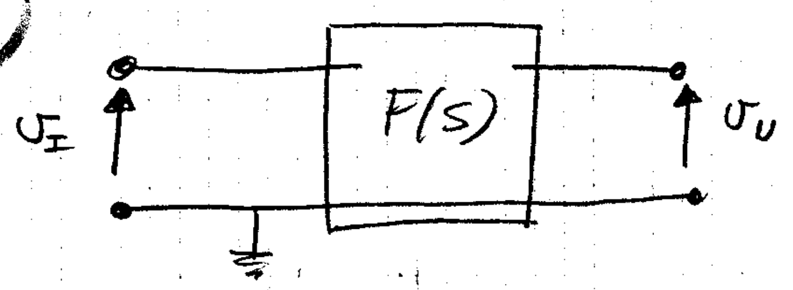




$\measuredangle F(j\omega)$ vs ω







F(s) di prima

$v_I(t) = V_0 \cos(5t)$ $\qquad V_0 = 1\ V$

t in secondi

? $v_U(t)$?

$\omega_s = 5\ r/s$

$v_U(t) = V^* \cos(\omega_s t + \varphi)$ perché RETE LIN.

$V^* = V_0 \cdot |F(j\omega_s)|$

$\varphi = \measuredangle F(j\omega_s)$

$$F(j\omega) = \frac{10}{j\omega} \cdot \frac{1+j\omega}{1+0.1\,j\omega}$$

$$|F(j\omega)| = \frac{10}{\omega} \cdot \sqrt{\frac{1+\omega^2}{1+0.01\,\omega^2}}$$

$$|F(j\omega_5)| = \frac{10}{5}\sqrt{\frac{1+25}{1+0.01\cdot 25}} = 2\cdot\sqrt{\frac{26}{1.25}} =$$
$$= 9.12$$

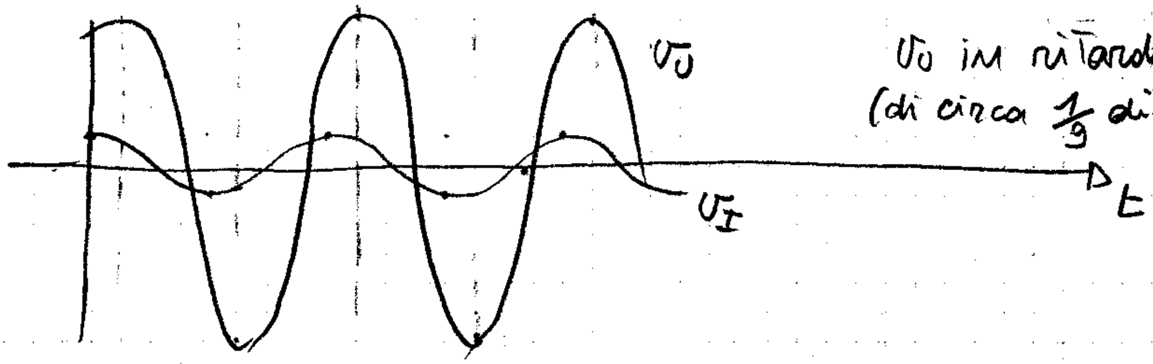
$V^* = 9.12\ V$

$$\angle[F(j\omega)] = \angle\left[\frac{10}{j\omega}\right] + \angle[1+j\omega] - \angle[1+0.1j\omega] =$$
$$= \angle\left[-j\frac{10}{\omega}\right] + \angle[1+j\omega] - \angle[1+0.1j\omega] =$$
$$= -90° + \mathrm{atan}(1\cdot\omega) - \mathrm{atan}(0.1\cdot\omega)$$

→ [sec] → OK DIMENSIONI!!

$$\angle[F(j\omega_5)] = -90° + \mathrm{atan}\,5 - \mathrm{atan}\,0.5 =$$
$$= -90° + 78.69° - 26.56° = -37.87°$$

$\varphi = -37.87° = -0.66$ rad



v_U in ritardo (di circa $\frac{1}{9}$ di periodo)

- VERIFICA: $|F(j\omega_5)|_{dB} = 20\cdot\log_{10} 9.12 = +19.2$ dB
CON DIAGR. APPROX.

OK!

!! IN GENERE è sufficiente guardare !!!
diagr. BODE

x4

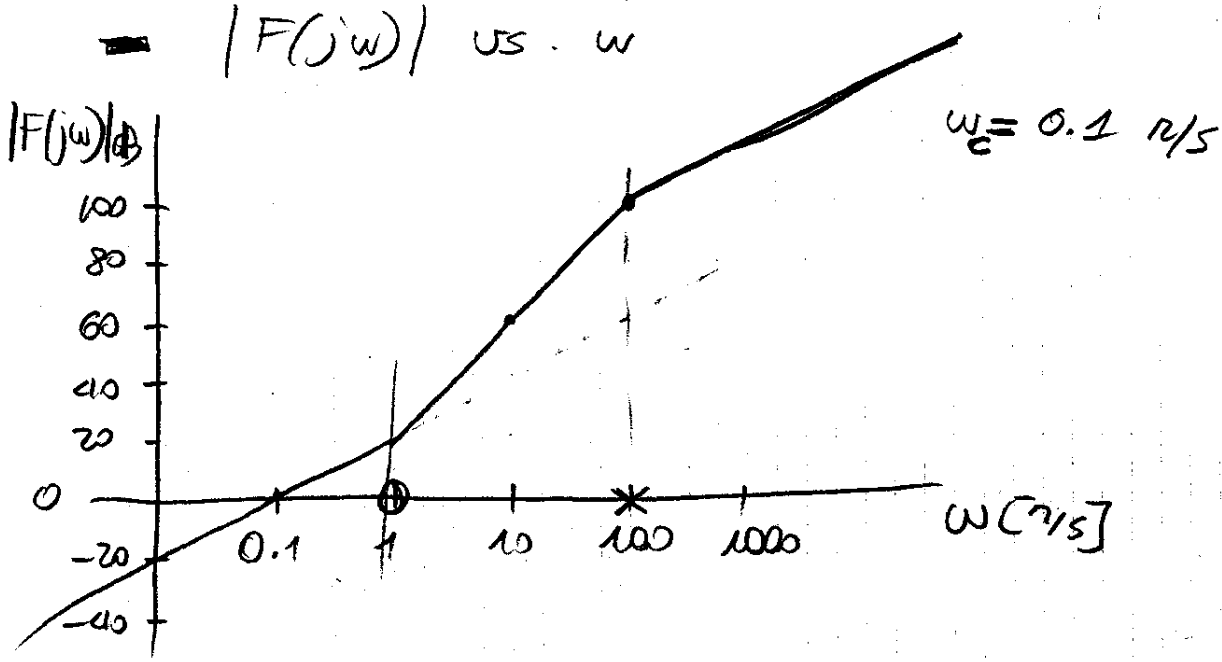
$$\boxed{F(s) = 10\,s \cdot \frac{1+s}{1+0.01s}}$$

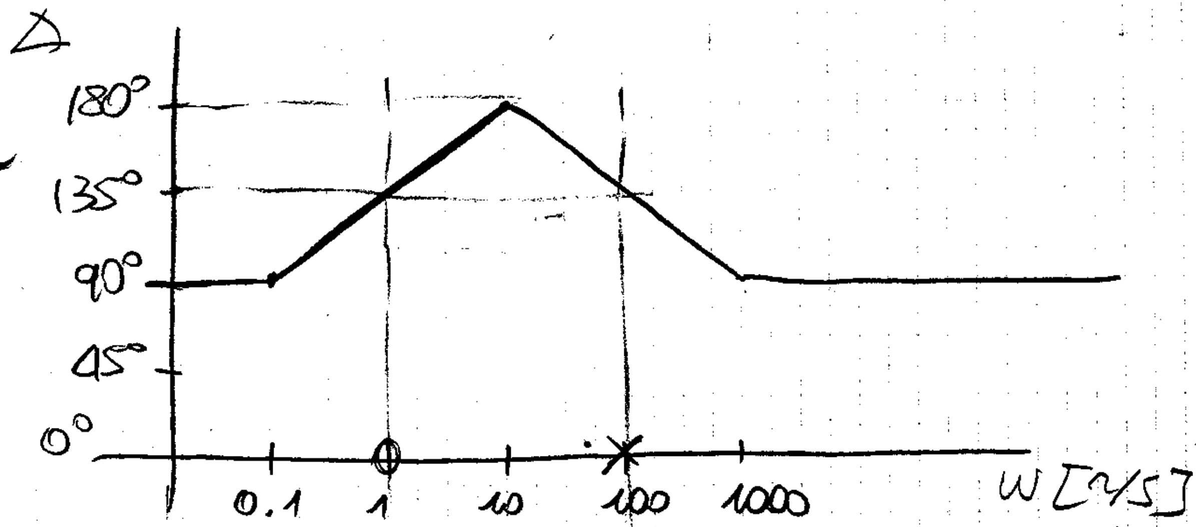
$z_1 = 0 \ r/s \longrightarrow \omega_{z_1} = 0 \ r/s$ (zero nell'ORIG)

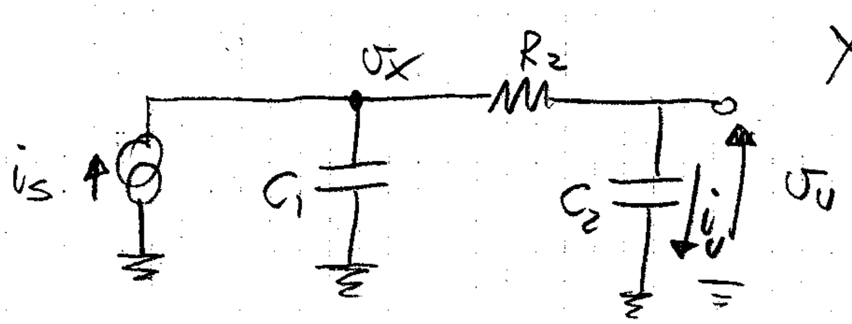
$z_2 = -1 \ r/s \longrightarrow \omega_{z_2} = 1 \ r/s$

$p_1 = -10^2 \ r/s \longrightarrow \omega_p = 10^2 \ r/s$

- $|F(j\omega)|$ vs. ω







$R_2 = 10\ k\Omega$
$C_1 = 10\ mF$
$C_2 = 1\ \mu F$

① $Z(s) = \dfrac{v_u}{i_s}$ ($[\Omega]$) e
Bode di $F(s) = \dfrac{Z(j\omega)}{R_2}$

② $T(s) = \dfrac{i_u}{i_s}$

$v_x = i_s \cdot Z_{eq}$

$$Z_{eq} = \frac{1}{sC_1} \,//\, \left(R_2 + \frac{1}{sC_2}\right) = \frac{\frac{1}{sC_1}\left(R_2 + \frac{1}{sC_2}\right)}{\frac{1}{sC_1} + R_2 + \frac{1}{sC_2}} =$$

$$= \frac{1}{\cancel{sC_1}} \cdot \frac{1 + sC_2R_2}{s\cancel{C_2}} \cdot \frac{\cancel{sC_1C_2}}{C_2 + sC_1C_2R_2 + C_1} =$$

$$= \frac{1 + sC_2R_2}{s(C_1+C_2)\left[1 + s\frac{C_1C_2}{C_1+C_2}R_2\right]} =$$

!! Dire che voglio forma così $(1+s\tau)$

$$= \frac{1}{s(C_1+C_2)} \cdot \frac{1 + sC_2R_2}{1 + s\frac{C_1C_2}{C_1+C_2}R_2}$$

$$v_u = v_x \cdot \frac{\frac{1}{sC_2}}{R_2 + \frac{1}{sC_2}} = i_s \cdot \frac{1}{s(C_1+C_2)} \cdot \frac{\cancel{1+sC_2R_2}}{1 + s\frac{C_1C_2}{C_1+C_2}R_2} \cdot \frac{1}{\cancel{1+sC_2R_2}}$$

$$Z(s) = \frac{v_u}{i_s} = \frac{1}{s(C_1+C_2)} \cdot \frac{1}{1 + s\frac{C_1C_2}{C_1+C_2}R_2}$$

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$$F(s) = \frac{Z(s)}{R_2} = \frac{1}{s(C_1+C_2)R_2} \cdot \frac{1}{1 + s\frac{C_1C_2}{C_1+C_2} \cdot R_2}$$

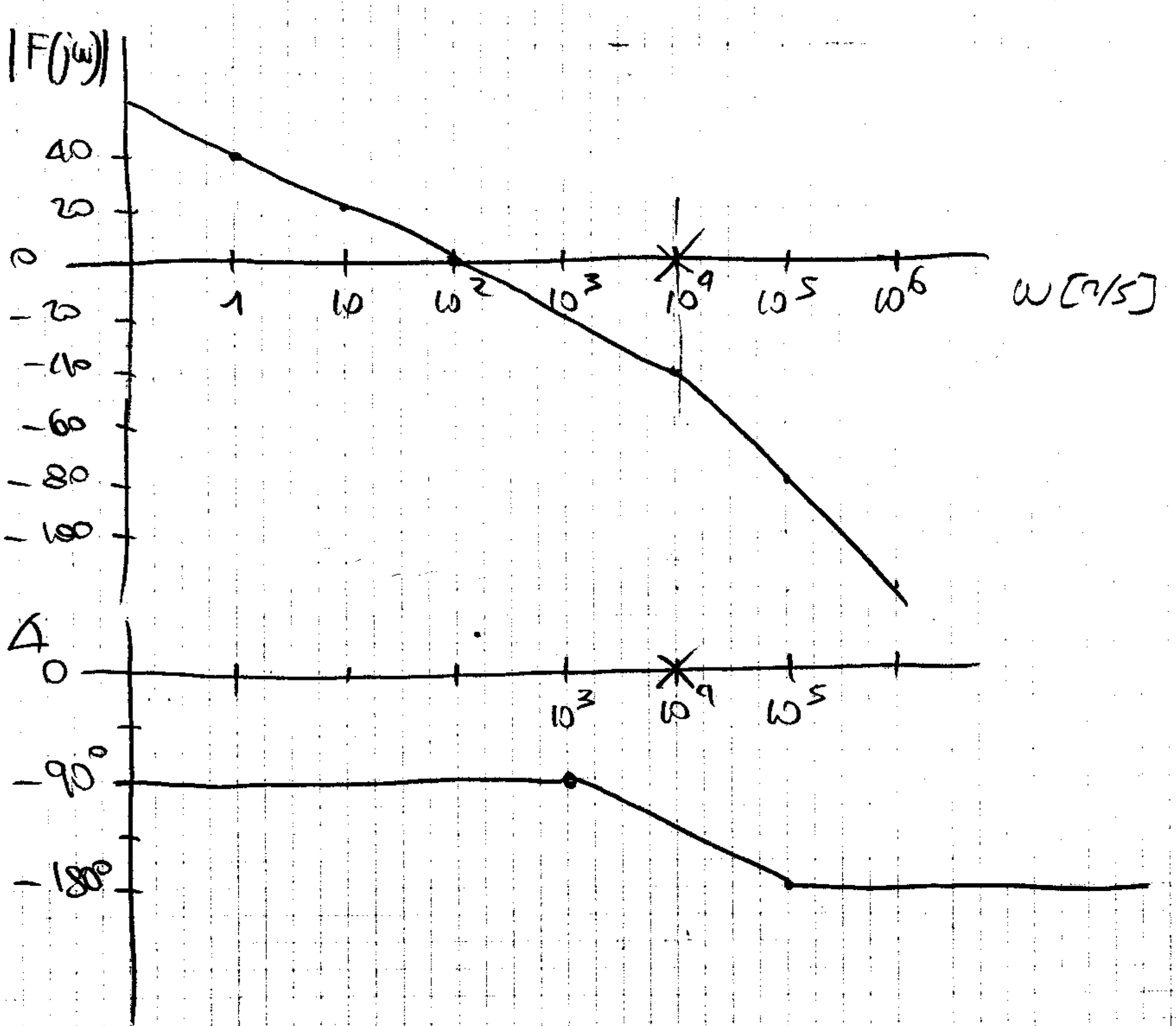
$$C_1 + C_2 \simeq C_2 = 1\,\mu F$$

$$\frac{C_1C_2}{C_1+C_2} \simeq C_1 = 10\,nF$$

$$F(s) = \frac{1}{10^{-6} \cdot 10^{4} \cdot s} \cdot \frac{1}{1 + s \cdot 10^{-8} \cdot 10^{4}} =$$

$$F(s) = \frac{1}{0.01\,s} \cdot \frac{1}{1 + 10^{-4}\,s}$$

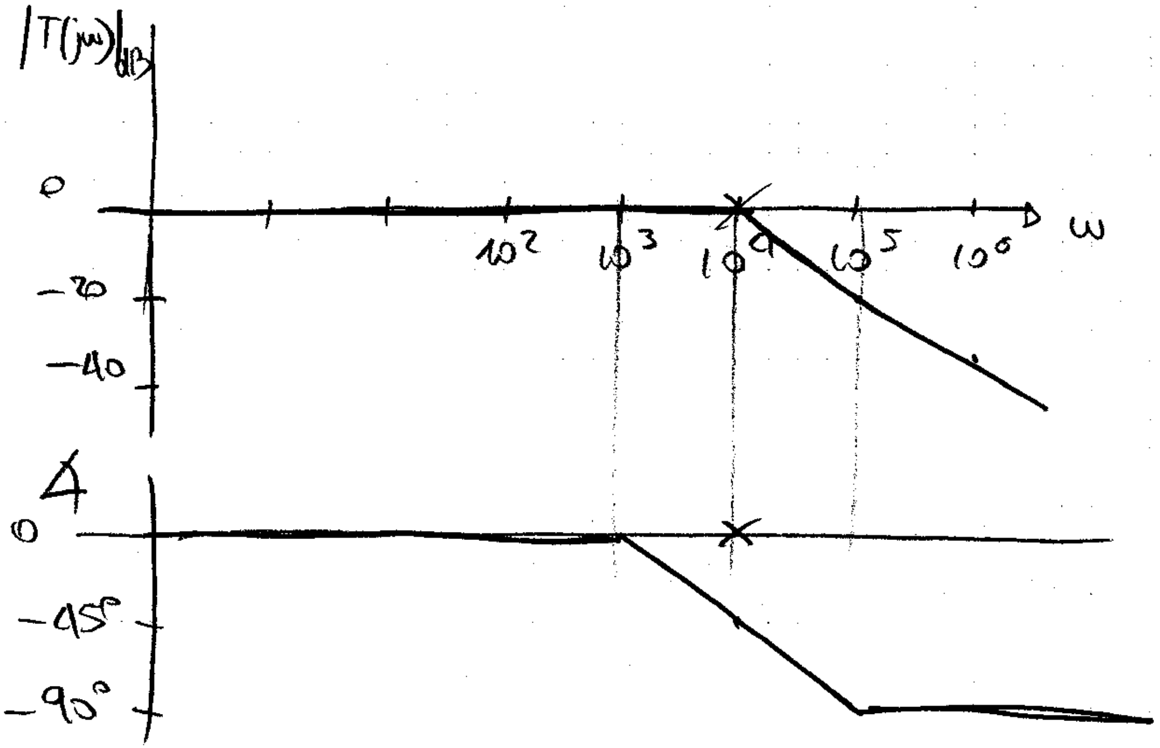
$$p_1 = 0 \qquad p_2 = 10^{4}\ r/s$$



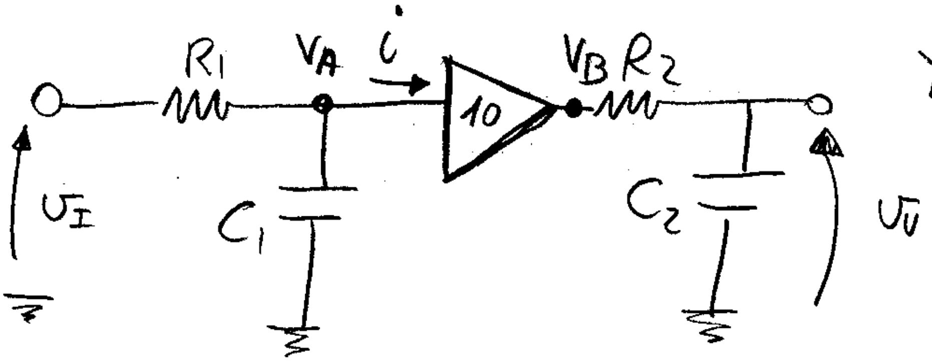
$$i_U = \frac{v_x}{R_2 + \frac{1}{sC_2}} = i_s \cdot \frac{1}{s(C_1+C_2)} \, \frac{\cancel{1+sC_2R_2}}{1+s\frac{C_1C_2}{C_1+C_2}R_2} \cdot \frac{sC_2}{\cancel{1+sC_2R_2}}$$

$$T(s) = \frac{i_u}{i_s} = \frac{C_2}{C_1+C_2} \cdot \frac{1}{1+s\frac{C_1C_2}{C_1+C_2}R_2}$$

$$T(s) \simeq \frac{1}{1+10^{-4}s}$$



<u>OSSERVAZ</u>: La RISP. IN FREQ. di UNA RETE DIPENDE DALLA GRANDEZZA di USCITA !



6

$R_1 = 10\ k\Omega$
$R_2 = 100\ \Omega$
$C_1 = 10\ nF$
$C_2 = 1\ \mu F$

? - $F(s) = \frac{v_U}{v_I}$
- Boole

Amplificatore IDEALE : $i = 0$

$v_B = 10 \cdot v_A$

$$v_A = v_I \cdot \frac{1}{1 + sC_1R_1}$$

$$v_U = v_B \cdot \frac{10}{1 + sC_2R_2}$$

$$F(s) = \frac{v_U}{v_I} = \frac{10}{(1 + sC_1R_1)(1 + sC_2R_2)}$$

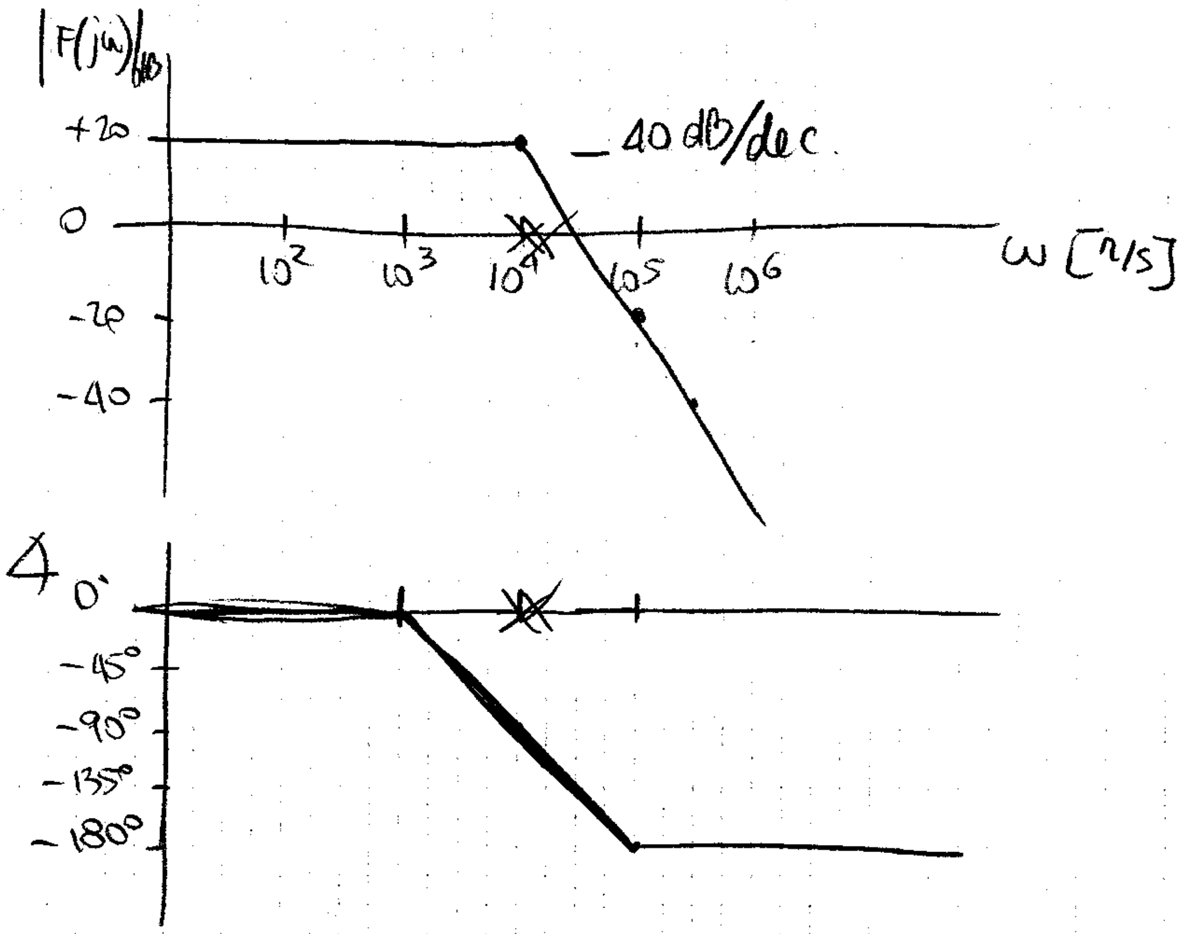
$C_1R_1 = 10^{-8} \cdot 10^4 = 10^{-4}\ s$

$C_2R_2 = 10^{-6} \cdot 10^2 = 10^{-4}\ s$

$$F(s) = \frac{10}{(1 + 10^{-4}s)(1 + 10^{-4}s)} = \frac{10}{(1 + 10^{-4}s)^2}$$

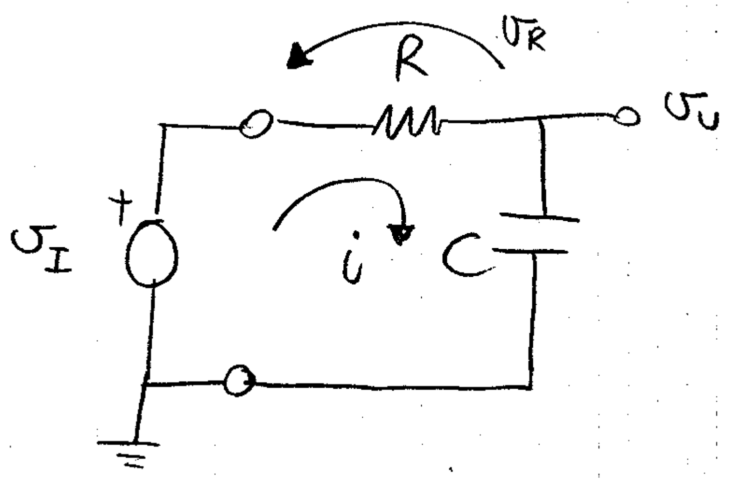
$P_1 = P_2 = -10^4\ r/s \longrightarrow \omega = 10^4\ r/s$

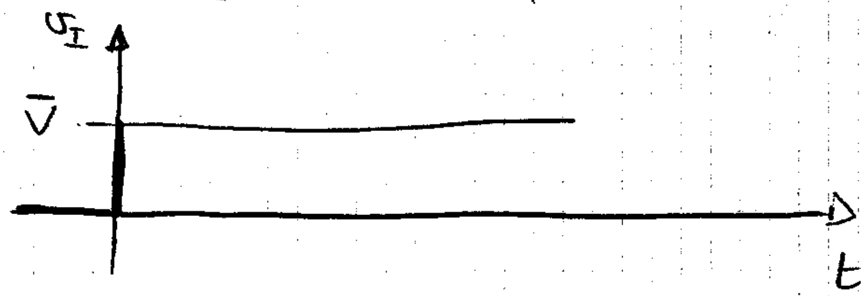
└ POLO DOPPIO


|F(jω)|dB
+20
0
-20
-40
10^2
10^3
10^4
10^5
10^6
-40 dB/dec
ω [r/s]
∠
0°
-45°
-90°
-135°
-180°

7

CIRCUITI RC, RISPOSTA AL GRADINO: SOLUZ. NEL DOMINIO DEL TEMPO





? $v_U(t)$?

$v_I = v_I(t)$; $i = i(t)$; $v_U = v_U(t)$

$$\begin{cases} i(t) = C \cdot \dfrac{d v_U(t)}{dt} \\ i(t) = \dfrac{v_I(t) - v_U(t)}{R} \end{cases}$$

$$C \frac{d}{dt} v_U(t) = \frac{v_I(t)}{R} - \frac{v_U(t)}{R}$$

$$\tau \frac{d}{dt} v_U(t) + v_U(t) = v_I(t) \quad ; \quad \tau = RC$$

→ Eq. diff. lineare, a coeff. cost., del 1° ordine

per $t > 0$: $\begin{cases} \tau \dfrac{d}{dt} v_U(t) + v_U(t) = \bar{V} \\ V_U(0) = 0 \end{cases}$ (cond. iniz. scarico)

$$v_U(t) = \underbrace{v_{U,0}(t)}_{\text{soluz. omogenea}} + \underbrace{v_{U,1}(t)}_{\text{soluz. partic.}}$$

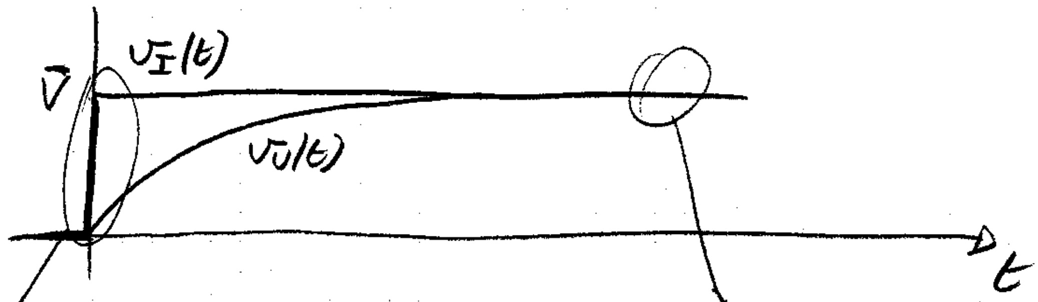
$$v_{U,1}(t) = \bar{V}$$

$$v_{U,0}(t) = V^* e^{-t/\tau}$$ da determ.

$$v_U(t) = \bar{V} + V^* e^{-t/\tau}$$

$$\begin{cases} v_U(0) = 0 \\ \bar{V} + V^* = 0 \end{cases} \longrightarrow V^* = -\bar{V}$$

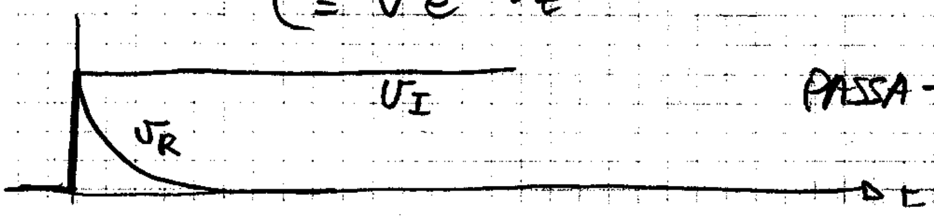
$$v_U(t) = \bar{V} - \bar{V} e^{-t/\tau} = \bar{V}(1 - e^{-t/\tau})$$



? TENS. AI CAPI della RESISTENZA ?

$$v_R(t) = v_I(t) - v_U(t)$$

$$v_R(t) = \begin{cases} 0 & t < 0 \\ \bar{V} - \bar{V}(1 - e^{-t/\tau}) = \\ = \bar{V} e^{-t/\tau} & t \geq 0 \end{cases}$$



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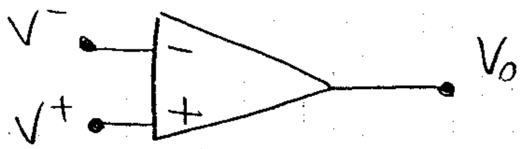
LEZ. 2 : - A.O.

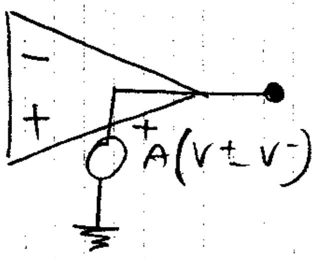
AMPLIFICATORE OPERAZIONALE : INTRODUZIONE

A.O. IDEALE



$$V_0 = A\,(V^+ - V^-)$$

- $A \to \infty$
- $R_{IN} \to \infty$
- $R_{OUT} = 0$



USCITA di A.O. ID. : È GEN. DI TENS. ID.

- Tempo di risposta nullo

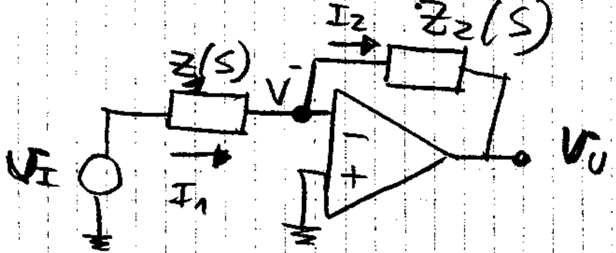
CONFIGURAZ. A REAZIONE NEGATIVA

V_0 FINITO ; $(V^+ - V^-) = \dfrac{V_0}{A} \longrightarrow 0$

$V^+ = V^-$ C.TO CIRC. VIRTUALE

(Se $V^+ = 0\,V \to$ MASSA VIRT.)

- INVERTENTE :



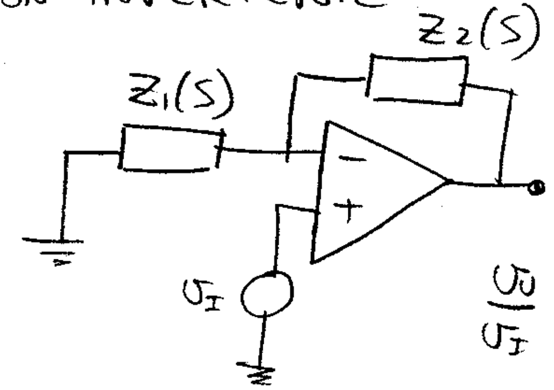
$$\frac{V_U}{V_I} = -\frac{Z_2(S)}{Z_1(S)}$$

Risoluz: $V^- = V^+ = 0\,V$

$I_1 = I_2$

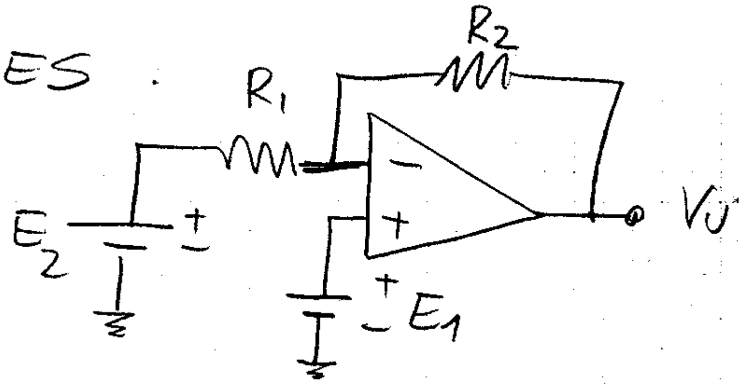
$I_1 = \dfrac{V_I}{Z_1(S)}$

- NON-INVERTENTE



$$\frac{V_U}{V_I} = 1 + \frac{Z_2(S)}{Z_1(S)}$$

- ES.



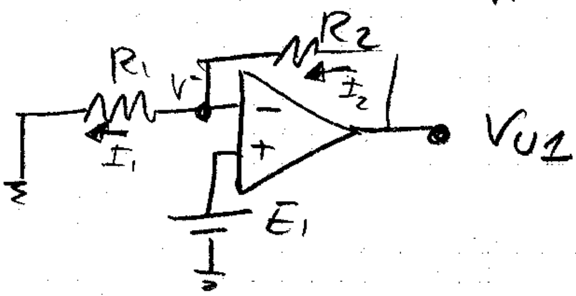
$R_1 = 1k\Omega$ $\quad E_1 = -2\,V$ $\quad A \to \infty$

$R_2 = 2k\Omega$ $\quad E_2 = +1\,V$

? V_U ?

- Reaz. neg. → Rete lin. → Sovrapp. eff.

(1) Spengo E_2 :



$V^+ = E_1$

$V^- = V^+ = E_1$

$I_1 = \frac{V^-}{R_1} = \frac{E_1}{R_1}$ $\qquad I_1 = I_2$

$V_{U1} = V^- + I_2 R_2 = E_1 + \frac{E_1}{R_1} R_2 = E_1\left(1 + \frac{R_2}{R_1}\right) =$

$= -2 \cdot (1+2) = -6\,V$

Anche: da config. non-inv.

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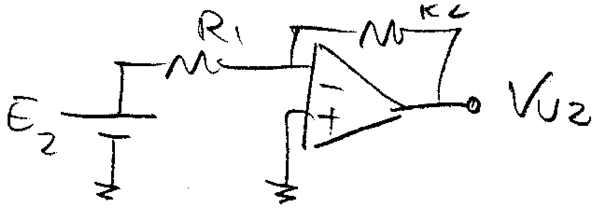
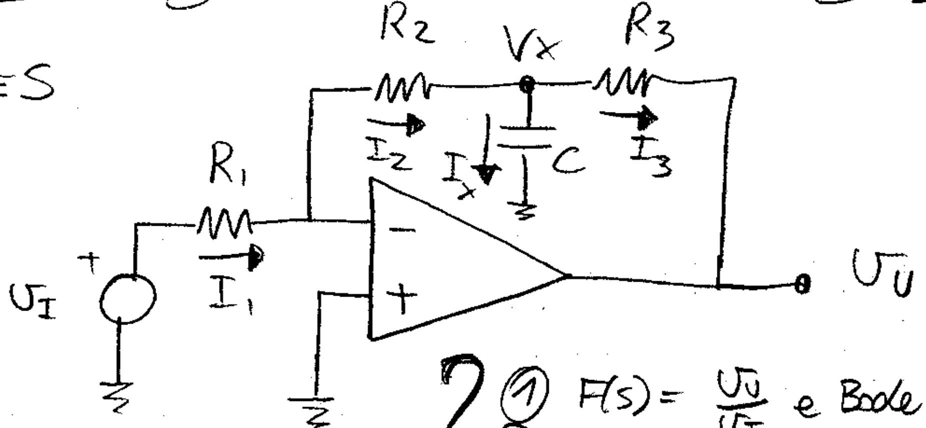
② Spengo E_1



$$V_{U2} = -E_2 \cdot \frac{R_2}{R_1} = -1 \cdot 2 = -2\ V$$

$$V_U = V_{U1} + V_{U2} = -6 - 2 = -8\ V$$

● ES



$A \to \infty$
$R_1 = 2\,K\Omega$
$R_2 = R_3 = 10\,K\Omega$
$C = 100\,mF$

? ① $F(s) = \frac{U_U}{U_I}$ e Bode
② $U_U(t)$ per $U_I(t)$ a rampa → $U_I(t) = 100 t$

- Reaz. Neg. ; $A \to \infty \Rightarrow V^- = V^+ = 0\ V$

① $I_1 = \frac{U_I - V^-}{R_1} = \frac{U_I}{R_1}$

$I_2 = I_1$

$V_x = 0 - I_2 R_2 = -I_1 R_2 = -U_I \cdot \frac{R_2}{R_1}$

(OSS: è come amp. inv.)

