

Corso di Elettronica Applicata II (N.O.)

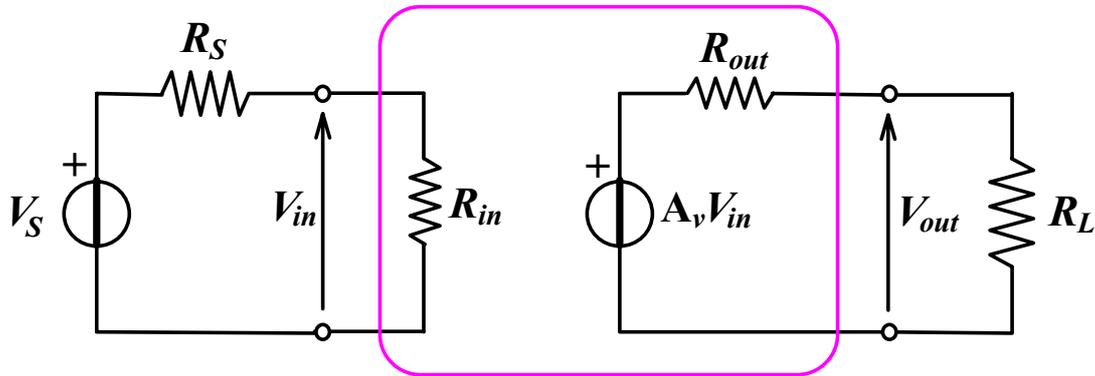
Prof. Ing. L. Masotti

■ **Libri di testo**

- Jacob Millman, Arvin Grabel:
Microelectronics
Mc Graw Hill, 1981
- Ulrich Tietze, Christoph Schenk:
Electronic circuits - Design and applications
Springer Verlag Heidelberg, 1991
- John G. Kassakian, Martin F. Schlecht, George C. Verghese:
Principles of power electronics
Addison-Wesley Publishing Company, Inc., 1992

Reti amplificatrici elementari

Amplificatore di tensione
(Convertitore tensione/tensione)



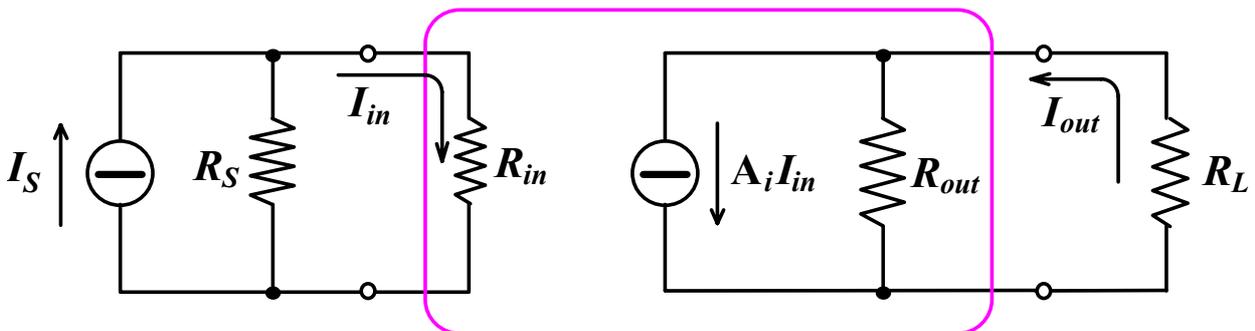
$$se R_{in} \gg R_S \Rightarrow V_{in} \cong V_S$$

$$se R_{out} \ll R_L \Rightarrow V_{out} \cong A_v V_{in}$$

$$\Rightarrow V_{out} \cong A_v V_S$$

$$A_v = \lim_{R_L \rightarrow \infty} \frac{V_{out}}{V_{in}}$$

Amplificatore di corrente
(Convertitore corrente/corrente)



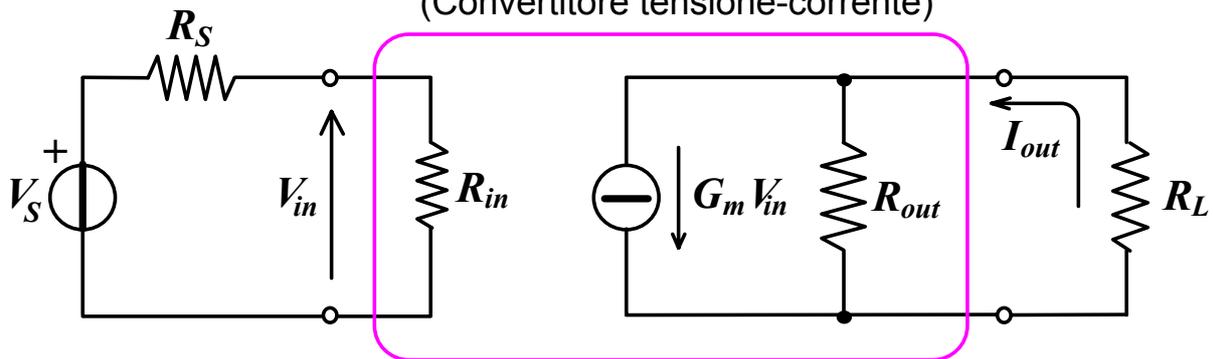
$$se R_{in} \ll R_S \Rightarrow I_{in} \cong I_S$$

$$se R_{out} \gg R_L \Rightarrow I_{out} \cong A_i I_{in}$$

$$\Rightarrow I_{out} \cong A_i I_S$$

$$A_i = \lim_{R_L \rightarrow 0} \frac{I_{out}}{I_{in}}$$

Amplificatore di transconduttanza
(Convertitore tensione-corrente)

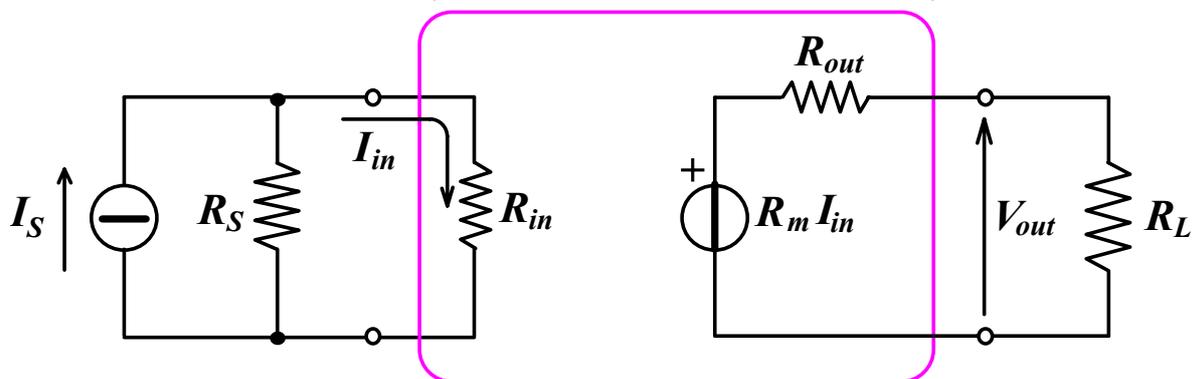


$se R_{in} \gg R_S \Rightarrow V_{in} \cong V_S$
 $se R_{out} \gg R_L \Rightarrow I_{out} \cong G_m V_{in}$

$I_{out} \cong G_m V_S$

$$G_m = \lim_{R_L \rightarrow 0} \frac{I_{out}}{V_{in}}$$

Amplificatore di transresistenza
(Convertitore corrente-tensione)

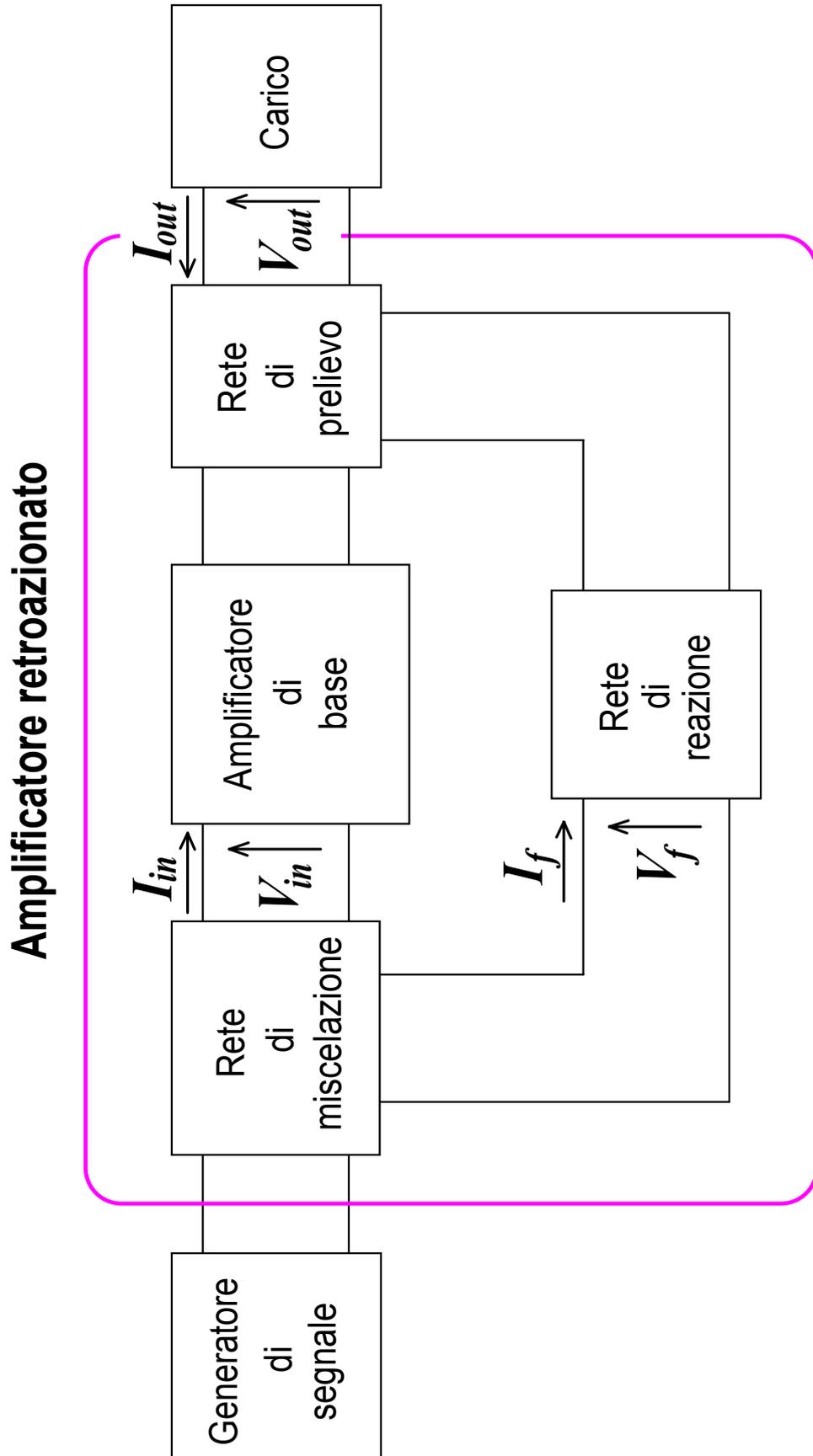


$se R_{in} \ll R_S \Rightarrow I_{in} \cong I_S$
 $se R_{out} \ll R_L \Rightarrow V_{out} \cong R_m I_{in}$

$V_{out} \cong R_m I_S$

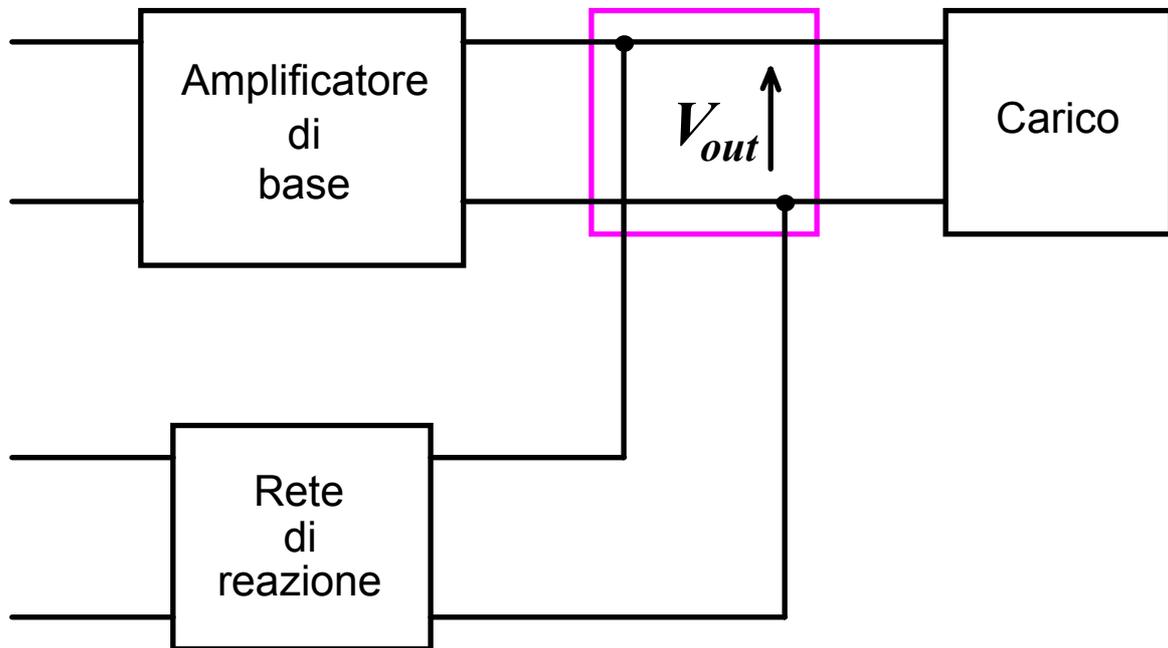
$$R_m = \lim_{R_L \rightarrow \infty} \frac{V_{out}}{I_{in}}$$