$I_x = \frac{U_x}{1/sC} = -\frac{sCR_2}{R_1} \cdot U_I$

$I_3 = I_2 - I_x = I_1 - I_x$

$U_U = U_x - I_3 R_3 = U_x - I_1 R_3 + I_x R_3 =$

$= -U_I \frac{R_2}{R_1} - U_I \cdot \frac{R_3}{R_1} - U_I \frac{sCR_2R_3}{R_1} =$

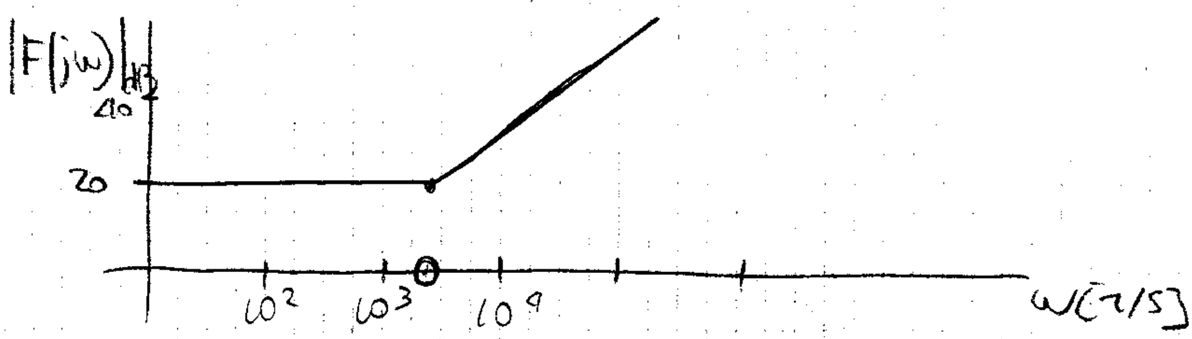
$= -U_I \left[\frac{1}{R_1}\left(R_2 + R_3 + sCR_2R_3\right)\right]$

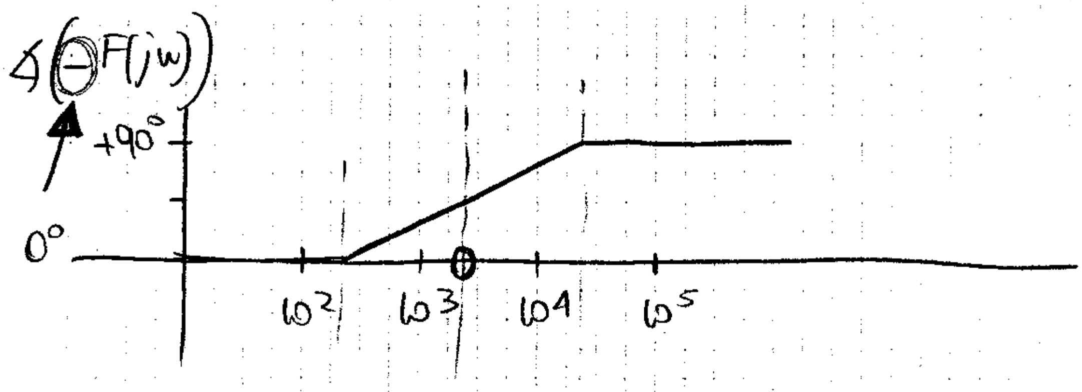
$$F(s) = \frac{v_U}{v_I} = -\frac{R_2+R_3}{R_1}\left(1 + sC\frac{R_2R_3}{R_2+R_3}\right)$$

$$F(s) = -10\,(1+\tau s) \qquad \tau = 5\cdot10^{-4}\,s$$

zero: $z = -\frac{1}{5\cdot10^{-4}} = -0.2\cdot10^{4} = -2\cdot10^{3}$ r/s

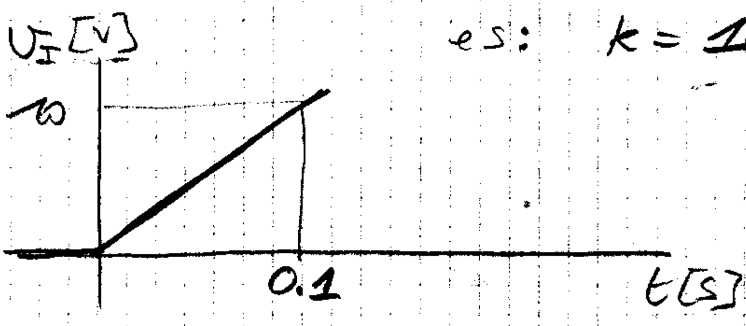
$\omega_z = 2\cdot10^{3}$ r/s





② $v_I(t) = \begin{cases} 0 & t<0 \\ kt\ [V] & t \geq 0 \end{cases}$

es: $k = 100\ V/s$



$F(s) = \frac{V_U(s)}{V_I(s)} \longrightarrow V_U(s) = F(s)\cdot V_I(s)$

$V_U(s) = -10\,(1+\tau s)\cdot V_I(s)$

$V_U(s) = -10\,V_I(s) - 10\tau\cdot s\cdot V_I(s)$

"s" è l'operatore __DERIVATA__

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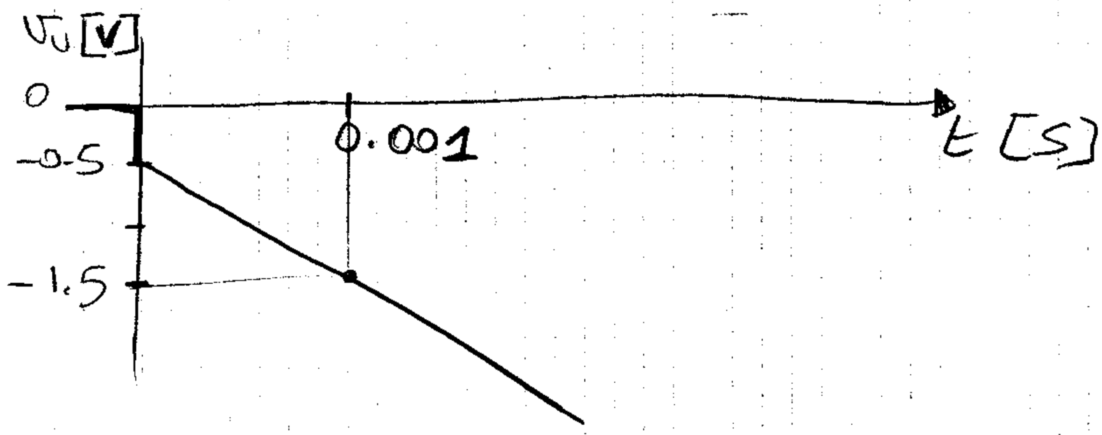
Dominio del tempo: (Questo è un caso FORTUNATO)

$$v_U(t) = -10\, v_I(t) - 10\tau \frac{d}{dt} v_I(t)$$

Dimensioni!!

$$v_U(t) = -10 \cdot \underbrace{K \cdot t}_{\text{rampa}} - 10\tau \cdot \underbrace{K}_{\text{costante}}$$

$$v_U(t) = \begin{cases} 0 & t<0 \\ -1000\,t - 0.5 \ \ V & t \geq 0 \end{cases}$$



- Verifica con TEOR. VAL. FINALE e INIZ.

$$v_I(s) = \frac{K}{s^2}$$

$$v_U(s) = F(s) \cdot v_I(s) = -10(1+s\tau) \cdot \frac{K}{s^2}$$

$$v_U(0^+) = \lim_{s \to +\infty} s \cdot v_U(s) = \lim_{s\to+\infty} -\cancel{s} \cdot 10(1+s\tau)\frac{K}{s^{\cancel{2}}} =$$

$$= \lim_{s\to+\infty}\left(-\frac{10K}{s}\right) + \lim_{s\to+\infty}\left(-10\tau K\frac{s}{\cancel{s}}\right) =$$

$$= 0 - 10\underbrace{\tau}_{[s]}\underbrace{K}_{[V/s]} = -10 \cdot 5 \cdot 10^{-4} \cdot 10^2 = -0.5\ V$$

$$v_U(\infty) = \lim_{s\to 0^+} s \cdot v_U(s) = \lim_{s\to 0^+} -10K\frac{1+s\tau}{s} = -\infty$$

- ES : SINTESI di RETE ①

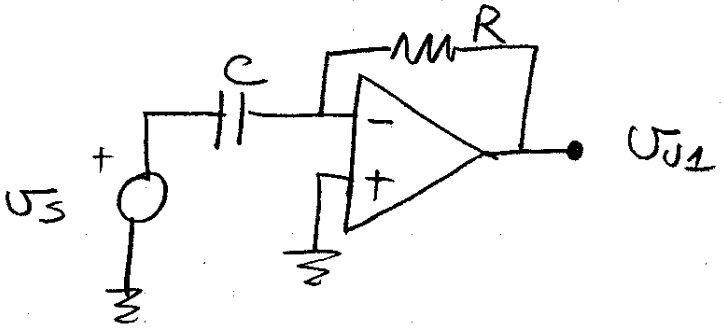
ho :

Voglio realizzare $v_U(t) = -0.3 \frac{d}{dt} v_S(t) + 5 \quad [V]$

(Tempo in [S]) $\quad 0.3 \to [S] \qquad \frac{d}{dt}v_S(t) \to [V/S]$

A disposizione : A.O. , R, C, L, Batteria
└ con alimentaz

① Realizzo $v_{U1}(t) = -0.3 \frac{d}{dt} v_S(t)$ → Derivatore (invertente)



$$\frac{v_{U1}}{v_S} = -\frac{R}{1/sC} = -sCR = -s\tau \qquad \tau = CR$$

$$v_{U1}(s) = -s\tau\, v_S(s)$$

$$\Updownarrow$$

$$v_{U1}(t) = -\tau \frac{d}{dt} v_S(t)$$

Dimensionamento : $\tau = 0.3\ s \longrightarrow$ Es: $\begin{cases} C = 1\mu F \\ R = 300k\Omega \end{cases}$

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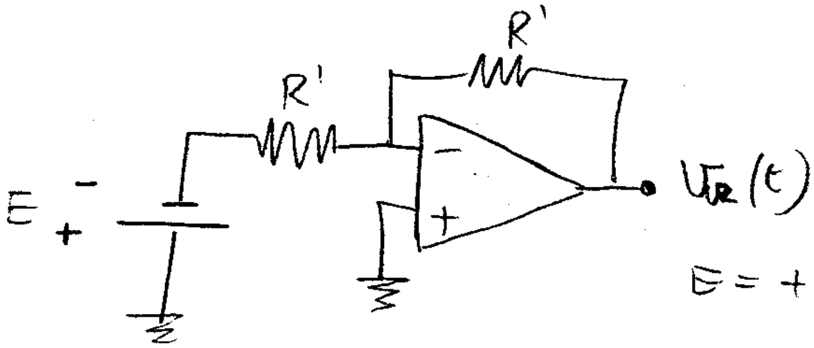
(2) Realizzo $v_{U2}(t) = +5 \ V$

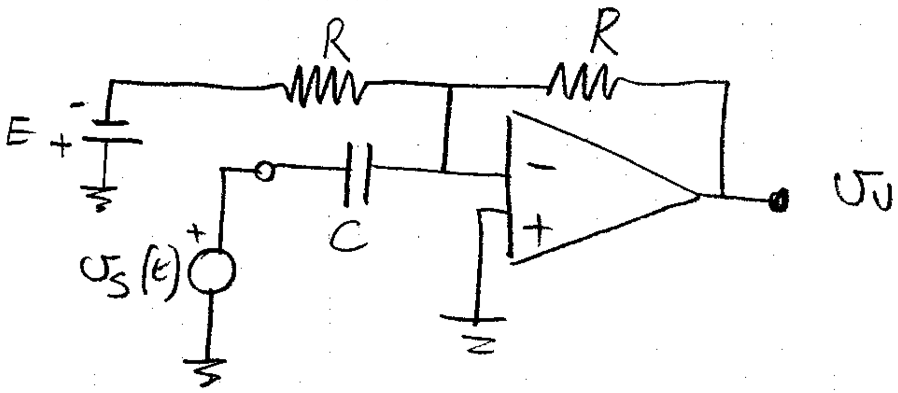
Varie possibilità. Scelgo questa: (batteria a scelta)



$E = +5 \ V$

$$v_{U2} = -\frac{R'}{R'} \cdot (-E) = -(-E) = E = +5 \ V$$

(TOT) Posso usare 1 SOLO A.O (SOVRAPP. EFFETTI)



$R = 300 \ k\Omega$
$C = 1 \ \mu F$
$E = +5 V$

- ES: $\boxed{\text{SINTESI di RETE (2)}}$

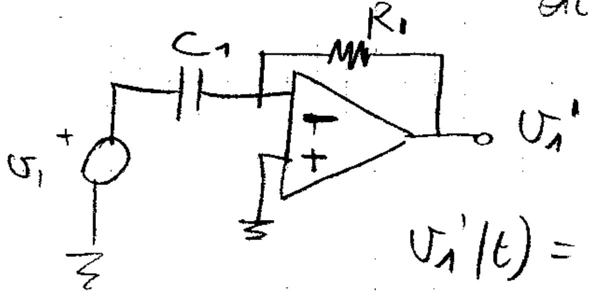
Ho $v_1(t)$; $v_2(t)$ – Voglio:

$$v_U(t) = \frac{d}{dt} v_1(t) + 100 \int_0^t v_2(t')\,dt' + 10 \quad [V]$$

c'è 1 [s]   [s^-1]   [V·s]

Alla fine uso Sommatore Invertente
(+ comodo!!)

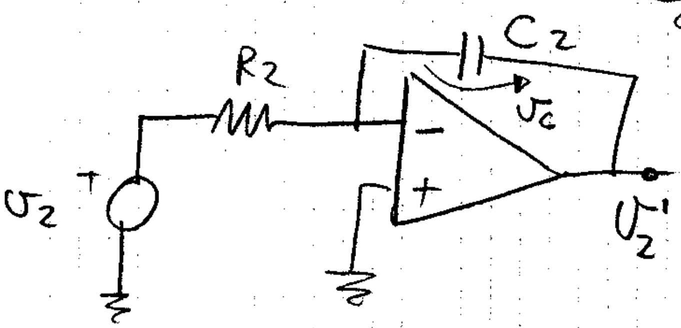
(1) Creo $v_1'(t) = -0.1 \frac{d}{dt} v_1(t)$



$$v_1'(t) = -\tau_1 \frac{d}{dt} v_1(t) \quad ; \quad \tau_1 = R_1 C_1$$

$$\tau_1 = 0.1 \text{ s} \rightarrow \begin{matrix} C = 1\,\mu F \\ R = 100\,k\Omega \end{matrix}$$

(2) Creo $v_2'(t) = -100 \int_0^t v_2(t')\,dt'$



$$\frac{v_2'}{v_2} = -\frac{1/sC_2}{R_2} = -\frac{1}{sC_2R_2} = -\frac{1}{s}\cdot\frac{1}{\tau_2} \quad ; \quad \tau_2 = C_2 R$$

$$\Updownarrow$$

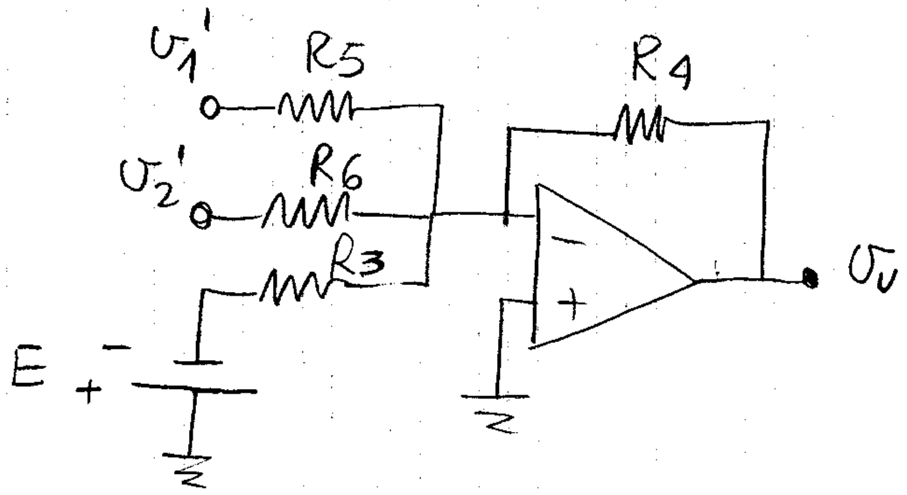
$$v_2'(t) = -\frac{1}{\tau_2}\int_0^t v_2(t')\,dt' + \underbrace{v_c(0)}_{= 0\,V}$$

(C scarico a $t = 0$)

voglio: $100 = \frac{1}{\tau_2} \rightarrow \tau_2 = 10^{-2}$ s

$$\begin{cases} C_2 = 100\,mF \\ R_2 = 100\,k\Omega \end{cases}$$

TOT USO SOMMATORE INVERTENTE
(E' + COMODO)!



Scelgo $R_4 = 1\ k\Omega$

$$R_5 = \frac{R_4}{10} = 100\ \Omega$$

$$R_6 = R_4 = 1\ k\Omega$$

$$E = +5 \Rightarrow R_3 = \frac{R_4}{2} = 500\ \Omega$$

■ NON-IDEALITÀ DELL'A.O.

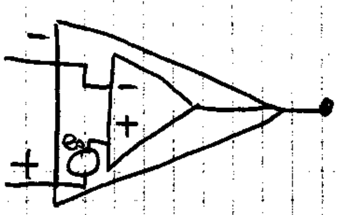
■ GUADAGNO FINITO

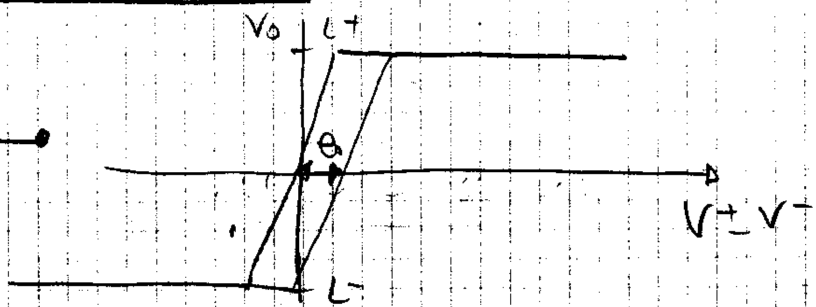
$A \neq \infty$ (TIP: $A = 10^3 \div 10^6$)

$\Rightarrow V^+ \neq V^-$

- Tecnica risolutiva: $V_0 = A(V^+ - V^-)$
  si scrivono 2 eq. e si elimina V^-

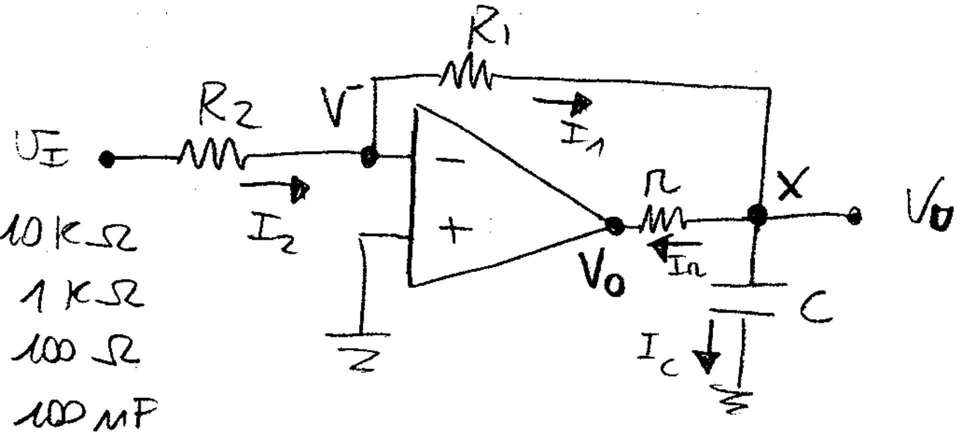
■ OFFSET DI TENSIONE





Gen. id. di Tens. in serie a mors. "+"
$|e_0|$ = qualche mV

- ES (TEMA D'ESAME 24/6/97)



$R_1 = 10\,K\Omega$
$R_2 = 1\,K\Omega$
$r = 100\,\Omega$
$C = 100\,nF$

? ① $A \to \infty$; det F.d.T. $\frac{V_U}{V_I}$
② Effetto di offset $e_0 = +5\,mV$ $(A \to \infty)$
③ $A = 100$ det $F(s) = \frac{V_U}{V_I}$, Bode, Risp. al gradino.

① $A \to \infty \Rightarrow V^+ = V^-$

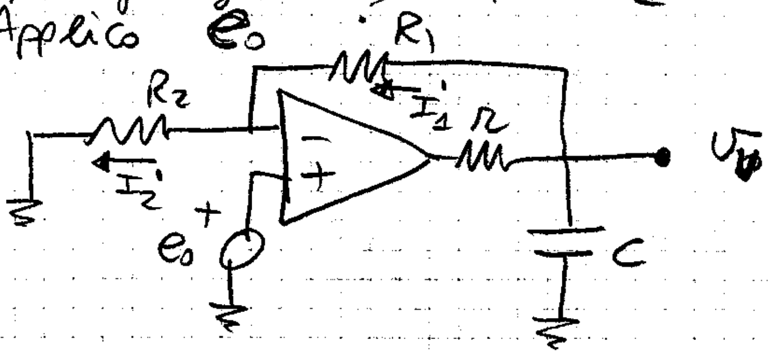
$V^- = 0\,V$
$I_1 = I_2$

$I_2 = \frac{V_I}{R_2}$

$V_U = -I_1 R_1 = -I_2 R_1 = -V_I \frac{R_1}{R_2}$

$F(s) = \frac{V_U}{V_I} = -\frac{R_1}{R_2} = -10$ (non dip. da r e C)

② Spengo gen. indip. V_I
Applico e_0



NON INV!

$A \to \infty \Rightarrow V^- = V^+ = e_0$
$V_U = e_0 + I_1' R_1 = e_0 + I_2' R_1 = e_0 + \frac{e_0}{R_2} R_1 = e_0\left(1 + \frac{R_1}{R_2}\right)$

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(3) $v_O = A\,(V^+ - V^-)$

$V^+ = 0 \longrightarrow \left.\begin{array}{l} v_0 = -A\,V^- \\ I_1 = I_2 \end{array}\right\}$ 2 eq. da propr. dell' A.O.

+

$I_1 = I_R + I_C \longleftarrow$ 1 eq. da legge Kirchhoff nodo X

= 3 eq. in 3 incognite (V^-, V_0, v_U)

$$I_2 = \frac{v_I - V^-}{R_2}$$

$$I_1 = \frac{V^- - v_U}{R_1}$$

$$I_R = \frac{v_U - V_0}{R}$$

$$I_C = \frac{v_U}{1/sC} = sC\,v_U$$

$$\begin{cases} V_0 = -A V^- & (1) \\ \dfrac{v_I - V^-}{R_2} = \dfrac{V^- - v_U}{R_1} & (2) \\ \dfrac{V^- - v_U}{R_1} = \dfrac{v_U - V_0}{R} + sC\,v_U & (3) \end{cases}$$

da (3) ricavo V^-:

$$V^- = v_U \frac{R_1}{R} - V_0 \frac{R_1}{R} + sCR_1 v_U + v_U$$

$$V^- = \left(1 + \frac{R_1}{R} + sCR_1\right) v_U - \frac{R_1}{R} V_0$$

sost. nella (1) e ricavo V_0

$$V_0 = -A\left(1 + \frac{R_1}{R} + sCR_1\right) v_U + A\frac{R_1}{R} V_0$$

$$V_0 = \frac{-A\left(1+\frac{R_1}{r}+sCR_1\right)}{1-A\frac{R_1}{r}}\, v_U$$

Dalla (1) calcolo V^-

$$V^- = -\frac{V_0}{A} = \frac{1+\frac{R_1}{r}+sCR_1}{1-A\frac{R_1}{r}}\, v_U$$

SOST. V^- nella (2)

$$(2):\quad R_1 v_I - R_1 V^- = R_2 V^- - R_2 v_U$$

$$R_1 v_I = (R_1+R_2)V^- - R_2 v_U$$

SOST: $$R_1 v_I = (R_1+R_2)\frac{1+\frac{R_1}{r}+sCR_1}{1-A\frac{R_1}{r}}\, v_U - R_2 v_U$$

$$F(s) = \frac{v_U}{v_I} = \frac{R_1}{(R_1+R_2)\frac{1+\frac{R_1}{r}+sCR_1}{1-A\frac{R_1}{r}} - R_2}$$

<u>Verifico</u>: $A \to \infty \Rightarrow F(s) \to -\frac{R_1}{R_2}$ OK.

$$F(s) = \frac{R_1\left(1-A\frac{R_1}{r}\right)}{(R_1+R_2)\left(1+\frac{R_1}{r}+sCR_1\right) - R_2 + A\frac{R_1R_2}{r}} =$$

$$= \frac{R_1\left(1-A\frac{R_1}{r}\right)}{(R_1+R_2)\left(1+\frac{R_1}{r}\right) + R_2\left(A\frac{R_1}{r}-1\right) + sCR_1(R_1+R_2)}$$

$$= \frac{\cancel{R_1}\left(1-A\,R_1/r\right)}{\cancel{R_1}\left(1+\frac{R_1}{r}\right) + R_2\left(\cancel{1}+\frac{\cancel{R_1}}{r}+A\frac{\cancel{R_1}}{r}-\cancel{1}\right)} \cdot \frac{1}{1+sC\frac{\cancel{R_1}(R_1+R_2)}{\cancel{R_1}\left(1+\frac{R_1}{r}\right)+R_2\frac{\cancel{R_1}}{r}(A+1)}}$$

$$F(s) = -\frac{A\frac{R_1}{r} - 1}{1+\frac{R_1}{r}+\frac{R_2}{r}(A+1)} \cdot \frac{1}{1+sC\dfrac{R_1+R_2}{1+\frac{R_1}{r}+\frac{R_2}{r}(A+1)}}$$

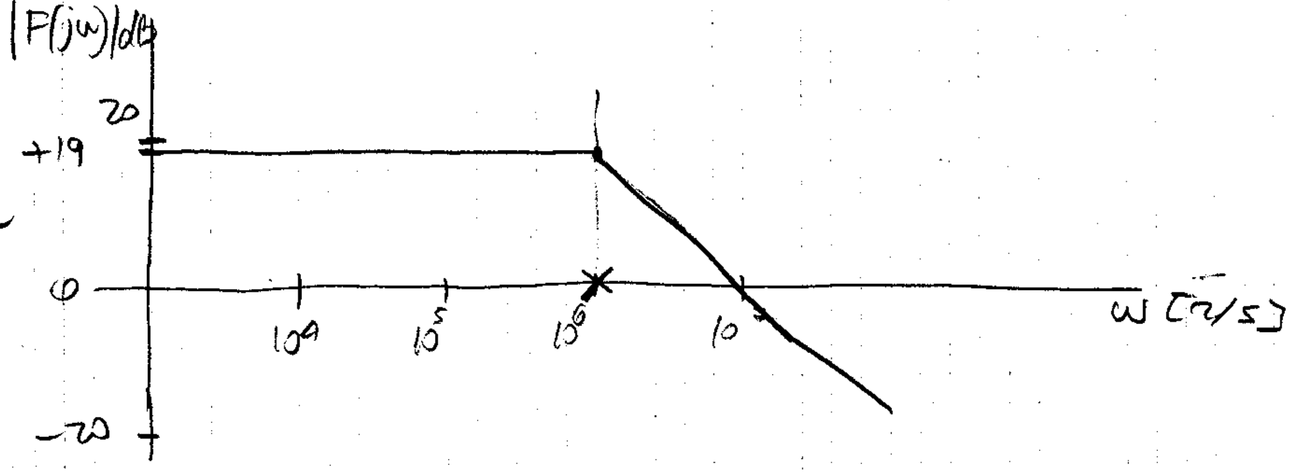
! DIRE CHE SE $A = A(s)$ CAMBIA LA F.d.T !

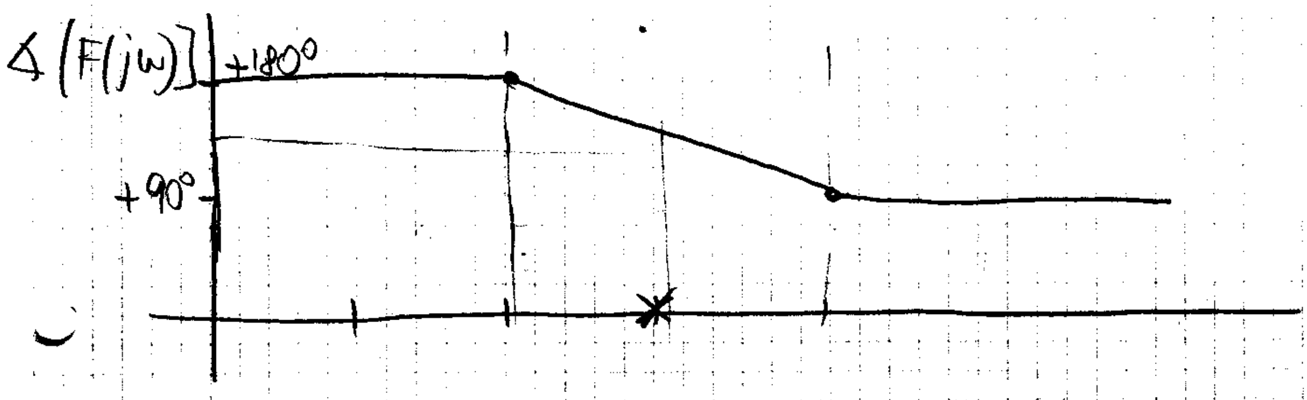
Numeri:
$$\frac{R_1}{r} = \frac{10^4}{10^2} = 100$$
$$\frac{R_2}{r} = \frac{10^3}{10^2} = 10$$

$$F(s) \simeq -\frac{10^4}{1+100+1010} \cdot \frac{1}{1+s\dfrac{C(R_1+R_2)}{1+100+1010}} =$$

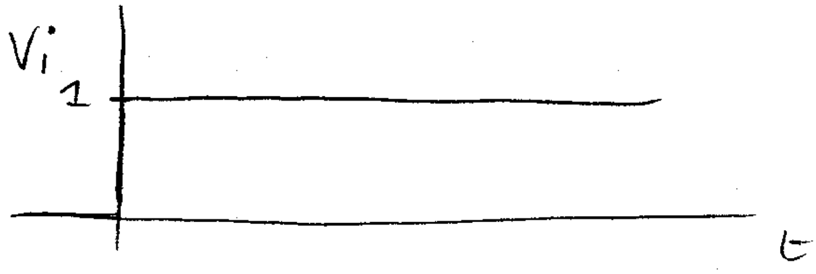
$$= -\frac{10^4}{1111} \cdot \frac{1}{1+s\cdot\dfrac{10^{-7}\cdot 11\cdot 10^3}{1111}} \simeq -9 \cdot \frac{1}{1+s\cdot 9.9\cdot 10^{-7}}$$

polo: $-1.01\cdot 10^6$ r/s $\rightarrow \omega_p = 1.01\cdot 10^6$ r/s



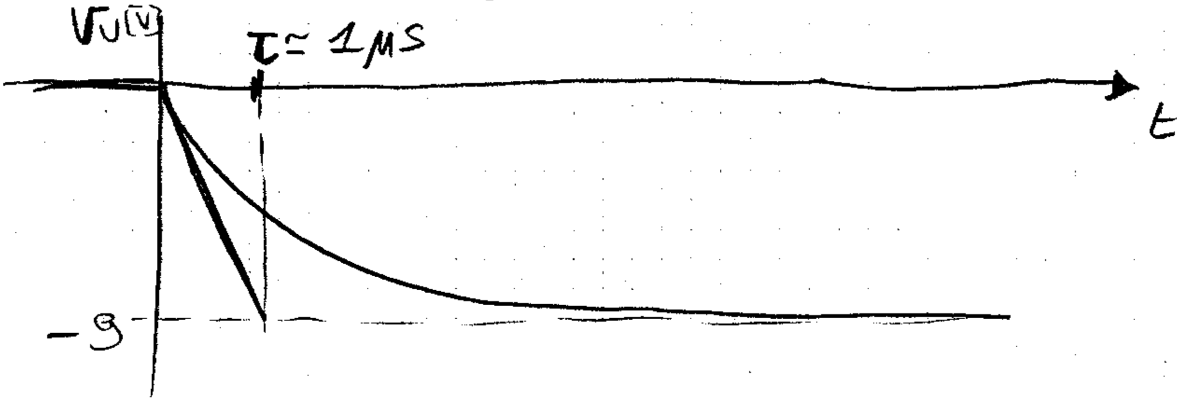


Risposta al gradino:



$$F(s) \simeq -9 \cdot \frac{1}{1+s\tau} \longrightarrow \text{PASSA-BASSO}$$

$$t \geq 0: V_U(t) = -9 \cdot \left(1 - e^{-t/\tau}\right) \quad ; \tau = 9.9 \cdot 10^{-7}\ \text{sec.}$$



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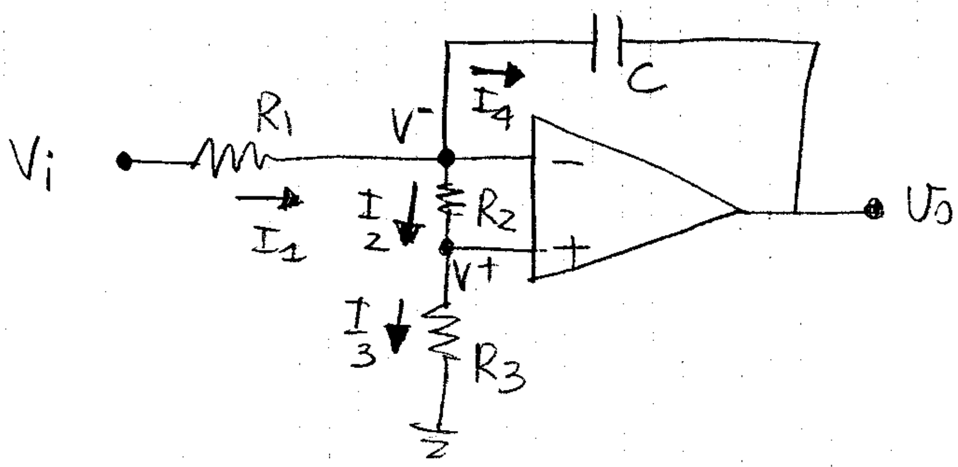
● ES (TEMA D'ESAME 12/2/97)



$C = 100\ nF$
$R_1 = 100\ k\Omega$
$R_2 = 1\ k\Omega$
$R_3 = 1\ k\Omega$

(1) A.O. id : F.d.t. $\frac{U_0}{U_i}$; Diagr. Bode ; risp. gradino

(2) A = 100 : Fdt $\frac{U_0}{U_i}$; Bode

(3) $v_i(t) = 10 \sin 10^3 t$ [V] ? $v_0(t)$

(1) $A \to \infty$, Reaz. neg $\Rightarrow V^+ = V^-$

$$\Rightarrow I_2 = \frac{V^- - V^+}{R_2} = 0$$

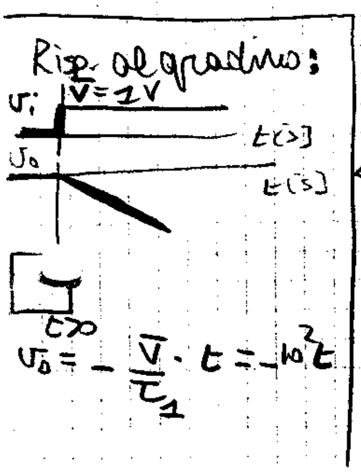
$$I_3 = 0 \Rightarrow V^- = V^+ = 0\,!$$

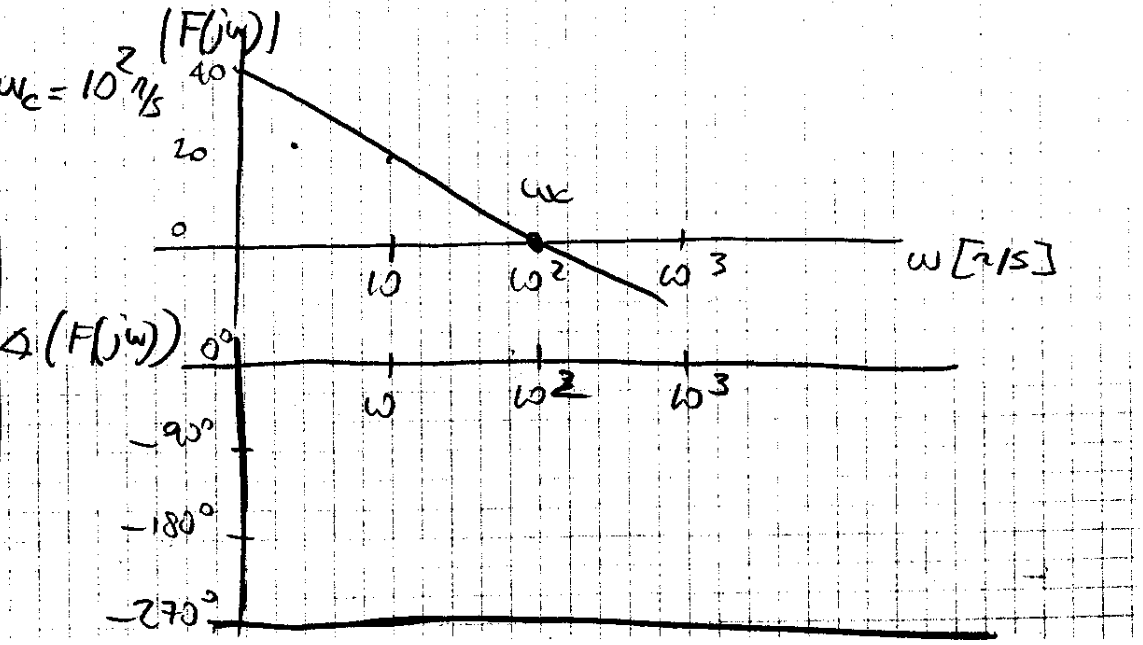
$\Rightarrow I_1 = I_4 \Rightarrow$ è integratore

$$F(s) = \frac{U_0}{U_i} = -\frac{1}{sCR_1} = -\frac{1}{s\tau_1};$$

$$\tau_1 = CR_1 = 10^{-7} \cdot 10^5 = 10^{-2}\ s$$

$|F(j\omega_c)| = 1 \to \omega_c = 10^2\ r/s$





② $A \neq \infty \Rightarrow V^+ \neq V^- \Rightarrow I_2 \neq 0$

$I_3 = I_2$

$I_1 = I_2 + I_4$

$$\left.\begin{aligned} I_2 &= \frac{V^- - V^+}{R_2} \\ (V^+ - V^-) &= \frac{v_0}{A} \end{aligned}\right\} \Rightarrow I_2 = -\frac{v_0}{AR_2}$$

¿V^-? $V^- = V^+ - \dfrac{v_0}{A} = I_2 R_3 - \dfrac{v_0}{A} = -\dfrac{v_0}{A}\dfrac{R_3}{R_2} - \dfrac{v_0}{A} =$

$$= -\frac{v_0}{A}\left(1 + \frac{R_3}{R_2}\right)$$

¿v_0? $v_0 = V^- - \dfrac{I_4}{sC}$

¿I_4? $I_4 = I_1 - I_2 = \dfrac{v_i - V^-}{R_1} - I_2 =$

$$= \frac{v_i}{R_1} + \frac{v_0}{AR_1}\left(1 + \frac{R_3}{R_2}\right) + \frac{v_0}{AR_2}$$

$$\Rightarrow v_0 = -\frac{v_0}{A}\left(1 + \frac{R_3}{R_2}\right) - \frac{1}{sC}\left[\frac{v_i}{R_1} + \frac{v_0}{A}\left(\frac{1}{R_1}\left(1 + \frac{R_3}{R_2}\right) + \frac{1}{R_2}\right)\right]$$

$$v_0\left[1 + \frac{1}{A}\frac{R_2+R_3}{R_2} + \frac{1}{A}\frac{1}{sC}\left(\frac{1}{R_1}\frac{R_2+R_3}{R_2} + \frac{1}{R_2}\right)\right] = -\frac{v_i}{sCR_1}$$

$$F(s) = -\frac{1}{sC_1R_1} \cdot \frac{1}{1 + \frac{R_2+R_3}{AR_2} + \frac{R_2+R_3}{AR_2}\frac{1}{sCR_1} + \frac{1}{A}\frac{1}{sCR_2}} =$$

$$= -\frac{1}{sC_1R_1} \cdot \frac{1}{\dfrac{AsCR_1R_2 + sCR_1(R_2+R_3) + R_2 + R_3 + R_1}{AsCR_1R_2}}$$