Schema di un amplificatore retroazionato

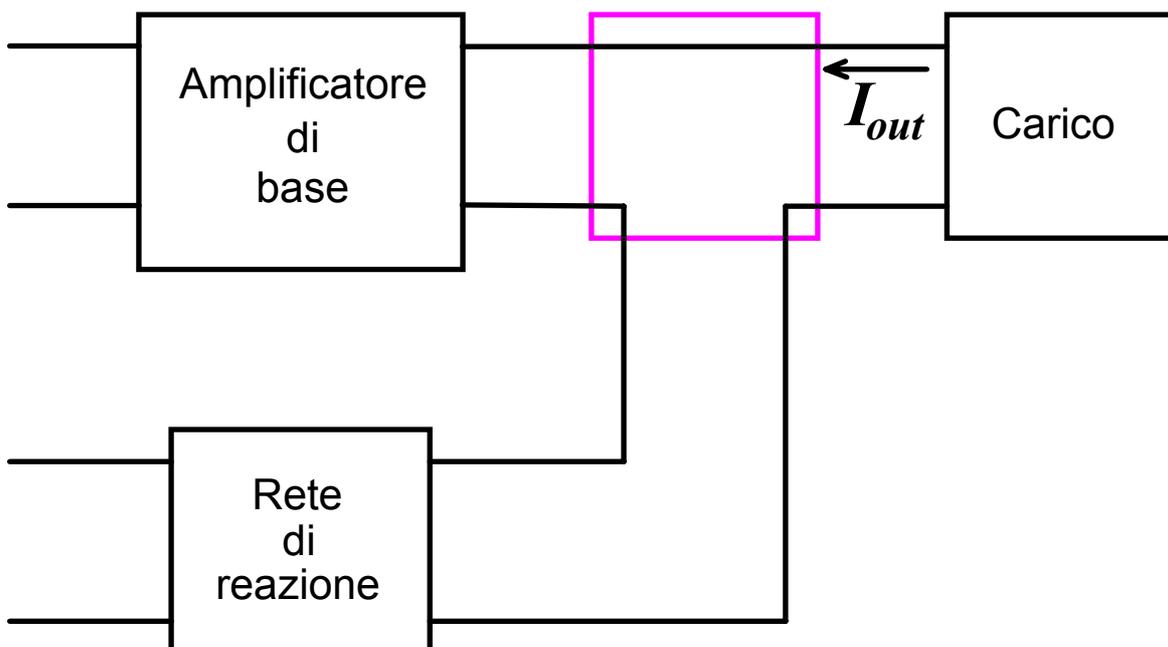


Reti di prelievo

Prelievo di tensione (parallelo)

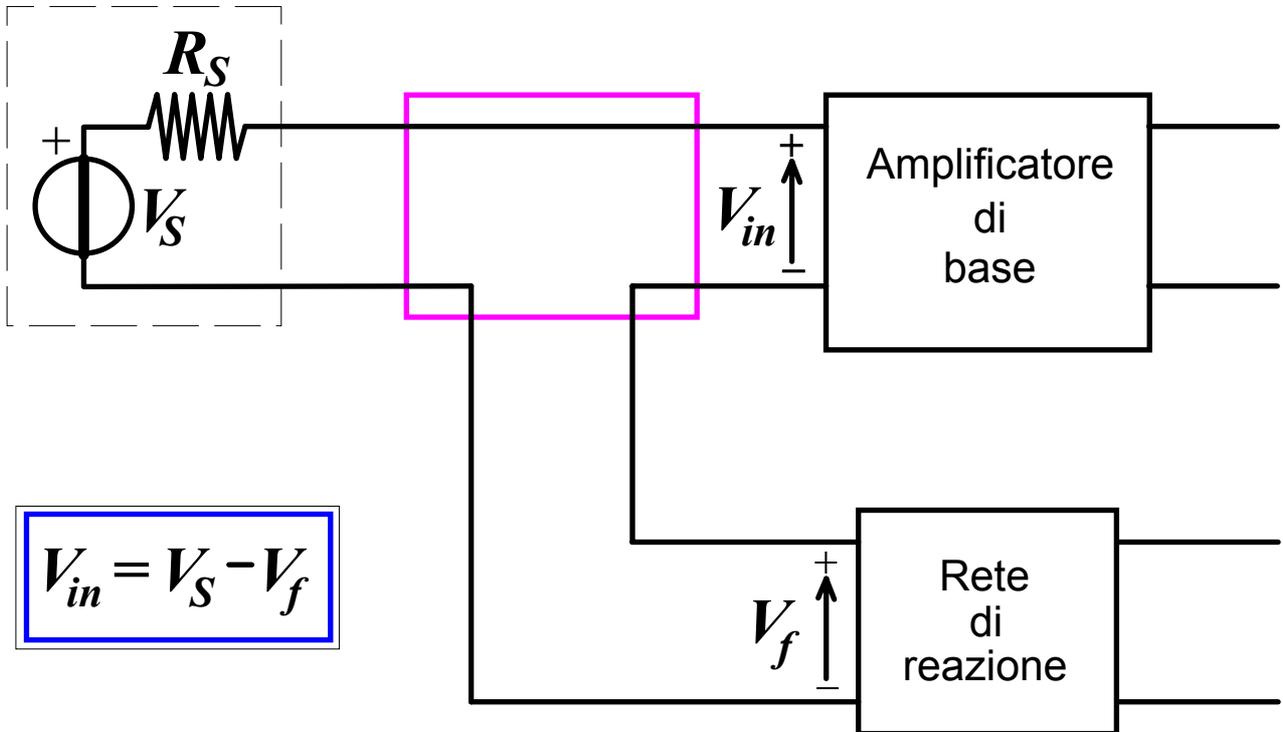


Prelievo di corrente (serie)

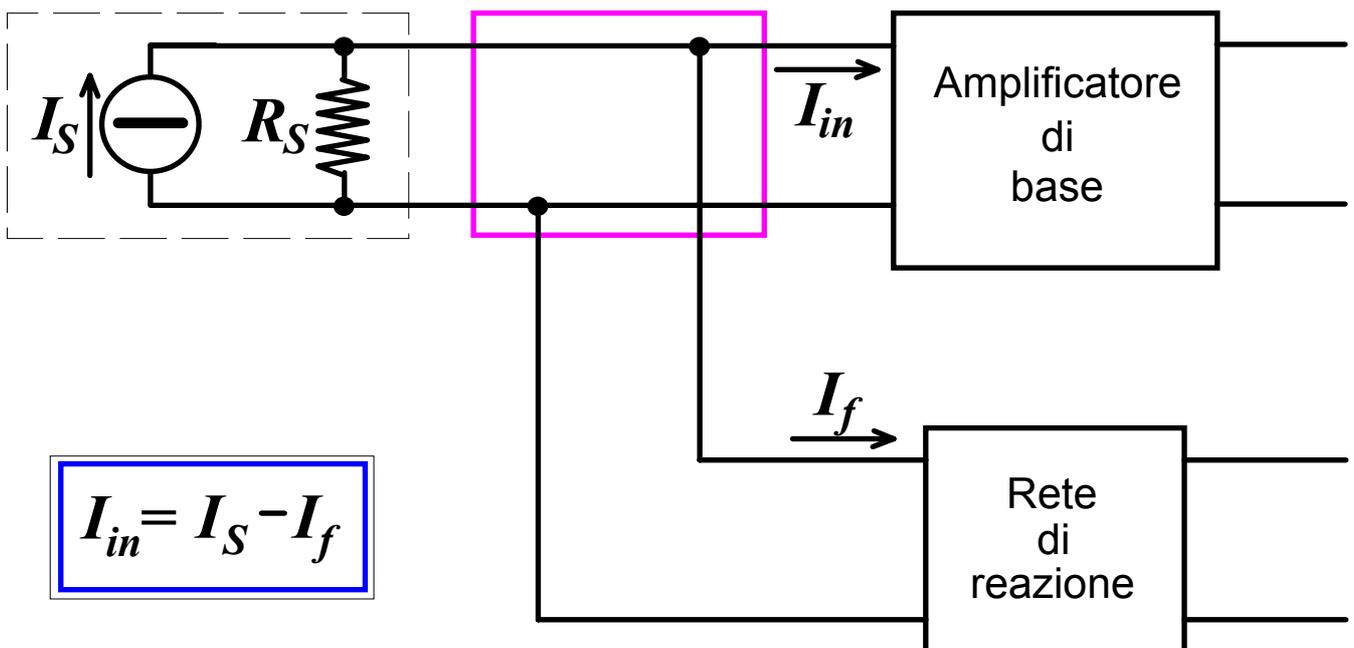


Reti di miscelazione

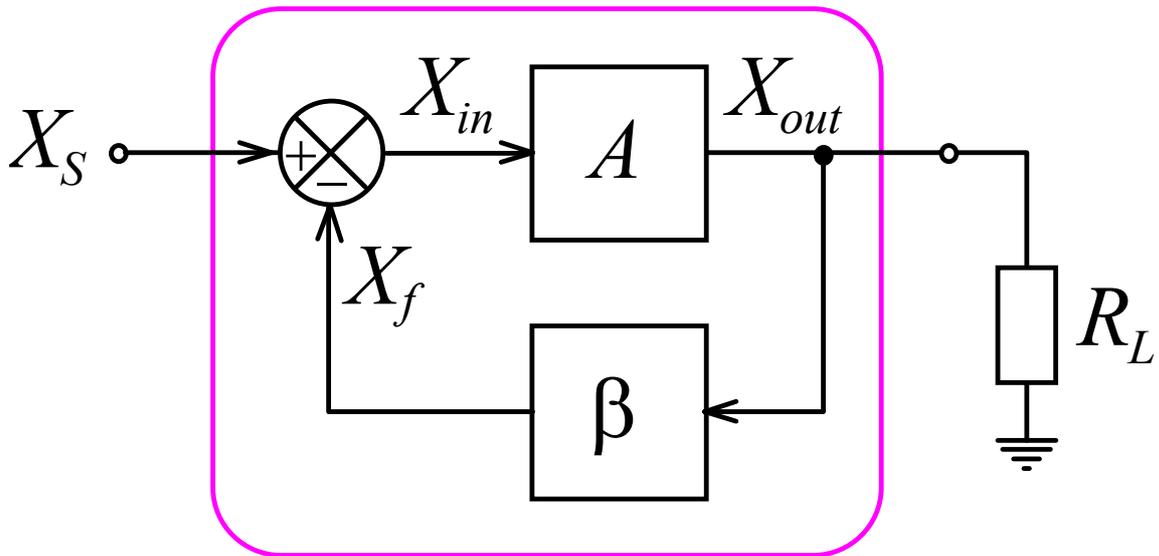
Miscelazione (somma) di tensioni (o confronto serie)



Miscelazione (somma) di correnti (o confronto parallelo)



Grandezze tipiche di un amplificatore retroazionato



$$X_{in} = X_S - X_f \quad A = \frac{X_{out}}{X_{in}} \quad A_f = \frac{X_{out}}{X_S} \quad \beta = \frac{X_f}{X_{out}}$$

$$X_{in} = X_S - \beta X_{out} = X_S - \beta A X_{in} \Rightarrow X_S = X_{in} (1 + \beta A)$$

⇓

$$A_f = \frac{X_{out}}{X_S} = \frac{X_{out}}{X_{in} (1 + \beta A)} = \boxed{\frac{A}{1 + \beta A}} \stackrel{\beta A \gg 1}{\approx} \frac{A}{A\beta} = \frac{1}{\beta}$$

⇓

$$|1 + \beta A| > 1 \Rightarrow |A_f| < |A| \Rightarrow \text{reazione negativa}$$

$$|1 + \beta A| < 1 \Rightarrow |A_f| > |A| \Rightarrow \text{reazione positiva}$$

Sensibilità e desensibilità

$$S = \frac{\frac{dA_f}{A_f}}{\frac{dA}{A}} \quad \text{ovvero} \quad S = \frac{dA_f}{dA} \cdot \frac{A}{A_f} \quad D = \frac{1}{S}$$

$$\frac{dA_f}{dA} = \frac{1}{1+\beta A} - \frac{\beta A}{(1+\beta A)^2} = \frac{1+\beta A - \beta A}{(1+\beta A)^2} = \frac{A}{A} \cdot \frac{1}{(1+\beta A)(1+\beta A)} = \frac{A_f}{A(1+\beta A)}$$

$$S = \frac{A_f}{A(1+\beta A)} \cdot \frac{A}{A_f} = \boxed{\frac{1}{1+\beta A}} \quad D = \boxed{1+\beta A}$$

Esempio: $\beta A = 9 \Rightarrow 1 + \beta A = 10$; $\frac{dA}{A} = 20\% \Rightarrow \frac{dA_f}{A_f} = 2\%$

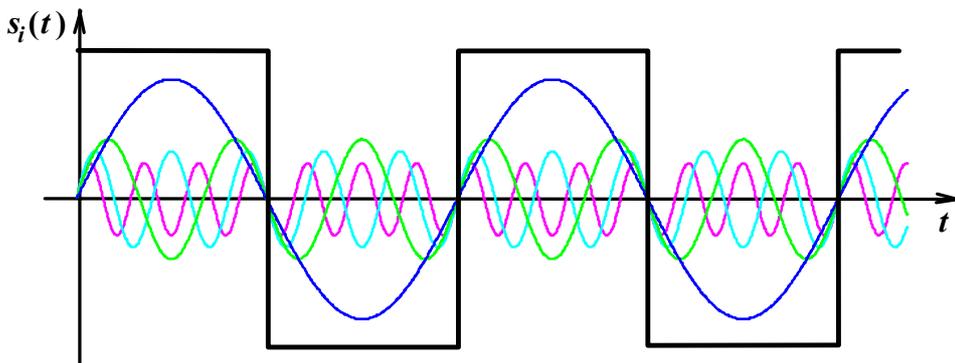
ovviamente se $A = 1000 \Rightarrow A_f = 100$

Ipotesi

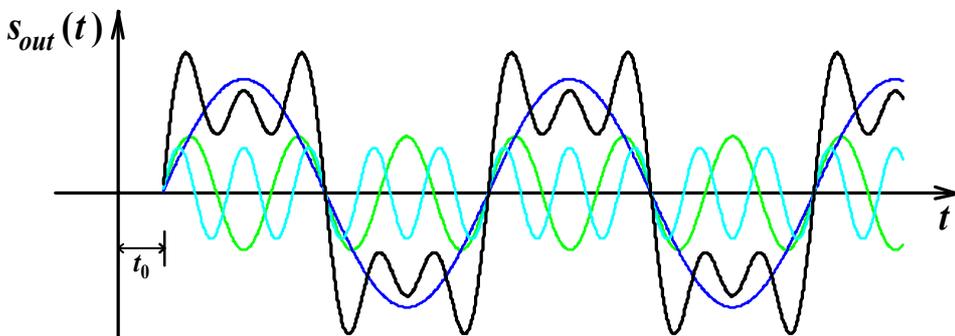
- 1) *Il segnale tra ingresso ed uscita è trasmesso soltanto attraverso A*
 Quindi $A = 0 \Rightarrow X_{out} = 0$.
[la rete β è unilaterale]
- 2) *Il segnale tra uscita ed ingresso è trasmesso soltanto attraverso β*
 Sono assenti sia l'effetto Early che l'effetto Miller.
[la rete A è unilaterale]

Distorsione lineare

$$\left\{ \begin{array}{l} |A(f)| = A_0 \\ \angle A(f) = \varphi(f) = kf \end{array} \right.$$

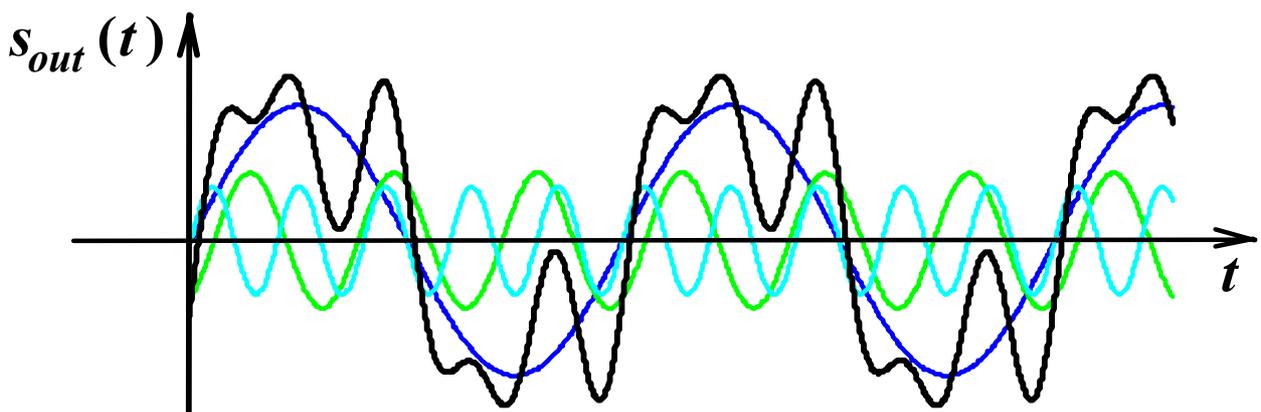


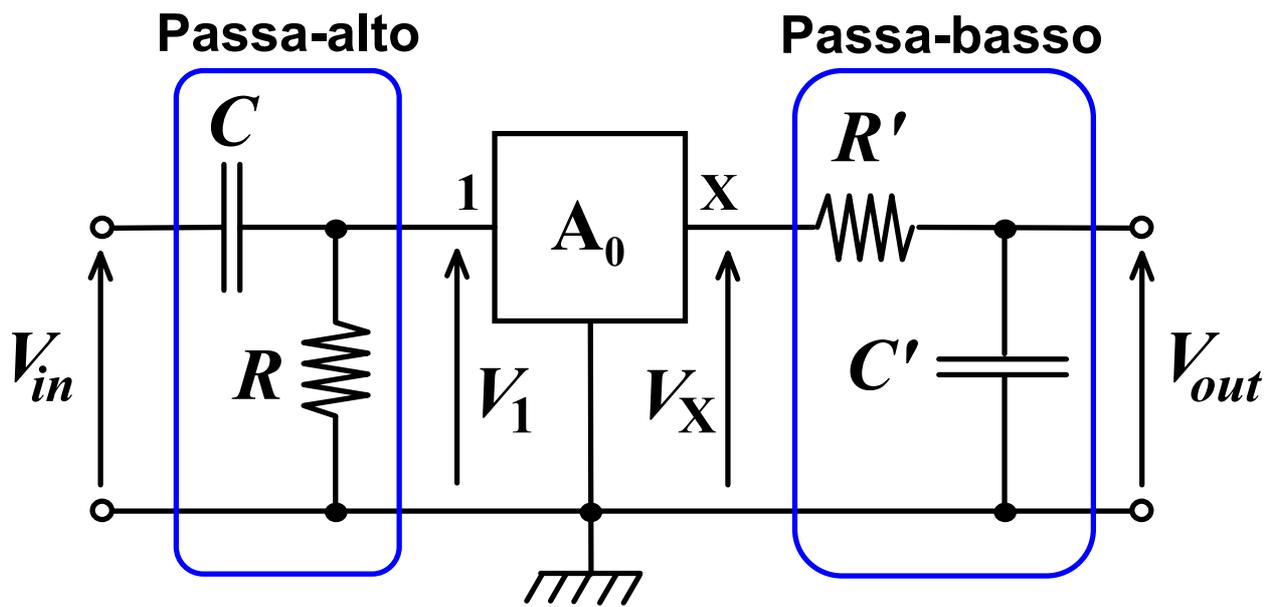
$$\begin{aligned} |S_{out}(\omega_1)| &= A_0 S_{in}(\omega_1) \\ |S_{out}(\omega_3)| &= A_0 S_{in}(\omega_3) \\ &\dots \\ &\dots \end{aligned}$$



$$\begin{aligned} \varphi_1 &= \omega_1 t_0 \\ \varphi_3 &= \omega_3 t_0 = 3\omega_1 t_0 \\ &\dots \\ &\dots \end{aligned}$$

Principio di causalità $\tau = t_0 = -\frac{d\varphi}{d\omega} > 0$ se $\begin{matrix} \varphi_1 = \omega_1 t'_0 \\ \varphi_3 = \omega_3 t''_0 \end{matrix}$ con $t'_0 \neq t''_0 \Rightarrow$ quadripolo dispersivo



Risposta in frequenza di un amplificatore retroazionato**Circuito passa-alto**

$$V_X = A_0 V_1$$

$$V_1 = \frac{R}{R + \frac{1}{j\omega C}} \cdot V_{in} = \frac{V_{in}}{1 + \frac{1}{j\omega RC}} = \frac{V_{in}}{1 - j \frac{\omega_L}{\omega}} \quad \text{con } \omega_L = \frac{1}{RC}$$

$$V_{out} \cong V_X = \frac{A_0 V_{in}}{1 - j \frac{f_L}{f}} \quad \text{per frequenze basse}$$

$$A(f) = \frac{V_{out}}{V_{in}} \cong \frac{A_0}{1 - j \frac{f_L}{f}}$$

Circuito passa-basso

$$V_{out} = \frac{\frac{1}{j\omega C'} \cdot V_X}{R' + \frac{1}{j\omega C'}} = \frac{V_X}{1 + j\omega R' C'} = \frac{V_X}{1 + j \frac{\omega}{\omega_H}} \quad \text{con} \quad \omega_H = \frac{1}{R' C'}$$

$V_X \cong A_0 V_{in}$ per frequenze alte

$$A(f) = \frac{V_{out}}{V_{in}} \cong \frac{A_0}{1 + j \frac{f}{f_H}}$$

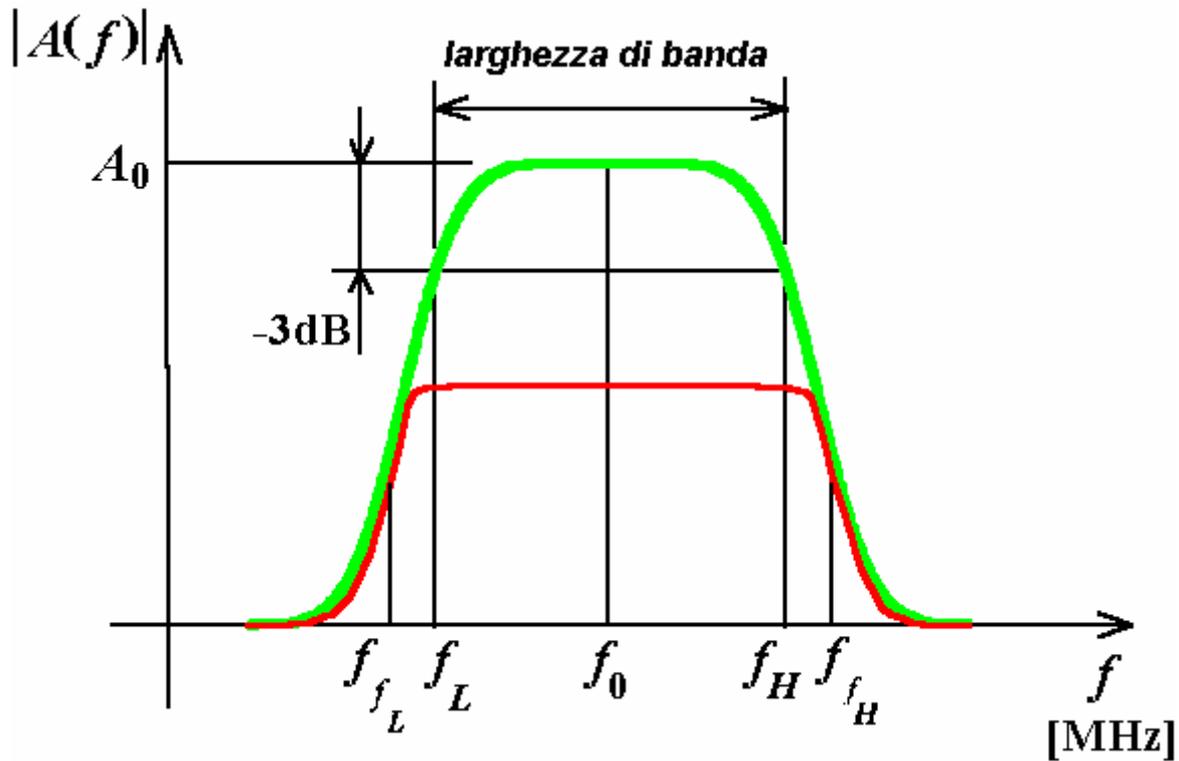
In bassa frequenza

$$A_f(f) = \frac{A(f)}{1 + \beta A(f)} = \frac{\frac{A_0}{1 - j \frac{f_L}{f}}}{1 + \beta \frac{A_0}{1 - j \frac{f_L}{f}}} = \frac{A_0}{1 - j \frac{f_L}{f} + \beta A_0} = \frac{\frac{A_0}{1 + \beta A_0}}{\frac{1 + \beta A_0}{1 + \beta A_0} - j \frac{f_L}{(1 + \beta A_0)f}}$$

$$A_{0f} = \frac{A_0}{1 + \beta A_0} \quad \Rightarrow \quad A_f(f) = \frac{A_{0f}}{1 - j \frac{f_{L_f}}{f}}$$

$$f_{L_f} = \frac{f_L}{1 + \beta A_0}$$

$$\varphi(f) = \text{arctg} \frac{\text{Im}(A_f(f))}{\text{Re}(A_f(f))} = \frac{f_{L_f}}{f} \quad - \frac{d\varphi}{d\omega} > 0$$



In alta frequenza

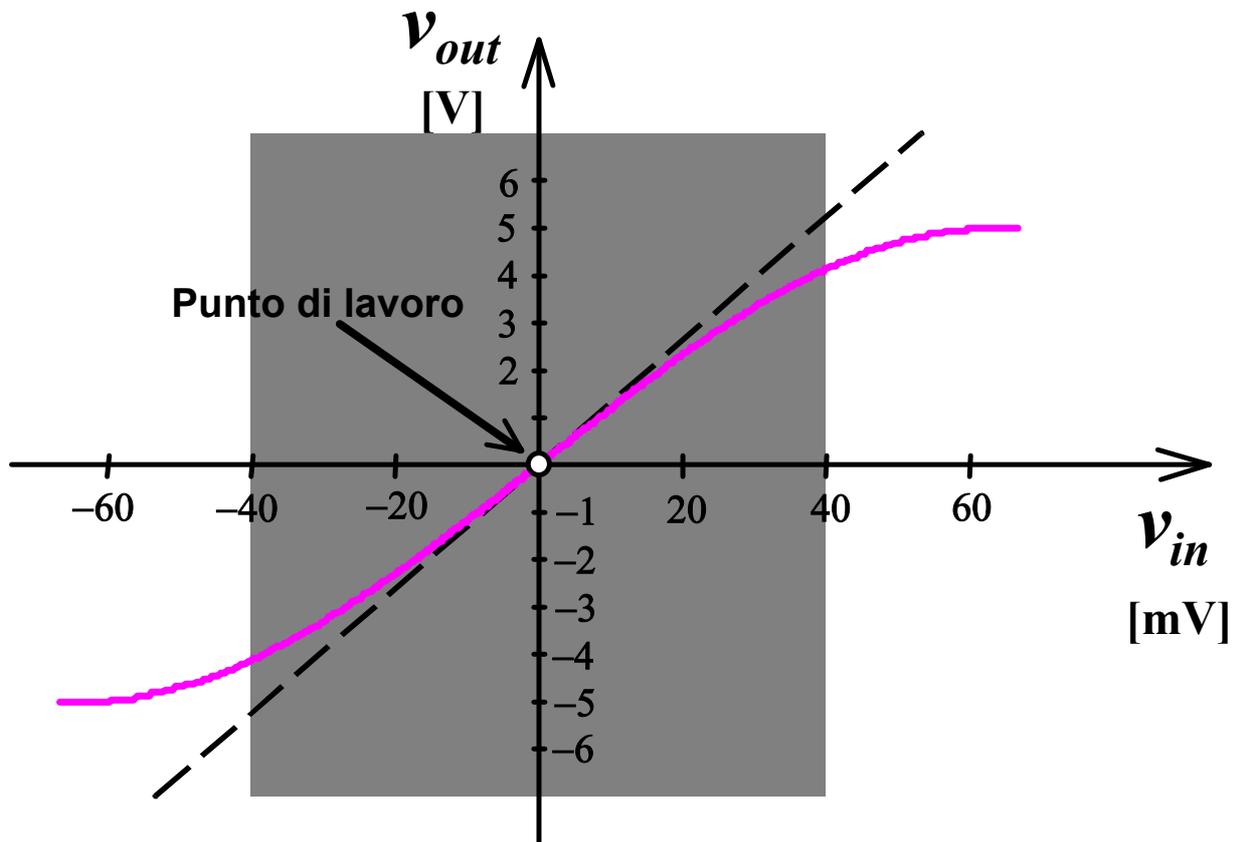
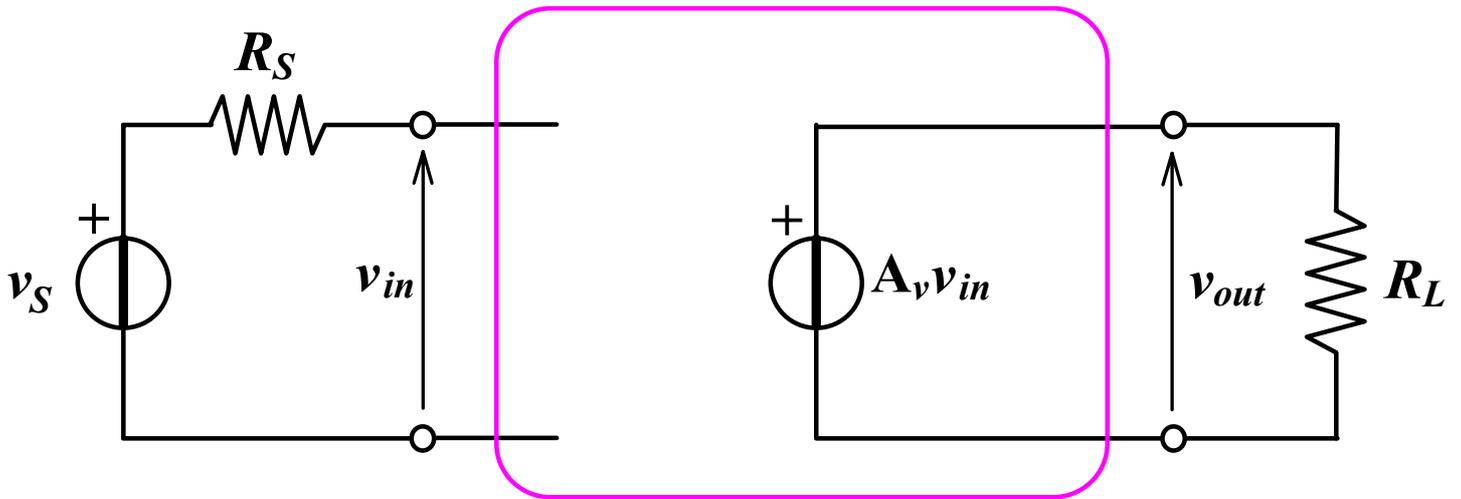
$$A_f(f) = \frac{A(f)}{1 + \beta A(f)} = \frac{\frac{A_0}{1 + j \frac{f}{f_H}}}{1 + \beta \frac{A_0}{1 + j \frac{f}{f_H}}} = \frac{A_0}{1 + j \frac{f}{f_H} + \beta A_0} = \frac{\frac{A_0}{1 + \beta A_0}}{1 + j \frac{f}{(1 + \beta A_0) f_H}}$$