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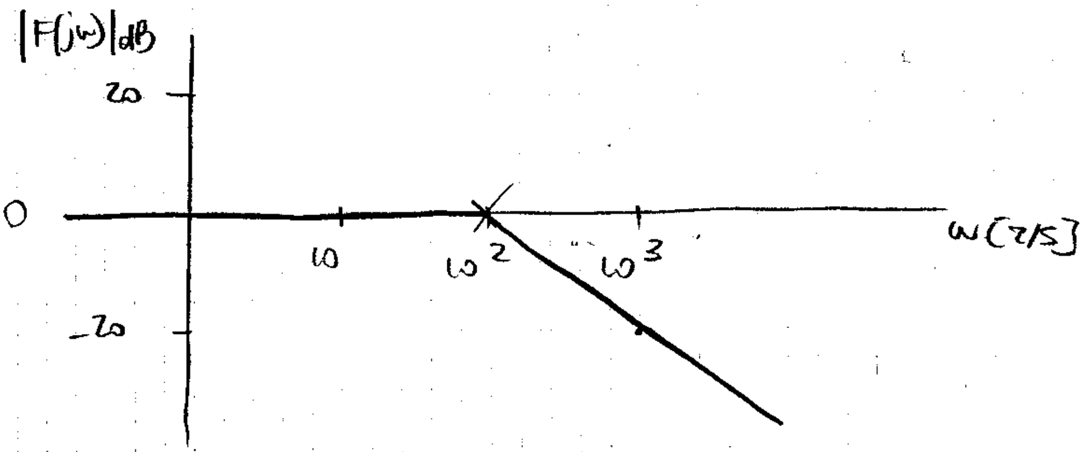
$$F(s) = -\frac{1}{\cancel{sCR_1}} \cdot \frac{A \cancel{sCR_1} R_2}{R_1+R_2+R_3 + sCR_1(AR_2+R_2+R_3)} =$$

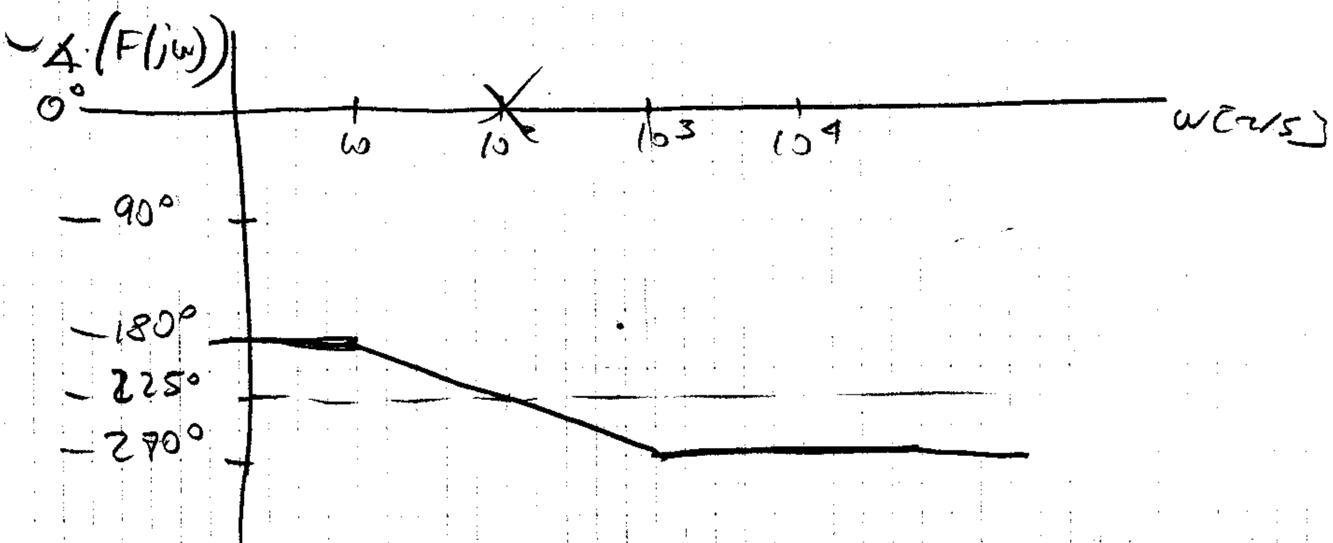
$$= -\frac{AR_2}{R_1+R_2+R_3} \cdot \frac{1}{1 + sC\frac{R_1 \cdot [(A+1)R_2+R_3]}{R_1+R_2+R_3}} =$$

OK se $A \to \infty$

$$F(s) = -\frac{10^2 \cdot 10^3}{102'000} \cdot \frac{1}{1+s\tau'} \simeq -\frac{1}{1+s\tau'}$$

$$\tau' = C \cdot \frac{R_1[(A+1)R_2+R_3]}{R_1+R_2+R_3} \simeq 10^{-7} \cdot 10^5 \cdot \frac{10^5}{10^5} = 10^{-2} s$$



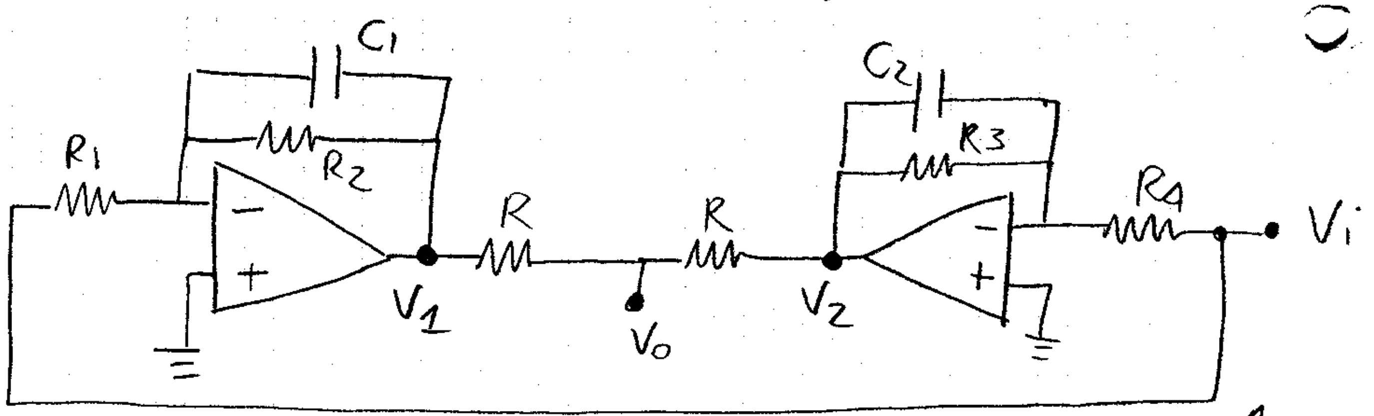


③ !! Aggiunta: $v_i(t) = 10 \sin 10^3 t$ [V] ? $v_o(t)$?

Dal diag.: $v_o(t) = 1 \sin(10^3 t + \varphi)$; $\varphi = -270°$

esatto: (OK amp.) $\varphi = -180° - \arctan\frac{10^3}{10^2} = -180° - 84° = -264°$

• ES (TEMA D'ESAME 19/11/96)



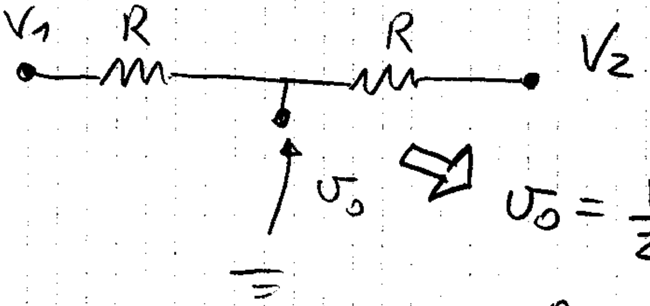
$A \to \infty$

$R = R_4 = 10\,k\Omega$; $R_1 = 1\,k\Omega$; $R_2 = 1\,M\Omega$;
$R_3 = 100\,k\Omega$; $C_1 = 100\,\mu F$; $C_2 = 1\,nF$

? (1) Det $F(s) = \frac{V_0}{V_i}$; Bode
(2) Risp. al grad.

(1) - Rete lineare
- Uscita di AO con $R_{out} = 0$ è gen. id. di Tens ⇒ x Trovare V_0 : sovrapp. effetti

Det. V_1 e V_2 poi:



$$V_0 = \frac{1}{2}\left(V_1 + V_2\right)$$

$$V_1 = -V_i \frac{R_2 // \frac{1}{sC_1}}{R_1} = -V_i \frac{\frac{R_2}{sC_1}}{R_2 + \frac{1}{sC_1}} \cdot \frac{1}{R_1} = -V_i \frac{R_2}{R_1} \cdot \frac{1}{1 + sC_1}$$

$$V_2 = -V_i \frac{R_3}{R_4} \cdot \frac{1}{1 + sC_2R_3}$$ x simmetria

$$F(s) = \frac{V_0}{V_i} = -\frac{1}{2}\left[\frac{R_2}{R_1} \cdot \frac{1}{1 + sC_1R_2} + \frac{R_3}{R_4} \cdot \frac{1}{1 + sC_2R_3}\right] =$$

$$F(s) = -\frac{1}{2} \cdot \frac{\frac{R_2}{R_1} + sC_2\frac{R_2R_3}{R_1} + \frac{R_3}{R_4} + sC_1\frac{R_2R_3}{R_4}}{(1+sC_1R_2)(1+sC_2R_3)} =$$

$$= -\frac{1}{2} \cdot \frac{\frac{R_2R_4+R_1R_3}{R_1R_4} + s\frac{C_2R_2R_3R_4 + C_1R_1R_2R_3}{R_1R_4}}{(\quad)(\quad)} =$$

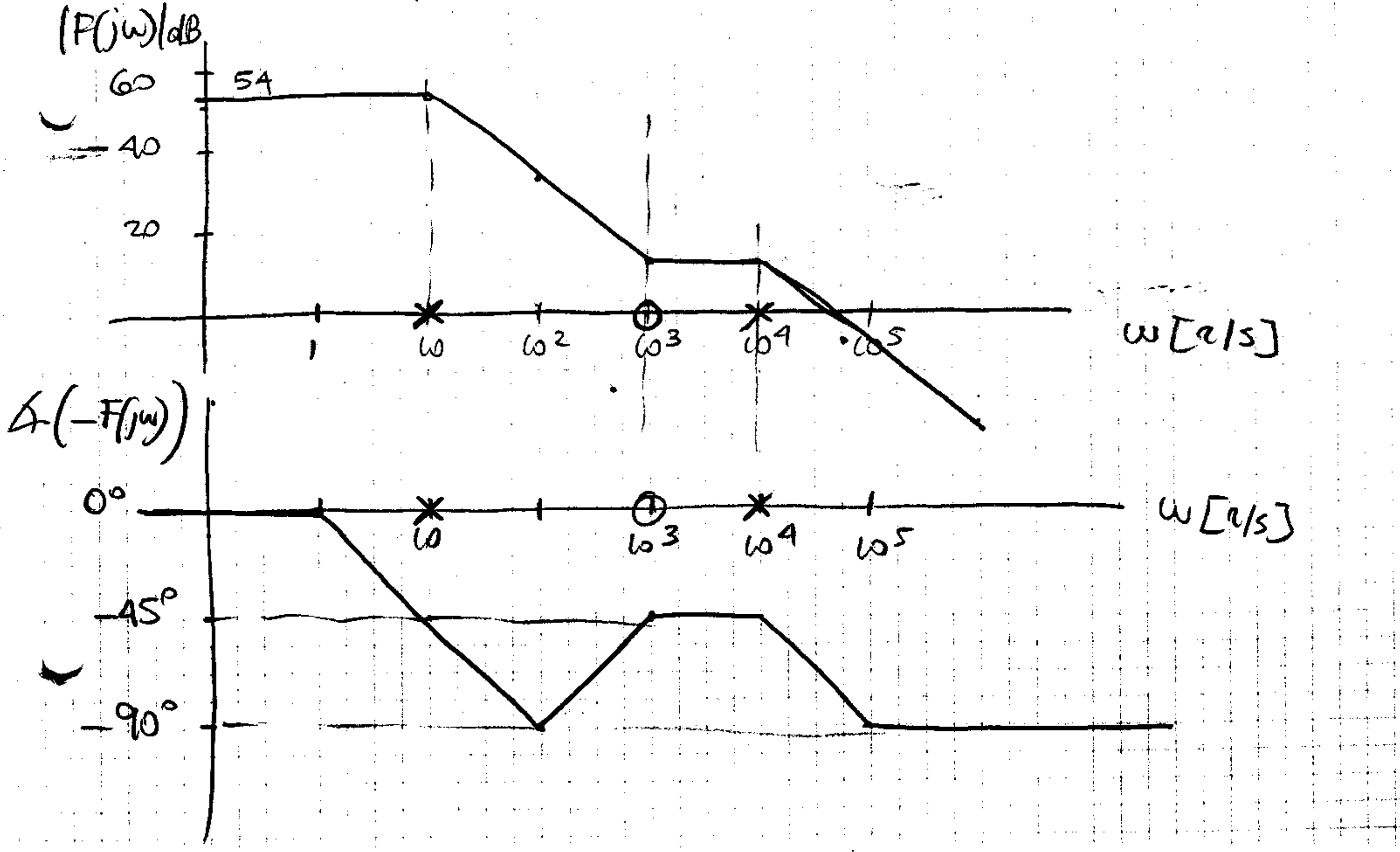
$$= -\frac{1}{2} \cdot \frac{R_2R_4+R_1R_3}{R_1R_4} \cdot \frac{1 + s\frac{C_2R_2R_3R_4+C_1R_1R_2R_3}{R_2R_4+R_1R_3}}{(1+sC_1R_2)(1+sC_2R_3)} =$$

$$= -\frac{1}{2} \cdot \frac{10^6\cdot10^4+10^3 10^5}{10^3\, 10^4} \cdot \frac{1+s\frac{10^{-9}10^6 10^5 10^4+10^{-7}10^3 10^6 10^5}{10^6 10^4+10^3\cdot10^5}}{(1+s\cdot10^{-7}10^6)(1+s10^{-9}10^5)} =$$

$$\cong -505 \cdot \frac{1+10^{-3}\cdot s}{(1+10^{-1}s)(1+10^{-4}s)}$$

$\omega_z = 10^3\ r/s$; $\omega_{p1} = 10\ r/s$; $\omega_{p2} = 10^4\ r/s$

$505 = 54\ dB$



(2) Risp. al grad:

NON È una F.d.T. della quale sia noto in maniera immediata la risp. al grad.

Usiamo Teor. del val. iniz. e fin.

$$F(s) = -505\,\frac{1+s\tau_1}{(1+s\tau_2)(1+s\tau_3)}$$

$\tau_1 = 10^{-3}\,s$

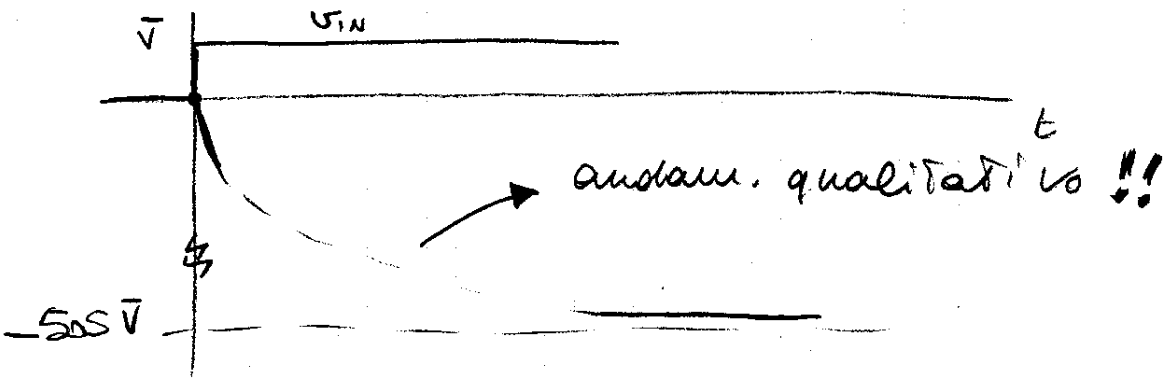
$\tau_2 = 10^{-1}\,s$

$\tau_3 = 10^{-4}\,s$

$$v_U(s) = F(s)\cdot v_i(s) = -505\,\frac{1+s\tau_1}{(1+s\tau_2)(1+s\tau_2)}\cdot\frac{\bar{V}}{s}$$

$$\lim_{t\to 0^+} v_U(t) = \lim_{s\to +\infty} s\, v_U(s) = 0$$

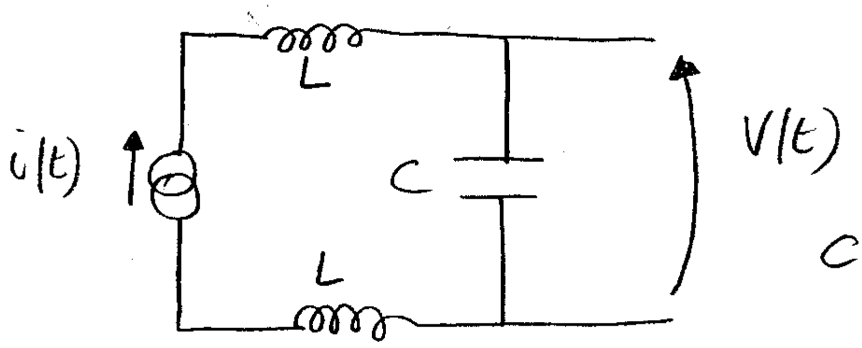
$$\lim_{t\to +\infty} v_U(t) = \lim_{s\to 0^+} s\cdot v_U(s) = -505\,\bar{V}$$



! Dal diagr. di Bode del mod.: è ≃ come passa basso!

- Freq. alte: Risposta → 0
- Freq. bass: Risposta → -50

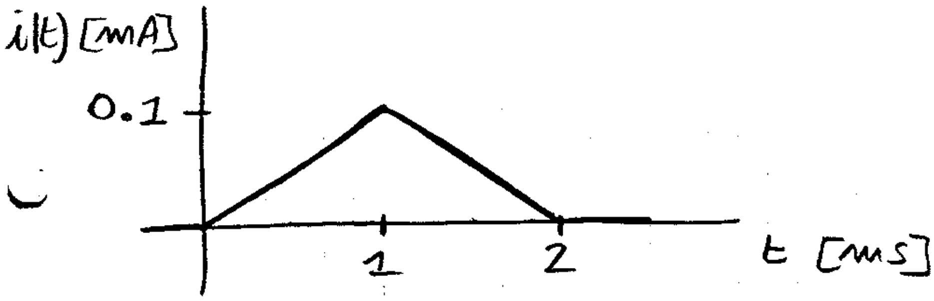
• ES (SCRITTO 3/4/97)



$L = 1\,mH$

$C = 10\,mF$

C scarico a $t=0$



? V(t) ?

Corrente nel condensatore è $i(t)$.

$$i(t) = C\,\frac{dV(t)}{dt}$$ → Le induttanze non hanno effetto su V(t) (c'è un gen. id. di corr.).

$$dV(t) = \frac{1}{C}\, i(t)\,dt$$

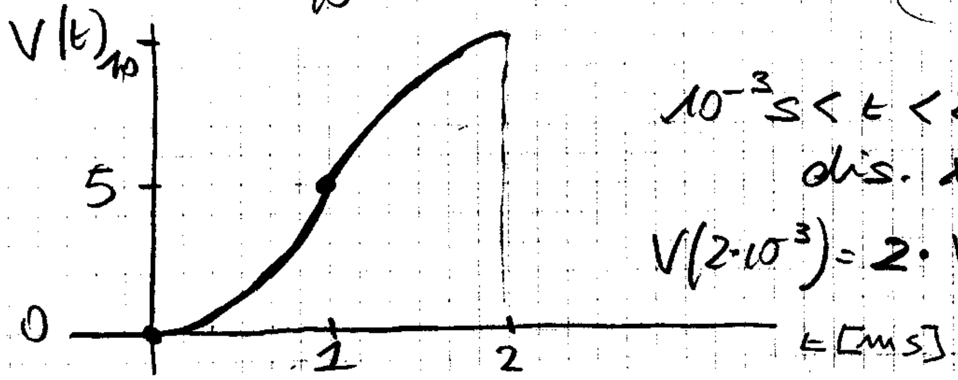
↓

$$\int_0^t dV(t') = \frac{1}{C}\int_0^t i(t')\,dt'$$

$0 < t < 10^{-3}\,s$: $i(t) = \frac{0.1\,mA}{1\,ms}\cdot t = 10^{-1}\cdot t$ [A] (t in sec.)

$$V(t) = \frac{10^{-1}}{10^{-8}}\int_0^t t'\,dt' = \frac{10^7}{2}\,t^2 \quad [V]$$

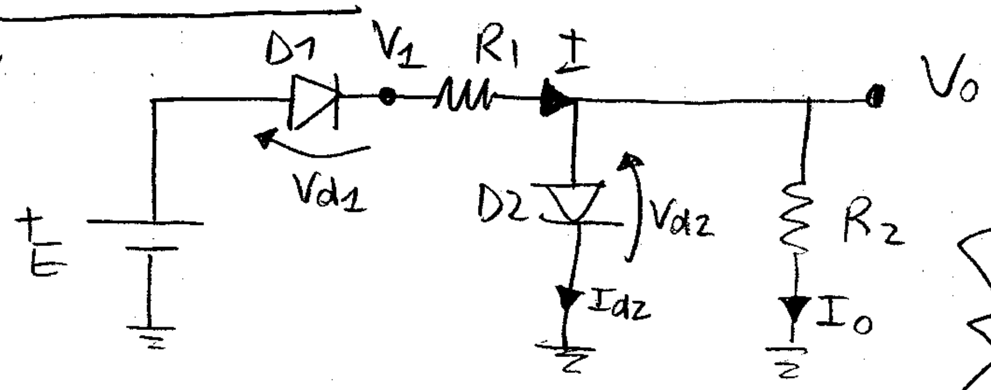
$V(10^{-3}) = \frac{10^7}{2}\cdot 10^{-6} = 5\,V$



$10^{-3}\,s < t < 2\cdot 10^{-3}\,s$:
dis. x simmetria

$V(2\cdot 10^{-3}) = 2\cdot V(10^{-3}) = 10\,V$ (2 area)

• ES – DIODI



Dire: corrente va sempre da pot. + alti a pot. + bassi

$V_\gamma = 0.7\,V$ $\quad R_1 = 9\,k\Omega$

$R_2 = 1\,k\Omega$

? Det V_o, I ? per: ① $E = +5\,V$

② $E = +10\,V$

① $E = +5V$ IPOTESI SU DIODI.

D1 OFF? Non sembra sensato.

• IP: $\begin{cases} D1 & \text{POL. DIR} \\ D2 & \text{OFF} \end{cases}$ Rifo disegno

D1 ON: è una batteria $V_{d1} = V_\gamma = 0.7\,V$

$$V_1 = E - V_{d1} = E - V_\gamma = 5 - 0.7 = 4.3\,V$$

D2 OFF: $I_o = I$ → V_o: partitore

$$V_o = V_1 \cdot \frac{R_2}{R_1 + R_2} = 4.3 \, \frac{1}{10} = 0.43\,V$$

$$I = \frac{V_1}{R_1 + R_2} = \frac{4.3}{10k} = 0.43\,mA$$

• VERIFICA IPOTESI: $I_{d1} = I > 0$ Ok

$V_{d2} = V_o = 0.43 < V_\gamma$ Ok

!! Dire che verifica si fa su I_d x D ON e su V_d x D OFF

• PROVO IP ERRATA: $\begin{cases} D1 & \text{POL. DIR.} \\ D2 & \text{POL. DIR} \end{cases}$ Rifo dis.

D1 è batteria : $V_{d1} = V_\gamma = 0.7$
D2 è batteria $V_{d2} = V_\gamma = 0.7$

$$V_0 = V_{d2} = V_\gamma = 0.7\ V$$

$$I = \frac{V_1 - V_0}{R_1} = \frac{4.3 - 0.7}{9k} = \frac{3.6}{9k} = 0.4\ mA$$

- VERIFICA IPOTESI :

$$I_{d1} = I = 0.4 mA > 0 \quad OK$$

$$I_{d2} = I - I_0$$

$$I_0 = \frac{V_0}{R_2} = \frac{0.7}{1k} = 0.7\ mA$$

$$I_{d2} = I - I_0 = +0.4 - 0.7 = -0.3\ mA$$

$I_{d2} < 0 \Longrightarrow$ IP. ERRATA !!

(2) $E = +10\ V$

- IP (ERRATA) : $\begin{cases} D1 & \text{POL. DIR} \\ D2 & \text{OFF} \end{cases}$ (come prima)

$$V_1 = E - V_\gamma = 10 - 0.7 = 9.3\ V$$

$$I_0 = I$$

$$V_0 = V_1 \cdot \frac{1}{10} = 0.93\ V$$

- VERIFICA : $V_{d2} = V_0 = 0.93 V > V_d$ NO!

- NUOVA IP : $\begin{cases} D1 & \text{POL DIR} \\ D2 & \text{POL DIR} \end{cases}$

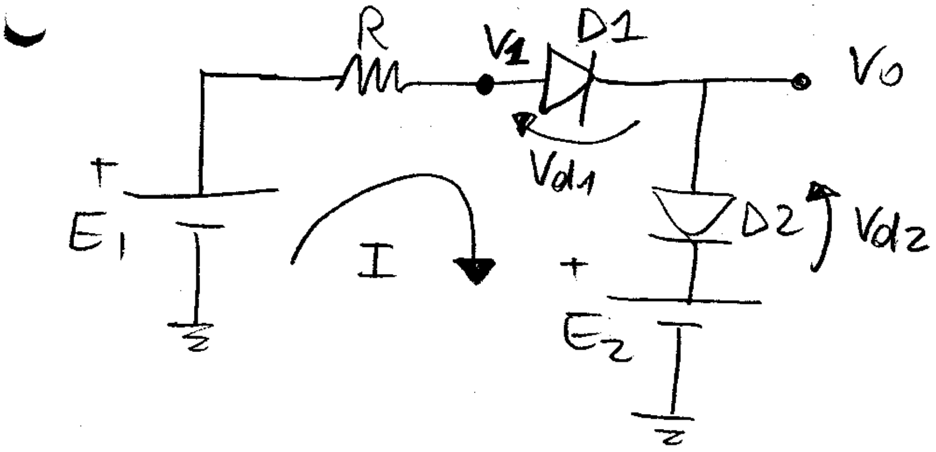
$$V_0 = V_{d2} = V_\gamma = 0.7\ V$$

$$I = \frac{V_1 - V_0}{R_1} = \frac{9.3 - 0.7}{9k} = \frac{8.6}{9k} = 0.95\ mA$$

- VERIFICA : $\begin{cases} I_{d1} = I > 0 \\ I_{d2} = I - I_0 = I - \frac{0.7}{1k} = 0.95 - 0.7 = +0.25 m \end{cases}$
OK

2C

• ES – DIODI (MOSTRA NO SOVRAPP. EFF).



$V_\gamma = 0.7$
$R = 1\ k\Omega$

? V_o ? se:

① $E_1 = +10\ V$; $E_2 = -2\ V$
② $E_1 = +10\ V$; $E_2 = 0\ V$
③ $E_1 = 0\ V$; $E_2 = -2\ V$

① • IP: $\begin{cases} D1 \text{ POL. DIR.} \\ D2 \text{ POL. DIR.} \end{cases}$ (x verso corrente)

$$\Longrightarrow \quad V_{d1} = V_\gamma = 0.7\ V$$
$$V_{d2} = V_\gamma = 0.7\ V$$

$$V_o = E_2 + V_{d2} = -2 + 0.7 = -1.3\ V$$

• VERIFICA: SU I (e $I = I_{d1} = I_{d2}$)

$$I = \frac{E_1 - V_1}{R}$$

$$V_1 = V_o + V_{d1} = -1.3 + 0.7 = -0.6\ V$$

$$I = \frac{10 - (-0.6)}{1k\Omega} = \frac{10.6}{1k} = +10.6\ mA$$

OK

② $E_1 = +10\ V$; $E_2 = 0\ V$ (Fare Dis)

• IP: $\begin{cases} D1 \text{ POL DIR} \\ D2 \text{ POL. DIR} \end{cases}$

$$V_o = 0 + V_{d2} = +0.7$$

• VERIFICA: $I = \dfrac{E_1 - V_1}{R} = \dfrac{10 - 1.4}{1k} = +8.6\ mA$

OK

(3) $E_1 = 0$; $E_2 = -2V$ (Fare dis)

- IP: $\begin{cases} D1 \text{ POL DIR} \\ D2 \text{ POL DIR} \end{cases}$

$$V_0 = E_2 + V_{d2} = -2 + 0.7 = -1.3\ V$$

- VERIFICA

$$I = \frac{0 - V_1}{R} = \frac{0 - (-0.6)}{R} = \frac{0.6}{R} = +0.6\ mA$$

OK

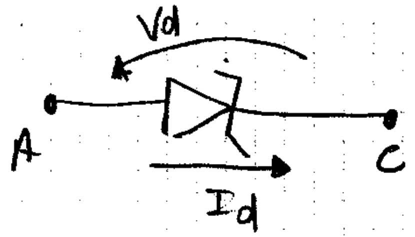
OSSERVAZIONE:

Notare che $V_0^{(1)} \neq V_0^{(2)} + V_0^{(3)}$

$$-1.3 \neq +0.7 - 1.3$$

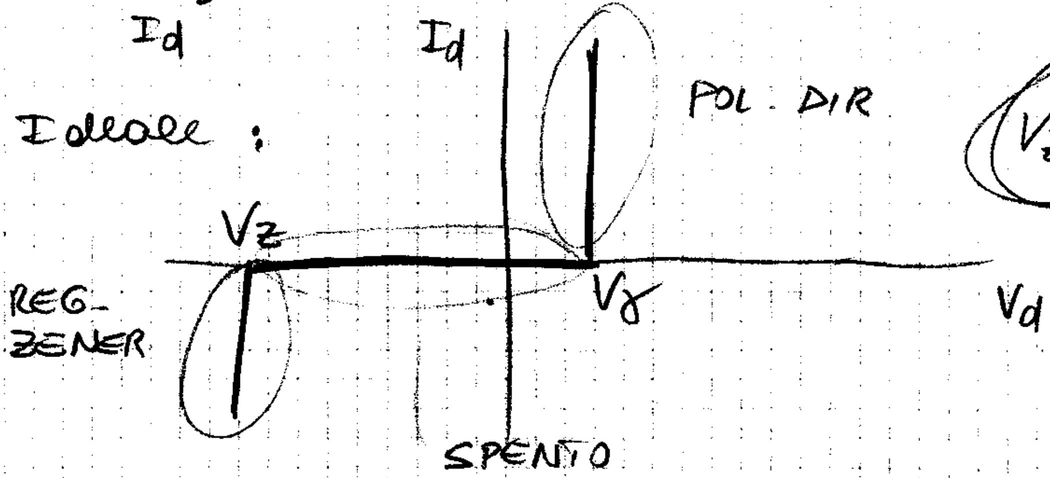
Non vale principio di sovrapp. effetti!

DIODO ZENER

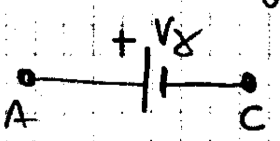
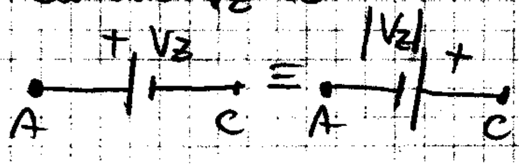
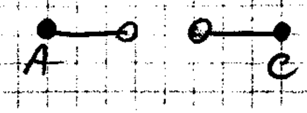


(stessa convenzione!)

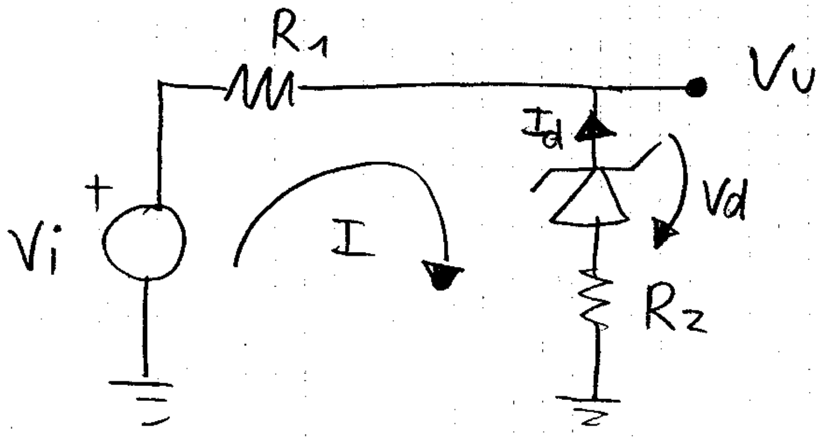
Ideale:



$V_Z < 0$!!

$I_d > 0$	$I_d < 0$	$V_Z < V_d < V_\gamma$
Batteria V_γ	Batteria $V_Z < 0$	Circ. ap.
		

• ES - DIODO ZENER



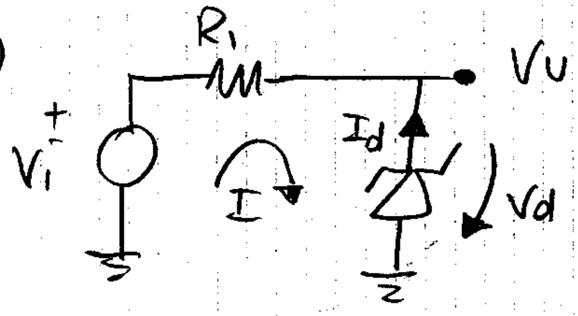
$V_\gamma = 0.7\ V$

$V_Z = -5\ V$

$R_1 = 1\ k\Omega$

? Det. caratteristiche di uscita V_U vs. V_i ? per: (1) $R_Z = 0$
I vs. V_i (2) $R_Z = 2k\Omega$

(1)



condizioni su $I = -I_d$ ➡ si deduce stato del diodo

• $I > 0$ $(I_d < 0) \Leftrightarrow$ D ZENER

$V_d = V_Z < 0$

$V_U = -V_d = -V_Z = +5\ V$

Per: $\begin{cases} I > 0 \\ I = \dfrac{V_i - V_U}{R} \end{cases} \rightarrow V_i > V_U = +5\ V$

• $I < 0$ $(I_d > 0) \Leftrightarrow$ D POL. DIR

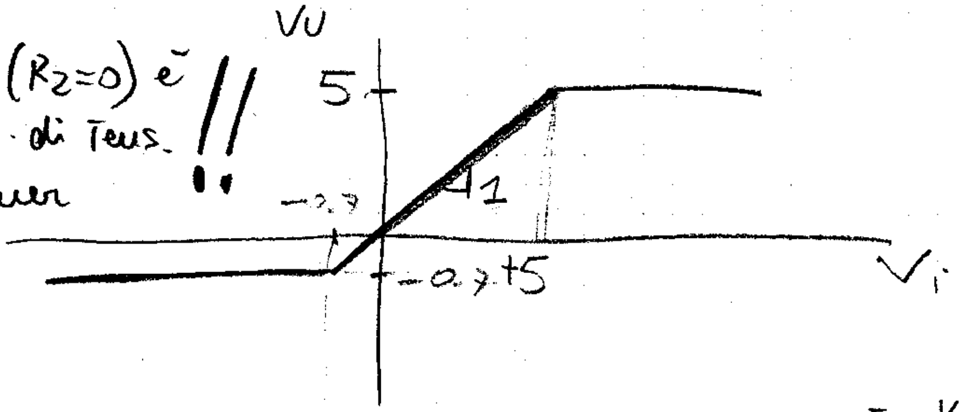
$V_d = V_\gamma = 0.7$

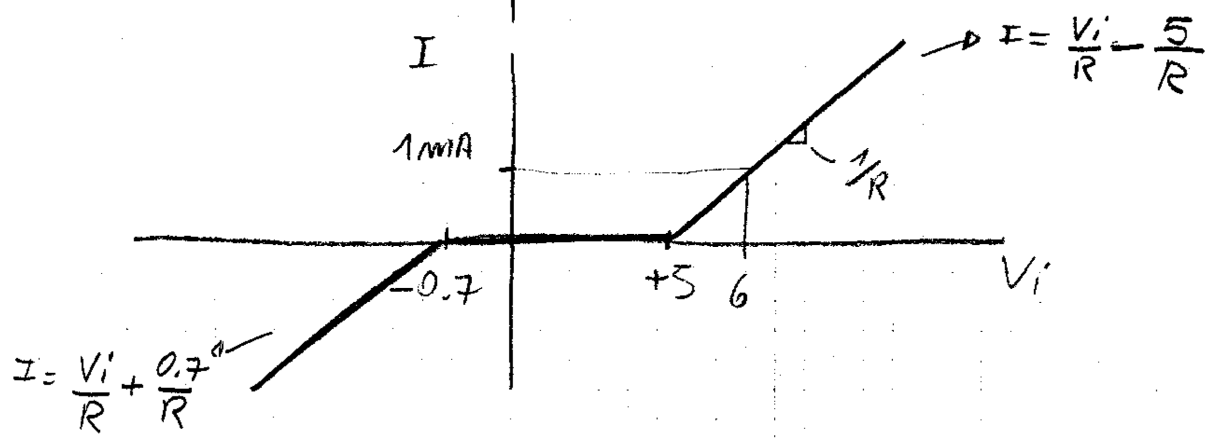
$V_U = -V_d = -0.7\ V$

Per: $\begin{cases} I < 0 \\ I = \dfrac{V_i - V_U}{R} \end{cases} \rightarrow V_i < V_U = -0.7$

• $I = 0$ $(I_d = 0)$ D OFF $\rightarrow V_U = V_i$ (per V_i: restanti casi)
→ ! FARE <u>VERIFICA</u> su V_d!

!! Questo ($R_Z=0$) è un reg. di tens. con zener !!





(2) $R_Z = 2K\Omega$

Equaz. alla maglia:

$$V_i - IR_1 + V_d - IR_Z = 0$$

$$V_i + V_d - I(R_1 + R_Z) = 0$$

$$I = \frac{V_i + V_d}{R_1 + R_Z}$$

Condizioni su $I = -I_d \Rightarrow$ si deduce stato del diodo

- $I > 0$ $(I_d < 0) \Leftrightarrow$ ZENER

$$V_d = V_Z = -5V$$

per $\begin{cases} I > 0 \\ I = \dfrac{V_i + V_d}{R_1 + R_Z} \end{cases} \Rightarrow V_i > -V_d = +5V$ (come prima!)

Legame $V_i - V_U$:

$$V_U = IR_Z - V_d = V_i \frac{R_Z}{R_1+R_Z} + V_d \frac{R_Z}{R_1+R_Z} - V_d =$$

$$= V_i \frac{R_Z}{R_1+R_Z} - V_d \frac{R_1}{R_1+R_Z} = \frac{2}{3} V_i + \frac{5}{3} \quad [V]$$

- $I<0$ $(I_d>0) \Leftrightarrow$ D POL DIR

$V_d = V_\gamma = 0.7\ V$

per $\begin{cases} I<0 \\ I = \dfrac{V_i + V_d}{R_1+R_2} \end{cases} \Rightarrow V_i < -V_d = -0.7$

(! come prima !)

Legame V_i - V_u:

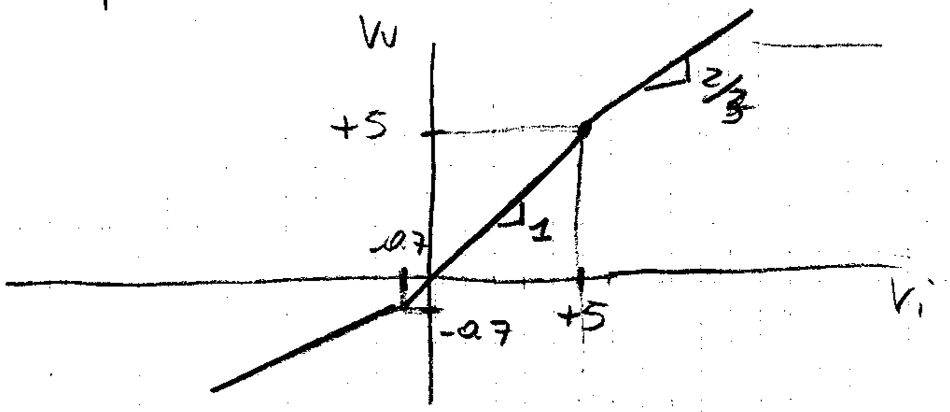
$V_U = I R_2 - V_d = V_i \dfrac{R_2}{R_1+R_2} - V_d \dfrac{R_1}{R_1+R_2} =$

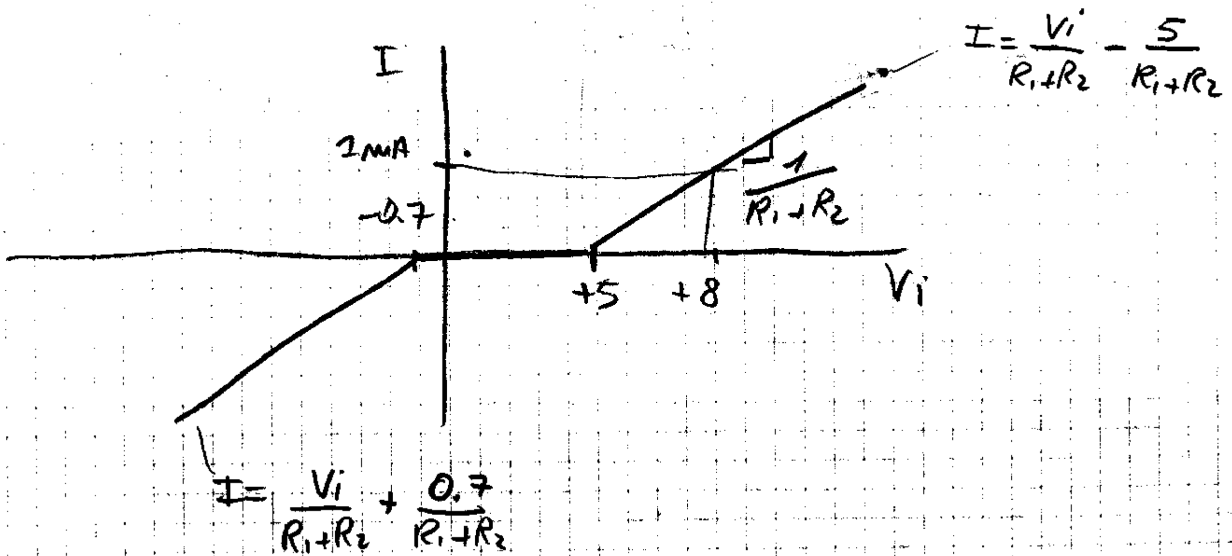
$= \dfrac{2}{3} V_i - \dfrac{0.7}{3}$

- $I=0$ $(I_d=0)$ D OFF

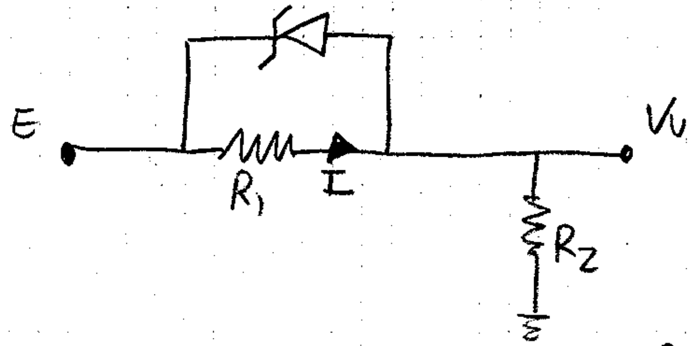
$V_U = V_i$ (fare VERIFICA)

per $-0.7 < V_i < 5$ [V]





- ES - DIODI (USO SOVRAPP. EFF. DOPO IP. SU DIODO)



$V_\gamma = 0.7$
$V_Z = -5V$
$R_1 = R_2 = 1k\Omega$

? V_U ; I ? per ① E = +2V
② E = −5V
③ E = +10V

① E = +2V

D OFF (E=+2V non basta a fare Zener)

$V_U = E \frac{R_2}{R_1+R_2} = \frac{E}{2} = +1V$

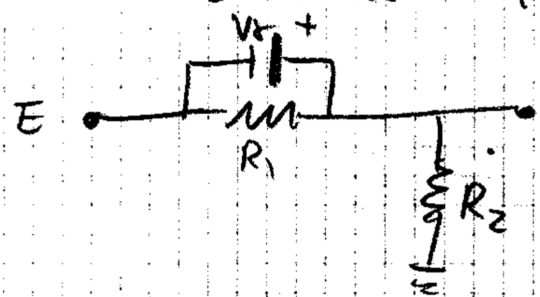
$I = \frac{E}{R_1+R_2} = +1mA$

<u>Verifica</u> : $V_d = V_U - E = 1-2 = -1V$ OK

$(-5 < V_d < 0.7)$

② E = −5V

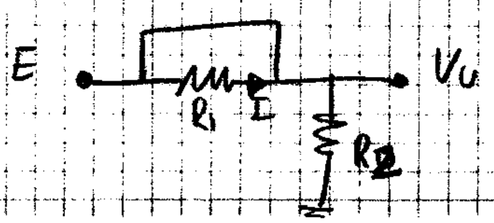
D POL. DIR. $(V_d = V_\gamma = +0.7)$



⇒ il circuito <u>ORA</u> è <u>LINEARE</u>

Uso <u>sovrapp. eff.</u>

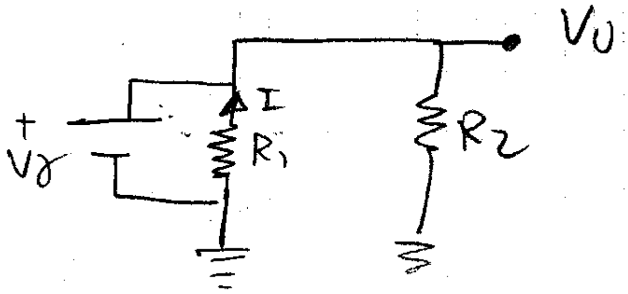
Ⓐ Batt. = C.TO C.TO



$V_U^{(A)} = E = -5V$

$I^{(A)} = 0$

(B) E = cto cto



$V_U^{(B)} = V_\gamma = +0.7$

$I^{(B)} = \frac{0 - V_U}{R_1} = -0.7\ mA$

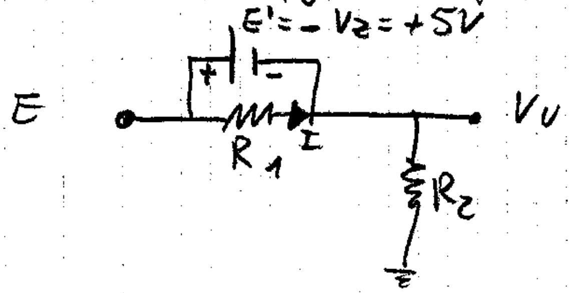
TOT $V_U = V_U^{(A)} + V_U^{(B)} = -5 + 0.7 = -4.3\ V$

$I = I^{(A)} + I^{(B)} = 0 - 0.7 = -0.7\ mA$

!! FARE VERIFICA !!

(3) $E = +10V$

D ZENER ($V_d = V_z = -5V$)



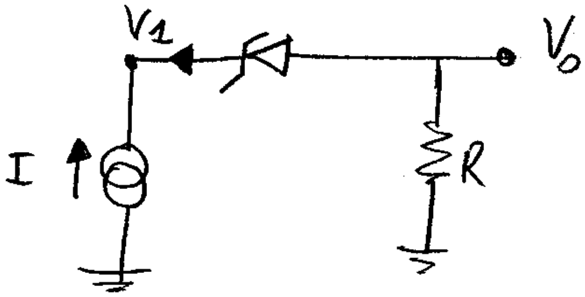
$V_U = E - E' = E - (-V_z) = +10 - 5 = +5\ V$

$I = \frac{E - V_U}{R_1} = \frac{10 - 5}{1k\Omega} = +5mA$

!! FARE VERIFICA !!

ES (SCRITTO © 22/11/96 n° 1)

(A)



$V_\gamma = 0.7\,V$

$V_Z = -5\,V$

$R = 1\,k\Omega$

? V_0 ? per
1. $I = 0$
2. $I = +1\,mA$
3. $I = -1\,mA$

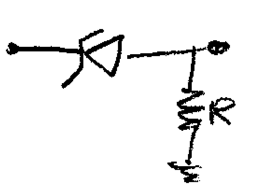
Dire che qui di corr. comando corr. nella maglia

① $I_d = -I$

- IP: D OFF

$V_0 = IR = 0\ V$

- VERIFICA: Non necessaria. (V_d è indet.)



$V_1 =$ indet.

② $I = +1\,mA$

$I_d = -I = -1\,mA < 0 \Rightarrow$ D ZENER

(verifica non nec.)

$V_0 = I \cdot R = +1\,V$

$(V_1 = +6\,V)$

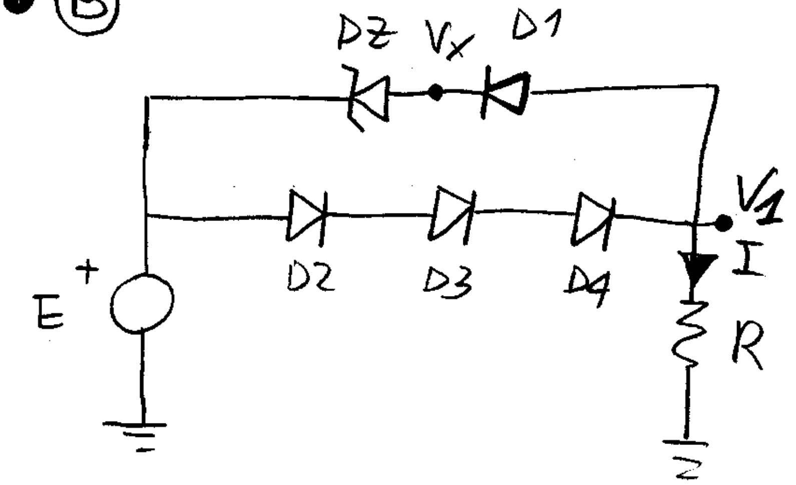
③ $I = -1\,mA$.

$I_d = -I = +1\,mA > 0 \Rightarrow$ D POL. DIR

$V_0 = I \cdot R = -1\,V$

$(V_1 = -1.7\,V)$

• (B)



$V_\gamma = 0.7$ V

$V_z = -5$ V

$R = 10$ KΩ

¿ I ? per
(1) $E = +15$ V
(2) $E = -15$ V
(3) $E = 0$ V

(1) $E = +15$ V

corr. può passare in D2, D3, D4
" non " " " DZ, D1 – a causa di D1

• IP: D2, D3, D4 POL DR

D1 OFF (DZ non interessa)

$$V_1 = E - 3V_\gamma = 15 - 2.1 = +12.9 \text{ V}$$

$$I = \frac{V_1}{R} = +\frac{12.9}{10k} = +1.29 \text{ mA}$$

• VERIFICA:

D2, D3, D4 : $I > 0$ OK

D1 : $V_1 - E = -2.1$ V

(In realtà tens. V_x è indeterm. con diodi ideali)

(2) $E = -15$ V

Corr. può passare in DZ, D1
" non " " " D2 ... D4

- IP: D_Z, D_1 POL. DIR
  $D_2 \dots D_4$ OFF

$$V_1 = E + 2V_\gamma = -15 + 1.4 = -13.6\,V$$

$$I = \frac{V_1}{R} = \frac{-13.6}{10k} = -1.36\,mA$$

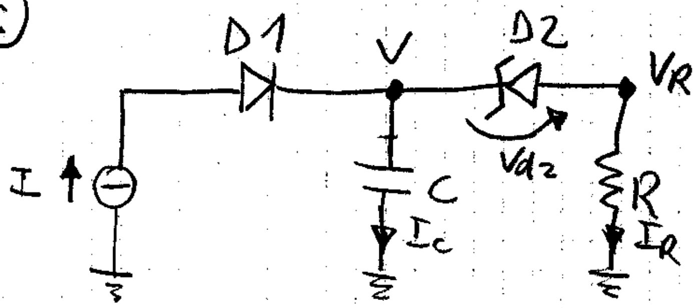
- VERIFICA:
  D_Z, D_1 . $I < 0$ OK
  $D_2, \dots D_4$: $E - V_1 = -1.4\,V$

(3) $E = 0\,V$

Non può passare corrente nei diodi

- IP $D_Z, D_1 \dots D_4$ OFF
  $I = 0$ $(V_1 = 0)$

- (C)



$V_\gamma = 0.7\,V$
$V_Z = -5\,V$
$C = 100\,nF$
$R = 10\,k\Omega$
$I = 1\,\mu A$

? (1) Cimiz. scarico: Det. ist. in cui $V = 5V$
- (2) grafico di $V(t)$ vs. t

(1) D1 sempre ON $(I_{d1} = I > 0)$

$t < 0$: $V(t) = 0$ (DZ OFF) $(V_{dz} = 0)$

C si carica

$$I = C\frac{dV}{dt} \Rightarrow V(t) = \frac{1}{C}\int_0^t I\,d\theta = \frac{I}{C}\cdot t$$

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$$\begin{cases} V(\bar{t}) = 5 \quad V \\ \frac{I}{C}\bar{t} = 5 \qquad \bar{t} = 5 \cdot \frac{C}{I} = 5 \cdot \frac{10^{-7}}{10^{-6}} = 0.5 \text{ s} \end{cases}$$

(2) Finché $V < 5V$ D2 OFF

$\boxed{t > \bar{t} = 0.5s}$: D2 ZENER ($V_{d2} = V_z = -5V$)

$$I = I_C + I_R$$

$$V_R(t) = V(t) + V_{d2} = V(t) + V_z$$

$$I_R(t) = \frac{V_R(t)}{R} = \frac{V(t)}{R} + \frac{V_z}{R}$$

$$I_C(t) = I - I_R(t) = I - \frac{V(t)}{R} - \frac{V_z}{R}$$

Vale ancora: $I_C(t) = C\frac{dV(t)}{dt}$

$$C\frac{dV(t)}{dt} = I - \frac{V(t)}{R} - \frac{V_z}{R}$$

$$\tau\frac{dV(t)}{dt} + V(t) = RI - V_z \qquad \tau = RC$$

$$V(t) = \underbrace{V^* e^{-\frac{t-\bar{t}}{\tau}}}_{\text{Sol. omog}} + \underbrace{RI - V_z}_{\text{Sol. part. compl.}} \qquad t > \bar{t}$$

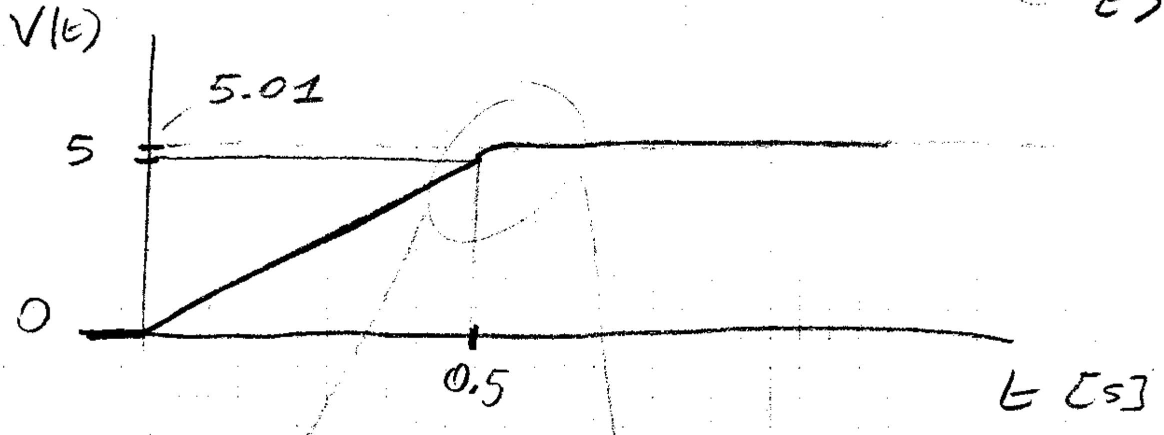
$$\begin{cases} V(\bar{t}) = +5V \\ V^* + RI - V_z = +5 \end{cases}$$

$$\to V^* = \cancel{5} + \cancel{V_z} - RI = -RI = -$$

$$V(t) = RI\left(1 - e^{-\frac{t-\bar{t}}{\tau}}\right) - V_z$$

$$V(t) = \begin{cases} \dfrac{I}{C} \cdot t = 10\,t & 0 < t < \bar{t} = 0.5\ s \\[2ex] RI\left(1 - e^{-\frac{t-\bar{t}}{\tau}}\right) - V_z = 10^{-2}\left(1 - e^{-\frac{t-\bar{t}}{\tau}}\right) + 5 & t > \bar{t} = 0.5\ s \end{cases}$$

$$\tau = RC = 10^{4} \cdot 10^{-7} = 10^{-3}\ s$$



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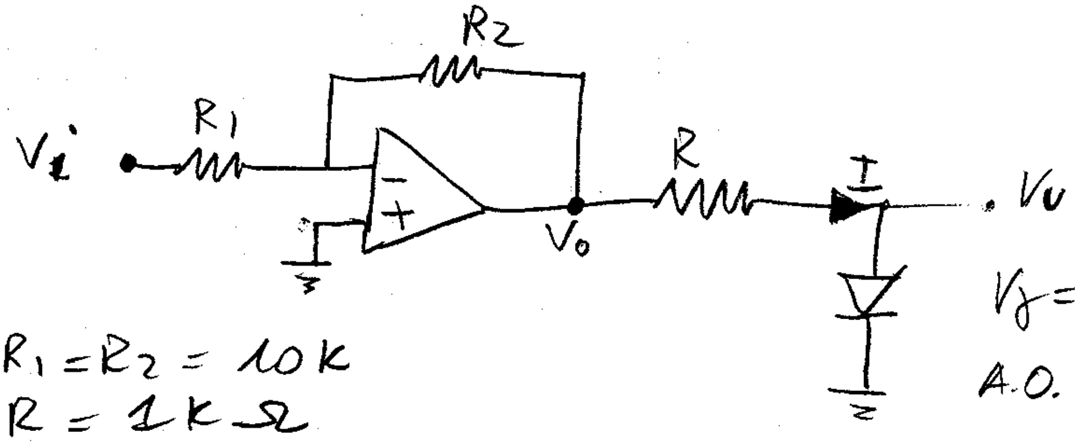
- ES - DIODI

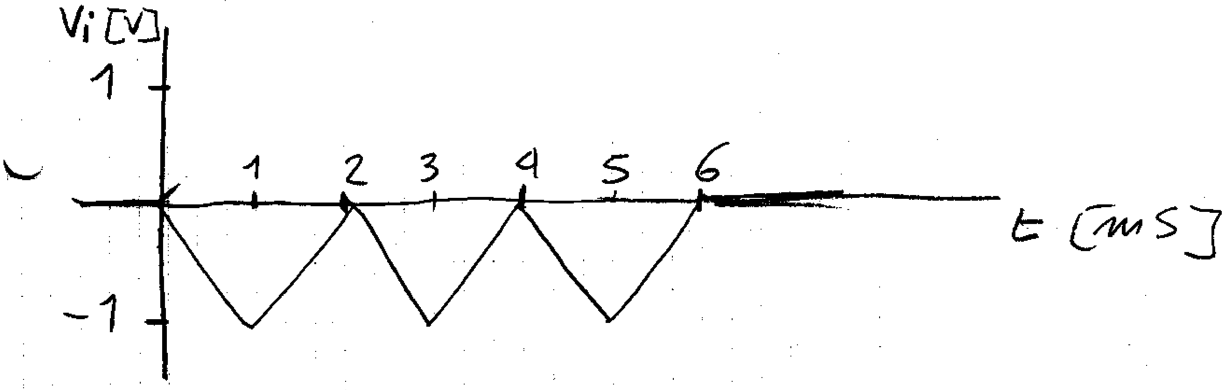


$V_\gamma = 0.5\,V$

A.O. ideale

$R_1 = R_2 = 10K$

$R = 1K\Omega$

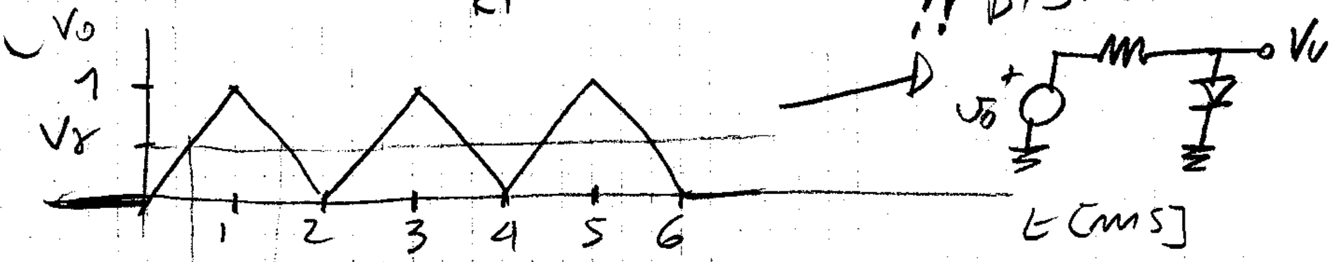


? andamento $I(t)$?

Determino prima V_0

$$V_0(t) = -\frac{R_2}{R_1} V_i(t) = -V_i(t)$$

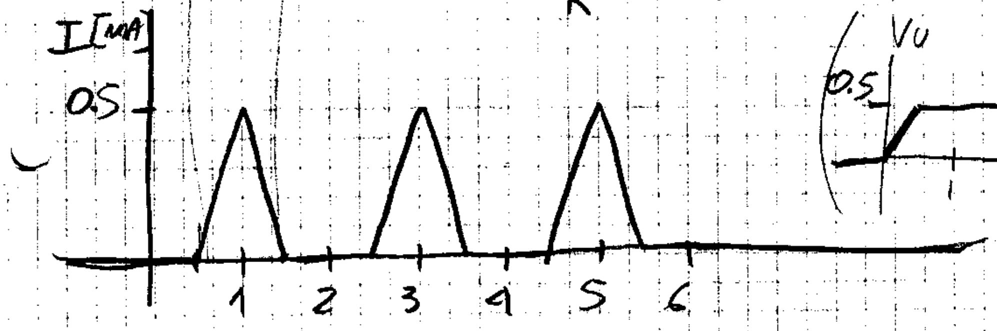
!! Dis. circ. equiv. !!

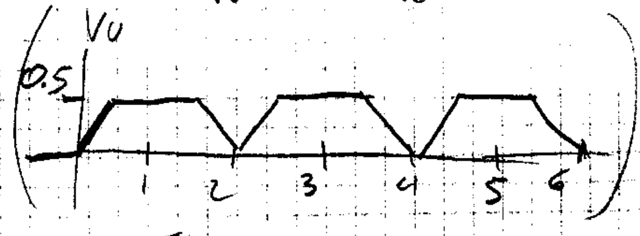


DIODO: ON se $V_0 > V_\gamma = 0.5\,V$

OFF se $V_0 < V_\gamma = 0.5\,V$ $(I = 0)$

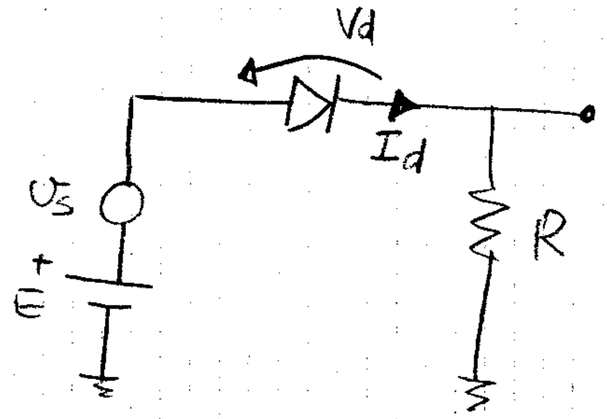
Diodo ON: $I = \dfrac{V_0 - V_\gamma}{R}$; $I_{MAX} = \dfrac{V_{0,MAX} - V_\gamma}{R} = \dfrac{0.5}{R} = 0.5\,mA$





DIODO REALE – MODELLO PER PICCOLI SEGNALI

- ES. di CIRCUITO:



$v_U = V_U + v_u$

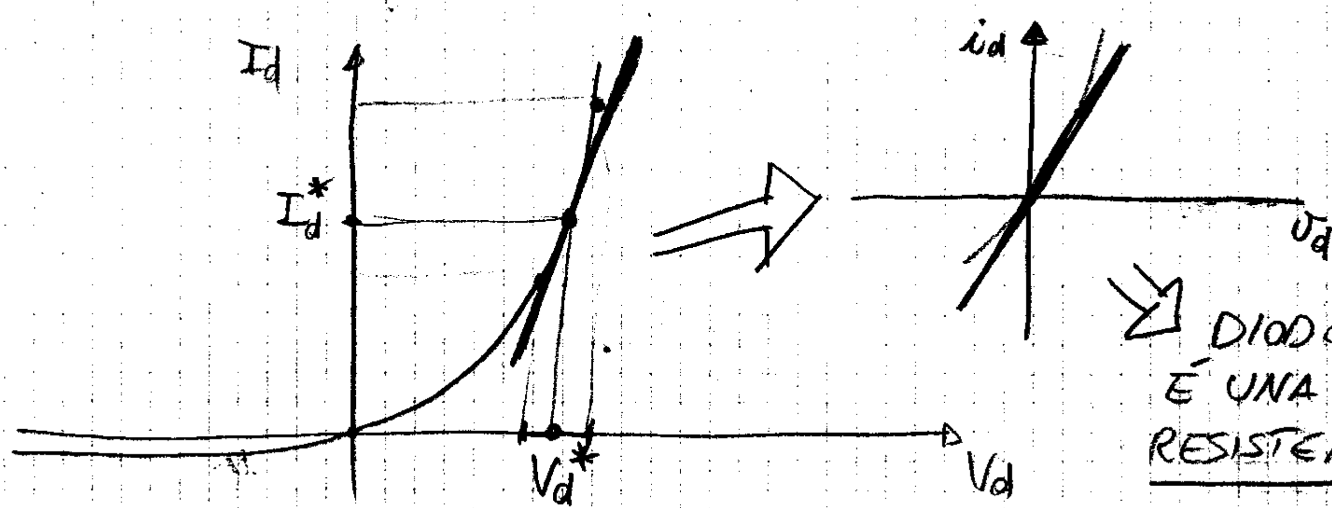
E : Batteria
v_S : Gen. piccolo segnale

DIODO REALE : $I_d = I_0 \left(e^{\frac{V_d}{V_T}} - 1\right)$

- PUNTO di LAVORO : $v_S = 0$
  - TROVO I_d^* ; V_d^* $\Rightarrow$ v_U

- PICCOLO SEGNALE : E è C.TO C.TO

? DIODO ? LO LINEARIZZO



$\Rightarrow$ DIODO È UNA RESISTENZA

$V_d = V_d^* + v_d$ con v_d piccolo segnale (decine di mV)

$\Rightarrow I_d = I_d^* + i_d$
└ piccolo seg.

$v_d = r_d \cdot i_d$? r_d ?

$$\frac{1}{r_d} = g_d = \left.\frac{\partial I_d}{\partial V_d}\right|_{V_d = V_d^*}$$

calcolo: $\left.\frac{1}{r_d} = I_0 \cdot e^{\frac{V_d}{V_T}} \cdot \frac{1}{V_T}\right|_{V_d = V_d^*}$

$$\frac{1}{r_d} = \frac{1}{V_T} \cdot I_0 \, e^{\frac{V_d^*}{V_T}}$$

- se $V_d^* \gtrsim 100\,mV \Rightarrow I_0 \, e^{\frac{V_d^*}{V_T}} \simeq I^*$

$$\frac{1}{r_d} = \frac{I_d^*}{V_T} \Rightarrow r_d = \frac{V_T}{I_d^*}$$

Es: $I_d^* = 1\,mA \rightarrow r_d = \frac{25\,mV}{1\,mA} = 25\,\Omega$ ← PICCOLA!

- se $V_d^* \lesssim -100\,mV \Rightarrow e^{\frac{V_d^*}{V_T}} \ll 1$

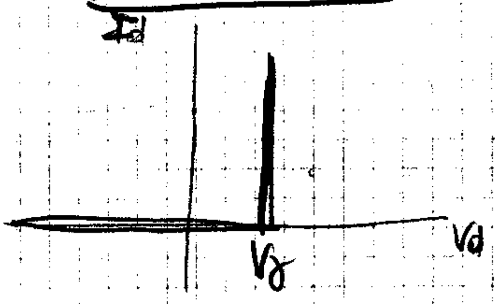
Es: $I_0 = 100\,pA = 10^{-10}\,A$

$V_d^* = -100\,mV$

$$r_d = \frac{V_T}{I_0 \, e^{\frac{V_d^*}{V_T}}} = \frac{25 \cdot 10^{-3}}{10^{-10} e^{-\frac{100}{25}}} = 13.6 \cdot 10^{9}\,\Omega = 13.6\,G\Omega \;!!$$

← GRANDE (la caratteristica è quasi orizzontale)

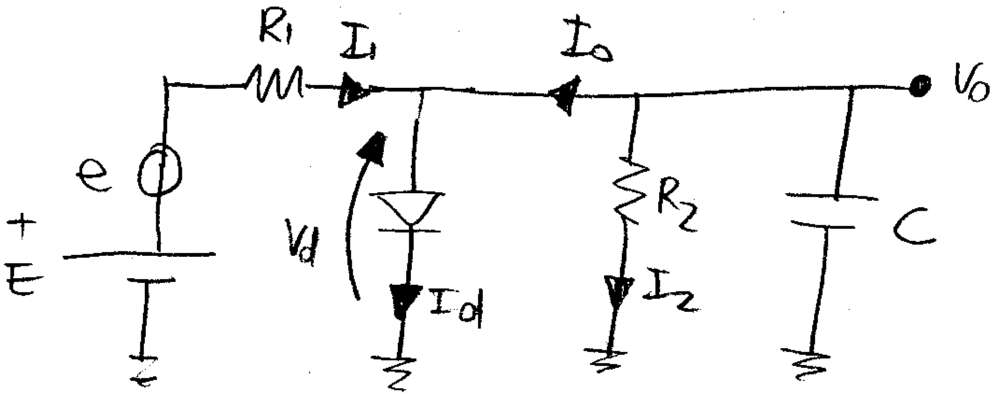
DIODO IDEALE:



ON: $r_d = 0$ (è c.to c.to)

OFF: $r_d = \infty$ (è circ. aperto)

- ES - DIODO (18/4/95 ES. 2)



$R_1 = R_2 = 1k\Omega$

$C = 1\mu F$

(A) $e=0$ DIODO ID ($V_\gamma = 0.7V$)

? I_o, V_o ? per (1) $E=+5V$ (2) $E=-5V$ (3) $E=0V$

(B) $I_d = I_s e^{V_d/V_t}$ (un po' diversa da reale)

$I_s = 1mA$

? Det uscita di piccolo segnale v_o ? per (1) $E=+5V$ (2) $E=-5V$ (3) $E=0V$

se $e = 10^{-3}\sin(50t)$ [V] [t] = s

(A)

(1) $E=+5V$

E = batteria (in continua) → C = circ. ap.

- IP: D POL. DIR.

$V_o = V_d = V_\gamma = +0.7V$

$I_o = -I_2 = -\frac{V_o}{R_2} = -\frac{0.7}{1k\Omega} = -0.7mA$

? VERIFICA ? $I_d > 0$?

! Calcolare I_d, serve dopo (B) !

$I_d = I_1 + I_o$

$I_1 = \frac{E - V_o}{R_1} = \frac{5 - 0.7}{1k} = +4.3mA$

$I_d = 4.3 - 0.7 = +3.6mA$ OK

(2) $E = -5V$

IP : D OFF $(I_d = 0)$

$$I_0 = \frac{0 - E}{R_1 + R_2} = \frac{0 + 5}{2k\Omega} = +2.5\ mA$$

$$V_0 = \text{partitore} = E \cdot \frac{R_2}{R_1 + R_2} = -2.5\ V$$

? VERIFICA ? $V_d < 0.7\ V$?

$V_d = V_0 = -2.5\ V$ OK

(3) $E = 0V$

IP : D OFF

$I_0 = 0\ A$

$V_0 = 0\ V$

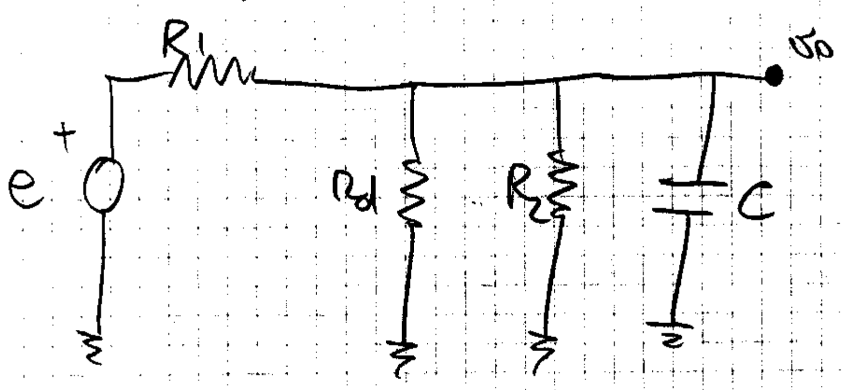
? VERIFICA ? $V_d = V_0 = 0 < 0.7$ OK

(B)

DIODO ? COME PRIMA (Era modello idealizzato ma realistico)

SUPPONGO VALIDI I RISULTATI PRECEDENTI per I_d, V_d –

Diodo è resistenza R_d



$$\frac{v_0}{e} = \frac{Z}{R_1 + Z} \qquad Z = \frac{1}{sC} // R_{eq} = \frac{R_{eq}}{1 + sR_{eq}C}$$

$$R_{eq} = r_d // R_2$$

$$F(s) = \frac{v_0}{e} = \frac{\frac{R_{eq}}{1+sR_{eq}C}}{R_1 + \frac{R_{eq}}{1+sR_{eq}C}} = \frac{R_{eq}}{R_1 + R_{eq} + sR_1R_{eq}C} =$$

$$= \frac{R_{eq}}{R_1 + R_{eq}} \cdot \frac{1}{1 + s\frac{R_1 R_{eq}}{R_1 + R_{eq}}C} = K \cdot \frac{1}{1 + s\tau}$$

? r_d ?

$$\frac{1}{r_d} = \frac{\partial I_d}{\partial V_d} = \frac{I_S}{V_T} \cdot e^{V_d/V_t}$$

ESPR. BUONA PER DIODO **OFF**

$$r_d = \frac{V_T}{I_S \; e^{V_d/V_t}} = \frac{V_T}{I_d}$$

ESPR. BUONA PER DIODO **ON**

(1) $E = +5\,V$ $\quad$ D ON $\quad$ ($I_d = +3.6\,mA$)

$$r_d = \frac{25\,mV}{3.6\,mA} = 6.9\,\Omega$$

$$R_{eq} \simeq r_d$$

$$F(s) = \frac{r_d}{R_1 + r_d} \cdot \frac{1}{1 + s\frac{R_1 r_d}{R_1 + r_d}C} = K \cdot \frac{1}{1 + s \cdot \tau}$$

Passa Basso

$K = 6.8 \cdot 10^{-3}$

$\tau \simeq r_d \cdot C = 6.8 \cdot 10^{-6} = 6.8 \cdot 10^{-6}\,s$

$\omega_c = 1.4 \cdot 10^5\,r/s$

$\omega = 50\,r/s \qquad \omega \ll \omega_c$

$v_0 = 6.8 \cdot 10^{-6} \sin(50t) \quad [V] \quad (\varphi = 0)$

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(2) $E = -5\ V$ $\underline{D\ \ OFF}$

$V_d = -2.5\ V$

$$r_d = \frac{V_T}{I_S\ e^{V_d/V_T}} = \frac{25 \cdot 10^{-3}}{10^{-9} \cdot e^{-\frac{2.500}{25}}} = 2.68 \cdot 10^{43}\ \Omega$$

$r_d = \infty$!!

$R_{eq} = R_2$

$K = \frac{1}{2}$

$\tau = \frac{R_1}{2} C = 5 \cdot 10^{2} \cdot 10^{-6} = 5 \cdot 10^{-4}\ s$

$\omega_c = 2 \cdot 10^{3}\ r/s = 2000\ r/s$

$\omega \ll \omega_c$

$v_0 = 0.5 \cdot 10^{-3} \sin(50 \cdot t)$

(3) $E = 0\ V$ $\underline{D\ OFF}$

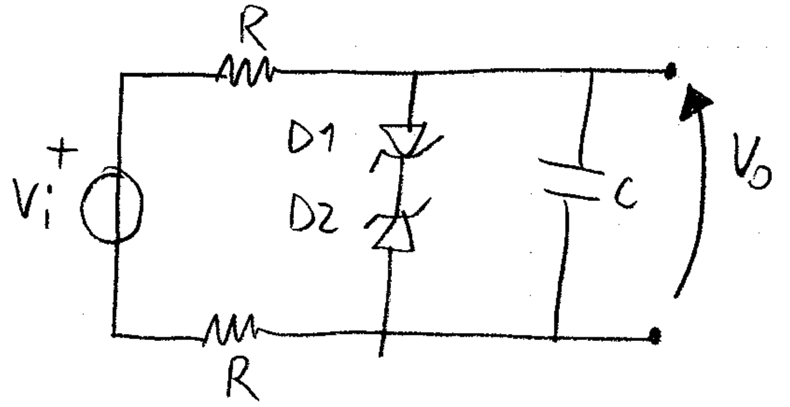
$V_d = 0$ (a rigore, per il modello $I_d > 0$)

$$r_d = \frac{V_T}{I_S\ e^{V_d/V_T}} = \frac{25 \cdot 10^{-3}}{10^{-9} \cdot 1} = 25 \cdot 10^{6}\ \Omega = 25\ M\Omega$$

$R_{eq} = R_2$

v_0 come punto (2)

- ES - DIODI (SCRITTO 26/9/97 ES 2)



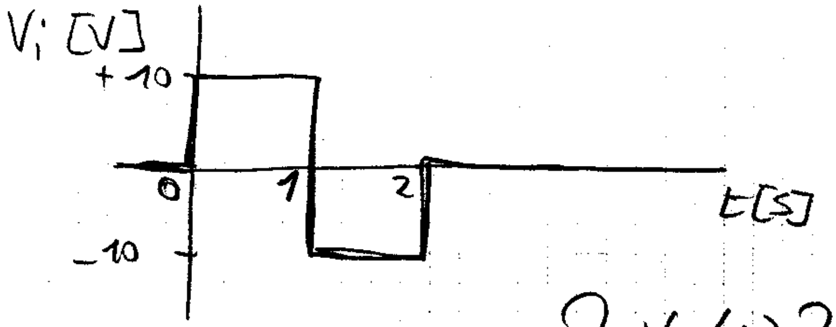
$R = 5\,k\Omega$

$C = 10\,\mu F$

$V_{\gamma 1} = V_{\gamma 2} = 0\,V$

$V_{z1} = -5\,V$

$V_{z2} = -7\,V$



? $V_o(t)$?