$$A_{0f} = \frac{A_0}{1 + \beta A_0} \Rightarrow A_f(f) = \frac{A_{0f}}{1 + j \frac{f}{f_{Hf}}}$$

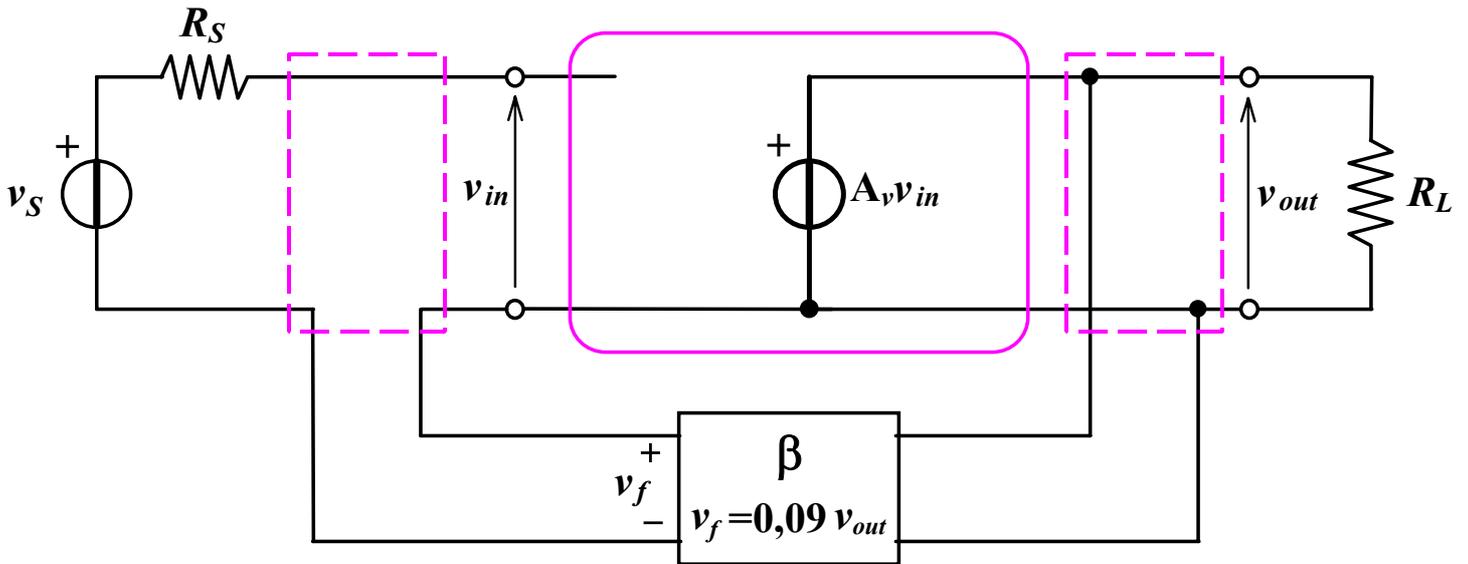
$$f_{Hf} = f_H (1 + \beta A_0)$$

$$\varphi(f) = -\arctg \frac{\text{Im}(A_f(f))}{\text{Re}(A_f(f))} = -\frac{f}{f_{Hf}} \quad -\frac{d\varphi}{d\omega} > 0$$

Distorsione non lineare



- $0 \leq |v_{in}| \leq 40\text{mV} \Rightarrow A_v = 100 \Rightarrow |v_{out}| = 100|v_{in}|$
- $40 \leq |v_{in}| \leq 60\text{mV} \Rightarrow A_v < 100 \Rightarrow |v_{out}| = 100|v_{in}| - 2500(|v_{in}| - 0,04)^2$
- $|v_{in}| > 60\text{mV} \Rightarrow A_v = 0 \Rightarrow |v_{out}| = \text{costante} = 5\text{V}$



$$v_f = 0,09 v_{out}$$

$$1 + \beta A_v = 1 + 100 \cdot 0,09 = 10$$

Tensione di ingresso:

$$v_{in} = v_S - v_f = v_S - \beta A_v v_{in} \Rightarrow v_{in} = \frac{v_S}{1 + \beta A_v}$$

Tensione di uscita:

$$v_{out} = A_v v_{in} = A_v v_S - A_v v_f = A_v v_S - \beta A_v v_{out} \Rightarrow v_{out} = \frac{A_v v_S}{1 + \beta A_v}$$

⇓

$$A_f = \frac{v_{out}}{v_S} = \frac{A_v}{1 + \beta A_v} = \frac{A_v}{10}$$

Risultati analitici

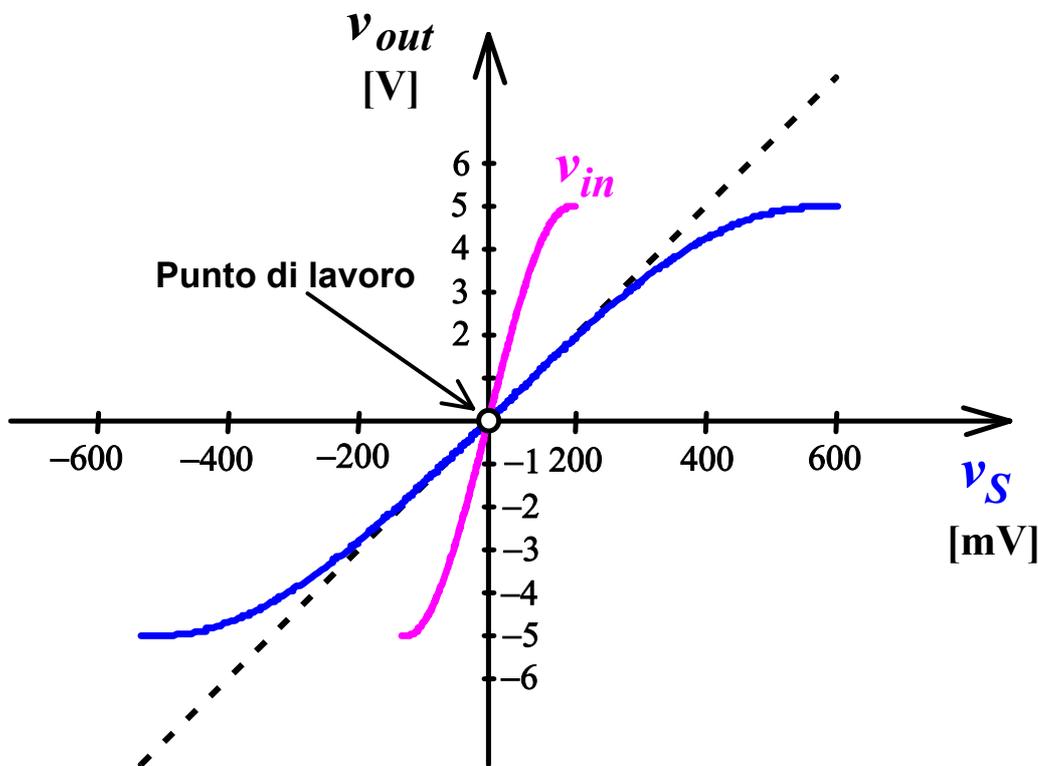
Rete senza reazione

$ v_{in} $ [mV]	v_{out} [V]	A	$\frac{dA}{A}$
10	1.0	100	0
20	2.0	100	0
30	3.0	100	0
40	4.0	100	0
45	4.44	98,6	1,4%
50	4.75	95	5%
55	4.94	89,8	10,2%
60	5.0	83,3	16,7%

zona di non linearità

Rete con reazione

$ v_S $ [mV]	v_{in} [mV]	v_{out} [V]	A_f	$\frac{dA_f}{A_f}$
100	10	1.0	10	0
200	20	2.0	10	0
300	30	3.0	10	0
400	40	4.0	10	0
444	45	4.44	10	0
478	50	4.75	9,93	0,7%
500	55	4.94	9,88	1,2%
510	60	5.0	9,8	2%



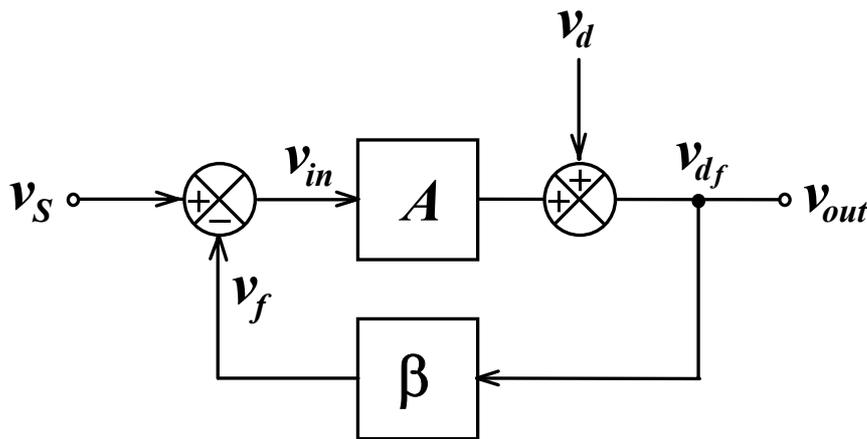
$$\frac{dA_f}{A_f} < \frac{dA}{A}$$

Effetti della retroazione nei confronti dei disturbi e del rumore

Per un segnale sinusoidale \Rightarrow termine quadratico (II armonica)

$$v_{in}(t) = V_{iM} \text{sen } \omega t \quad \xrightarrow{V_{iM} > 40mV} \quad \text{sen}^2 \omega t = \frac{1}{2} - \frac{1}{2} \cos 2\omega t$$

In generale \Rightarrow intermodulazioni



Per la sola v_d si ha:

$$v_{d_f} = v_d - v_{d_f} \beta A$$

$$v_{d_f} = \frac{v_d}{1 + \beta A}$$

$$v_{out} = A v_S + v_d \quad (\text{senza reazione})$$

$$v_{out} = A_f v_S + v_{d_f} \quad (\text{con reazione})$$

Utilizzo di un preamplificatore $\Rightarrow v'_S = A_P v_S = (1 + \beta A) v_S$

\Downarrow

$$v_{out_{f,P}} = A_f v'_S + v_{d_f} = A_f (1 + \beta A) v_S + v_{d_f} \quad (\text{con reazione})$$

In presenza di rumore si ha: $v_{N_f} = \frac{v_N}{1 + \beta A}$

Ma deve risultare $v_{N_P} \ll v_N$ poichè:

$$v_{N_{totale}} = v_{N_f} + v_{N_P} \cdot A_f = \frac{1}{1 + \beta A} (v_N + A \cdot v_{N_P})$$

Effetti sulla resistenza di ingresso

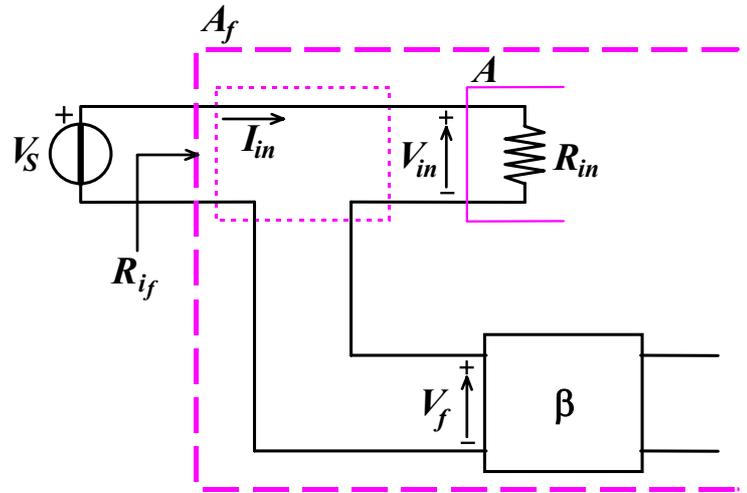
Reazione serie

$$V_S = V_{in} + V_f = V_{in} + \beta A V_{in} =$$

$$= V_{in} (1 + \beta A)$$

$$V_f = \beta X_{out} \begin{cases} X_{out} = I_{out} \\ X_{out} = V_{out} \end{cases}$$

$$X_{out} = A V_{in}$$



$$R_{if} = \frac{V_S}{I_{in}} = \frac{V_S}{\frac{V_{in}}{R_{in}}} = \frac{V_{in} (1 + \beta A)}{V_{in}} R_{in} = \boxed{(1 + \beta A) R_{in}}$$