SOLUZ : PRIMA <u>SENZA DIODI</u>

$\omega \to 0 \quad V_o = V_i$

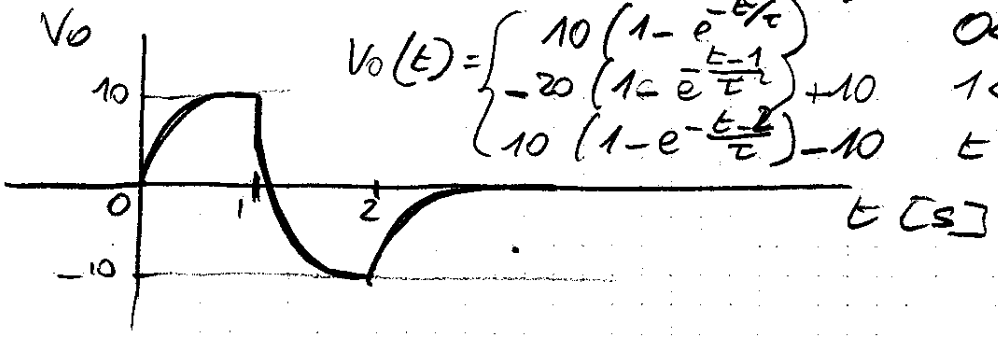
$\omega \to \infty \quad V_o = 0$

Passa basso

$$\frac{V_o}{V_i} = \frac{1}{1 + s\tau}$$

$\tau = (R+R)\,C = 10^4 \cdot 10^{-5} = 0.1\,s$

$$V_o(t) = \begin{cases} 10\left(1 - e^{-t/\tau}\right) & 0 < t < 1\,s \\ -20\left(1 - e^{-\frac{t-1}{\tau}}\right) + 10 & 1 < t < 2 \\ 10\left(1 - e^{-\frac{t-2}{\tau}}\right) - 10 & t > 2 \end{cases}$$



- DIODI : 2 CASI "ON"
  - D1 POL DIR + D2 ZENER → $V_o = +7\,V$
  - D1 ZENER + D2 POL DIR → $V_o = -5\,V$

⇒ L'uscita V_o è limitata a +7 e -5 V

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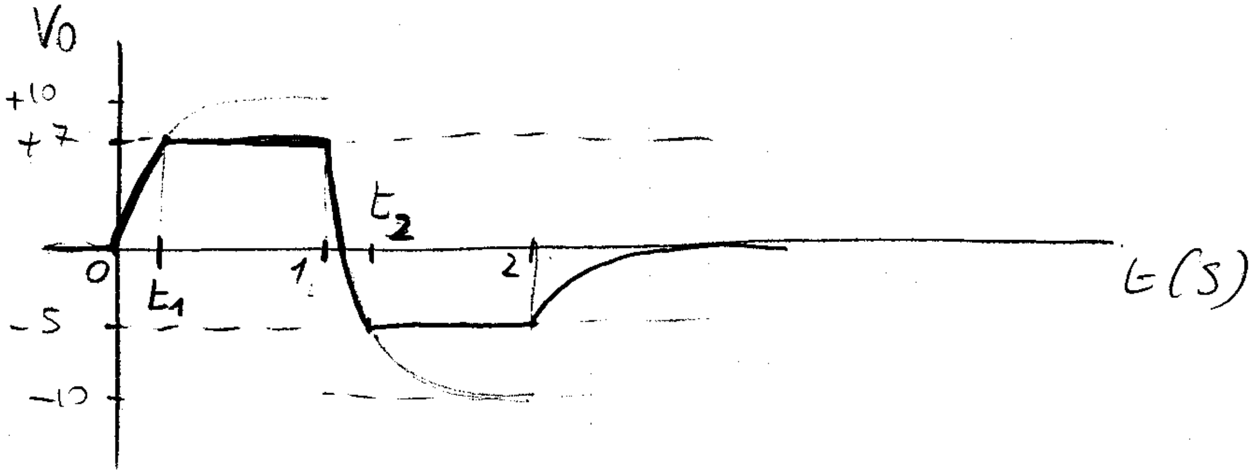


$0 < t < t_1 \qquad V_0(t) = 10\left(1 - e^{-t/\tau}\right)$ V

$t_1 < t < 1 \qquad V_0(t) = -V_{Z2} = +7\,V$ V

$1 < t < t_2 \qquad V_0(t) = (-10-7)\left(1 - e^{-\frac{t-1}{\tau}}\right) + 7 =$

$= -17\left(1 - e^{-\frac{t-1}{\tau}}\right) + 7 =$

$= -10 + 17\, e^{-\frac{t-1}{\tau}}$ V

$t_2 < t < 2s \qquad V_0(t) = -V_{Z1} = +5\,V$

$t > 2s \qquad V_0(t) = (0-(-5))\left(1 - e^{-\frac{t-2}{\tau}}\right) - 5 =$

$= +5\left(1 - e^{-\frac{t-2}{\tau}}\right) - 5 =$

$= -5\, e^{-\frac{t-2}{\tau}}$ V

- calcolo istanti temporali

$V_0(t_1) = +7\,V$

$10\left(1 - e^{-t_1/\tau}\right) = +7$

$1 - e^{-t_1/\tau} = \frac{7}{10}$

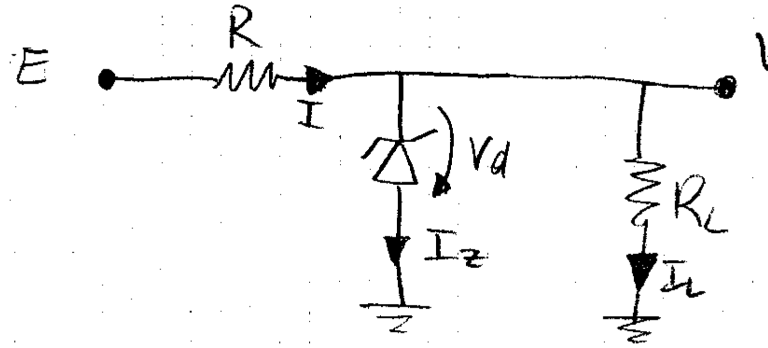
$e^{-\frac{t_1}{\tau}} = \frac{3}{10}$

$-\frac{t_1}{\tau} = \ln\frac{3}{10}$

$t_1 = -\tau \ln\frac{3}{10} = +0.1 \cdot 1.2 = +0.12\ s$

• ES (SCRITTO © 24/11/95)

(A)



$E = +15\,V$
$R = 1\,k\Omega$
$V_\gamma = 0.7\,V$
$V_Z = -6\,V$

? I, I_z, V ? per
(1) $R_L = 0$
(2) $R_L \to \infty$
(3) $R_L = 1\,k\Omega$
(4) $R_L = 250\,\Omega$

(1) $R_L = 0$ (Facile Dis)

IP : D OFF (perché $V_d = -V = 0$)

$V = 0$

$I_z = 0$

$$I = \frac{E}{R} = \frac{15}{1k\Omega} = +15\,mA$$

(2) $R_L \to \infty$ (Facile Dis)

IP: D ZENER

$V_d = V_Z = -6\,V$

$V = -V_d = -V_Z = +6\,V$

$$I = I_Z = \frac{E - V}{R} = \frac{15 - 6}{10^3} = +9\,mA$$

? Verifica ? $I_d = -I_Z < 0$ <u>OK</u>

(3) $R_L = 1\,k\Omega$

IP : D OFF (Non si sa se è + simile a (1) o (2))

$I_z = 0$

$V = E \cdot \frac{R_L}{R+R_L} = 15 \cdot \frac{1}{2} = +7.5V$

? VERIFICA ? $V_d = -V = -7.5V < V_z$!!

↳ IP. ERRATA!

IP: D ZENER

$V = -V_d = -V_z = +6V$

$I = \frac{E-V}{R} = \frac{15-6}{10^3} = +9mA$

$I_z = I - I_L$

$I_L = \frac{V}{R_L} = \frac{6}{10^3} = +6mA$

$I_z = 9 - 6 = +3mA$

? VERIF ? $I_d = -I_z = -3mA < 0$ <u>OK</u>

④ $R_L = 250\,\Omega$

IP: D OFF

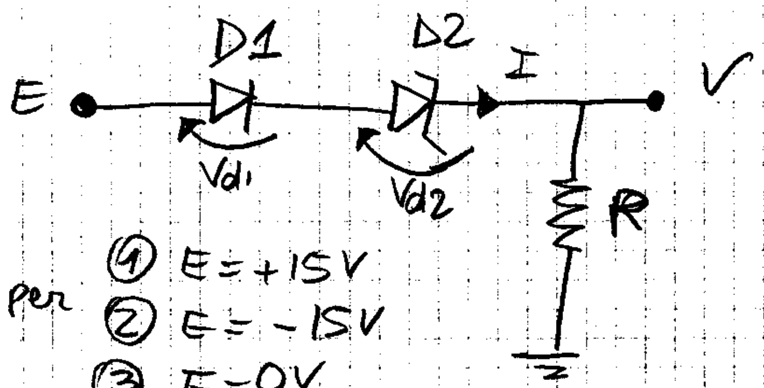
$V = E \frac{R_L}{R+R_L} = E \frac{250}{1250} = E \cdot \frac{1}{5} = +3V$

$I_z = 0$

$I = \frac{E}{R+R_L} = \frac{15}{1250} = +12mA$

? VERIF ? $V_d = -V = -3V$ <u>OK</u>

Ⓑ



$R = 1k\Omega$

$V_\gamma = 0.7V$

$V_z = -6V$

? I ? per ① $E = +15V$

② $E = -15V$

③ $E = 0V$

① $E = +15\,V$

IP: D1 POL DIR
D2 POL DIR

$V_{d1} = V_{d2} = V_\gamma = +0.7\,V$

$V = E - V_{d1} - V_{d2} = E - 2V_\gamma = 15 - 1.4 = +13.6$

$I = \frac{V}{R} = \frac{13.6}{10^3} = 13.6\,mA > 0$ OK

② $E = -15\,V$

IP: (D2 potrebbe essere ZENER. Ma D1 non può. Quindi:)
D1, D2 OFF

$V = 0$

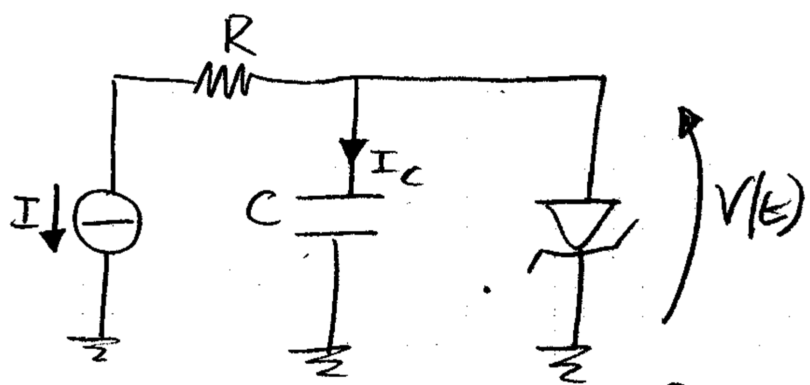
$I = \frac{V}{R} = 0$ OK

③ $E = 0\,V$

D1, D2 OFF

$I = 0$

Ⓒ



$I = +10\,\mu A$
$C = 10\,mF$
$R = 1\,k\Omega$
$V_\gamma = 0.7\,V$
$V_z = -6\,V$

t=0 : C scarico

? V(t) ?

$t = 0$: $V(0) = 0 \rightarrow$ D OFF

C si carica a corr. cost.

$I_C = C\frac{dV(t)}{dt}$ $\quad I_C = -I$

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$t>0$: $V(t) = -\frac{I}{C}\int_0^t dt' + V(0) = -\frac{I}{C}\cdot t =$

$= -\frac{10^{-5}}{10^{-8}}\,t = -10^3\,t$

? Quando $V(t) = V_Z$?

per $t = \bar{t}$ $\quad V(\bar{t}) = V_Z = -6\,V$

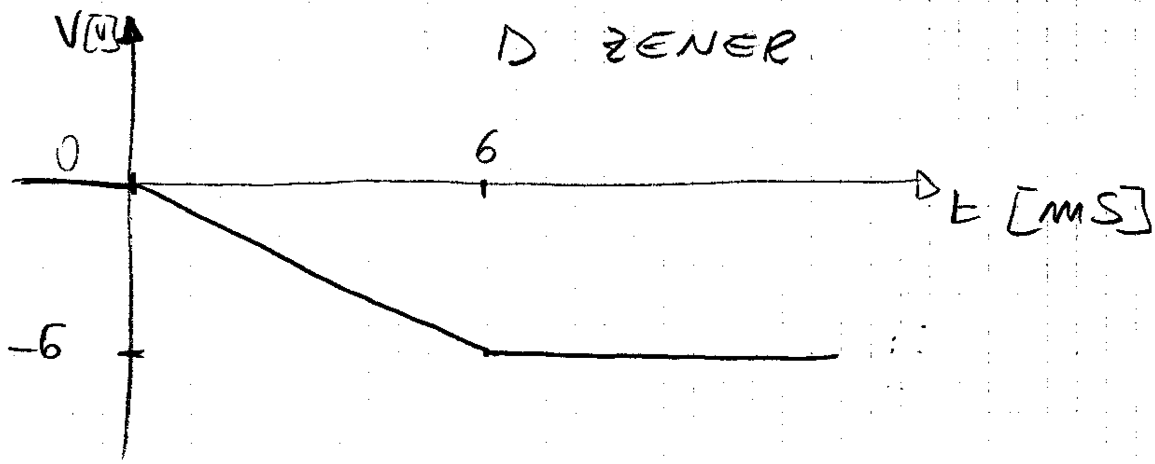
$-\frac{I}{C}\,\bar{t} = V_Z$

$\bar{t} = -\frac{C}{I}V_Z = -\frac{10^{-8}}{10^{-5}}\cdot(-6) =$

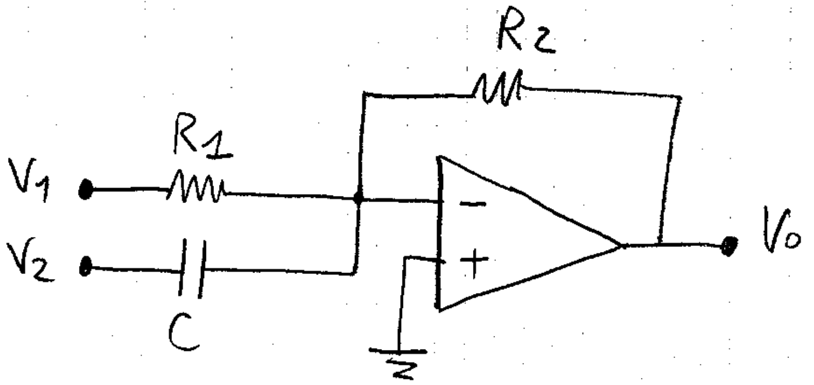
$= 6\cdot 10^{-3}\,s = 6\,ms$

per $t > \bar{t}$: $\quad V(t) = V_Z = -6\,V$

D ZENER



• ES (SCRITTO © 15/11/94)



$R_1 = 100\ \Omega$
$R_2 = 1\ k\Omega$
$C = 100\ nF$

① Per $V_1 = V_2 = V_i$, $A \to \infty$, det $F(S) = \frac{V_o(S)}{V_i(S)}$
Bode, Risp. gradino unitario (+1 V)

② $V_2 = 0$; $A \to \infty$, det $F_1(S) = \frac{V_o}{V_1}$

③ $V_2 = 0$; $A = 100$; det. $F_1' = \frac{V_o}{V_1}$

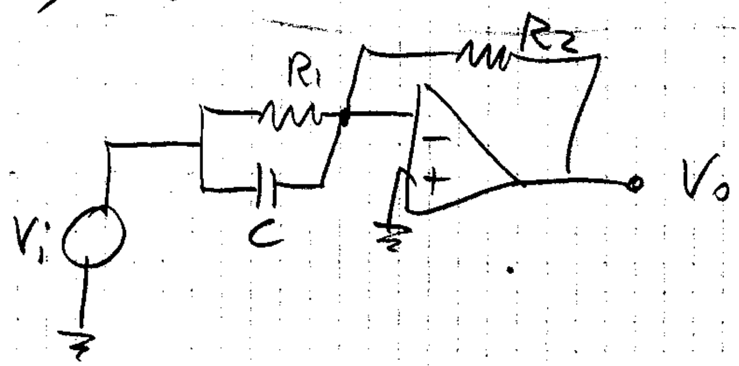
④ Det. Z_{IN} in casi ①, ②

⑤ Caso ①: Det. risp. a grad. unitario (1V) se AO ha liv. di sat. $L^+ = +10V$ $L^- = -10V$

⑥ Caso ①: Det $V_o(t)$ per $V_i(t) = 0.02 \sin 10^5 t$ [V]

!FARE ANALISI PRELIMINARE!! $\omega \to 0$; $\omega \to \infty$

①



$F(S) = -\frac{R_2}{Z}$; $Z = R_1 // \frac{1}{SC} = \frac{R_1}{1 + SCR_1}$

$F(s) = -\frac{R_2}{R_1} \cdot (1 + SCR_1) = -10 \cdot (1 + S \cdot 10^{-4})$

zero: $z = -10^4\ r/s$

$\omega_z = 10^4\ r/s$

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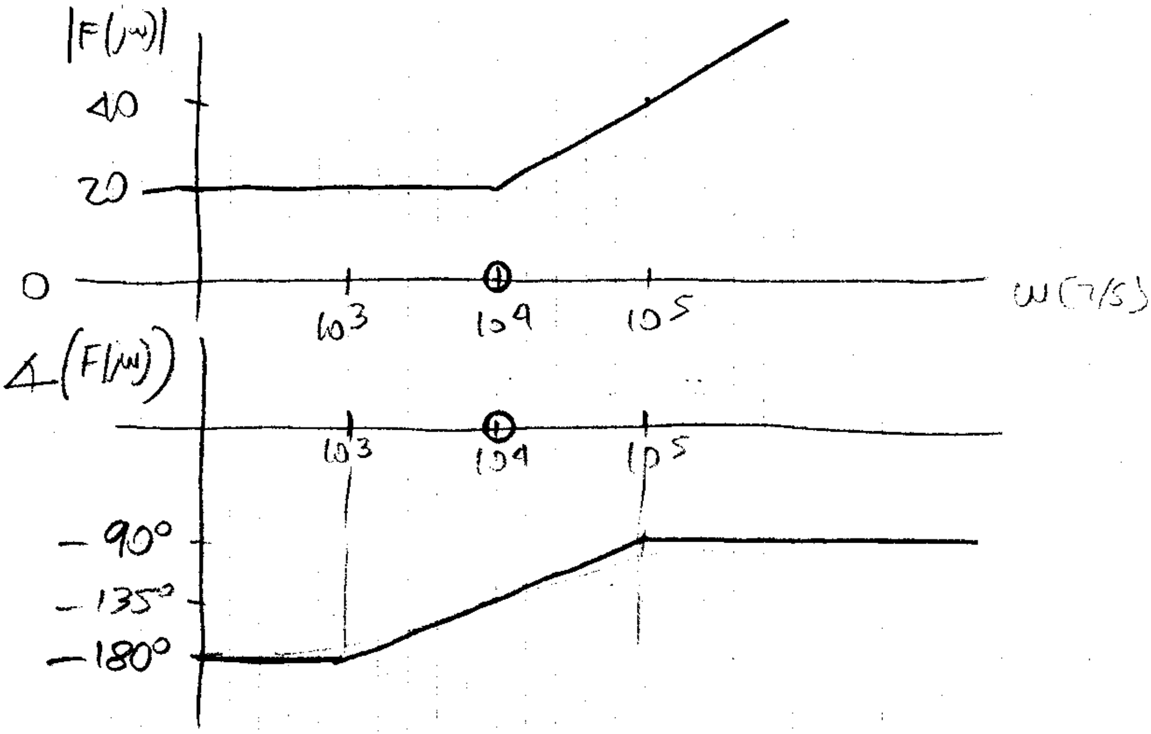


Risp. al grad.: $v_i(t) = 1 \cdot sca(t)$

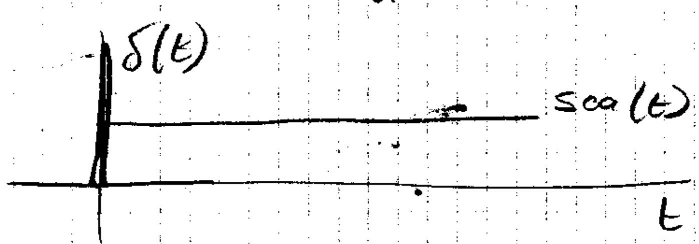
$$V_o(s) = F(s) \cdot V_i(s)$$

$$V_o(s) = -10\,(1 + sCR_1) \cdot V_i(s) \overset{!}{=} -10\, V_i(s) - 10 \cdot CR_1 \cdot s \cdot V_i(s)$$

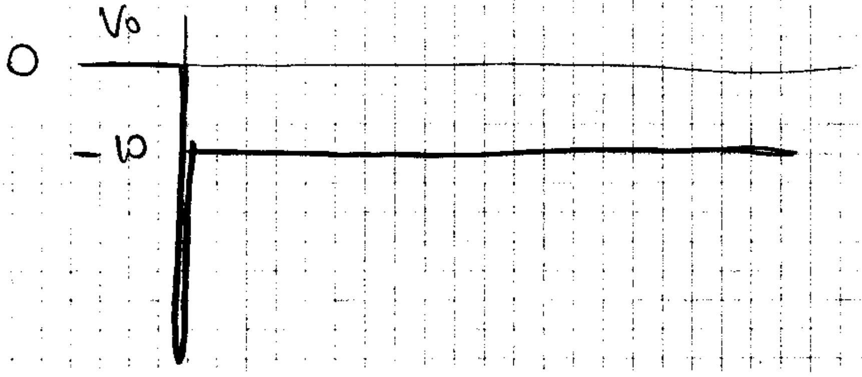
$$\Updownarrow$$

$$V_o(t) = -10\, V_i(t) - 10 \cdot CR_1 \cdot \frac{d}{dt} V_i(t)$$

$$\frac{d}{dt} v_i(t) = \frac{d}{dt}\left[sca(t)\right] = \delta(t)$$ dim: $\left[\frac{V}{s}\right]$!!



$$V_o(t) = -10\, sca(t) - 10\, CR_1 \cdot \delta(t) \qquad [V]$$



Verifico: Teor. val. iniz. e finale:

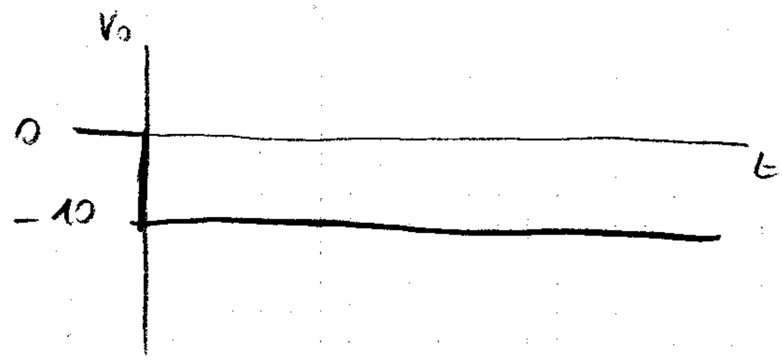
$$\lim_{t \to 0^+} V_0(t) = \lim_{s \to +\infty} s \cdot V_0(s) = \lim_{s \to +\infty} s \cdot (-10)(1+sCR_1)\frac{1}{s}$$

$$= \lim_{s \to \infty} (-10 - 10sCR_1) = -\infty \quad [V]$$

$$\lim_{t \to +\infty} V_0(t) = \lim_{s \to 0^+} s\, V_0(s) = \lim_{s \to 0^+} (-10 - 10sCR_1) = -10\,[V]$$

OK

(5) $L^+ = +10\,V$
$L^- = -10\,V$



(6) $V_i(t) = \bar{V} \sin \omega_s t \qquad \bar{V} = 0.02\ V$
$\omega_s = 10^5\ r/s$

$V_0(t) = V^* \sin(\omega_s t + \varphi)$

$|F(j\omega_s)| = \frac{V^*}{\bar{V}} \qquad V^* = \bar{V} \cdot |F(j\omega_s)| = 0.02 \cdot 10^2 = 2\,[V]$

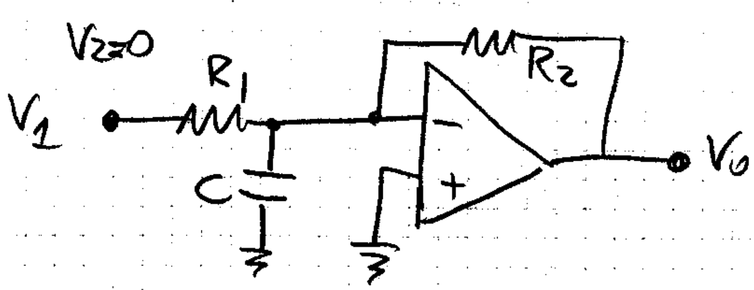
$\varphi \simeq -90°$ (approx)

esatto: $\varphi = -180° + \arctan \frac{\omega_s}{\omega_z} = -180° + \arctan \frac{10^5}{10^4} =$

$= -180° + 84.28° = -95.71° = -1.66\ rad$

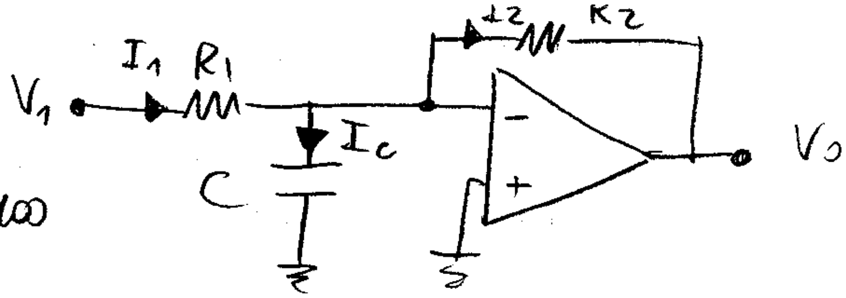
$V_0(t) = 2 \sin(10^5 t - 1.66)$ rad!!!

(2) $V_2 = 0$



$V^- = V^+ = 0\,V \rightarrow$ è Inv: $\frac{V_0}{V_i} = -\frac{R_2}{R_1} = -10$

(3)



$A = 100$

$A \neq \infty \;;\quad V^+ \neq V^-$

$$V_o = A\left(V^+ - V^-\right)$$

$$V^+ = 0 \longrightarrow V_o = -AV^- \longleftrightarrow V^- = -\frac{V_o}{A}$$

$$\left.\begin{cases} V_o = V^- - I_2 R_2 \\ V_o = -AV^- \end{cases}\right\} \text{ricavo } V^- :$$

$$-AV^- = V^- - I_2 R_2$$

$$V^- = \frac{I_2 R_2}{A+1}$$

$$I_1 = I_c + I_2$$

$$I_1 = \frac{V_1 - V^-}{R_1} = \frac{V_1}{R_1} - I_2 \cdot \frac{R_2}{R_1(A+1)}$$

$$I_c = \frac{V^-}{1/sC} = I_2 \frac{sCR_2}{A+1}$$

Ricavo I_2 :

$$\frac{V_1}{R_1} - I_2 \frac{R_2}{R_1(A+1)} = I_2 \frac{sCR_2}{(A+1)} + I_2$$

$$I_2\left(1 + \frac{sCR_2}{A+1} + \frac{R_2}{R_1(A+1)}\right) = \frac{V_1}{R_1}$$

$$I_2 = V_1 \cdot \frac{1}{\cancel{R_1}} \cdot \frac{\cancel{R_1}(A+1)}{R_1(A+1) + sCR_1R_2 + R_2}$$

Espr. per V_o :

$$V_o = V^- - I_2 R_2 = I_2 \frac{R_2}{A+1} - I_2 R_2 =$$

$$= I_2 R_2 \left(\frac{1}{A+1} - 1\right) = -I_2 R_2 \frac{A}{A+1}$$

$$F_1'(S) = \frac{V_0}{V_1} = -R_2\frac{A}{\cancel{A+1}}\cdot\frac{\cancel{A+1}}{R_1(A+1)+SCR_1R_2+R_2} =$$

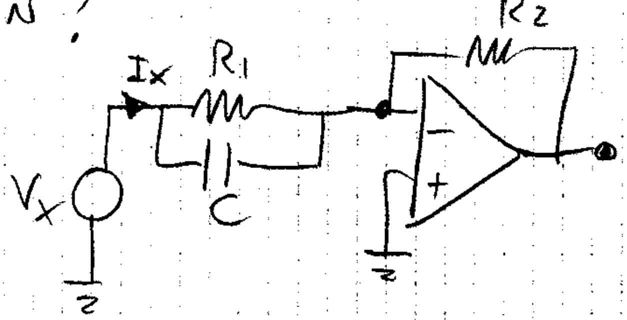
$$= -\frac{AR_2}{R_1(A+1)+R_2+SCR_1R_2} =$$

$$= -\frac{AR_2}{R_1(A+1)+R_2}\cdot\frac{1}{1+SC\cdot\frac{R_1R_2}{R_1(A+1)+R_2}}$$

? verifica ?: $A \to \infty \to -\frac{R_2}{R_1}$ OK

④ Z_{IN} ?

1)

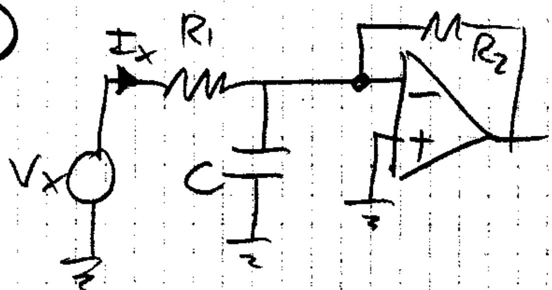


$$Z_{IN} = \frac{V_x}{I_x}$$

$$I_x = \frac{V_x - V^-}{R_1 // \frac{1}{SC}} = \frac{V_x}{R_1 // \frac{1}{SC}}$$

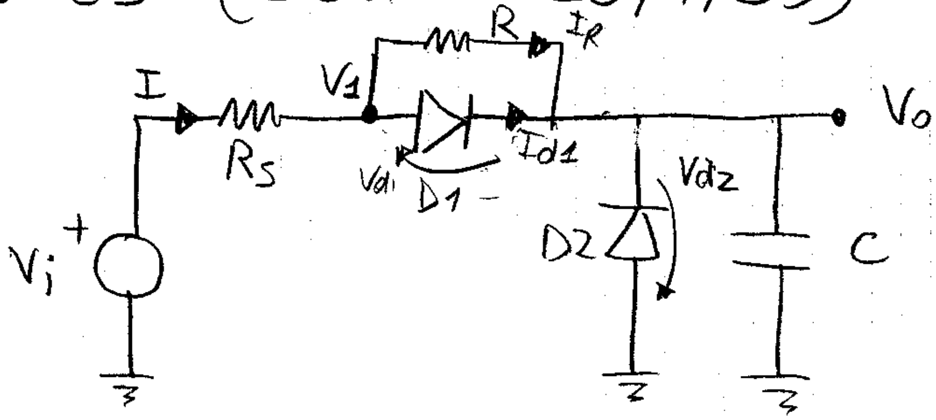
$$Z_{IN} = R_1 // \frac{1}{SC} = \frac{R_1}{1+SCR_1}$$

2)

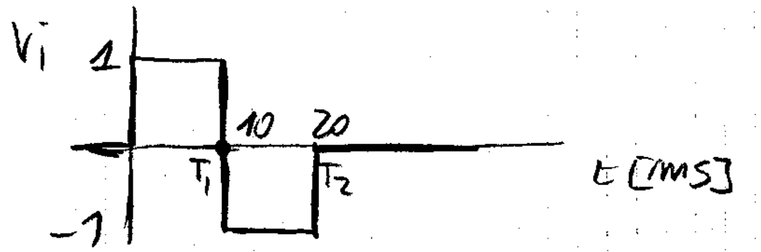


$$Z_{IN} = R_1$$

- ES (SCRITTO 25/7/95)



$R = 1\,M\Omega$
$R_S = 100\,k\Omega$
$C = 1\,nF$



C scarico per $t=0$

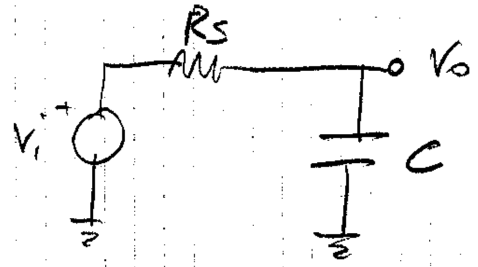
? $V_o(t)$? per:
(1) $V_\gamma = 0\,V$
(2) $V_\gamma = 0.7\,V$

(1) $V_\gamma = 0\,V$

$\boxed{0 < t < T_1}$

$V_i = 1\,V$

D1 ON
D2 OFF



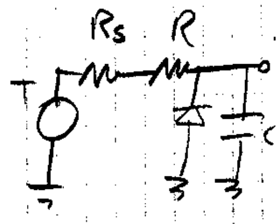
$V_o(t) = 1\left(1 - e^{-t/\tau_1}\right)$

$\tau_1 = R_S C = 10^5 \cdot 10^{-9} = 10^{-4}\,s = 0.1\,mS$

$\boxed{T_1 < t < T_2}$

$V_i = -1\,V$

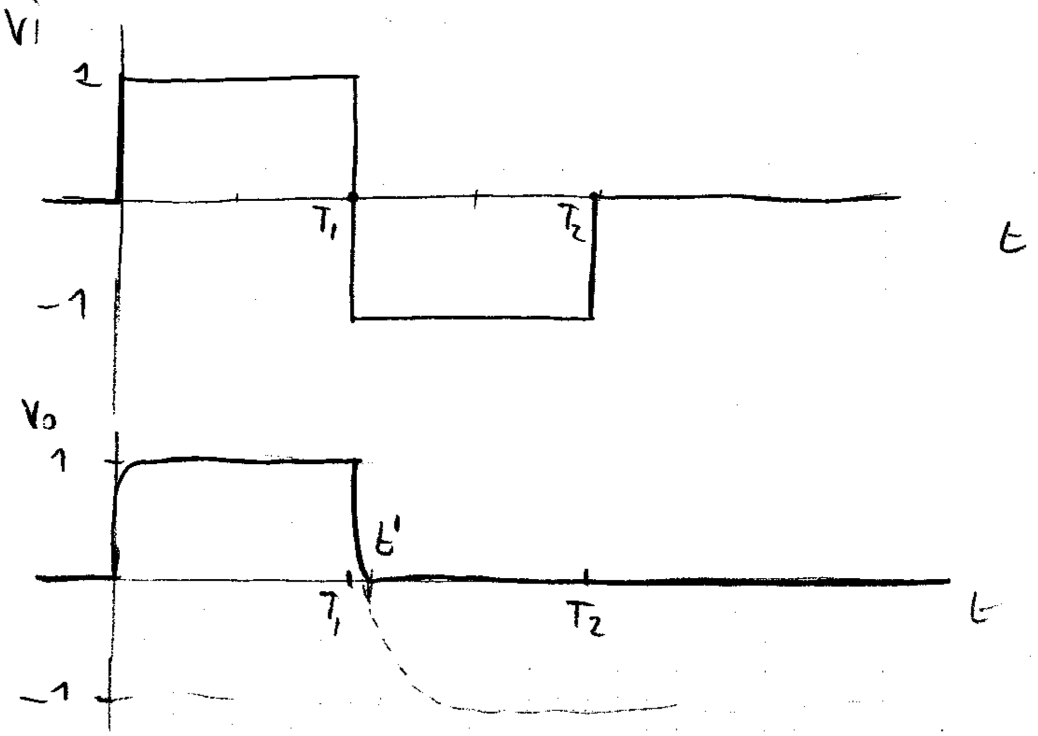
D1 OFF
D2 OFF (INIZ.)



$V_o(t)$: Tenderebbe a -1 con exp.
$(\tau_2 = (R_S + R)C = 1.1 \cdot 10^6 \cdot 10^{-9} = 1.1\,mS$

$V_o(t') = 0$: D2 ON

$\boxed{t > T_2}$ $V_i = 0$:
D1 OFF
D2 OFF



② $V_\gamma = 0.7\,V$

$\boxed{0<t<T_1}$ $V_i = 1\ V$

D2 OFF
D1 ?

x Avere D1 ON ci vuole caduta di 0.7V su D1 - C si carica, I dimin-

Condiz. per D1 ON : $I_{d1} > 0$
(è cond. su V_o)

$$I_{d1} = I - I_R$$

$$I = \frac{V_i - V_1}{R_s} = \frac{V_i - (V_o + V_\gamma)}{R_s} = \frac{V_i - V_o - V_\gamma}{R_s}$$

$$I_R = \frac{V_\gamma}{R}$$

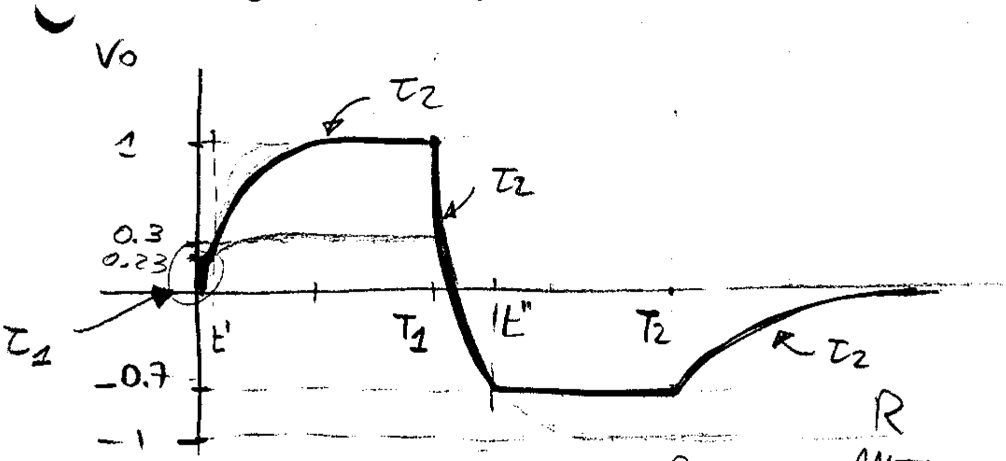
$$I_{d1} = \frac{V_i}{R_s} - \frac{V_o}{R_s} - \frac{V_\gamma}{R_s} - \frac{V_\gamma}{R} > 0$$

$$\frac{V_o}{R_s} < \frac{V_i}{R_s} - \frac{V_\gamma}{R_s} - \frac{V_\gamma}{R}$$

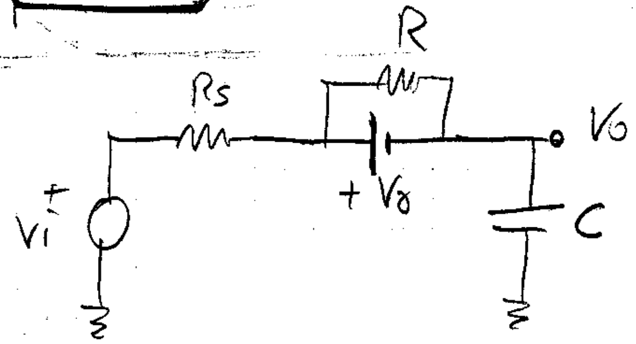
$$\boxed{V_o < V_i - V_\gamma\left(1+\frac{R_s}{R}\right)} = 1 - 0.7 \cdot 1.1 = 1 - 0.77 = +0.23\ V$$

$0 < V_o < 0.23$ V   D1 ON

$V_o > 0.23$ V   D1 OFF



D1 ON:



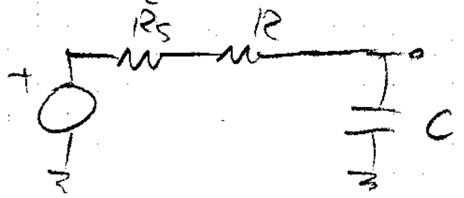
V_o : andam. exp.

- val. asintotico: $V^* = V_i - V_\gamma = +0.3$ V
- $\tau_1 = R_S C = 0.1$ ms

~~Questo andam.~~ finisce a t' ($V_o(t') = 0.23$ V)

!! NON È POSSIB. VAL. DI REGIME $V_o = 0.3$ V !!

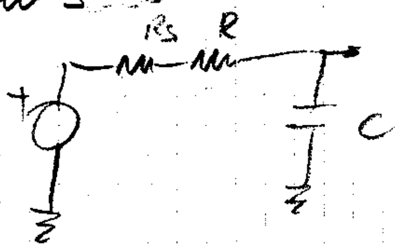
$t > t'$: D1 OFF



V_o : andam. exp.