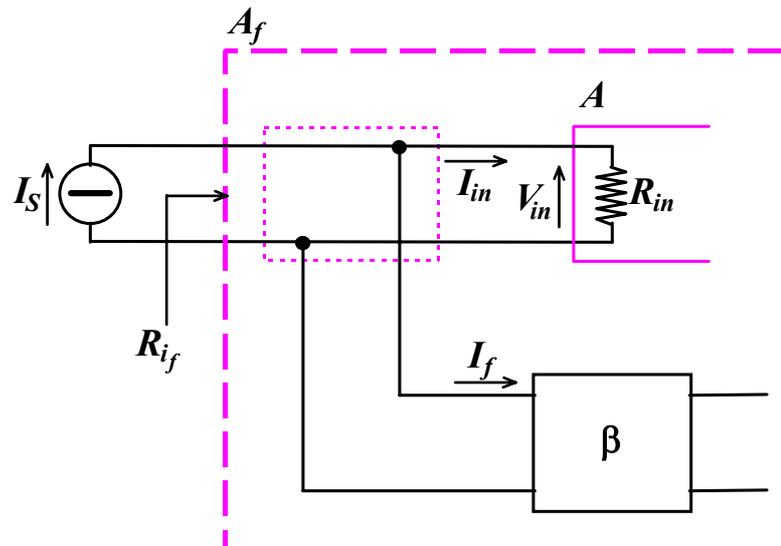
Reazione parallelo

$$I_S = I_{in} + I_f = I_{in} + \beta A I_{in} =$$

$$= I_{in} (1 + \beta A)$$

$$I_f = \beta X_{out} \begin{cases} X_{out} = I_{out} \\ X_{out} = V_{out} \end{cases}$$

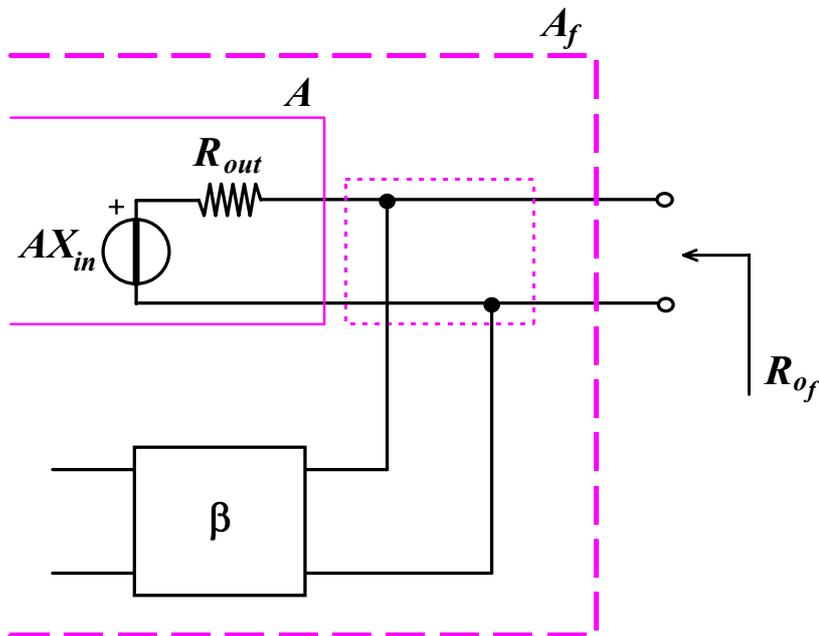
$$X_{out} = A I_{in}$$



$$R_{if} = \frac{V_{in}}{I_S} = \frac{R_{in} I_{in}}{I_S} = \frac{R_{in} I_{in}}{I_{in} (1 + \beta A)} = \boxed{\frac{R_{in}}{1 + \beta A}}$$

Effetti sulla resistenza di uscita

Reazione di tensione (serie-parallelo, parallelo-parallelo)



Ipotesi:

- A unidirezionale
- β unidirezionale
- A non risente degli effetti di carico

$$R_{of} = \frac{V_{oc}}{I_{sc}}$$

$oc = open\ circuit$

$sc = short\ circuit$

Poichè $X_S = X_{in} + X_f = X_{in} + \beta AX_{in} \Rightarrow X_{in} = \frac{X_S}{1 + \beta A}$

\Downarrow

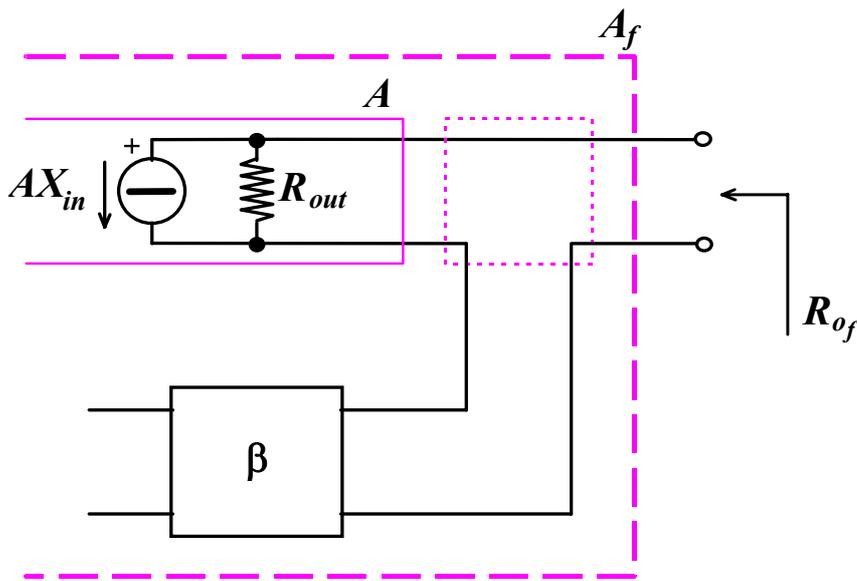
$$V_{oc} = AX_{in} = \frac{AX_S}{1 + \beta A}$$

Se l'uscita è s.c.: $V_{out} = 0 \Rightarrow X_f = 0 \Rightarrow X_S = X_{in} \Rightarrow I_{sc} = \frac{AX_S}{R_{out}}$

\Downarrow

$$R_{of} = \frac{AX_S}{1 + \beta A} \frac{R_{out}}{AX_S} = \boxed{\frac{R_{out}}{1 + \beta A}}$$

Reazione di corrente (serie-serie, parallelo-serie)



Ipotesi:

- A unidirezionale
- β unidirezionale
- A non risente degli effetti di carico

$$R_{of} = \frac{V_{oc}}{I_{sc}}$$

oc = open circuit

sc = short circuit

Poichè quando l'uscita è o.c. non scorre corrente si ha:

$$X_f = 0 \Rightarrow X_{in} = X_S$$

⇓

$$V_{oc} = -AX_{in} \cdot R_{out} = -AX_S \cdot R_{out}$$

Essendo $I_{sc} = -AX_{in} = -\frac{AX_S}{1 + \beta A}$

⇓

$$R_{of} = \frac{-AX_S R_{out}}{-AX_S} \cdot (1 + \beta A) = R_{out} (1 + \beta A)$$

In realtà:

- la rete A non è unidirezionale e risente degli effetti di carico della rete β , del carico R_L e della resistenza interna R_S del generatore di segnale.
- la rete β non è unidirezionale, carica l'amplificatore di base A e risente del carico R_L e della resistenza interna R_S del generatore di segnale.

A_{\square} = guadagno unidirezionale reale che tiene conto della resistenza di carico (A_V, A_I, R_M, G_M)

A = guadagno unidirezionale ideale (A_v, A_i, R_m, G_m) dove

$$A_v = \lim_{R_L \rightarrow \infty} A_V \quad A_i = \lim_{R_L \rightarrow 0} A_I \quad R_m = \lim_{R_L \rightarrow \infty} R_M$$

$$G_m = \lim_{R_L \rightarrow 0} G_M$$

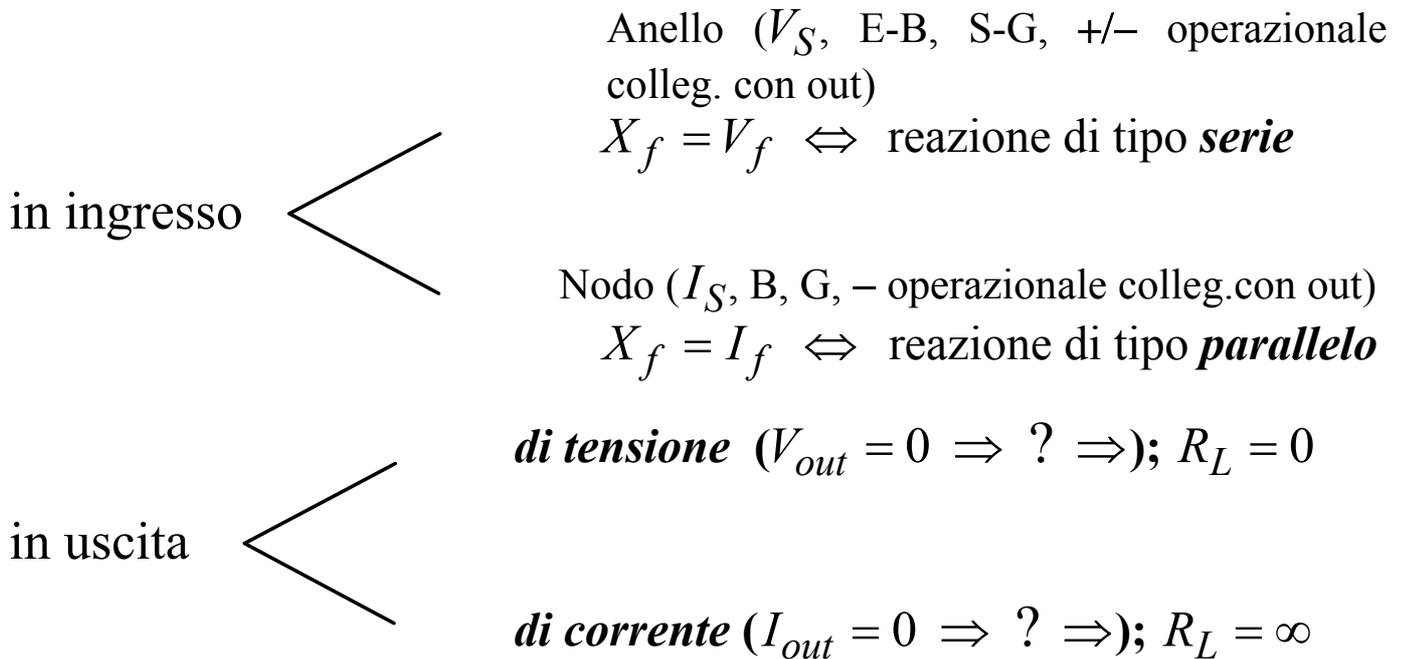
Tabella riassuntiva

Grandezza	Tipo di reazione			
	serie di tensione (serie-parallelo)	serie di corrente (serie-serie)	parallelo di corrente (parallelo-serie)	parallelo di tensione (parallelo-parallelo)
R_{of}	$\frac{R_{out}}{1 + \beta A_v}$	$R_{out} (1 + \beta G_m)$	$R_{out} (1 + \beta A_i)$	$\frac{R_{out}}{1 + \beta R_m}$
R'_{of}	$\frac{R'_{out}}{1 + \beta A_V}$	$\frac{R'_{out} (1 + \beta G_m)}{1 + \beta G_M}$	$\frac{R'_{out} (1 + \beta A_i)}{1 + \beta A_I}$	$\frac{R'_{out}}{1 + \beta R_M}$
R_{if}	$R_{in} (1 + \beta A_V)$	$R_{in} (1 + \beta G_M)$	$\frac{R_{in}}{1 + \beta A_I}$	$\frac{R_{in}}{1 + \beta R_M}$

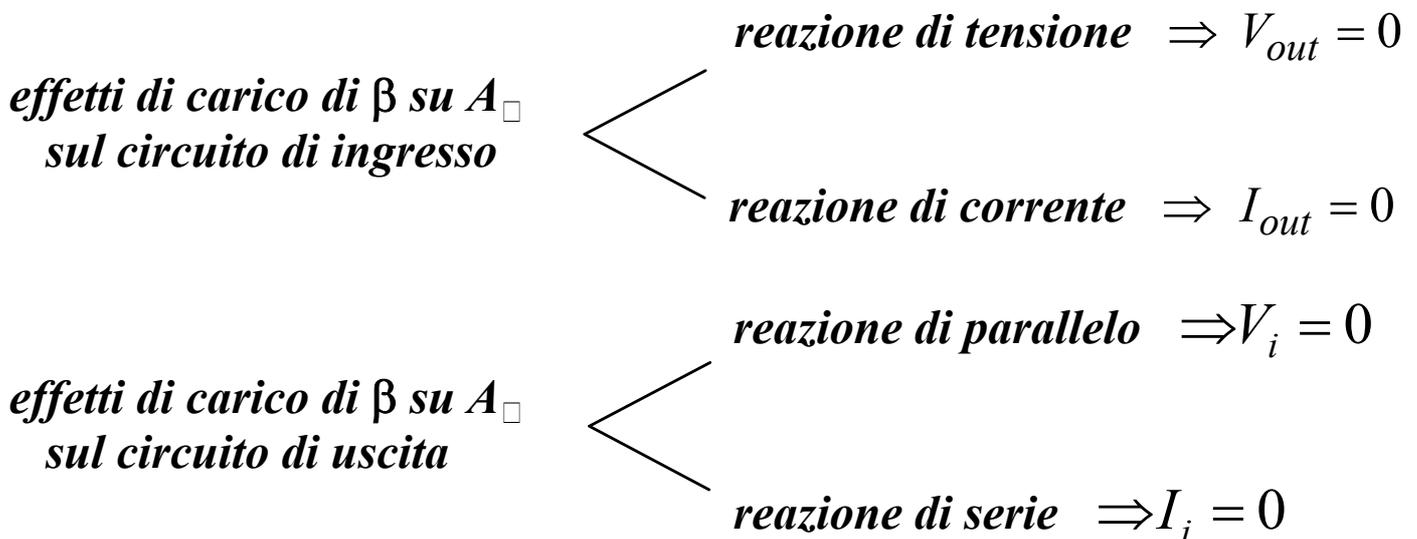
avendo posto $R'_{of} = R_{of} \parallel R_L$ e $R'_{out} = R_{out} \parallel R_L$

Analisi di circuiti in retroazione

(1) Classificazione del tipo di reazione



(2) Rappresentazione dell'amplificatore di base



(3) Sostituzione dei circuiti equivalenti al posto dei dispositivi attivi

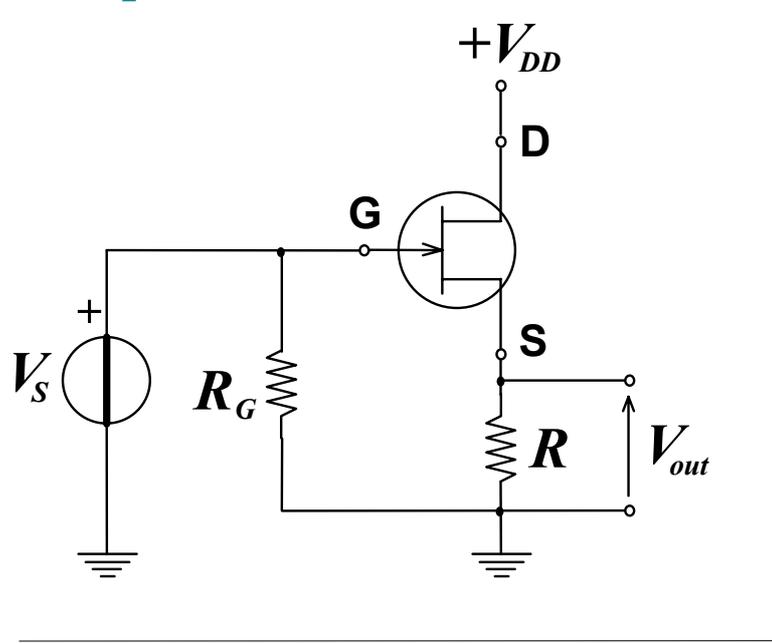
(4) Calcolo di X_f e X_{out}

(5) Determinazione di $\beta = \frac{X_f}{X_{out}}$

(6) Calcolo di A_v in base alle leggi di Kirchhoff alle maglie e ai nodi

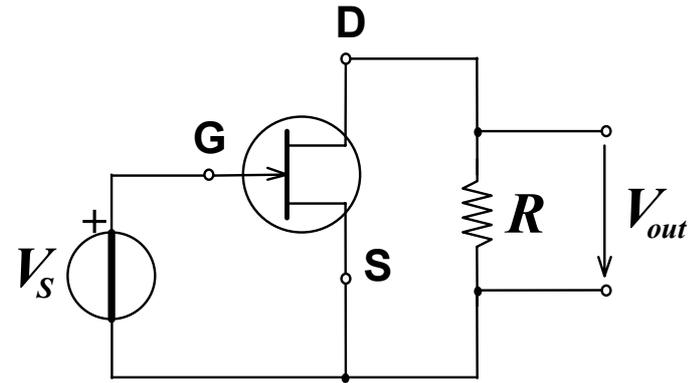
(7) Calcolo di $S, D, A_f, R_{if}, R_{of}, R'_{of}$ con le formule note

Esempio 1

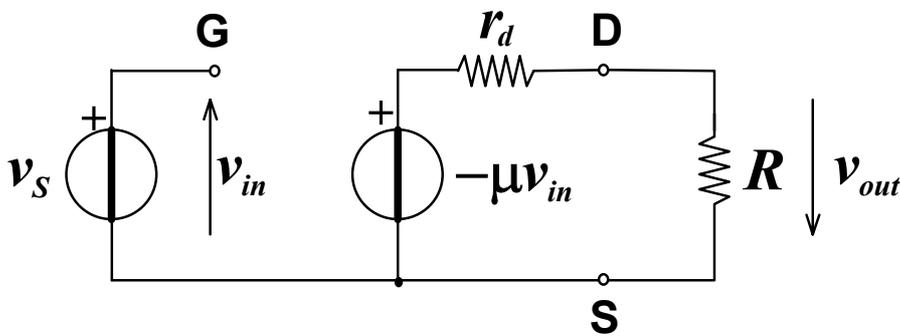


(1) reazione *serie di tensione*

(2)



(3)

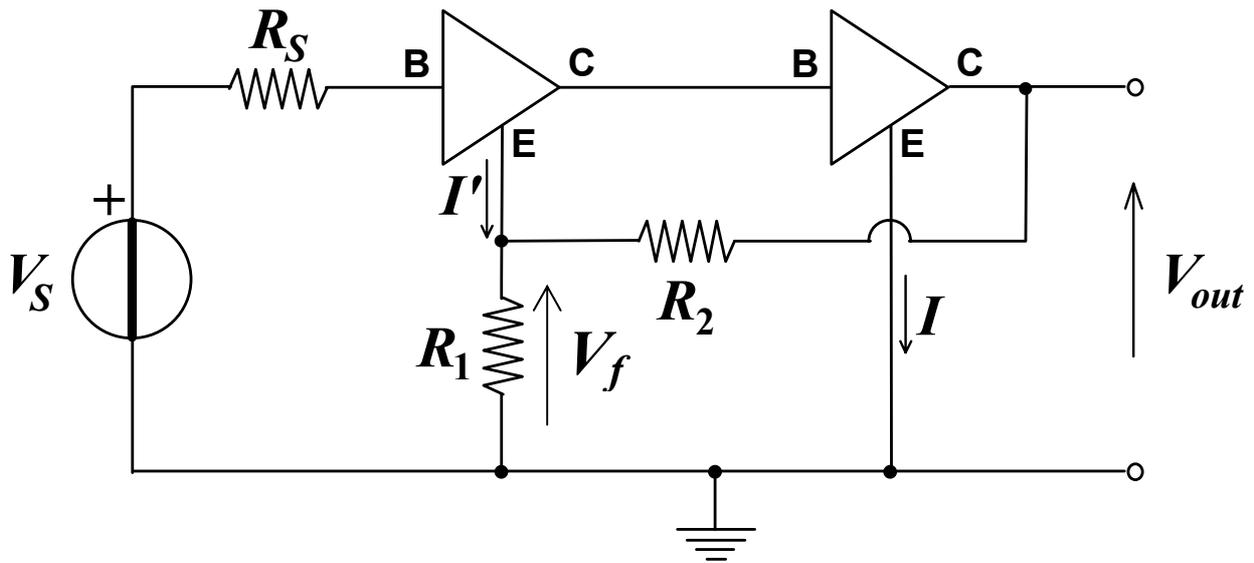


(4) $V_f = V_{out}$ (5) $\beta = \frac{V_f}{V_{out}} = 1$ (6) $A_V = \frac{V_{out}}{V_{in}} = \frac{\mu V_{in}}{V_{in}} \cdot \frac{R}{R + r_d}$

$V_{in} \equiv V_s$

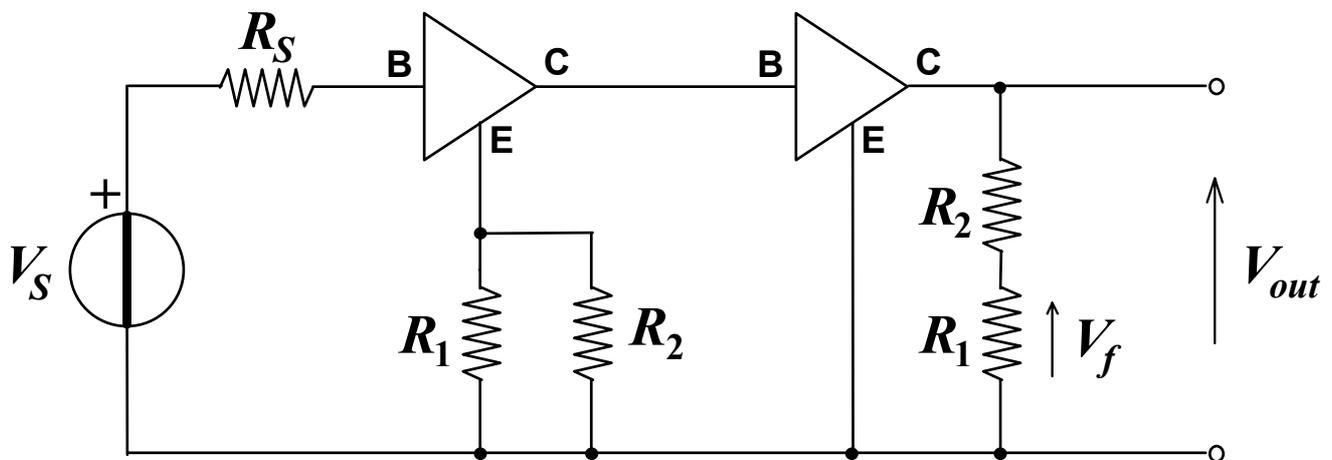
$$D = 1 + \beta A = \frac{r_d + R(1 + \mu)}{R + r_d} \qquad A_{v_f} = \frac{A_v}{D} = \frac{\mu R}{r_d + R(1 + \mu)}$$

Esempio 2



(1) reazione *serie di tensione*

(2) ($I' \ll I$)

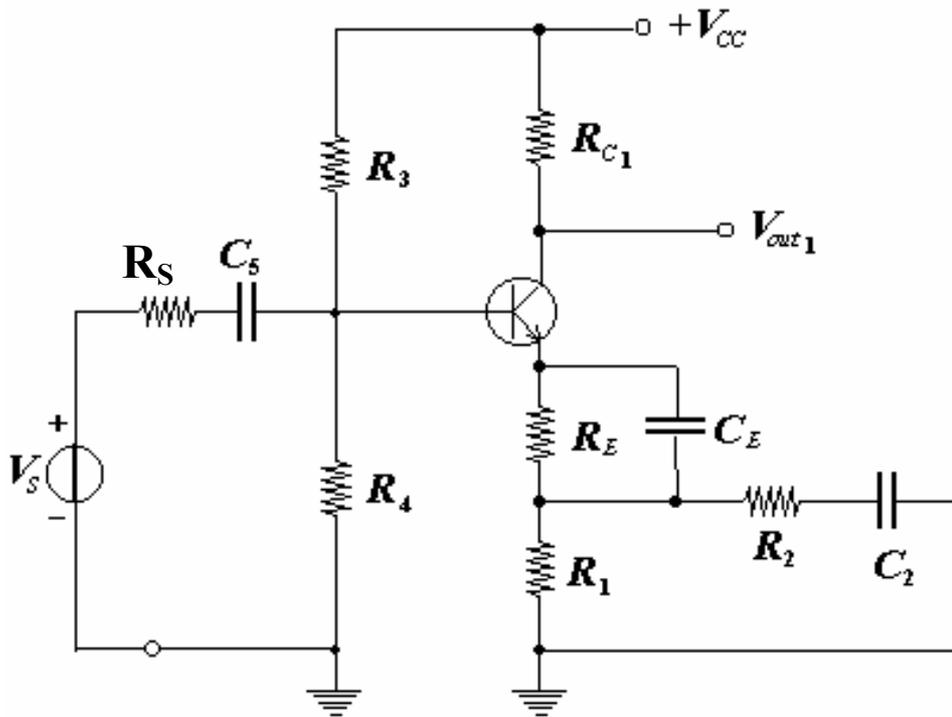


$$(4) V_f = \frac{R_1}{R_1 + R_2} V_{out}$$

$$(5) \beta = \frac{R_1}{R_1 + R_2}$$

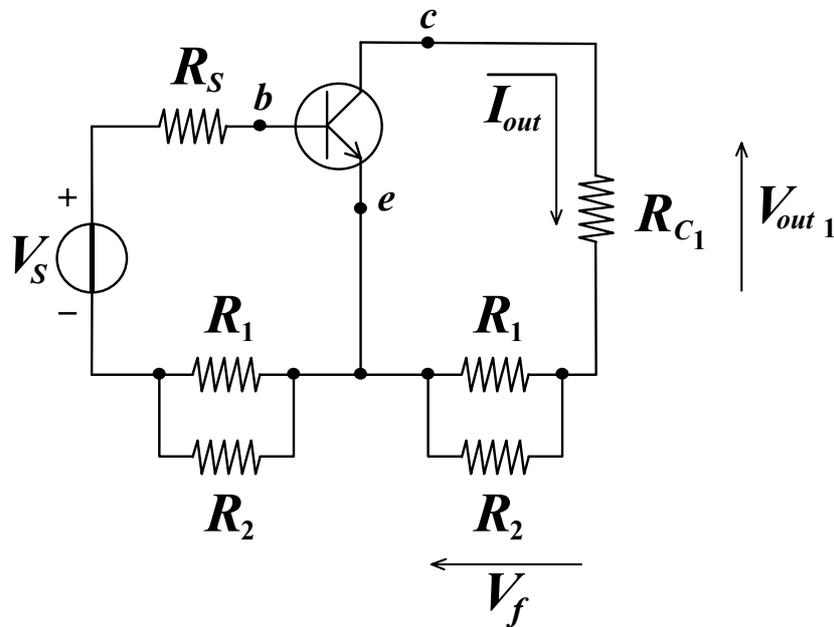
Oss.: $A \gg 1 \Rightarrow A_{V_f} \cong \frac{1}{\beta}$

Esempio 3



(1) reazione *serie di corrente*

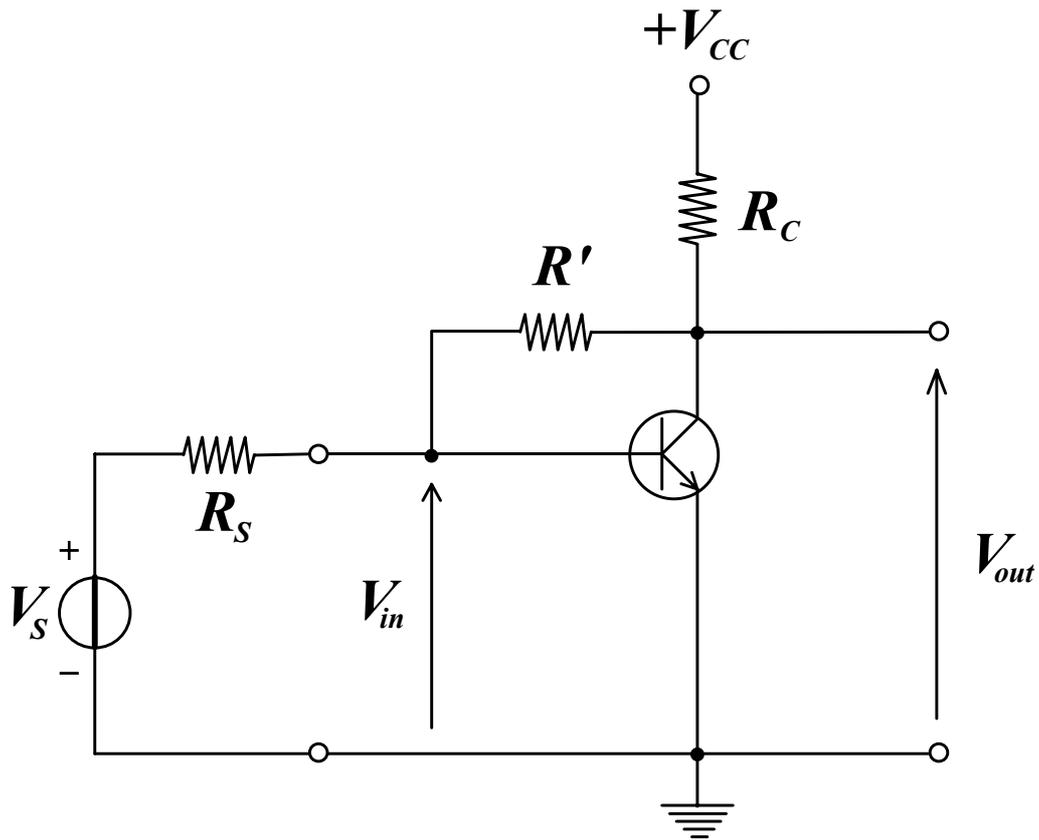
(2)