- val. asint.: $V_i = +1$ V
- $\tau_2 = (R_s + R) C = 1.1$ ms

$\boxed{t > T_1}$ D1 OFF
D2 OFF (INIZ.)



V_o : andam. exp

- val. asint = $V_i = -1$ V
- $\tau_2 = 1.1$ ms

$t = t''$: D2 ON ($V_o(t'') = -V_\gamma = -0.7$ V)

$t > t''$: $V_o(t) = -0.7$

$\boxed{t > T_2}$ $V_i = 0\,V$

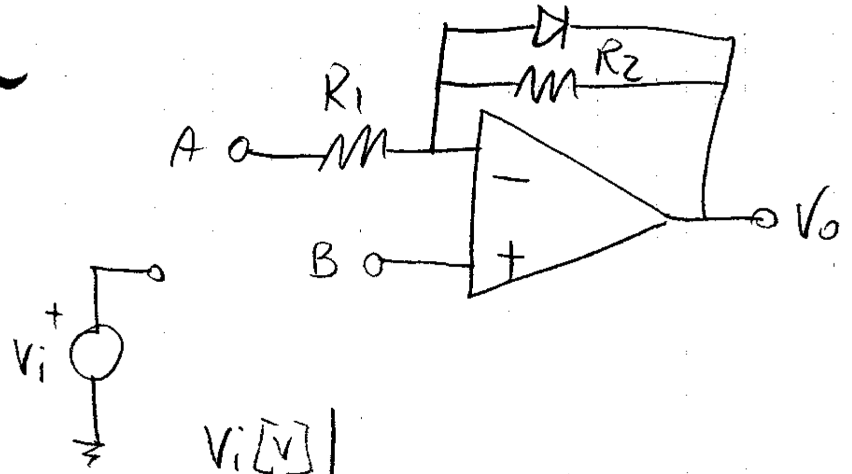
D1 OFF
D2 OFF

V_0 : exp
- Val asint : $V_i = 0V$
- $\tau_2 = 1.1\ ms$

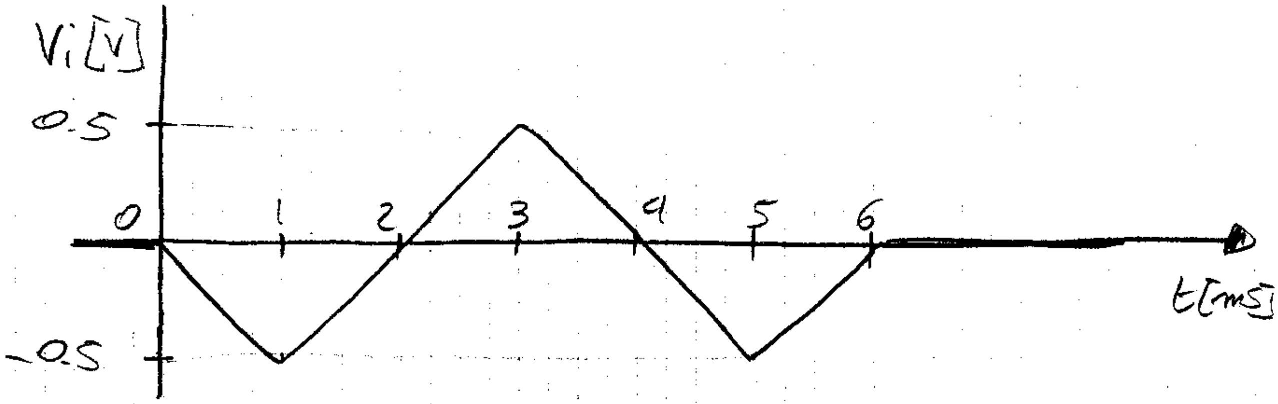
OSSERVAZIONE :

- Differenza tra i casi ① e ② :
è nel comportam. di D1 –
Caso ① : basta $V_i > V_0$ per avere D1 ON
Caso ② : ($V_\gamma = 0.7$) Accensione D1 dipende da I_{d1} → dipende da V_0.
$t = 0^+$: D1 ON
Durata accensione : dip. da R_s, R
! Non possibile $V_0 = 0.3$ come val. di regime !

ES DIODI + AO (DIODI IN REAZ.) 37

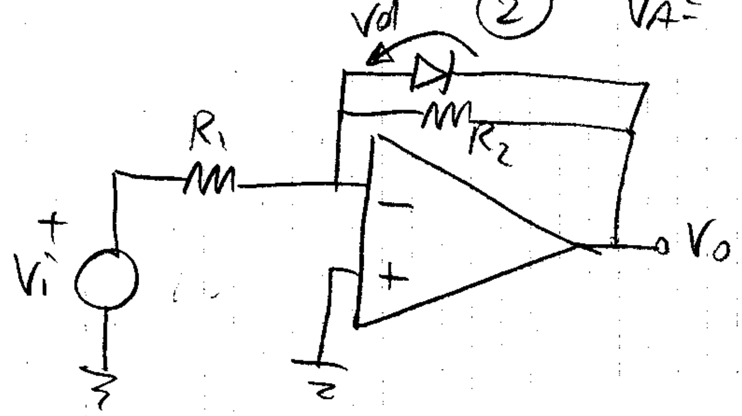


$R_2 = 20k\Omega$
$R_1 = 10k\Omega$
$V_\gamma = 0.5V$



? Vo(t) ? per
(1) $V_A = V_i$; $V_B = 0$
(2) $V_A = 0$; $V_B = V_i$

(1)



- Diodo in reazione : reaz. è sempre negativa (sia + D ON che + D OFF)
- Senza DIODO :

$$V_o = -\frac{R_2}{R_1} V_i = -2V_i$$

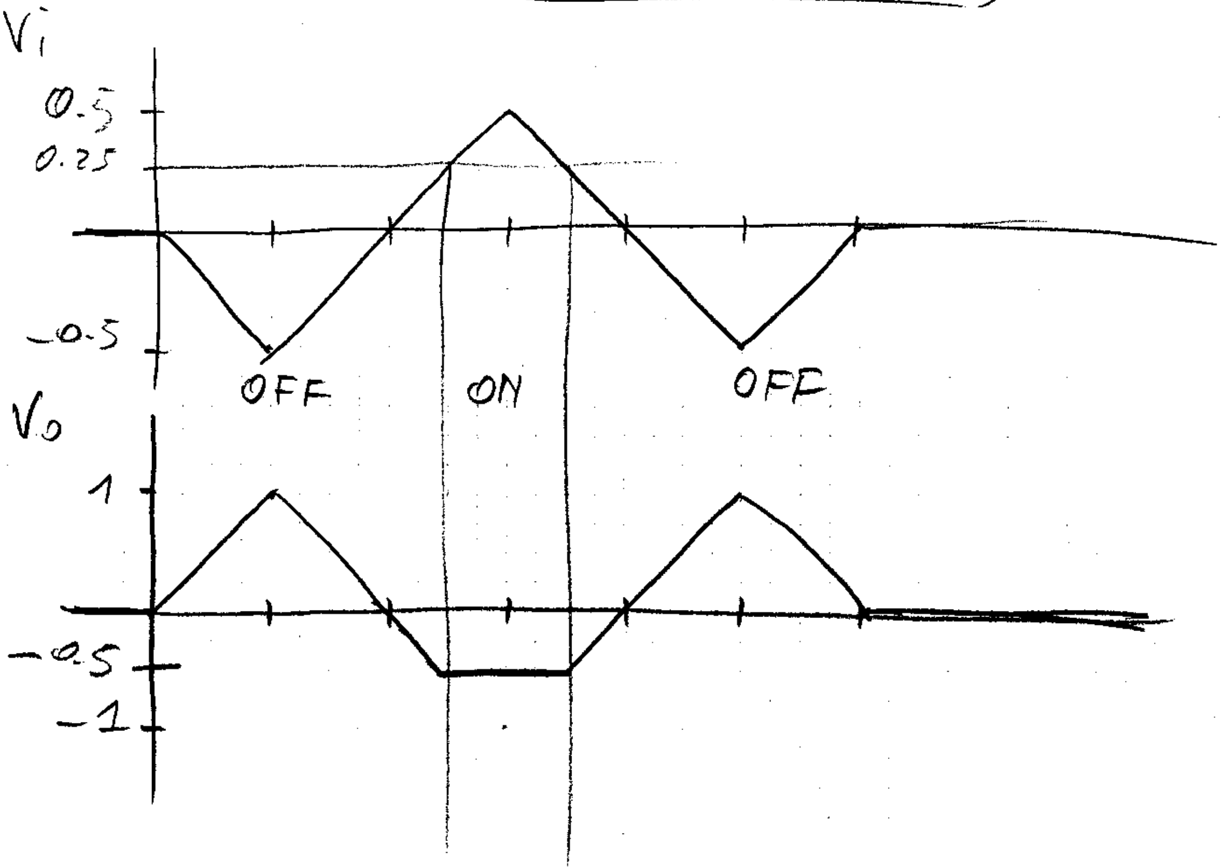
DIODO : OFF se $V_d < V_\gamma = 0.5V$

$$V_d = V^- - V_o = 0 - V_o = -V_o = +2V_i$$

D OFF : $2 V_i < V_\gamma$

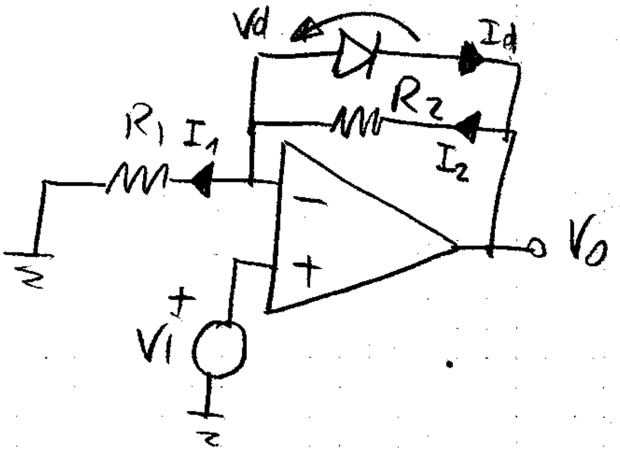
$$V_i < \frac{V_\gamma}{2} = +0.25\ V$$

(altrim. : D ON)



D ON : $V_0 = -V_\gamma = -0.5$

(2)



- Senza DIODO :

$$V_0 = \left(1 + \frac{R_2}{R_1}\right) V_i = +3 V_i$$

$$V_d = V^- - V_0 = V_i - 3 V_i = -2 V_i$$

D OFF se $V_d < V_\gamma = 0.5\ V$

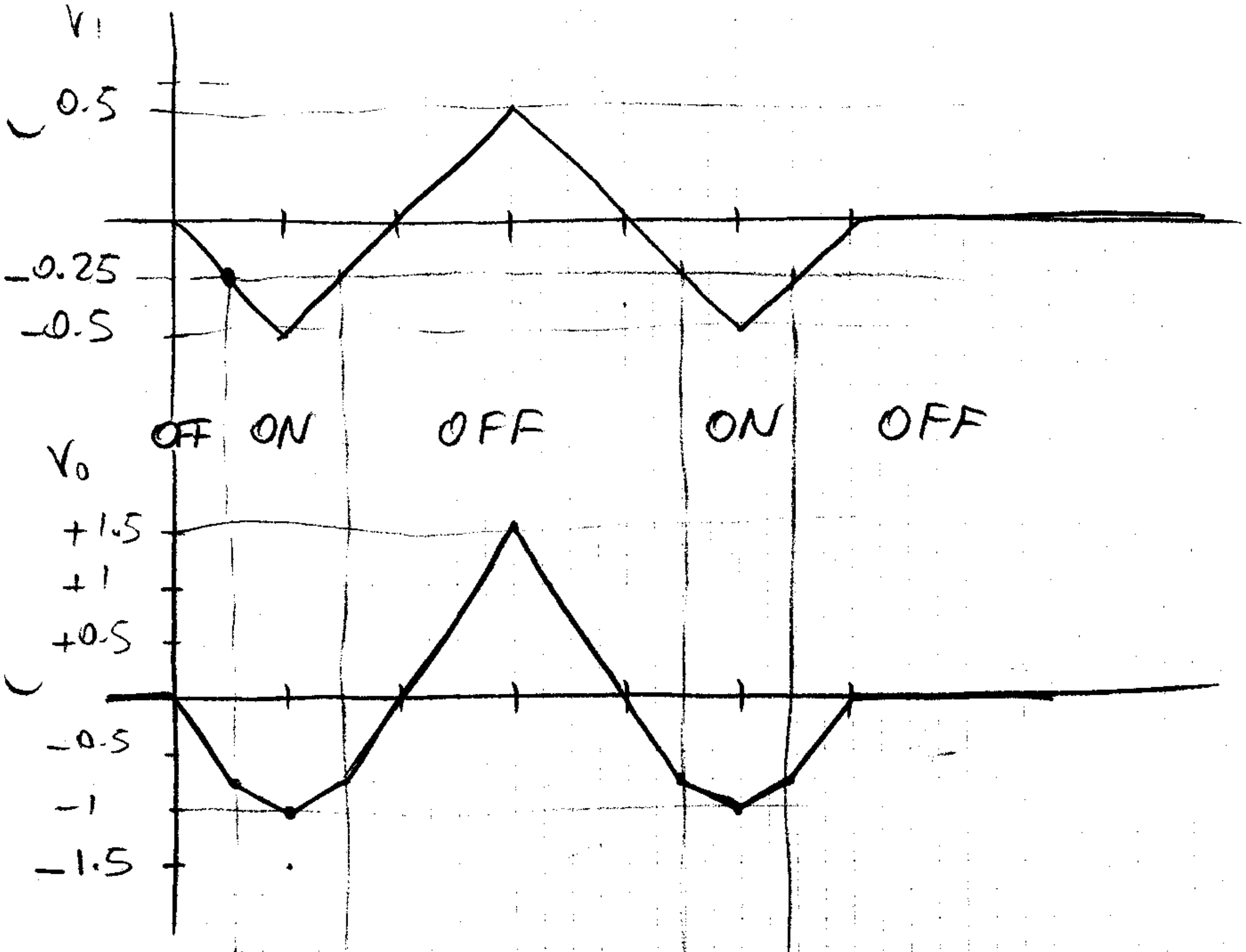
D OFF : $-2V_i < V_\gamma$

$$V_i > -\frac{V_\gamma}{2} = -0.25\,V$$

(altrim. : D ON)

D OFF : $V_o = +3V_i$

D ON : $V_o = V^- - V_d = V_i - V_\gamma = V_i - 0.5$



Verifica D ON : ? $I_d \geq 0$?

$I_d = I_2 - I_1$

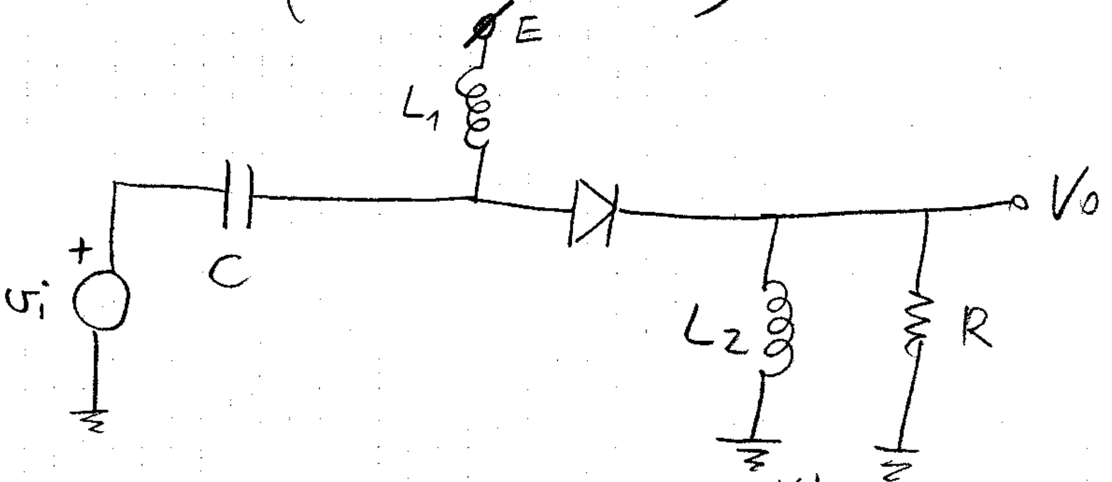
$$I_1 = \frac{V^-}{R_1} = \frac{V_i}{R_1}$$

$$I_2 = -\frac{V_\gamma}{R_2}$$

$$I_d = -\frac{V_\gamma}{R_2} - \frac{V_i}{R_1} \geq 0 \rightarrow V_i \leq -\frac{R_1}{R_2} V_\gamma$$

$$V_i \leq -\frac{V_\gamma}{2} = -0.25\,V \quad \text{Ok}$$

• ES - (SC. 17/5/96)



DIODO REALE: $I_d = I_S \left(e^{V_d/V_T} - 1 \right)$; $I_S = 5 \cdot 10^{-15}$ A

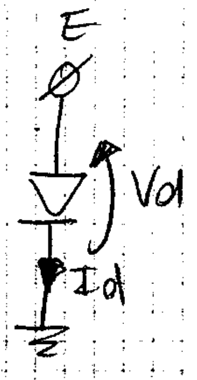
$R = 1\ k\Omega$
$E = +0.65\ V$

1. Punto di lavoro
2. r_d del diodo ?
3. $\frac{v_o}{v_i}$ per $\omega \to \infty$
4. Det $F(s) = \frac{v_o}{v_i}$ per $L_1, L_2 \to \infty$, $C = 10mF$ Bode
5. ? Val. di E per cui $\frac{v_o}{v_i} = 0$ per $\omega \to \infty$

---

1. <u>Punto di lavoro</u> : in <u>CONTINUA</u> delle correnti e tens.

(C → aperto
L → cto cto)



Se D fosse ideale : sarebbe <u>ON</u>

Quindi : $I_d \simeq I_S\, e^{V_d/V_T}$

$V_d = E$

$I_d \simeq I_S\, e^{V_d/V_T} = 5 \cdot 10^{-15} \cdot e^{\frac{0.65}{0.025}} =$
$= 0.98\ mA$

$V_0 = 0$

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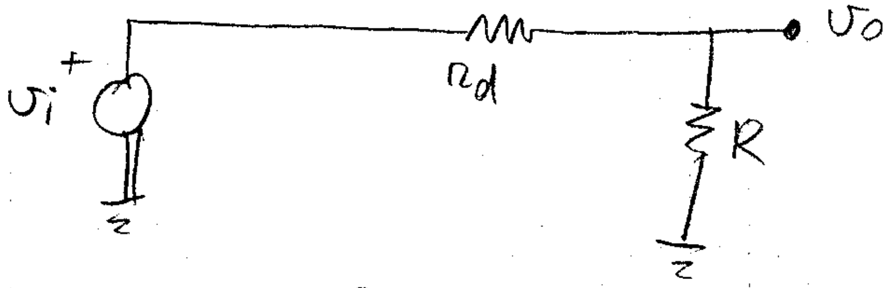
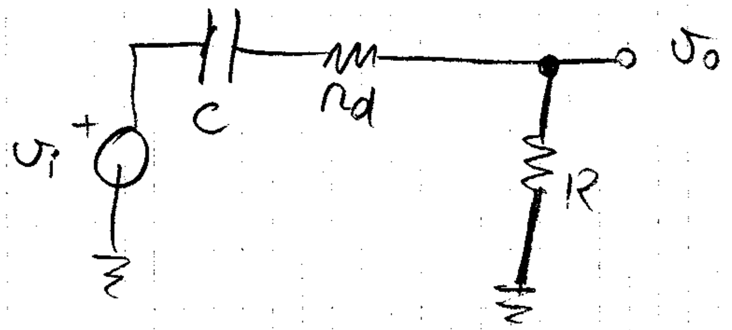
(2) $r_d \simeq \dfrac{V_T}{I_d} = \dfrac{25\,mV}{0.98\,mA} \simeq 25\,\Omega$

(3) $\omega \to \infty$: $C \to$ c.to c.to
$L \to$ circ. ap.



$$\frac{v_o}{v_i} = \frac{R}{R+R_d} = \frac{1000}{1025} = 0.975$$

(4) $Z_L = s \cdot L$ $\quad L \to \infty \Rightarrow Z_L \to \infty$
$L \to$ circ. ap.



$\omega \to 0 \qquad F(s) = 0$

$\omega \to \infty \qquad F(s) = \dfrac{R}{R+r_d}$

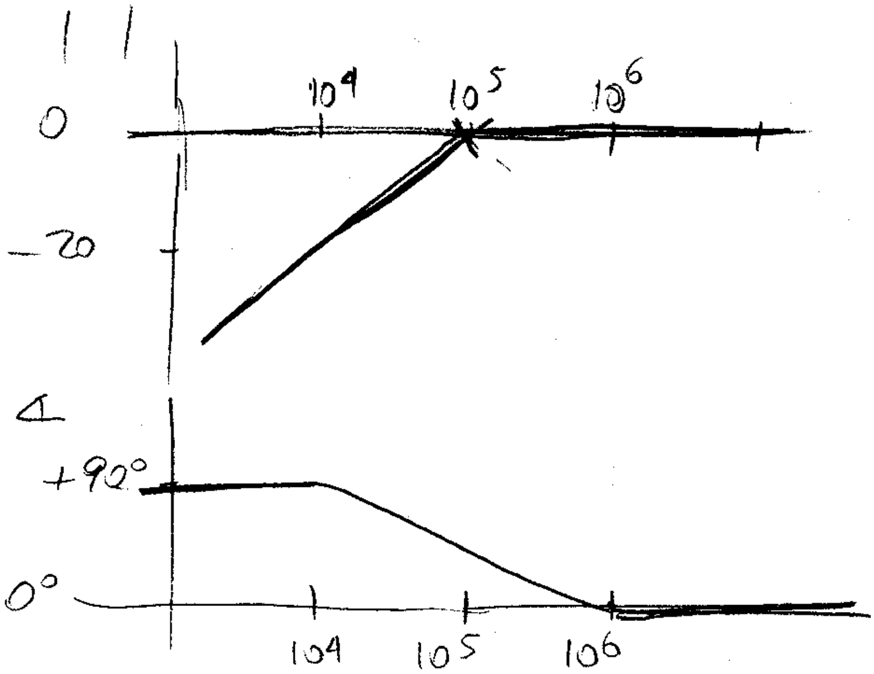
$F(s)$ è F.d.T. passa - alto

$$F(s) = k \cdot \frac{s\tau}{1+s\tau}$$

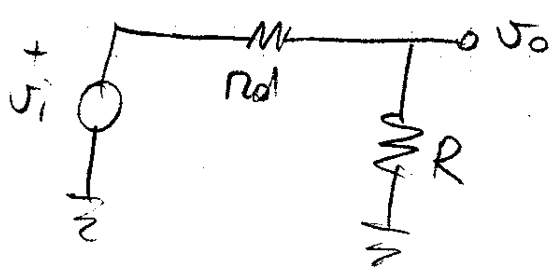
$$k = \frac{R}{R+r_d} = 0.975 = -0.2\,dB$$

$$\tau = C(r_d+R) = 10^{-8} \cdot 1025 \simeq 10^{-5}\,s$$

$$z_p = -10^{5}\,r/s$$



(5) $\omega \to \infty$



Prendo $E \leq 0$ V

Voglio $\dfrac{v_o}{v_i} \to 0 \Rightarrow \dfrac{R}{R + r_d} \to 0 \Rightarrow r_d \gg R$

$$r_d = \frac{V_T}{I_S \cdot e^{V_d/V_T}} = \frac{V_T}{I_S \cdot e^{E/V_T}} \gg R$$

$$e^{E/V_T} \underset{=}{\ll} \frac{V_T}{I_S R} \quad \text{uso} =$$

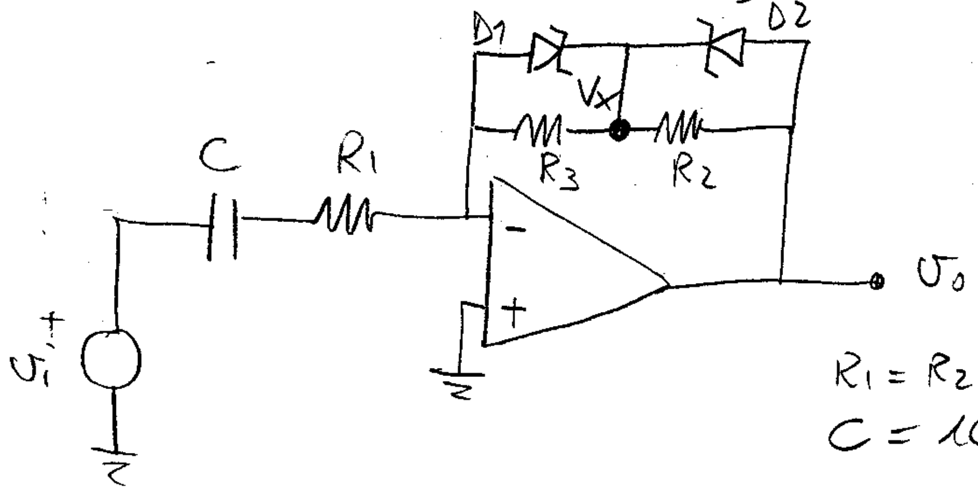
$$E = V_T \ln \frac{V_T}{I_S R} = 25 \cdot 10^{-3} \cdot \ln \frac{25 \cdot 10^{-3}}{5 \cdot 10^{-15} \cdot 10^3} =$$

$$= 25 \cdot 10^{-3} \cdot 22.33 = 0.558 \text{ V}$$

Esempio: prendo $E = 0.5$ V:

$$r_d = \frac{25 \cdot 10^{-3}}{5 \cdot 10^{-15} \cdot e^{\frac{0.5}{0.025}}} = 10\ \text{k}\Omega \quad \left(\frac{v_o}{v_i} \simeq 0.1 \right)$$

• ES. (SCRITTO © 30/11/93)



$V_\gamma = 0.7\ V$

$V_Z = -5.1\ V$

$R_1 = R_2 = R_3 = 10\,k\Omega$

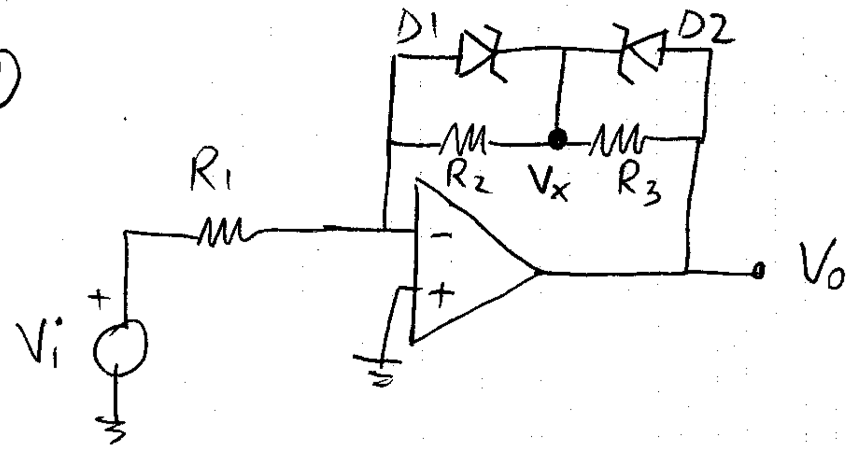
$C = 100\,\mu F$

! (1) C = cto cto : $V_0 = V_0(V_i)$

(2) NO DIODI : F.d.T $\frac{v_0}{v_i}$ e Bode

(3) SI DIODI, SI C : risposta grad. unit.

(1)



- <u>NO DIODI</u> : $V_0 = -\frac{R_2+R_3}{R_1} \cdot V_i = -2\,V_i$

$$V_x = \frac{V_0}{2} = -V_i$$

- <u>DIODI</u> : $V_{d1} = V^- - V_x = -V_x = V_i$

$V_{d2} = V_0 - V_x = -V_i$

! reaz. sempre chiusa

→ Diodi: non entrambi in Zener o Pol. Dir
non uno OFF e l'altro Zener
(prima uno va in POL DIR)

D1 D2

(A) OFF OFF $\Rightarrow$ $\boxed{V_0 = -2V_i}$

$V_z < V_i < V_\gamma$ $V_z < V_i < V_\gamma$ $\longrightarrow$ $\begin{cases} V_z < V_i < V_\gamma \\ -V_\gamma < V_i < -V_z \end{cases} \Rightarrow \underline{-V_\gamma < V_i < V_\gamma}$

(B) OFF POL. DIR $\Longrightarrow$ $V_x = -V_i$

$V_z < V_i < V_\gamma$ $V_{d2} = V_\gamma$ $\boxed{V_0 = V_x + V_{d2} = -V_i + V_\gamma}$

complementare a caso (A):

$\underline{V_z < V_i < -V_\gamma}$

(C) ZENER POL. DIR $\Longrightarrow$ $\boxed{V_0 = -V_{d1} + V_{d2} = -V_z + V_\gamma =}$

$V_{d1} = V_z$ $V_{d2} = V_\gamma$ $= +5.8\ V$

quando si avrebbe (senza diodi):

$V_{d1} < V_z$

$\underline{V_i < V_z = -5.1}$

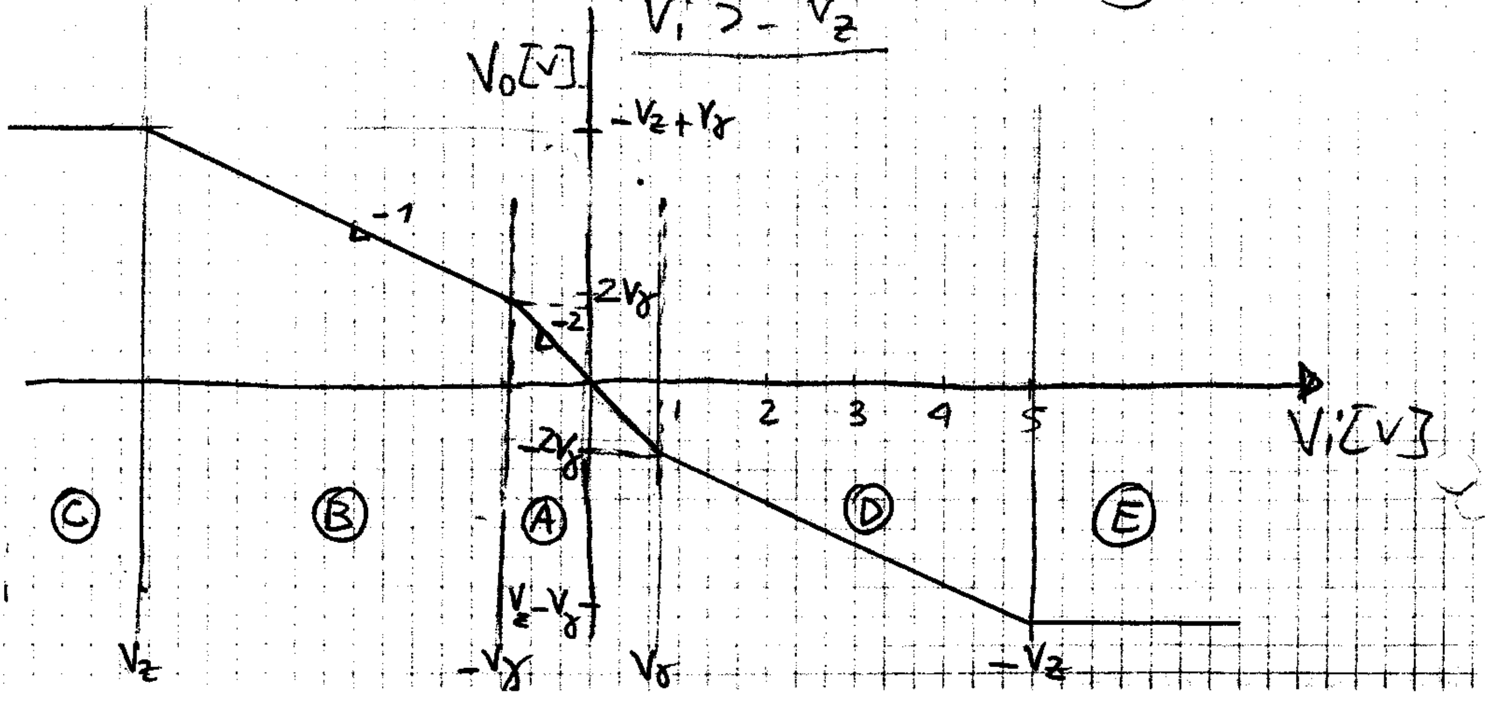
(D) POL DIR OFF $\Longrightarrow$ $\boxed{V_0 = -V_i - V_\gamma}$

$V_{d1} = V_d$ $V_z < -V_i < V_\gamma$ $\rightarrow$ $\underline{V_\gamma < V_i < -V_z}$

(E) POL DIR ZENER $\Longrightarrow$ $\boxed{V_0 = -V_\gamma + V_z}$

$\underline{V_i > -V_z}$

SIMMETRICI Risp. (B), (C)



(2) $F(s) = \frac{V_o}{V_i} = \frac{-Z_2}{Z_1} = -\frac{R_2+R_3}{R_1+\frac{1}{sC}} =$

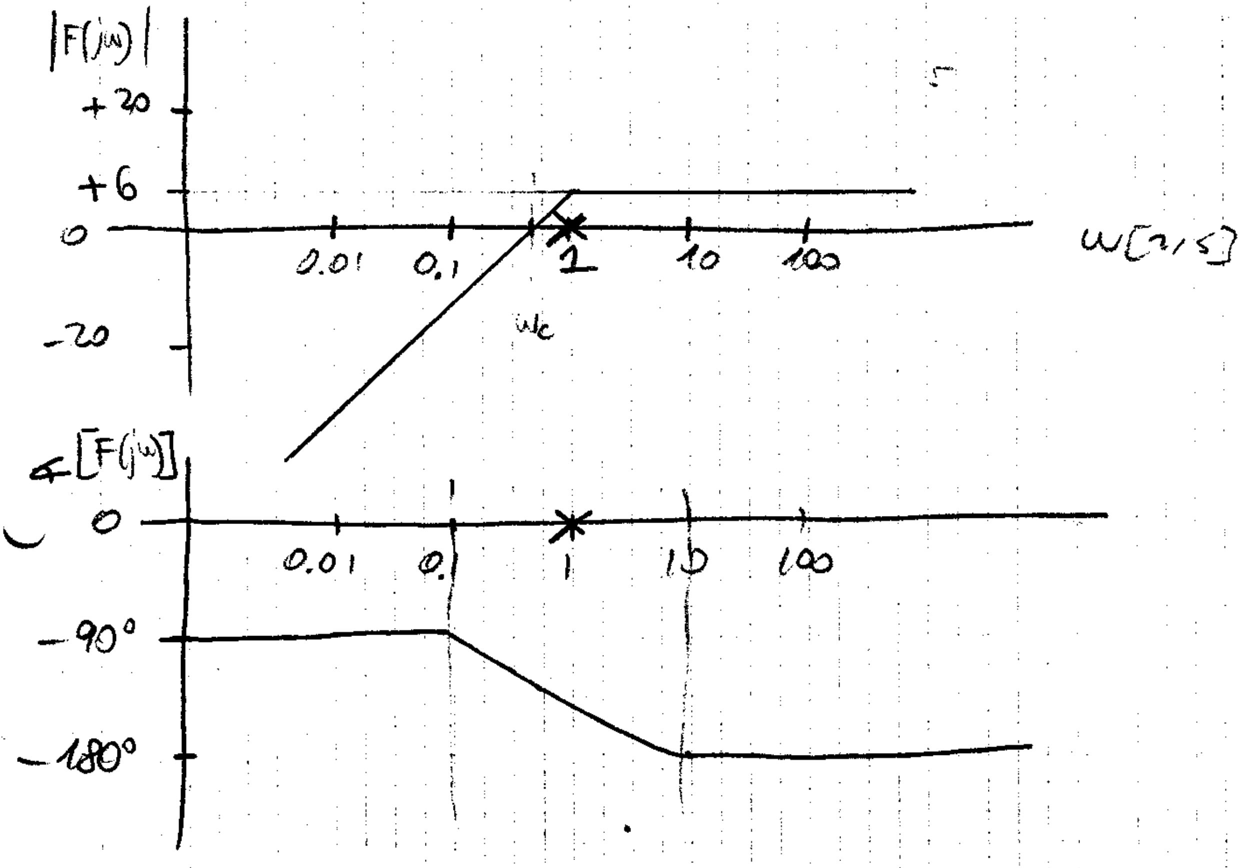
$= -\frac{sC(R_2+R_3)}{1+sCR_1}$

Zero nell'orig.

polo : $-\frac{1}{CR_1} \rightarrow \omega_p = \frac{1}{CR_1} = \frac{1}{10^{-4}\cdot 10^{4}} = 1\ r/s$

solo zero : $\omega_c = \frac{1}{C(R_2+R_3)} = 0.5\ r/s$

$\omega \rightarrow \infty$: $|F| \rightarrow 2 = +6dB$



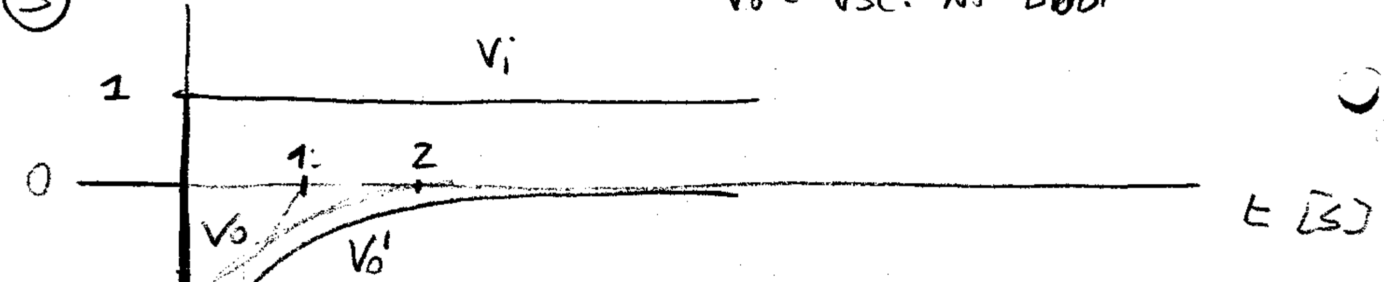
ANCHE : (+ facile) :

$F(s) = -\frac{R_2+R_3}{R_1} \cdot \frac{sCR_1}{1+sCR_1} = -2 \cdot \frac{s\cdot 1}{1+s\cdot 1}$

è PASSA ALTO con guad = 2 = 6dB
e $\omega_p = 1\ r/s$

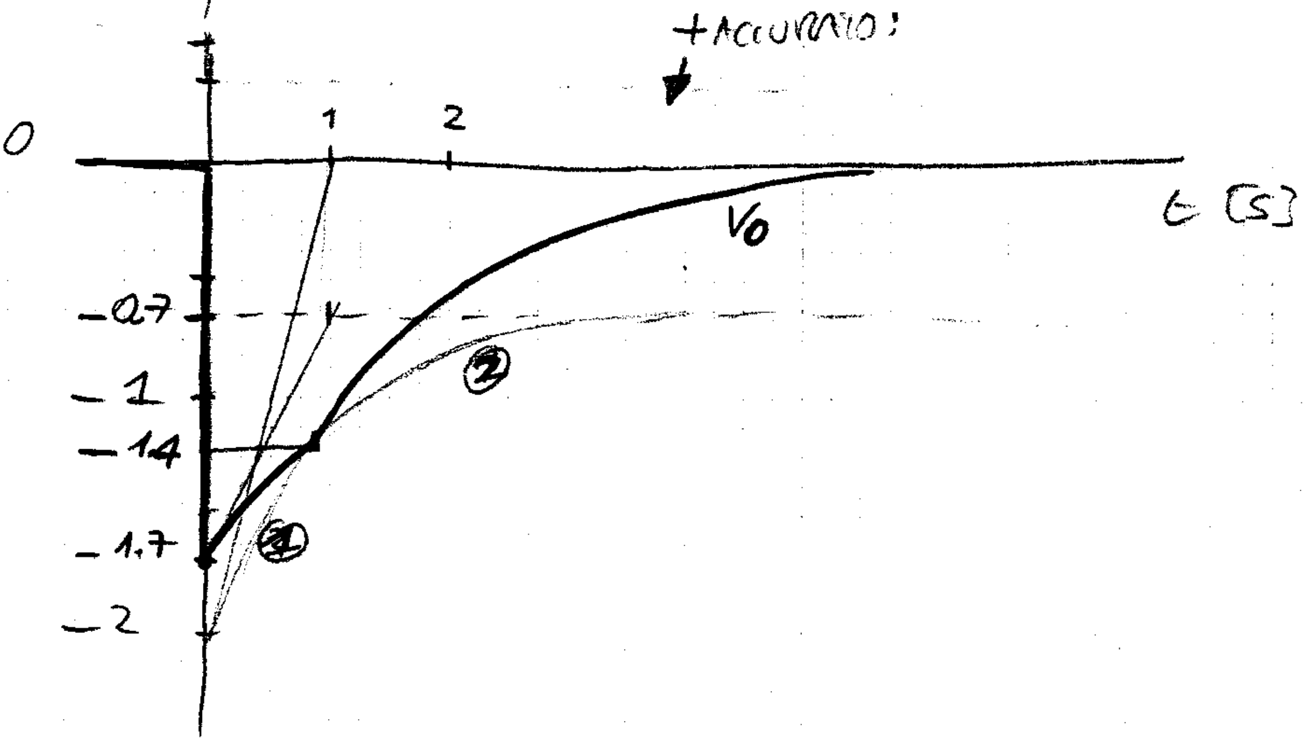
(3)

$V_o' =$ USC. NO DIODI



$t = 0^+ :$ C → C.TO C.TO → è caso (D)

$\Rightarrow V_o(0^+) = -V_i - V_\gamma = -1.7\,V$



andamento (1) parte da -1.7
tende a -0.7 ($\Delta V = 1\,V$)

" (2) da -2
a 0

INTERSEZ : (D2 ON → OFF) per $V_o = -1.4\,V$

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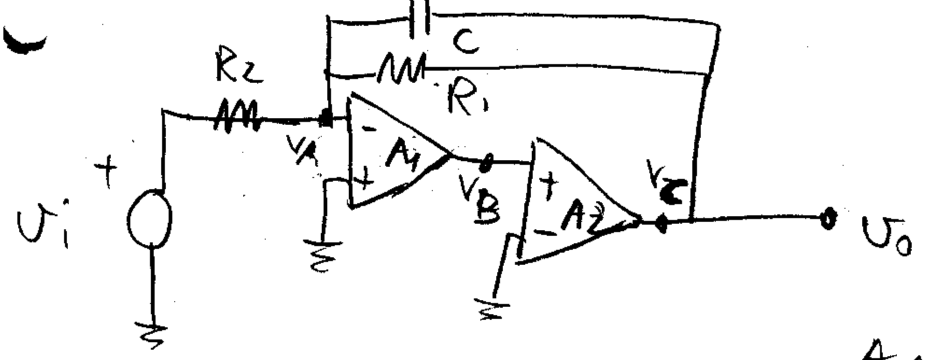
• SC. 21/6/94 (IMPOSTAZIONE)



$R_1 = 1\ k\Omega$
$R_2 = 10\ k\Omega$
$C = 100\ nF$

$A_1 = 10^6$
$A_2 = 10$

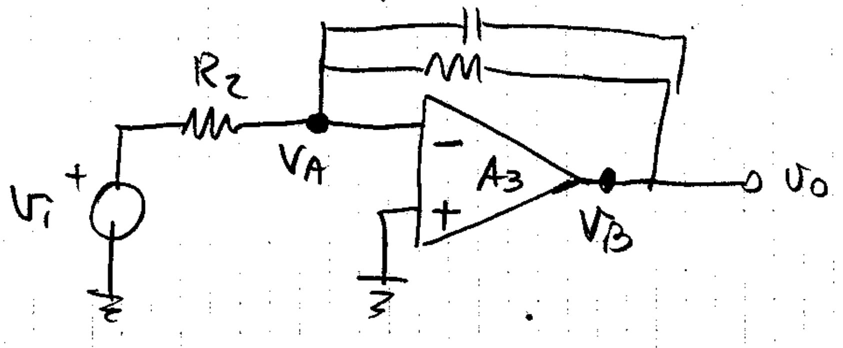
AO id (tranne guad)

(1) F.d.T $\frac{v_0}{v_i}$ e Bode (ragionevoli approx!)

(2) risp. gradino

$$V_B = A_1 (V_1^+ - V_1^-) = -A_1 V_A$$
$$V_C = A_2 (V_2^+ - V_2^-) = A_2 V_2^+ = A_2 \cdot V_B =$$
$$= A_2 (-A_1 V_A) = -A_1 \cdot A_2 \cdot V_A$$

circ. equivalente:

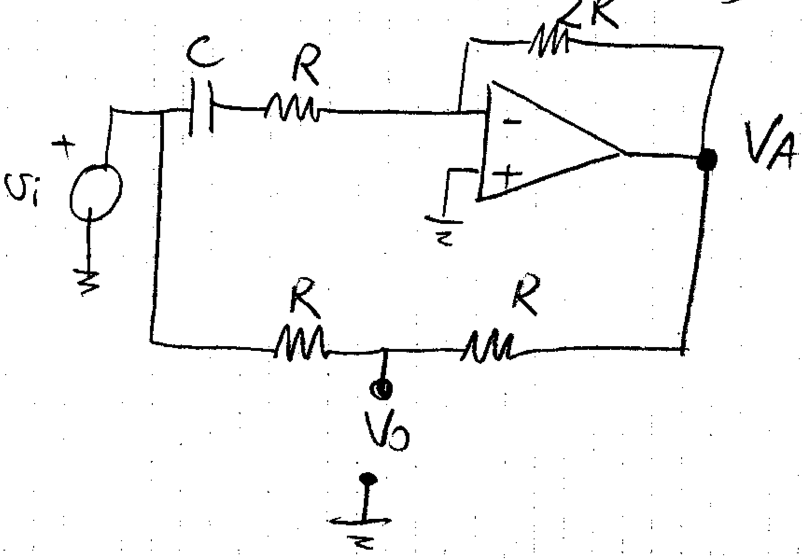


$$A_3 = A_1 \cdot A_2 = 10^6 \cdot 10 = 10^7$$

$$V_A = -\frac{v_0}{A_3} = -\frac{v_0}{10^7} \simeq 0 \ \ldots$$

Buona approx: v_A = massa virt.

• ES (SC. 27/9/94)



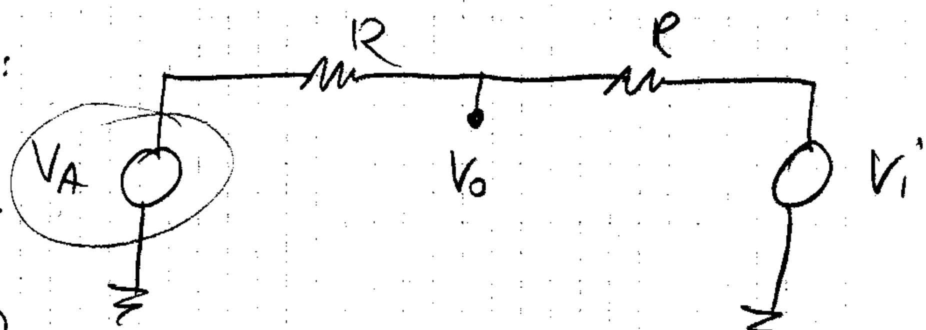
$C = 1\,\mu F$

$R = 10\,k\Omega$

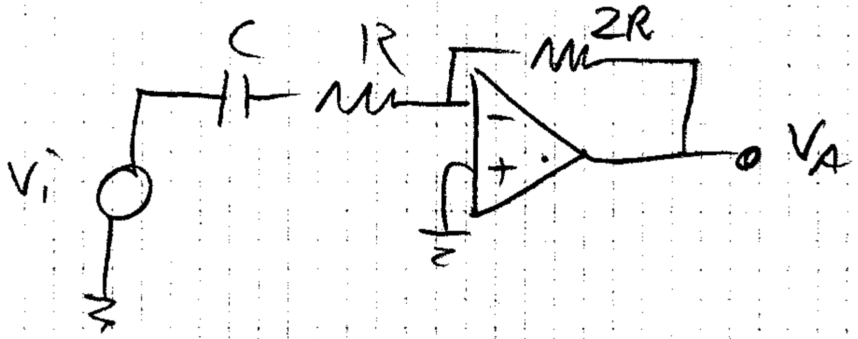
(1) F.d.T. $\frac{V_0}{V_i}$ e Bode

(2) ? V_0 ? per $v_i(t) = 1 + \text{sen}(1000\,t)$ [V]

(1) è come:



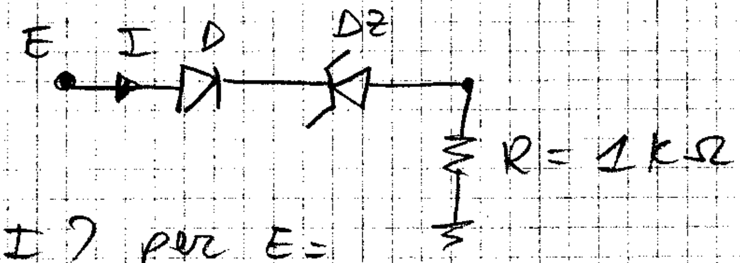
Uscita di A.O.
id. non dip. da ciò che c'è tra uscita (V_A) e massa



CORREZIONE COMPITO IN ITINERE 21/11/97 — 43

ES. 1

(A)



$V_\gamma = 0.7$ V
$V_z = -5$ V

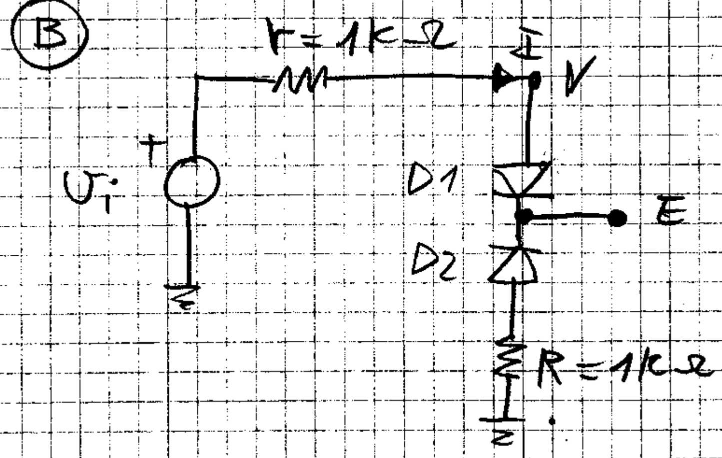
? I ? per E =
+15 V
−15 V
0 V

- $E = 0$ $I = 0$
- $E = +15$ V D ON, DZ ZENER

$$I = \frac{E - V_\gamma + V_z}{R} = \frac{15 - 0.7 - 5}{10^3} = \frac{9.3}{10^3} = +9.3 \text{ mA}$$

- $E = -15$ V $I = 0$

(B)

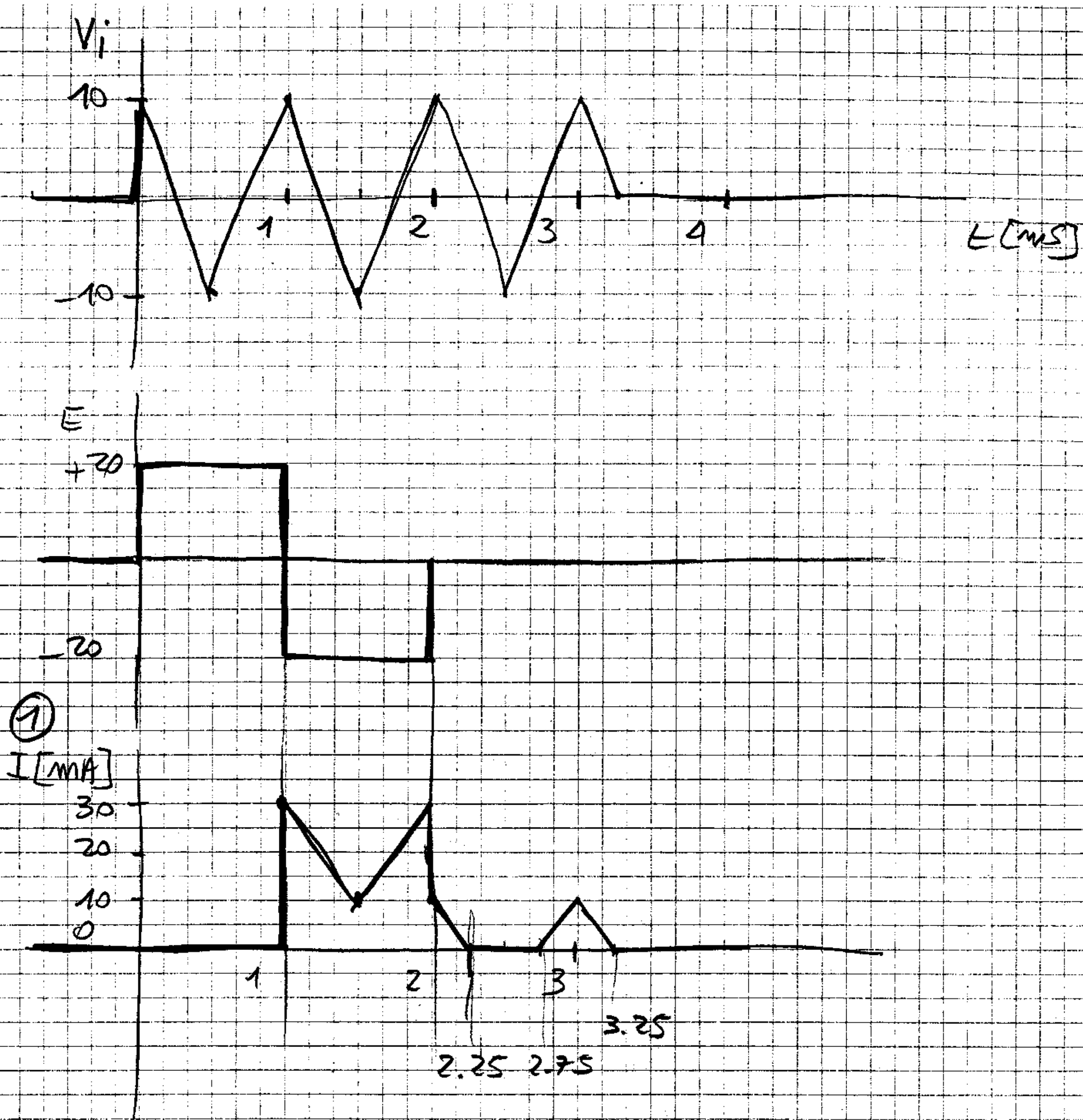


$V_\gamma = 0$ V

$V_i(t)$
$E(t)$ vedi figura

(1) $I(t)$

(2) $I(t)$ in assenza di E



- $t < 0$ $\quad I = 0$
- $0 < t < 1$ $\quad E = +20\ V$ $\quad \left.\begin{array}{l} D2 = OFF \\ D1 = OFF \end{array}\right\} I = 0$
- $1 < t < 2$ $\quad E = -20\ V$ $\quad \begin{array}{l} D2\ ON \\ D1\ ON \end{array}$

$$I(t) = \frac{V_i(t) - V(t)}{r} = \frac{V_i(t) - E(t)}{r}$$

$$I_{max} = \frac{10 - (-20)}{10^3} = +30\ mA$$

$$I_{min} = \frac{-10 - (-20)}{10^3} = +10\ mA$$

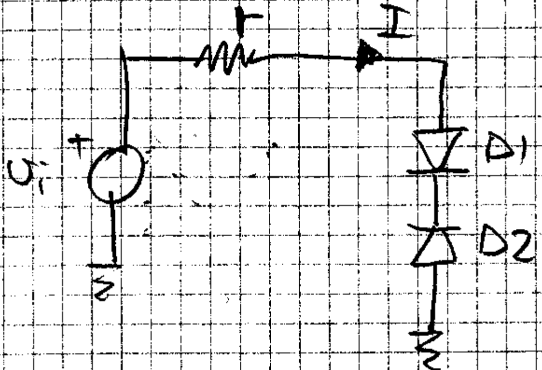
- $t > 2$ $E = 0$ D2 OFF (= ON)

$$D1 \begin{cases} \text{ON se } V_i > 0 \\ \text{OFF se } V_i < 0 \end{cases}$$

$$I(t) \begin{cases} 0 \text{ se } V_i < 0 \\ \dfrac{V_i(t) - 0}{r} = \dfrac{V_i(t)}{r} \quad V_i > 0 \end{cases}$$

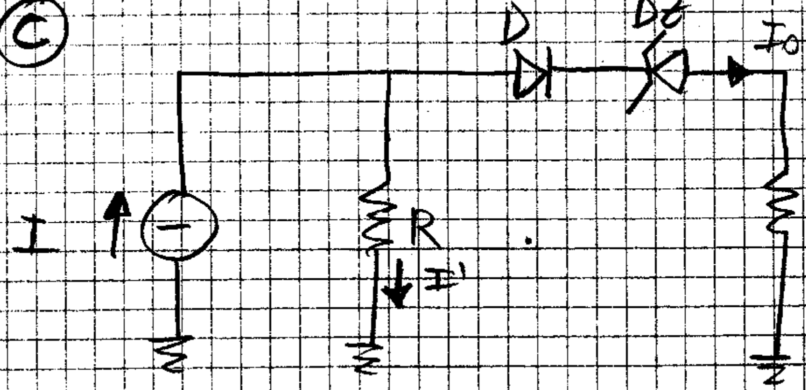
$$I_{max} = \frac{10}{10^3} = 10\,mA$$

(2) NO E:



2 diodi id. in serie –
Unica possib.:
D1 OFF, D2 OFF
(∀ qualunque V_i)
$I = 0$

(C)



$R = R' = 1\,k\Omega$

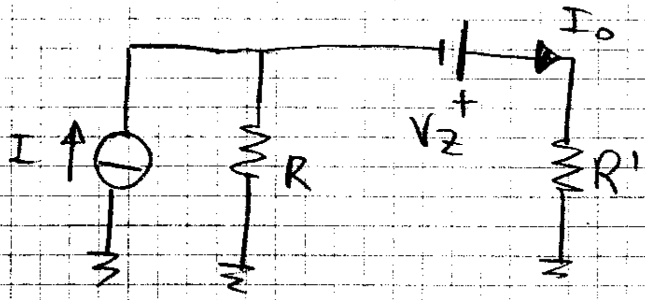
$V_\gamma = 0\ V$
$V_z = -5\ V$

? I_o ? per $I = \begin{matrix} +10 \\ 0 \\ -10 \end{matrix}$ mA

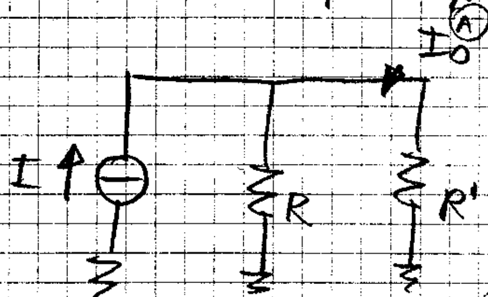
- $I = 0$ D OFF $I_0 = 0$
  Dz OFF

- $I = -10\,mA$ D OFF $I_0 = 0$
  Dz OFF

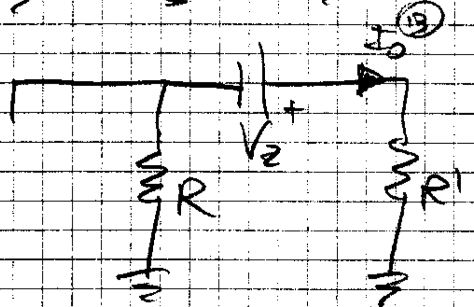
- $I = +10\,mA$ D ON
  Dz ZENER



Uso sovrapp. effetti:



$$I_0^{A} = I \cdot \frac{R}{R+R'} = \frac{I}{2} = +5\,mA$$



$$I_0^{B} = \frac{V_z}{R+R'} = \frac{-5}{2 \cdot 10^3} =$$

$$= -2.5\,mA$$

$$I_0 = I_0^{A} + I_0^{B} = +5 - 2.5 = +2.5\,mA$$

? Verifica ? Immediata (Io>0)

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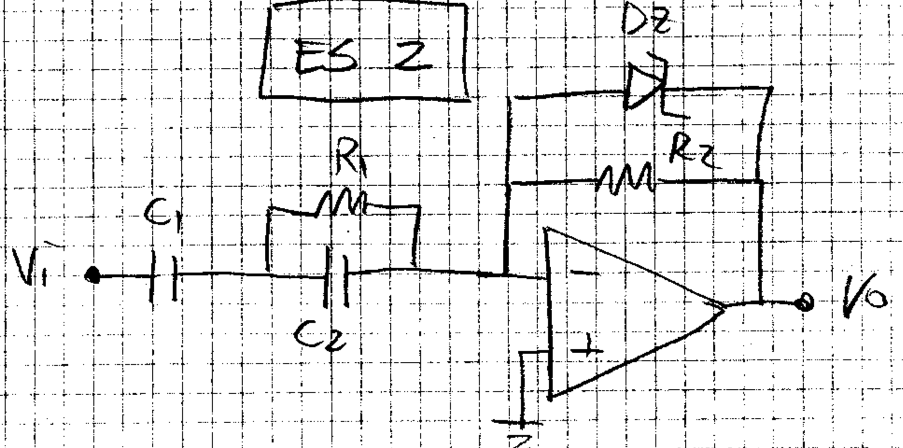
ES 2



$R_1 = 1\,k\Omega$
$R_2 = 100\,k\Omega$
$C_1 = 100\,nF$
$C_2 = 10\,nF$

$V_\gamma = 0.7\,V$
$V_z = -5V$
AO id

① NO Dz: $\frac{v_o}{v_i}$, Bode, grad
② $e_{OFF} = +5\,mV$
③ ? v_o per $v_i(t) = 10^{-2}\sin(10^6 t)$ V
④ Si Dz: Vi sinus amp. 100 mV
$f = 160\,kHz$

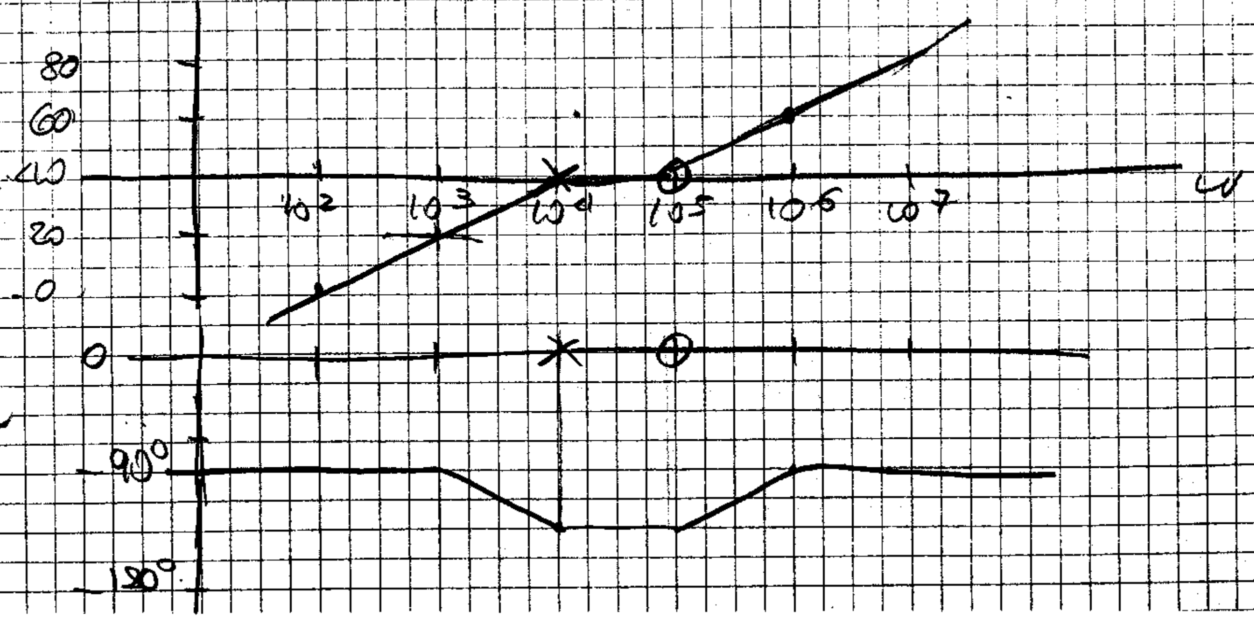
① $\frac{v_o}{v_i} = -\frac{R_2}{Z}$

$$Z = \frac{1}{sC_1} + \frac{R_1/sC_2}{R_1 + \frac{1}{sC_2}} = \frac{1 + sR_1(C_1+C_2)}{sC_1(1+sR_1C_2)}$$

$$\frac{V_o}{V_i} = -\frac{R_2}{Z} = -\frac{sC_1R_2(1+sR_1C_2)}{1+sR_1(C_1+C_2)}$$

$$T(s) = -s\cdot 10^{-2}\,\frac{1+s\cdot 10^{-5}}{1+s\cdot 1.1\cdot 10^{-9}}$$

$\omega_c = 10^2$ r/s



Risposta al gradino: Teor. val iniz. e fin.:

$$\lim_{t\to 0^+} V_0(t) = -\infty \quad ; \quad \lim_{t\to +\infty} V_0(t) = 0$$

$$T(s) = -s\tau_1 \frac{(1+s\tau_2)}{1+s\tau_3} = -s\tau_1\left[\frac{1}{1+s\tau_3} + \frac{s\tau_2}{1+s\tau_3}\right]$$

$$= -s\tau_1\left[\frac{1}{1+s\tau_3} + \frac{\tau_2}{\tau_3}\cdot\frac{s\tau_3}{1+s\tau_3}\right]$$

$\tau_1 = 10^{-2}\,s$
$\tau_2 = 10^{-5}\,s$
$\tau_3 \simeq 10^{-4}\,s$

$$V_0(t) = -\tau_1 \cdot \frac{d}{dt}\left[V_{0,PB}(t) + \frac{\tau_2}{\tau_3} V_{0,PA}(t)\right]$$

$$V_{0,PB}(t) = \left(1 - e^{-t/\tau_3}\right)\cdot sca(t)$$

$$V_{0,PA}(t) = \frac{\tau_2}{\tau_3}\cdot e^{-t/\tau_3}\cdot sca(t) \simeq 0.1\, e^{-t/\tau_3}\cdot sca(t)$$

$$V_0(t) = -\tau_1 \frac{d}{dt}\left\{\left[1 - e^{-t/\tau_3} + 0.1\, e^{-t/\tau_3}\right]\cdot sca(t)\right\}$$

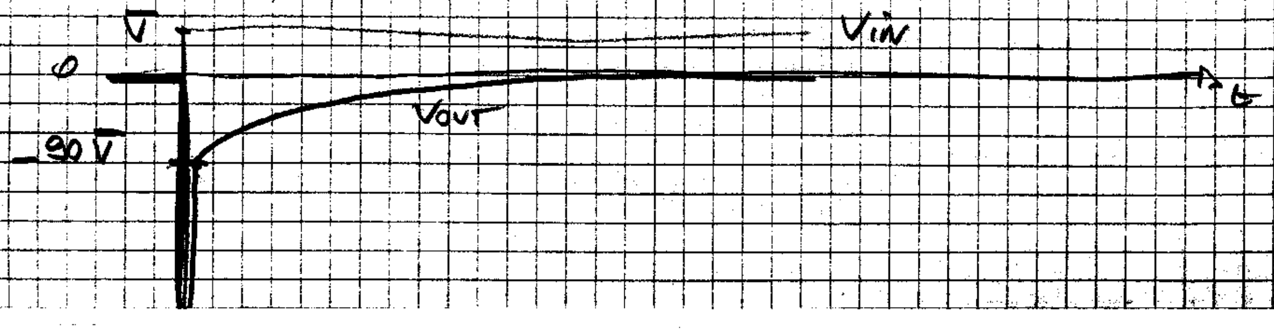
$$= -\tau_1 \frac{d}{dt}\left\{\left[1 - 0.9\, e^{-t/\tau_3}\right]\cdot sca(t)\right\} =$$

$$= -\tau_1\left[\delta(t) + \frac{0.9}{\tau_3} e^{-t/\tau_3}\cdot sca(t)\right] =$$

$$\delta(t)\cdot f(t) = \delta(t)\cdot f(0)$$

$$= -k\,\delta(t) - 0.9\frac{\tau_1}{\tau_3}\cdot e^{-t/\tau_3}\, sca(t) =$$

$$= -k\,\delta(t) - 90\, e^{-t/\tau_3}\cdot sca(t)$$



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2. $e_{OFF} = +5\ mV$, $V_0 = +e_{OFF} = +5\ mV$

3. $\omega_S = 10^6\ r/s$

$V_{in}(t) = 10^{-2} \sin(10^6 t)$

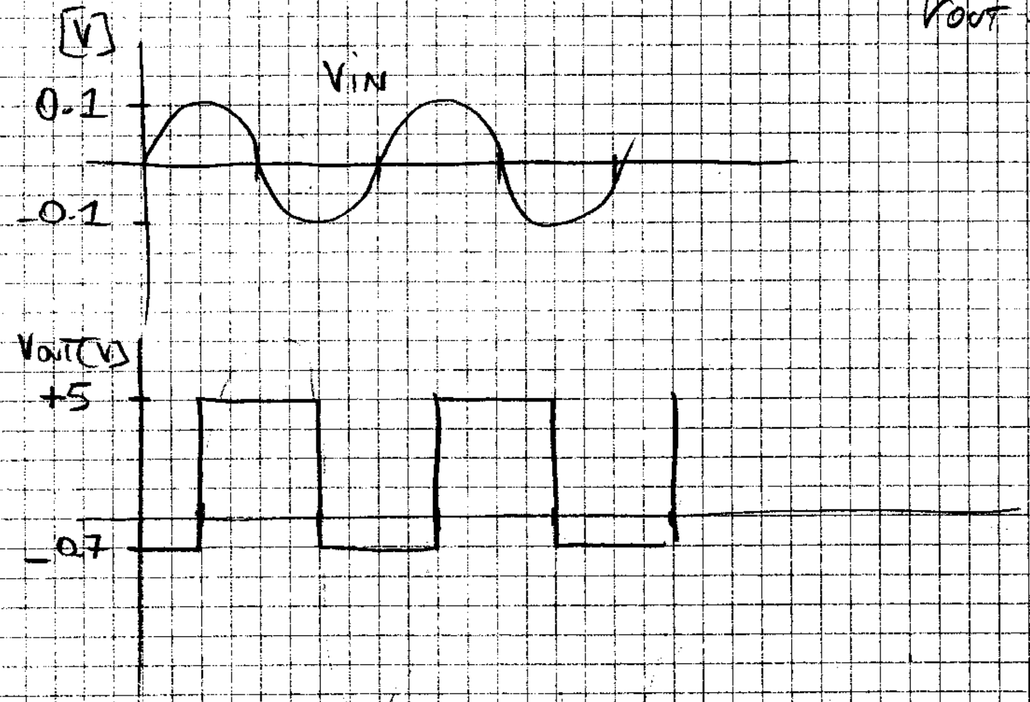
$V_{OUT}(t) = 10 \sin\left(10^6 t - \frac{\pi}{2}\right)$

4. $f_S = 160\ KHz$

$\omega_S = 2\pi f_S \simeq 10^6\ r/s$

$|F(j\omega)| = +60\ dB = 1000$

$\overline{V_{OUT}} = 100\ V$!!

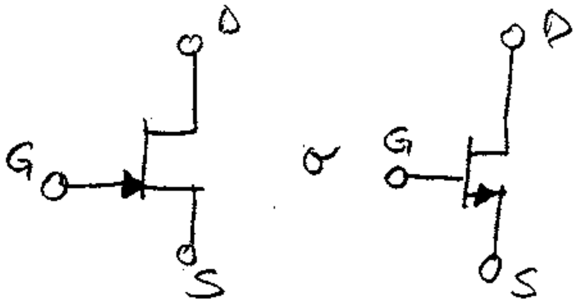


J-FET

- **INTRODUZIONE**

- Dispositivo a 3 terminali -
- " non-lineare (serve però + circ. lineari (si linearizza x piccoli segnali) —

- J-FET a canale n :



- Funzionam. come amplificatore: in PINCH-OFF (altra zona: TRIODO o SPENTO)
- Occorre fare IPOTESI su stato J-FET - Poi VERIFICA (come diodo)

in PINCH-OFF (è un gen. di corrente)

canale n ($V_P<0$)

($V_{GS} \leq 0$)

$$I_D = I_{DSS}\left(1-\frac{V_{GS}}{V_P}\right)^2 = \frac{I_{DSS}}{V_P^2}\left(V_{GS}-V_P\right)^2$$

cond: $V_{DS} \geq V_{GS}-V_P$

o

$V_{DG} \geq -V_P$

e $V_{GS} > V_P$ (accensione)

canale p ($V_P>0$)

($V_{SG} \leq 0$)

$$I_D = I_{DSS}\left(1+\frac{V_{SG}}{V_P}\right)^2 = \frac{I_{DSS}}{V_P^2}\left(V_{SG}+V_P\right)^2$$

$V_{SD} \geq V_{SG}+V_P$

$V_{GD} \geq V_P$

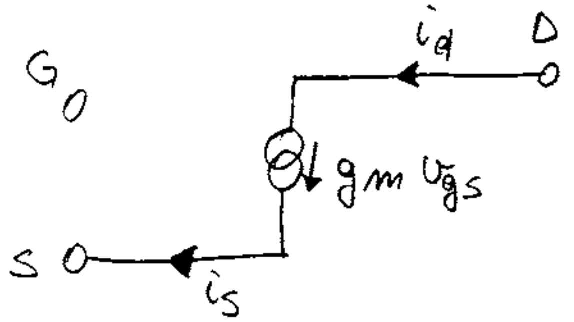
$V_{SG} > -V_P$

TRIODO:

$$I_D = I_{DSS}\left[2\left(1-\frac{V_{GS}}{V_P}\right)\left(\frac{V_{DS}}{-V_P}\right)-\left(\frac{V_{DS}}{V_P}\right)^2\right]$$

- CALCOLO PUNTO DI LAVORO

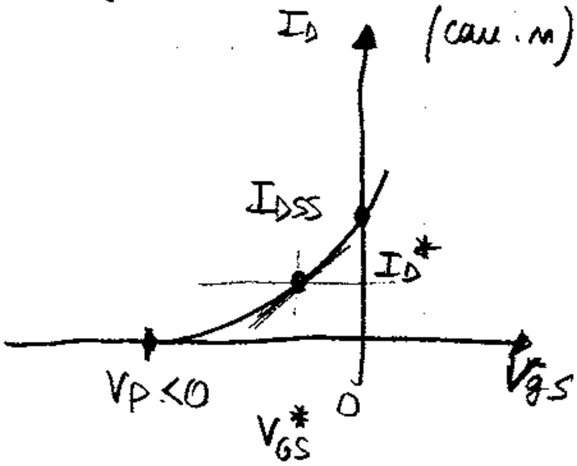
- GUAD. × PICCOLI SEGN. (MOD × PICCOLI SEGN.):



! uguale × can. n e p!

$i_d = i_s$!!

g_m da Transcaratteristica

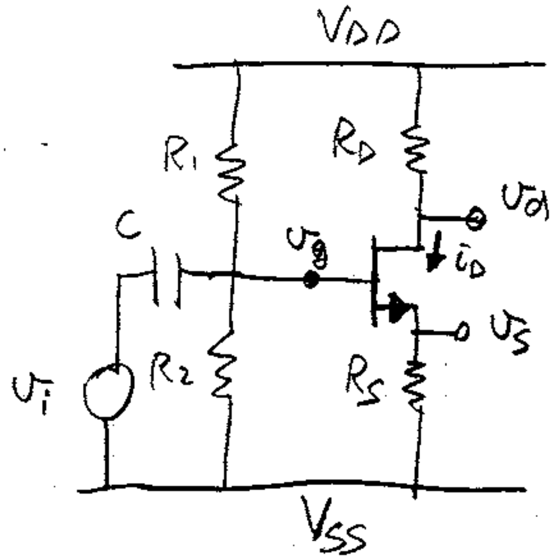


$$g_m = \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{I_D = I_D^*}$$

$$g_m = \frac{2 I_{DSS}}{|V_P|}\left(1 - \frac{V_{GS}^*}{V_P}\right) =$$

$$= \frac{2 I_{DSS}}{|V_P|} \cdot \sqrt{\frac{I_D^*}{I_{DSS}}} = \frac{2}{|V_P|}\sqrt{I_D^* I_{DSS}}$$

RELAZIONI TRA TENSIONI di SEGNALE (DA RICORDARE)



$v_g = v_i$

? v_s, v_d, v_{gs} ?

$$\boxed{v_s = v_g \cdot \frac{g_m R_S}{1 + g_m R_S} \left(\simeq v_g\right)}$$

$$\boxed{v_{gs} = v_g - v_s = v_g \cdot \frac{1}{1 + g_m R_S}}$$

$$\boxed{v_d = - v_g \cdot \frac{g_m R_D}{1 + g_m R_S}}$$

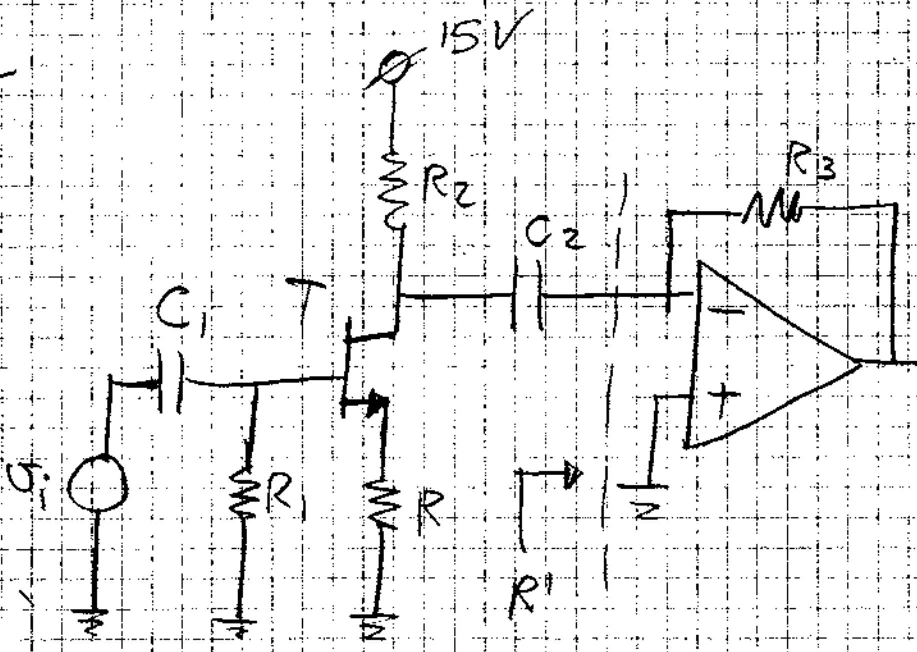
calcolo:

$v_d = - i_D \cdot R_D = - g_m v_{gs} R_D$

IMPEDENZE (piccolo segnale)

(Trascurando r_0) Infinite tra tutti i morsetti
tranne che tra S e G (da S) $= \frac{1}{g_m}$

• ES (SCRITTO 28/1/94)



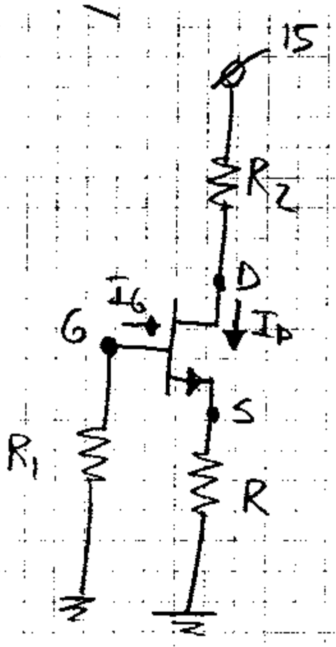
AO id.
$R_1 = 1\,M\Omega$
$R_2 = 5\,k\Omega$
$R_3 = 100\,k\Omega$
$C_1 = 1\,\mu F$
$C_2 \to \infty$

$I_{DSS} = 2\,mA$
$V_P = -5\,V$

1. Det R tale che T in pinch-off e $I_D = 1\,mA$
2. In media freq: R_{IN}, R_{OUT}, R'
3. g_m e $\frac{v_o}{v_i}$ in media freq.
4. Tipo di F.d.T e freq di taglio

1) Punto di lav. (in cont.) $\Rightarrow$ - cond = circ ap.