(4) $V_f = -I_{out} R_{eq}.$

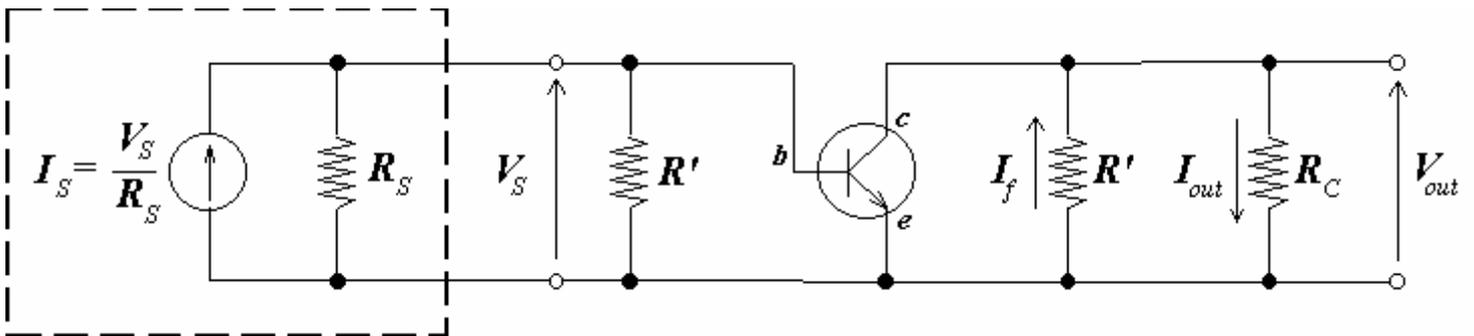
(5) $\beta = -R_{eq}.$ con $R_{eq} = R_1 \parallel R_2$

Esempio 4



(1) reazione *parallelo di tensione*

(2)



(4) $I_f = -\frac{V_{out}}{R'}$

(5) $\beta = -\frac{1}{R'}$

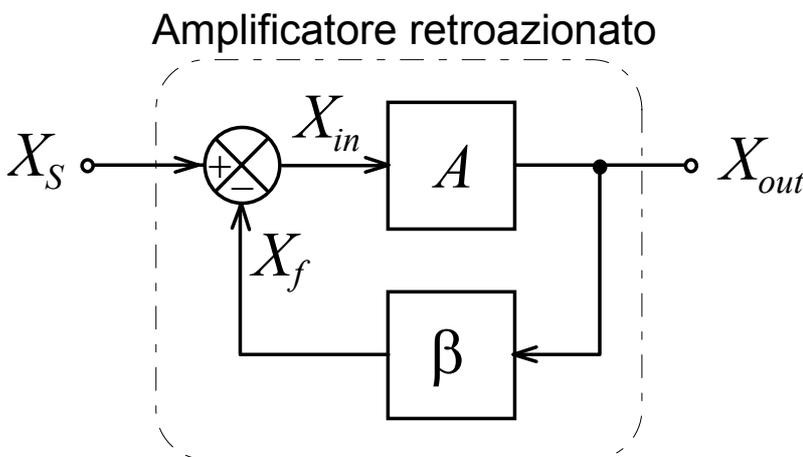
Stabilità dei sistemi retroazionati

La reazione è **positiva** (rigenerativa) quando $|A_f| > |A|$

$$|1 + \beta A| < 1 \Rightarrow \beta A < 0 \begin{cases} -1 \leq \beta A < 0 \\ \beta A < -1 \end{cases}$$

⇓

$$S = \frac{\frac{dA_f}{A_f}}{\frac{dA}{A}} = \frac{1}{|1 + \beta A|} > 1$$



Con $X_S = 0$ si ha:

$$X_{in} = X_S - X_f = -X_f$$

$$X_f = \beta X_{out}$$

⇓

$$X_{out} = AX_{in} = -\beta AX_{out}$$

Condizioni di Barkhausen: $\beta A = -1 \Leftrightarrow \begin{cases} |\beta A| = 1 \\ \angle \beta A = -180^\circ \end{cases}$

Nascita di una oscillazione che si autosostiene \Rightarrow vantaggioso per realizzare un **oscillatore**

Non linearità dei dispositivi attivi \Rightarrow Nascita di **intermodulazioni**

Interessamento delle porzioni di interdizione e saturazione \Rightarrow **Spostamento del punto di lavoro**

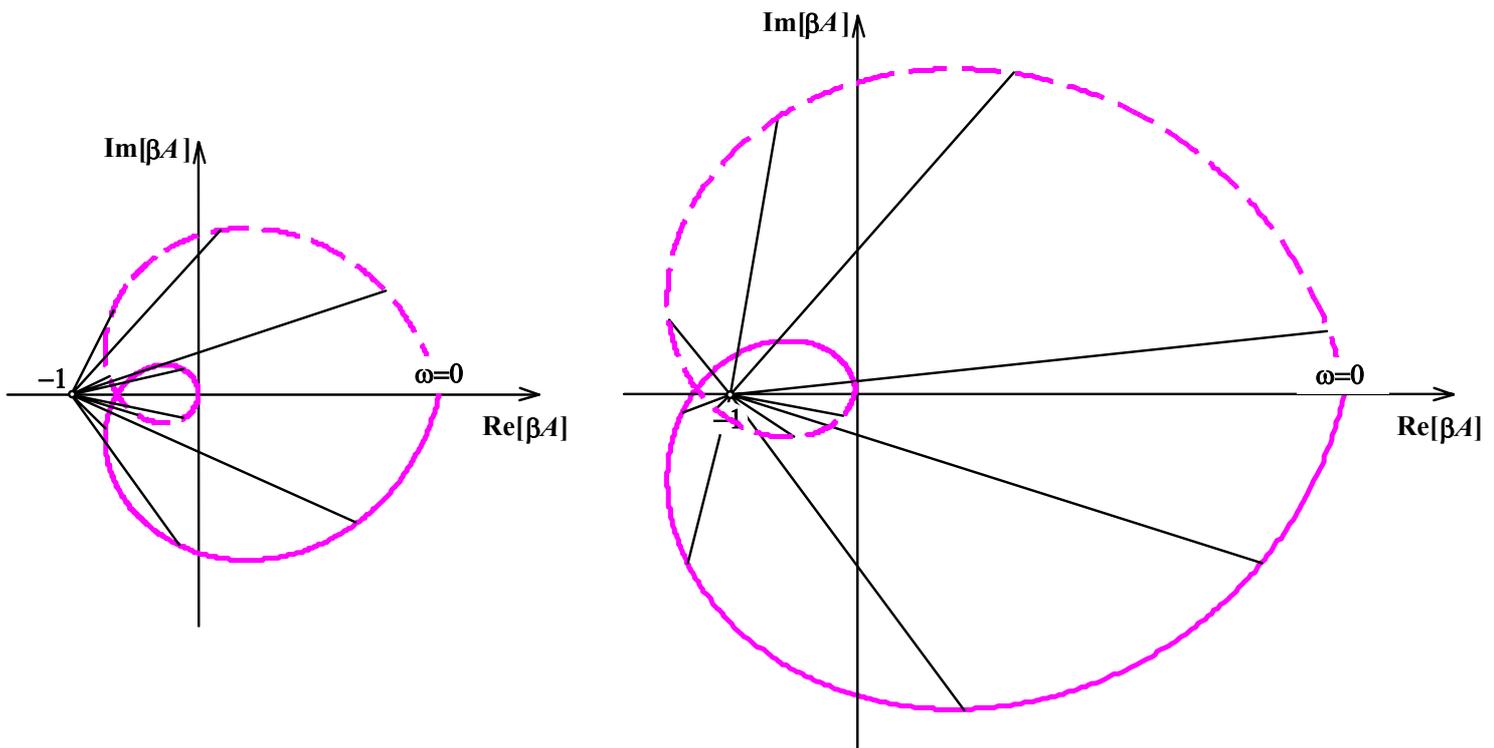
Studio della stabilità

- Un amplificatore deve essere stabile sia in banda che fuori banda;
- Un sistema fisico stabile eccitato con un segnale limitato nel tempo non può rispondere con un segnale non limitato nel tempo, o che tende a crescere indipendentemente, e la funzione di trasferimento del sistema non presenta poli né nel semipiano destro né sull'asse immaginario. **Se A è stabile lo sarà anche A_f purché $1 + \beta A$ abbia zeri solamente nel semipiano sinistro aperto.**

Metodi per lo studio della stabilità di un sistema:

- Determinazione delle radici dell'equazione algebrica che si ottiene eguagliando a 0 il deno-minatore della funzione di trasferimento;
- Criterio di Nyquist (1931);
- Diagramma di Bode.

Criterio di Nyquist



Proprietà delle funzioni di trasferimento delle reti elettriche:

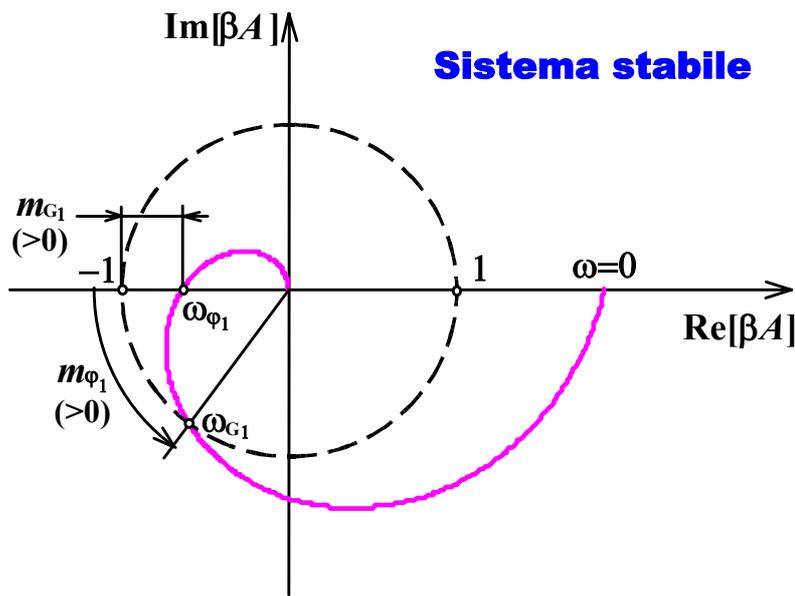
$$\beta A(j\omega) = [\beta A(-j\omega)]^*$$

Margini di guadagno e di fase

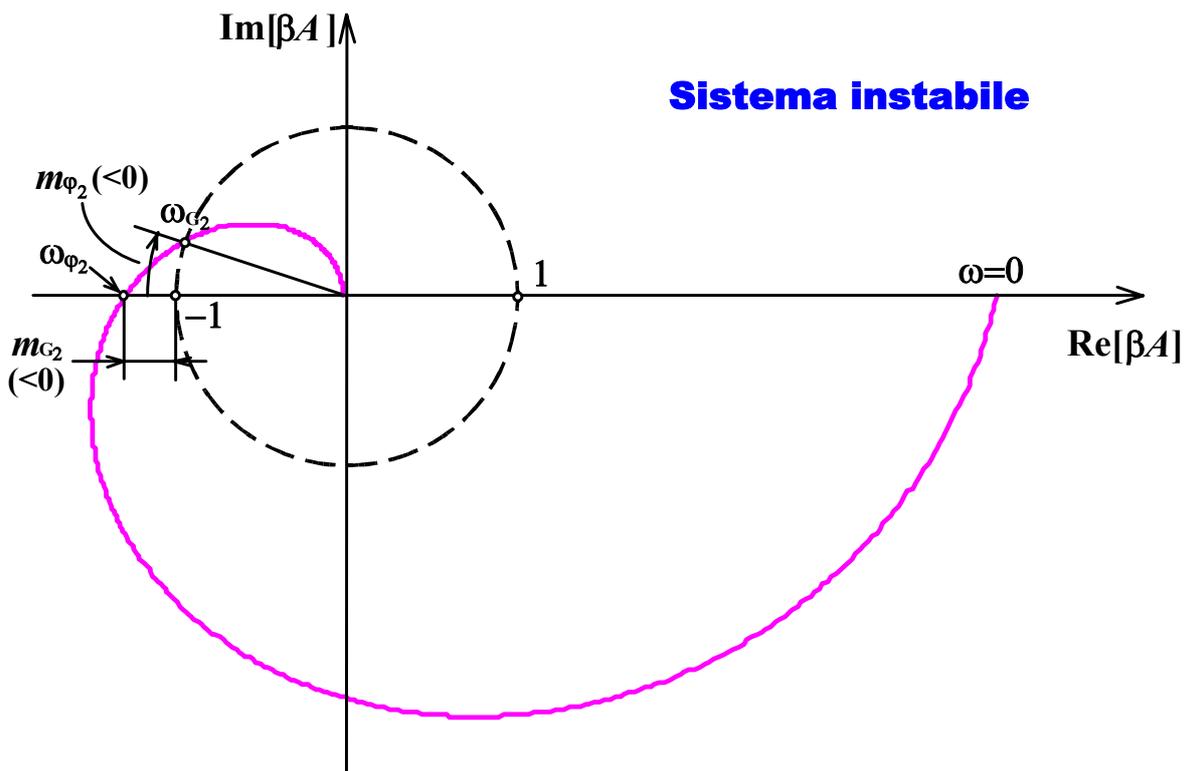
$$m_G = 20 \log 1 - 20 \log(\beta A|_{\omega=\omega_\phi}) = -[\beta A(j\omega_\phi)] \quad \text{dB}$$

$$(m_G \geq 10\text{dB})$$

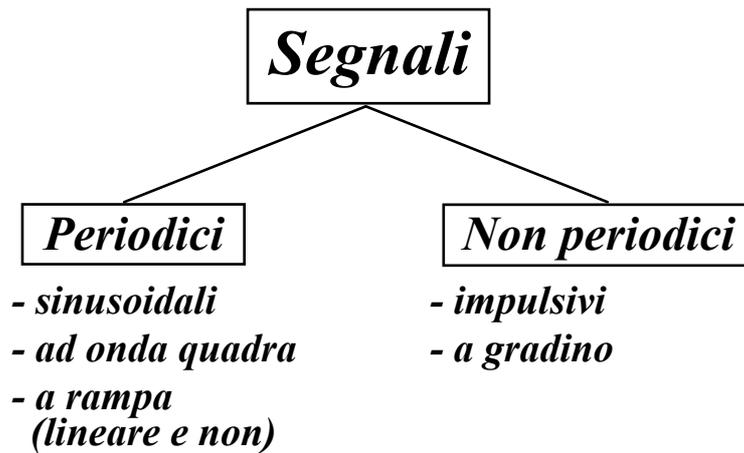
$$m_\phi = \Phi[\beta A(j\omega_G)] + 180^\circ \quad (m_\phi \geq 45^\circ) \quad \Phi[\beta A(j\omega_\phi)] = -180^\circ$$