Det: V_G, V_S, V_D, I_D — - Gen di segn è cto cto



$$I_G = 0$$

$$\boxed{V_G} = I_G \cdot R_1 = \boxed{0\ V}$$

IPOTESI: Pinch-off

$$I_D = \frac{I_{DSS}}{V_P^2}\left(V_{GS} - V_P\right)^2$$

? V_S ?

$$V_S = 0 + I_D \cdot R = I_D R$$

Sistema: $\begin{cases} I_D = \frac{I_{DSS}}{V_P^2}\left(V_{GS} - V_P\right)^2 \\ V_{GS} = V_G - V_S = 0 - I_D R = -I_D R \end{cases}$

$$I_D = \frac{I_{DSS}}{V_P^2}\left(-I_D R - V_P\right)^2$$

Impongo I_D, Trovo R

$$\left(I_D R + V_P\right)^2 = V_P^2 \frac{I_D}{I_{DSS}}$$

$I_D R + V_P = \pm\sqrt{V_P^2 \frac{I_D}{I_{DSS}}}$ ho 2 soluz. x R:

$$R = \frac{-V_P \pm \sqrt{V_P^2 \frac{I_D}{I_{DSS}}}}{I_D}$$

$$R^+ = \frac{-V_P + \sqrt{V_P^2 \frac{I_D}{I_{DSS}}}}{I_D} = \frac{5 + \sqrt{25 \cdot \frac{1 \cdot 10^{-3}}{2 \cdot 10^{-3}}}}{1 \cdot 10^{-3}} = 8.53 \cdot 10^{3}\ \Omega$$

$$= 8.53\ k\Omega$$

$$R^- = \frac{-V_P - \sqrt{V_P^2 \frac{I_D}{I_{DSS}}}}{I_D} = \frac{5 - \sqrt{}}{1 \cdot 10^{-3}} = 1.46\ k\Omega$$

Quale valore scelgo? Il J-FET deve essere <u>ACCESO</u> : $V_{GS} > V_P$

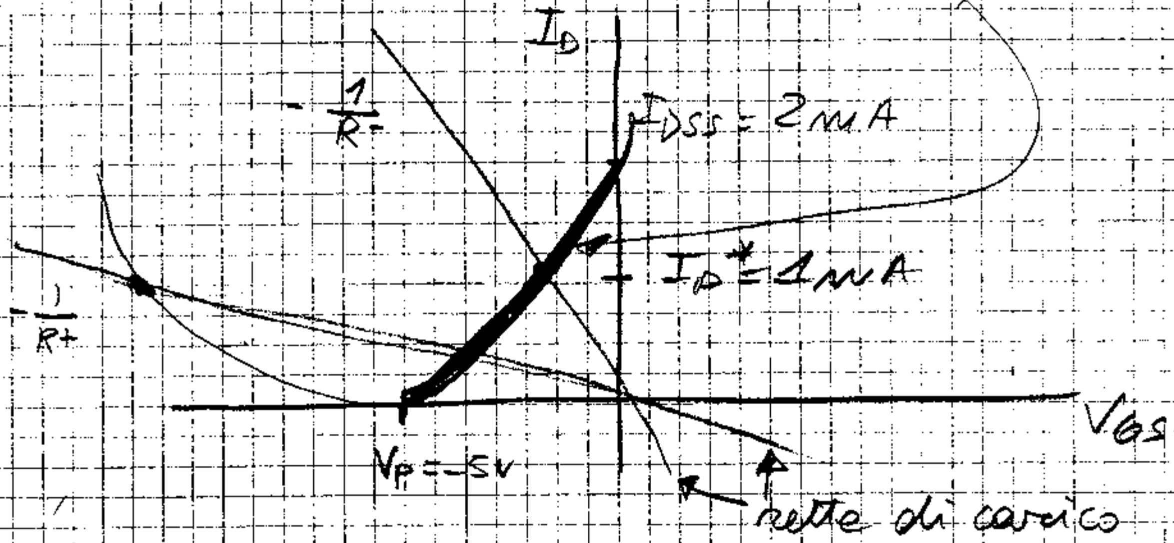
$V_{GS} = -I_D R$

$V_{GS}^+ = -I_D R^+ = -1 \cdot 10^{-3} \cdot 8.53 \cdot 10^{3} = -8.53V$

$V_{GS}^- = -I_D R^- = -1.46 V$

$V_P = -5V \rightarrow$ prendo $\underline{R = R^- = 1.46 k\Omega}$

Motivo delle 2 soluz. x R: Eq. I_D in pinch-off è parabola - Solo 1 tratto è "fisico"



<u>VERIFICA Pinch-off</u>

? $V_{DG} > -V_P$?

$V_D = 15 - I_D R_2 = 15 - 10^{-3} \cdot 5 \cdot 10^{3} = +10V$

$V_{DG} = V_D - V_G = 10 - 0 = +10V$. <u>OK</u>

!! Fare rassunto p.to lav. !!

(2) Media freq : Tutti i C = c.to c.to.

↳ dip. da FdT !!!

(HP: C → c.to c.to
LP: C → aperto)

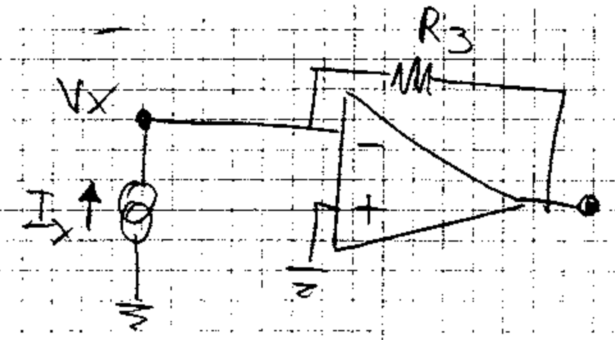
!! Significato Media freq (C → c.to c.to, No parassiti)

$R_{IN} = R_1 = 1 M\Omega$

$R_{OUT} = 0$ (A.O. id)

R' ?

$\boxed{\text{! BATTERIE = MASSA !}}$



$R' = \frac{V_x}{I_x}$

$V_x = V^- = V^+ = 0$

$R' = 0$

(3) $gm = 2 \cdot \frac{\sqrt{I_D \cdot I_{DSS}}}{|V_P|} = 2 \cdot \frac{\sqrt{1 \cdot 10^{-3} \cdot 2 \cdot 10^{-3}}}{5} =$

$= 0.56 \cdot 10^{-3} \frac{A}{V} = 0.56 \frac{mA}{V}$

Calcolo il guadagno: $(C = c_{TOC} \cdot T_0)$

c'è una corr. di piccolo segnale i_d

$i_d = g_m v_{gs}$

$v_g = v_i$

$v_{gs} = v_g \cdot \frac{1}{1 + g_m R} = v_i \frac{1}{1 + g_m R}$

! i_d scorre in R_3 (poiché per il segnale il drain è a massa e in R_2 non scorre corr.)

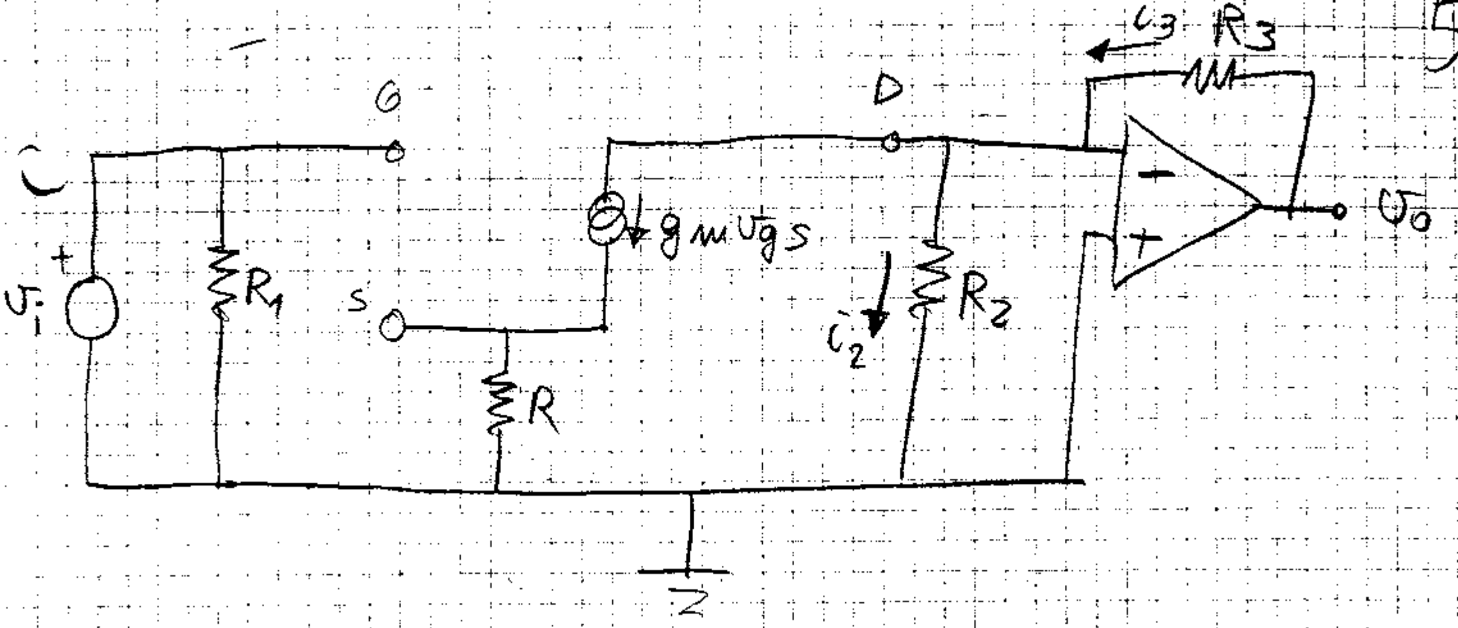
$v_o = + i_d \cdot R_3 = + g_m v_i \frac{1}{1 + g_m R} R_3$

$\frac{v_o}{v_i} = \frac{g_m R_3}{1 + g_m R}$ (è simile a "senza el. a massa" ma con segno cambiato)

!! scrivo g_m in $\frac{mA}{V}$ e Res. in $k\Omega$!!

$\frac{v_o}{v_i} = \frac{0.56 \cdot 100}{1 + 0.56 \, 1.46} = \frac{56}{1.81} = 30.80$

con circuito equivalente:



$v_d = V^- = V^+ = 0$

$$i_2 = \frac{v_D - 0}{R_2} = \frac{0-0}{R_2} = 0$$

$i_3 = g_m v_{gs}$

$v_O = V^- + i_3 R_3 = + i_3 R_3$

Devo trovare $v_{gs} = v_g - v_s$

$v_G = v_i$

? v_s ? $\quad v_s = g_m v_{gs} \cdot R$

$v_s = v_g g_m R - v_s g_m R$

$$v_s = v_g \frac{g_m R}{1 + g_m R}$$

$$v_{gs} = v_g \left(1 - \frac{g_m R}{1 + g_m R}\right) = v_g \frac{1}{1 + g_m R}$$

$$v_O = i_3 R_3 = g_m v_{gs} R_3 = g_m \cdot v_i \frac{1}{1 + g_m R} \cdot R_3$$

$$\frac{v_o}{v_i} = \frac{g_m R_3}{1 + g_m R}$$

(4) $C_2 \to \infty$

$C_1 = 1\,nF$

F.d.T è passa alto.

Taglio: $\omega_c = \frac{1}{\tau}$

$\tau = R_1 C_1 = 10^6 \cdot 10^{-9} = 10^{-3}\,s$

$\omega_c = 10^3\,r/s$

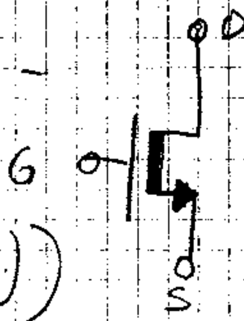
$f_c = \frac{\omega_c}{2\pi} = 159\,Hz$.

$\Rightarrow$ La "media freq" di prima sono le "alte" freq ($\gg f_c$)

MOS-FET

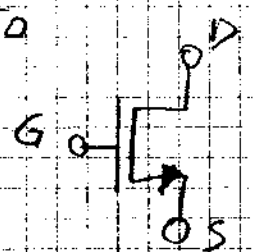
- MOS-FET A SVUOTAMENTO -

  - è come J-FET, ma può jure in arricchimento ($V_{GS} > 0$ (n ch) ; $V_{SG} > 0$ (p ch))



con n (no substrato)

- MOS-FET AD ARRICCHIMENTO



con n

canale n ($V_t > 0$) | canale p ($V_t < 0$)

PINCH-OFF (o SATURAZIONE)

$$I_D = K\,(V_{GS} - V_t)^2 \qquad\qquad I_D = K\,(V_{SG} + V_t)^2$$

$$K = \frac{1}{2}\mu_n C_{ox}\frac{W}{L} \quad [A/V^2] \qquad\qquad K = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}$$

cond: $V_{DS} \geq V_{GS} - V_t$ o $V_{DG} \geq -V_t$ | cond: $V_{SD} \geq V_{SG} + V_t$ o $V_{GD} \geq +V_t$

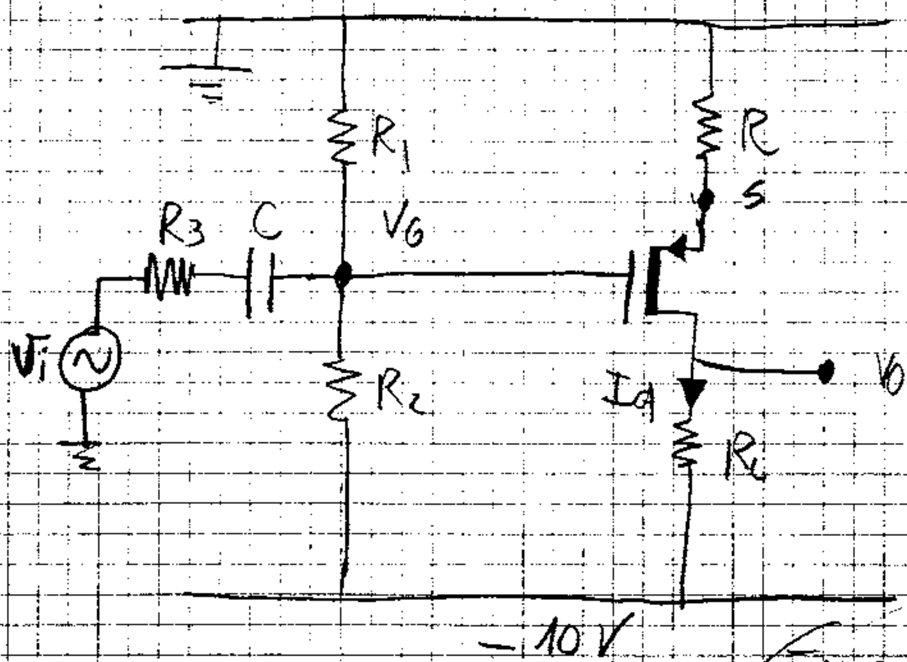
e $V_{GS} > V_t$ | e $V_{SG} > -V_t$

TRIODO: $I_D = K\left[2(V_{GS} - V_t)V_{DS} - V_{DS}^2\right]$

TRANSCONDUTTANZA:

$$g_m = 2K\,(V_{GS} - V_t) = 2\sqrt{K}\sqrt{I_d} = \sqrt{2\mu_n C_{ox}}\cdot\sqrt{\frac{W}{L}}\cdot\sqrt{I_d}$$

• ES MOS (SC. 27/9/96)



è MOS a SVUOTAM. (P)
Ha $V_P > 0$, Visto come ARRICCHIM. ha $V_T = V_P > 0$ (come svuotam. avrebbe $V_T < 0$)

$K = 1 mA/V^2$ $\quad V_T = +2V$

$C \to \infty$ $\quad R_1 = 4 M\Omega$; $R_2 = 6 M\Omega$; $R_3 = 1K\Omega$; $R_L = 700\ \Omega$

① Val R x saturaz. con $I_D = 4 mA$ - Det. pto lav.

② In media freq $\frac{v_o}{v_i}$

③ Max val R_L x MOS in sat (con R del pto ①)

① POLARIZZAZIONE

$I_G \cong 0 \Rightarrow V_G$ si trova tramite partitore

$$\boxed{V_G} = -10 + [0-(-10)] \cdot \frac{R_2}{R_1+R_2} =$$

$$= -10 + 10 \frac{R_2}{R_1+R_2} = -10 + 10 \cdot \frac{6}{10} = \boxed{-4 V}$$

!! OSS: corrente in Pinch-off è det. da tens. su gate (fissata da R_1, R_2) e da res. su SOURCE (R) -

IP: Pinch-off

è come: $I_D = \frac{I_{DSS}}{V_P^2}\left(V_{SG}+V_P\right)^2$

$$\begin{cases} I_D = K\left(V_{SG}+V_T\right)^2 \\ V_S = 0 - I_D \cdot R \end{cases}$$

$$V_S = -I_D \cdot R$$

$$I_D = K\left(V_S - V_G + V_T\right)^2$$

$$I_D = K\left(-I_D R - V_G + V_T\right)^2$$

$+ \quad + \quad -$

$$I_D R + V_G - V_T = \pm\sqrt{\frac{I_D}{K}}$$

$$R = \frac{-V_G + V_T \pm \sqrt{\frac{I_D}{K}}}{I_D}$$

mA

[a [V]]

mA/V²

$$R^+ = \frac{+4+2+\sqrt{\frac{4}{1}}}{4} = 2\,k\Omega$$

mA (→ kΩ)

$$R^- = \frac{+4+2-\sqrt{4/1}}{4} = 1\,k\Omega$$

? Quale scelgo ?

mA kΩ

$V_S^+ = -I_D R^+ = -4 \cdot 2 = -8V$

$V_S^- = -4 \cdot 1 = -4V$

Deve essere: $V_{SG} \geq -V_P = -V_T = -2V$

$V_{SG}^+ = V_S^+ - V_G = -8-(-4) = -4 < -2$ NO

$V_{SG}^- = V_S^- - V_G = -4-(-4) = 0 > -2$ OK

scelgo $R = 1k\Omega$

(prendo il val + basso per R perché il disp. deve funz. con una V_S NON TROPPO NEG.)

Calcolo V_D : $V_D = -10 + I_D \cdot R_L = -10 + 4 \cdot 0.7 =$

$= -10 + 2.8 = -7.2 \text{ V}$

<u>Verifica</u> Pinch-off

$V_{GD} \geq V_P = V_T = 2 \text{ V}$

$V_{GD} = V_G - V_D = -4 + 7.2 = +3.2 > 2$ <u>Ok</u>

Occorre anche det. corr. in R_1 e R_2!!

<u>OSS</u> : Se devo det. una resist. (come qui) devono essere verif. le 2 cond:
- MOS acceso
- MOS in pinch-off -

(2) A occhio : $v_g = v_i \cdot \dfrac{R_1 // R_2}{R_3 + R_1 // R_2}$

conf. senza el. a massa : $\dfrac{v_o}{v_g} = -\dfrac{g_m R_{DRAIN}}{1 + g_m R_{SOURCE}} = -\dfrac{g_m R_L}{1 + g_m R}$

$$\frac{v_o}{v_i} = -\frac{R_1 // R_2}{R_3 + R_1 // R_2} \cdot \frac{g_m R_L}{1 + g_m R}$$

$g_m = 2K (V_{SG} + V_T) = 2\sqrt{K}\sqrt{I_D} = 2 \cdot \sqrt{1} \cdot \sqrt{4}$
$= 4 \text{ mA/V}$

$R_1 // R_2 = \dfrac{4 \cdot 6}{4+6} = 2.4 \text{ M}\Omega$

$$\frac{v_o}{v_i} \simeq -\frac{4 \cdot 0.7}{1 + 4 \cdot 1} = -\frac{2.8}{5} = -5.6$$

③ MOS esce da saturaz (entra in triodo) quando:

$V_G - V_D < V_P = V_T$

Se R_L è grande, V_D sale e V_{GD} diminuisce

$V_D = -10 + I_D \cdot R_L$

$V_G + 10 - I_D R_L = V_T$

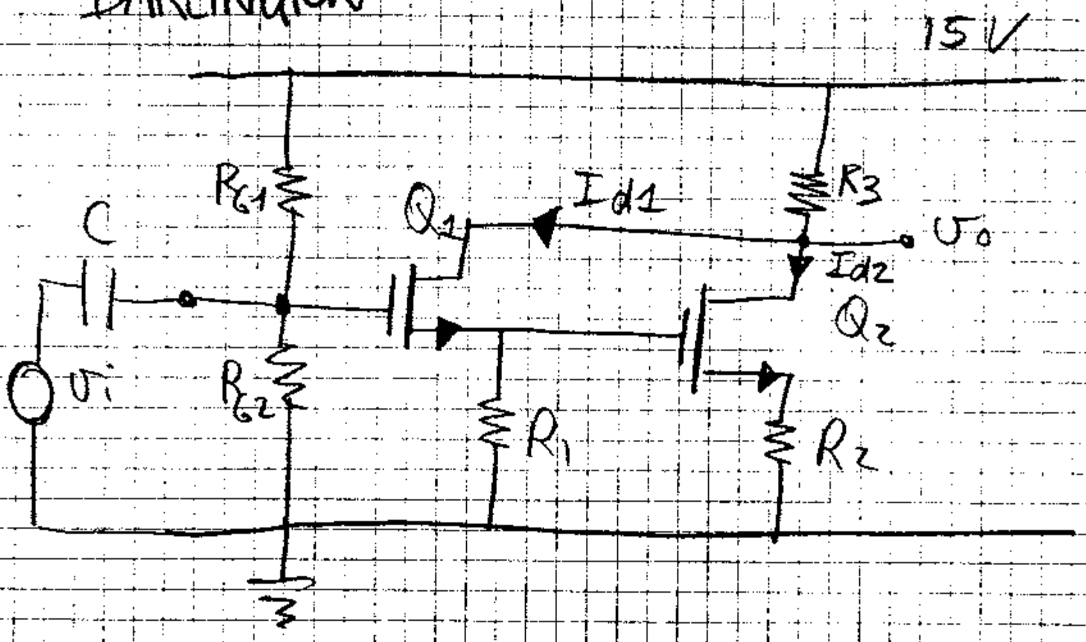
$$R_L = \frac{V_G + 10 - V_T}{I_D} = \frac{-4+10-2}{4} = 1\,k\Omega$$

val. max R_L

OSS: In genere res. troppo grandi sul drain fanno entrare in triodo.
(⇒ non si può avere un guad. troppo alto)

● ES MOS (SC. 8/2/93)

DARLINGTON



$K = 1\,mA/V^2 \quad V_t = +3\,V$

$R_1 = 1\,K\Omega \;;\; R_2 = 100\,\Omega \;;\; R_3 = 1\,K\Omega$

(1) con $R_{G1} = 100K\Omega$, $R_{G2} = 200\,K\Omega$, det p.to di lav. e g_m dei MOS

(2) Rifo punto (1) con $R_{G1} = 200K\Omega$; $R_{G2} = 100K\Omega$

(3) Caso (1): det. in media freq: R_{IN}, R_{OUT}, $\frac{v_o}{v_i}$

(1) Ipotesi: MOS in saturaz. (è + semplice)

$$V_{G1} = 15 \cdot \frac{R_{G2}}{R_{G1}+R_{G2}} = 15\,\frac{200}{100+200} = +10\,V$$

$$\begin{cases} I_{D1} = K\,(V_{GS1} - V_t)^2 \\ V_{S1} = I_{D1} \cdot R_1 \end{cases}$$

$$I_{D1} = K\,(V_{G1} - V_{S1} - V_t)^2$$

$$I_{D1} = K\,(V_{G1} - I_{D1}R_1 - V_t)^2$$

$$I_{D1} = K R_1^2\, I_{D1}^2 + K(V_{G1} - V_t)^2 - 2KR_1(V_{G1} - V_t)I_{D1}$$

$$K R_1^2 I_{D1}^2 - \left[1 + 2 K R_1 (V_{G1} - V_t)\right] I_{D1} + K (V_{G1} - V_t)^2 = 0$$ 54

$$I_{D1} = \frac{1 + 2KR_1(V_{G1} - V_t) \pm \sqrt{[\quad]^2 - 4}}{}$$

dopo verifica dimensionale, inserisco val. numerici.

$$I_{D1}^2 - 15\, I_{D1} + 49 = 0$$

$$I_{D1} = \frac{15 \pm \sqrt{15^2 - 4 \cdot 49}}{2} = \begin{cases} 10.19\ mA & (a) \\ 4.80\ mA & (b) \end{cases}$$

Per l'accensione di Q_1: $V_{GS1} > V_t$

(a) $V_{S1} = 10.19\ V$ $\quad V_{GS1} = 10 - 10.19 = -0.19\ V < 3$ NO

(b) $V_{S2} = 4.8\ V$ $\quad V_{GS1} = 10 - 4.8 = 5.2\ V > 3\ V$ OK

? V_{D1} ? lo calcolo dopo

$$V_{G2} = V_{S1} = 4.8\ V$$

$$\begin{cases} I_{D2} = K (V_{GS2} - V_t)^2 \\ V_{S2} = I_{D2} R_2 \end{cases}$$

Ottengo equaz. come prima:

$$K R_2^2 I_{D2}^2 - \left[1 + 2KR_2(V_{G2} - V_t)\right] I_{D2} + K(V_{G1} - V_t)^2 = 0$$

$$10^{-2} I_{D2}^2 - 1.36\, I_{D2} + 3.24 = 0$$

$$I_{D2} = \frac{1.36 \pm \sqrt{1.36^2 - \cancel{0.04} \cdot 3.24}}{0.02} = \begin{cases} 133.6\ mA & (a) \\ 2.42\ mA & (b) \end{cases}$$

? accensione di Q_2 ?

(a) Troppo grande (si spegne)

(b) $V_{GS2} > V_t$?

$V_{S2} = 0.24\ V \quad V_{GS2} = 4.8 - 0.24 = 4.56 > 3$ Ok

? Verifica Pinch-off per Q_1, Q_i ?

$$V_{D1} = V_{D2} = 15 - (I_{D1} + I_{D2}) \cdot R_3 =$$
$$= 15 - (4.8 + 2.92) \cdot 1 =$$
$$= 15 - 7.22 = +7.77\ V$$

? $V_{DG} \geq -V_t$?

$V_{DG1} = 7.77 - 10 = -2.23 > -3$ OK Q_1

$V_{DG2} = 7.77 - 4.8 = 2.97 > -3$ OK Q_2

Completato p.to lav.

Calcolo gm

$$g_{m1} = 2K(V_{GS1} - V_t) = 2 \cdot (10 - 4.8 - 3) =$$
$$= 2 \cdot 2.2 = 4.4\ mA/V$$

$$g_{m2} = 2K(V_{GS2} - V_t) = 2 \cdot (4.8 - 0.24 - 3) =$$
$$= 2 \cdot 1.56 = 3.12\ mA/V$$

(2) Faccio stesse ip.

$V_{G1} = 15 \cdot \frac{1}{3} = +5V$

!! Noto che: $V_{G1} > V_{GS1} + V_{GS2}$

Poiché $V_{G1} = 5V < 2V_t$, i due MOS non possono essere entrambi accesi

(ci vorrebbe $V_{GS1} > V_t$; $V_{GS2} > V_t$)

IP: Q_1 acceso in Pinch-off

$$\begin{cases} I_{D1} = k\,(V_{G1} - V_{S1} - V_t)^2 \\ V_{S1} = I_{D1} R_1 \end{cases}$$

Ottengo stessa eq. di prima, ma con:

$$I_{D1}^2 - 5 I_{D1} + 4 = 0$$

$$I_{D1} = \frac{5 \pm \sqrt{25-16}}{2} = \frac{5 \pm 3}{2} = \begin{cases} 4\ mA & (a) \\ 1\ mA & (b) \end{cases}$$

(a) $V_{S1} = +4\ V$ $\quad V_{GS1} = 1\ V < V_t$ NO

(b) $V_{S1} = +1\ V$ $\quad V_{GS1} = 4\ V > V_t$ ok

Q_2: $V_{G2} = V_{S1} = +1\ V$

! V_{S2} ha un pot. compreso tra 0 V e 15 V

$\Rightarrow$ Q_2 spento perché non posso avere $V_{GS2} > V_t = 3V$

$\Rightarrow I_{D2} = 0 \longrightarrow V_{S2} = 0\ V$

? verifica pinch-off ?

$V_{D1} = 15 - I_{D1} \cdot R_3 = 15 - 1 = +14\ V$

$V_{DG1} = 14 - 5 = 9\ V > -V_t = -3\ V$ ok

calcolo g_m

$g_{m1} = 2k\,(V_{GS1} - V_t) = 2 \cdot (4-3) = 2\ mA/V$

g_{m2} non è definito (vale solo se disp. è in Pinch-off)

$\hookrightarrow$ il MOS spento o in triodo NON è un gen. di corrente

③ caso ①, calcolo R_{IN}, R_{OUT}, $\frac{v_0}{v_i}$ in media freq.

$$-R_{IN} = R_{G1} // R_{G2} = \frac{100 \cdot 200}{100 + 200} = \frac{20000}{300} = 66\,K\Omega$$

$$-R_{OUT} = R_3 = 1\,K\Omega$$

trascuro r_o

- guadagno: 2 correnti di segnale forzate su R_3 - uso sovrapp. eff.

$$Q_1 : v_{o1} = v_i \cdot \left(- \frac{g_{m1} R_3}{1 + g_{m1} R_1} \right)$$ è stadio senza el a massa.

$$Q_2 : v_{o2} = v_{g2} \cdot \left(- \frac{g_{m2} R_3}{1 + g_{m2} R_2} \right) =$$

$$= v_i \cdot \frac{g_{m1} R_1}{1 + g_{m1} R_1} \cdot \left(- \frac{g_{m2} R_3}{1 + g_{m2} R_2} \right)$$

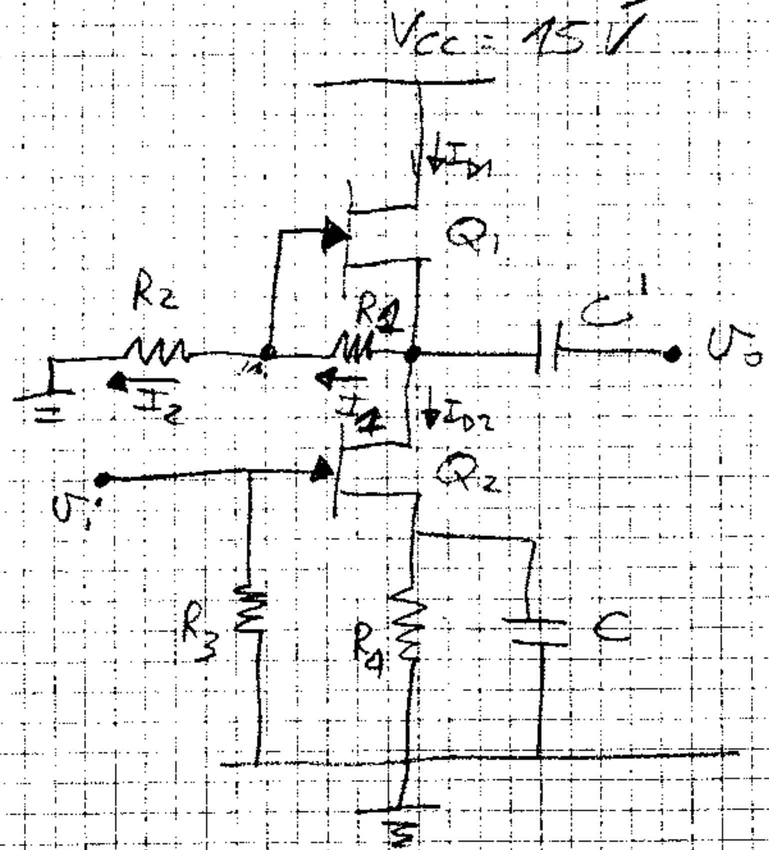
$$TOT : \frac{v_0}{v_i} = - \left[\frac{g_{m1} R_3}{1 + g_{m1} R_1} + \frac{g_{m1} R_1}{1 + g_{m1} R_1} \cdot \frac{g_{m2} R_3}{1 + g_{m2} R_2} \right] =$$

$$= - \frac{g_{m1} R_3}{1 + g_{m1} R_1} \left[1 + \frac{g_{m2} R_1}{1 + g_{m2} R_2} \right] =$$

$$= - \frac{4.4 \cdot 1}{1 + 4.4 \cdot 1} \left[1 + \frac{3.12 \cdot 1}{1 + 3.12 \cdot 0.1} \right] =$$

$$= - \frac{4.4}{5.4} \left[1 + \frac{3.12}{1.31} \right] = -2.75$$

• ES (SC. 25/10/96) 66



$R_1 = 10\,M\Omega$
$R_2 = 15\,M\Omega$
$R_3 = 1\,M\Omega$
$R_4 = 2.5k$

SN
$C, C' \to \infty$

$I_{DSS} = 4mA$
$V_P = -5V$

1. punto di lav. (ragionevole approx)
2. $\frac{v_o}{v_i}$ in media freq (" ")

1. $v_{G2} = 0\,V$

calcolo I_{D2} (IP: FET in Pinch-off)

$$I_{D2} = \frac{I_{DSS}}{V_P^2}(V_{GS} - V_P)^2$$

$$V_{GS} = 0 - V_S = -I_{D2}R_4$$

$$I_{D2} = \frac{I_{DSS}}{V_P^2}(0 - I_D R_4 - V_P)^2$$

$$\frac{25}{4} I_{D2} = (-2.5\,I_{D2} + 5)^2$$

$$6.25\,I_{D2}^2 - 31.25\,I_{D2} + 25 = 0$$

$$I_{D2} = \frac{31.25 \pm \sqrt{}^{\,18.75}}{12.5}$$

4 mA a)

1 mA b)

condiz. di accensione:

$V_{GS} > V_P = -5V$

a) $V_{GS} = -4 \cdot 2.5 = -10V < -5V$ NO

b) $V_{GS} = -1 \cdot 2.5 = -2.5 > -5V$ OK

Ipotesi $I_{D1} \simeq I_{D2} = 1\ mA$

sensata perché $I_1 = I_2$ è piccola risp. a I_{D2} – ~~e mostra $R_2 \gg R_3$ quindi $V_{G1} \simeq V_{S1} \Rightarrow V_{GS1} = 0$~~

~~verifica:~~

Verifica (calcolo)

Ricavo: $V_{GS1} = V_{GS2} = -2.5\ V$

(stessa $I_D \leftrightarrow$ stessa V_{GS})

$$I_1 = \frac{V_{SG1}}{R_1} = \frac{2.5}{10^4} = 0.25\ \mu A \ll I_D \quad OK$$

$\Downarrow$

Calcolo V_{G1}

$$V_{G1} = I_2 \cdot R_2 = I_1 R_2 = 0.25 \cdot 10^{-6} \cdot 15 \cdot 10^6 = 3.75\ V$$

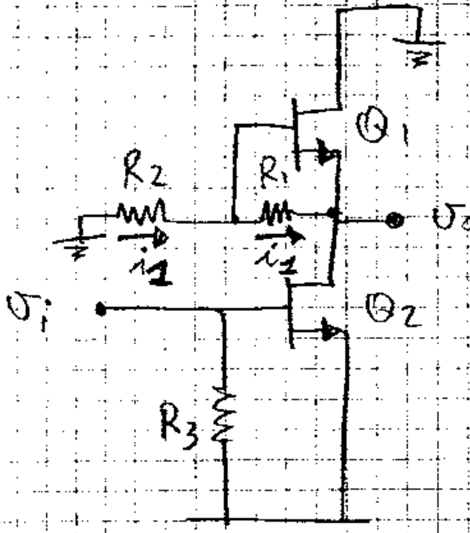
$$V_{S1} = V_{D2} = V_{G1} - V_{GS1} = 3.75 + 2.5 = +6.25\ V$$

Verifica Pinch-off: $V_{DG} \geq -V_P = +5V$

Q_2: $V_{DG2} = 6.25 - 0 = 6.25\ V > 5V$ OK

Q_1: $V_{DG1} = 15 - 3.75 = 11.25\ V > 5V$ OK

② $\frac{v_o}{v_i}$ –



- Soluzione approx: i due FET ~~hanno~~ sono uguali e hanno ≃ stessa I_d

Pertanto: anche $i_{d1} \simeq i_{d2}$ (Approx vale se $i_1 \ll i_{d1}$!!)

$\Downarrow$

$$v_{gs1} = v_{gs2} = v_i$$

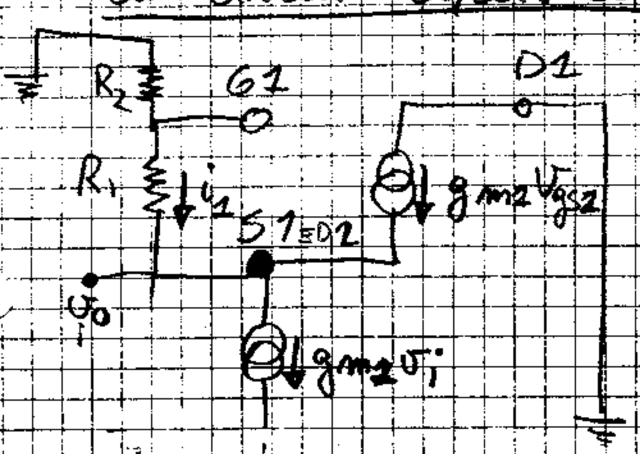
$$i_1 = \frac{v_{gs1}}{R_1} = \frac{v_i}{R_1}$$

$$v_o = -i_1 \cdot (R_1 + R_2) = -v_i \frac{R_1 + R_2}{R_1}$$

$$\frac{v_o}{v_i} = - \frac{R_1 + R_2}{R_1} = -\frac{25}{10} = -2.5$$

segno "–" è ok (è come common source + carico attivo)

- Con circuito equivalente:



VERIFICA:

$g_m v_i \gg \frac{v_i}{R_1} \rightarrow g_m R_1 \gg 1$ ok

$v_o = -i_1 (R_1 + R_2)$

$$\begin{cases} i_1 + g_{m2} v_{gs2} = g_{m1} v_i \\ i_1 = \dfrac{v_{gs2}}{R_1} \end{cases}$$

$$\frac{v_{gs2}}{R_1} + g_{m2} v_{gs2} = g_{m1} v_i$$

$$v_{gs2} \left(\frac{1}{R_1} + g_{m2} \right) = g_{m1} v_i$$

$$v_{gs2} = \frac{g_m}{\frac{1}{R_1} + g_m} v_i$$

$$v_{gs2} = \frac{g_m R_1}{1 + g_m R_1} v_i$$

$$v_o = -i_1 (R_1 + R_2) = -v_{gs2} \frac{R_1 + R_2}{R_1} =$$

$$\frac{v_o}{v_i} = -\frac{g_m R_1}{1 + g_m R_1} \frac{R_1 + R_2}{R_1}$$

$$g_m = \frac{2}{|V_P|} \sqrt{I_D I_{DSS}} = \frac{2}{5} \sqrt{1 \cdot 4} = \frac{4}{5} = 0.8 \text{ mA/V}$$

$$\frac{v_o}{v_i} = -\underbrace{\frac{0.8 \cdot 10^4}{1 + 0.8 \cdot 10^4}}_{\simeq 1} \cdot \frac{R_1 + R_2}{R_1} \simeq -\frac{R_1 + R_2}{R_1} = -2.5$$