<i>Stabilità</i>	<i>Instabilità</i>
$\omega_\phi > \omega_G$	$\omega_\phi < \omega_G$
$m_G > 0$	$m_G < 0$
$m_\phi > 0$	$m_\phi < 0$



Generazione di segnali



Generazione di segnali sinusoidali - Oscillatori

Condizioni di

Barkhausen:

$$\beta A = -1 \Leftrightarrow \begin{cases} |\beta A| = 1 \\ \angle \beta A = -180^\circ \end{cases} \Leftrightarrow \begin{cases} \omega_G \equiv \omega_\phi \\ m_G = 0; m_\phi = 0^\circ \end{cases}$$

$$\begin{aligned} \beta A &= -1 \\ \Downarrow \\ A_f &= \frac{V_{out}}{V_S} = \frac{A}{1 + \beta A} \rightarrow \infty \\ \Downarrow \\ V_{out} &= A_f \cdot V_S \rightarrow \infty \cdot 0 \end{aligned}$$

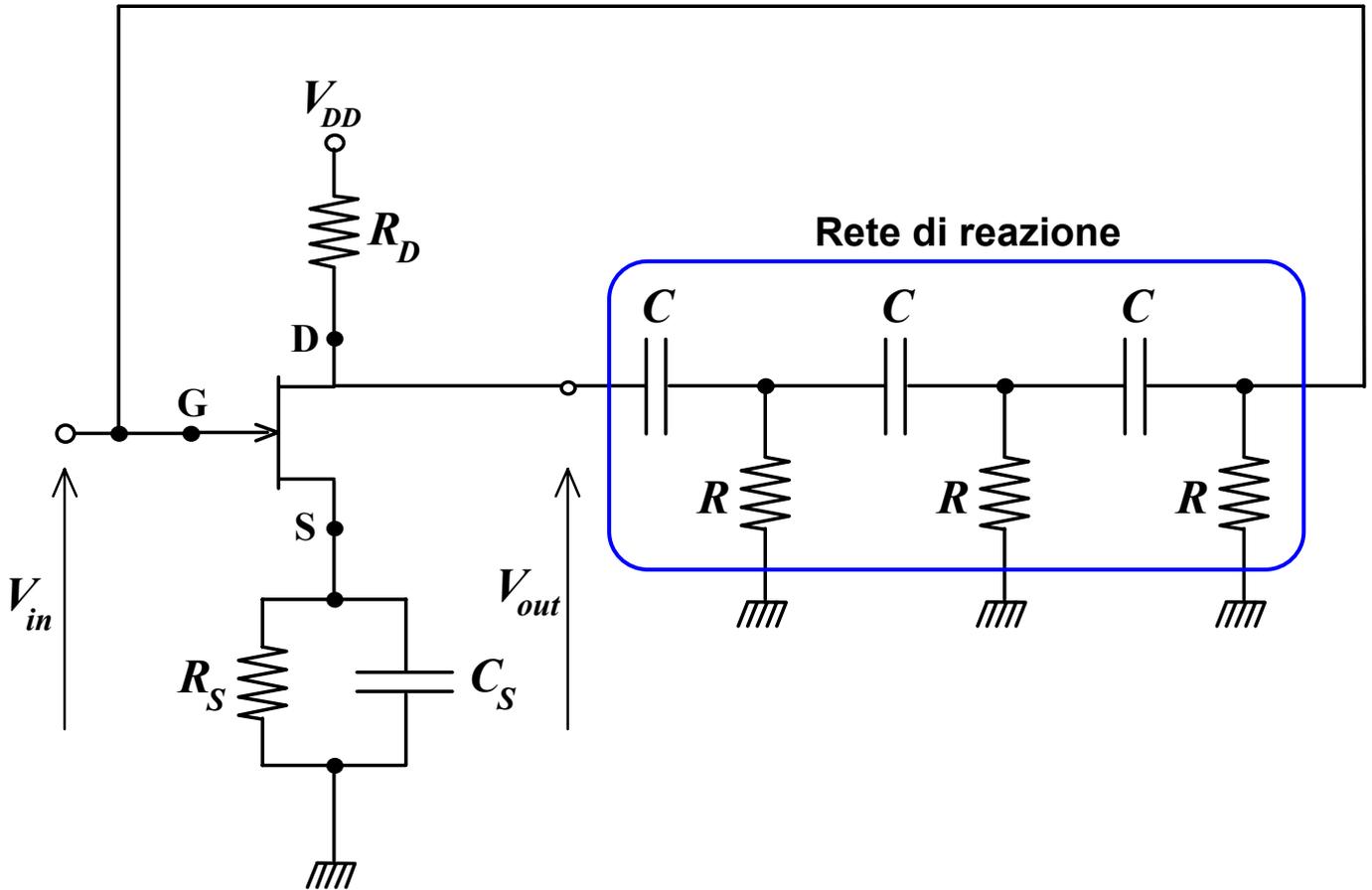
Questa condizione viene soddisfatta per un determinato valore della pulsazione ($\omega = \omega_G = \omega_\phi$, vedi diagramma di Nyquist).

Teoricamente lo spettro del segnale generato è costituito da una sola riga. In realtà, per effetto della non costanza dei parametri nel tempo, si ha un allargamento delle righe per cui lo spettro degenera in una banda.

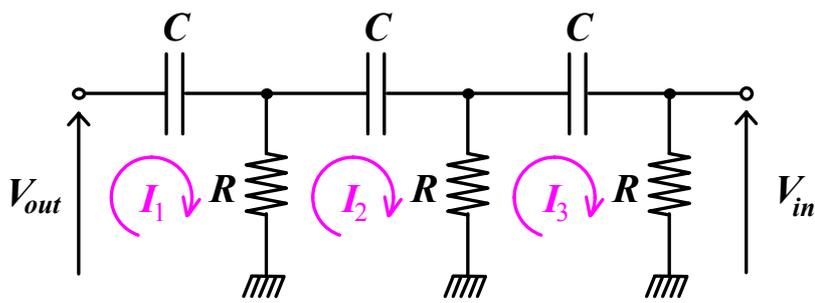
Oscillatore a sfasamento (100's kHz)

(a FET, config. CS)

Reazione serie di tensione



- Ipotesi:**
- 1) A_V costante al variare di $f \quad \forall f \in B$
 - 2) $R_{in} \gg R$
 - 3) $Z_{eq.} \gg R_{out}$



$$\begin{cases} V_{out} = I_1 \left(\frac{1}{j\omega C} + R \right) - I_2 R \\ 0 = -I_1 R + I_2 \left(\frac{1}{j\omega C} + 2R \right) - I_3 R \\ 0 = -I_2 R + I_3 \left(\frac{1}{j\omega C} + 2R \right) \end{cases}$$

Posto $\alpha = \frac{1}{\omega RC}$ si trova

$$\begin{cases} \frac{V_{out}}{R} = I_1(1 - j\alpha) - I_2 \\ 0 = -I_1 + I_2(2 - j\alpha) - I_3 \Rightarrow I_3 = \frac{V_{out}}{R[1 - 5\alpha^2 + j(\alpha^3 - 6\alpha)]} \\ 0 = -I_2 + I_3(2 - j\alpha) \end{cases}$$

⇓

$$\frac{V_{in}}{V_{out}} = \frac{I_3 R}{V_{out}} \Rightarrow \frac{V_{in}}{V_{out}} = \frac{1}{1 - 5\alpha^2 + j(\alpha^3 - 6\alpha)}$$

⇓

$$\alpha^3 - 6\alpha = 0 \Rightarrow \alpha = \pm\sqrt{6} \Rightarrow \alpha = \frac{1}{\omega RC} = \sqrt{6} \Rightarrow \omega_{osc} = \frac{1}{RC\sqrt{6}}$$

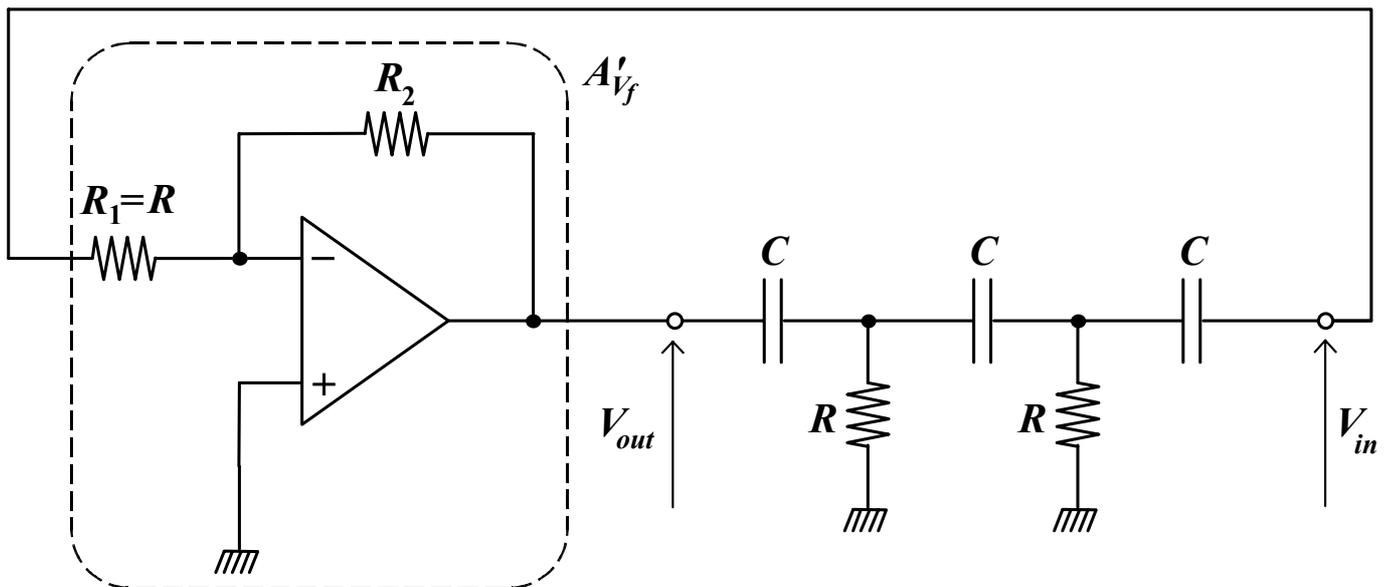
Sostituendo si ottiene $\left(\frac{V_{in}}{V_{out}}\right)_{\omega=\omega_{osc}} = -\frac{1}{29}$ $V_{in} = V_S - V_f$ $V_{in} = -V_f$

⇓

$$|\beta A| = 1 \Rightarrow |A_V| = \frac{1}{|\beta|} = 29 \text{ (meglio } |A_V| = 29 \cdot 1,05 \text{ (+5\%))}$$

(con a.o.)

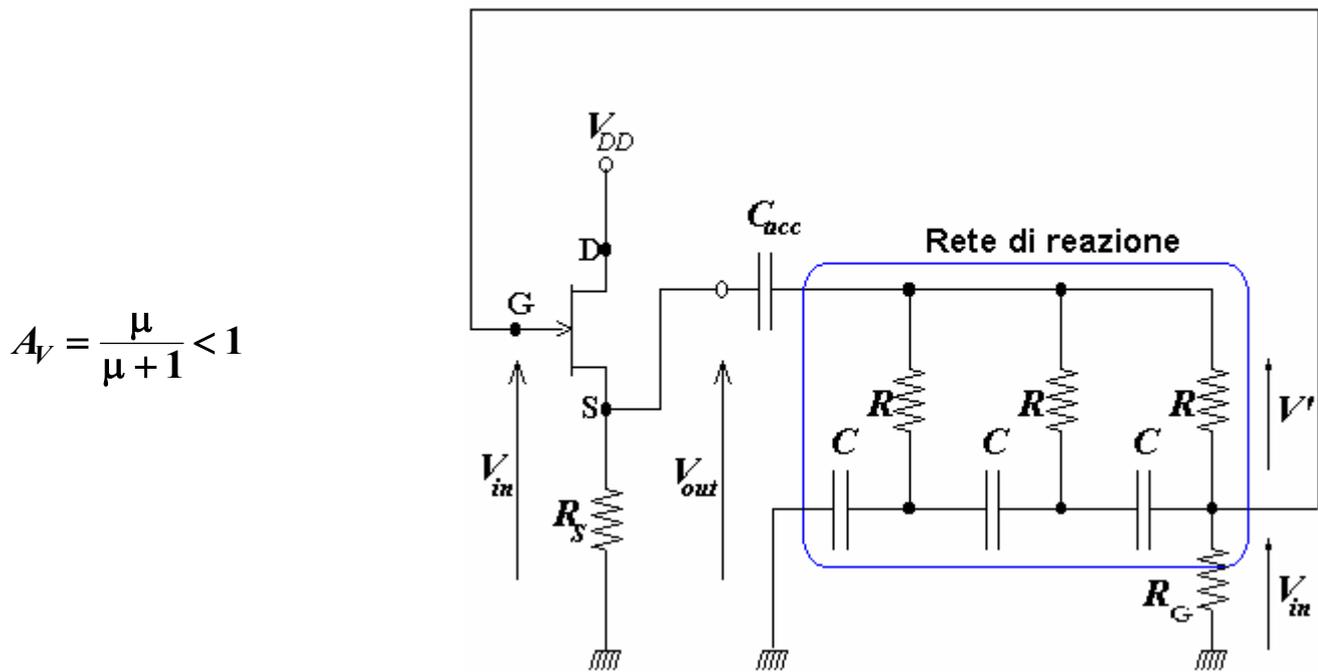
Reazione positiva serie di tensione



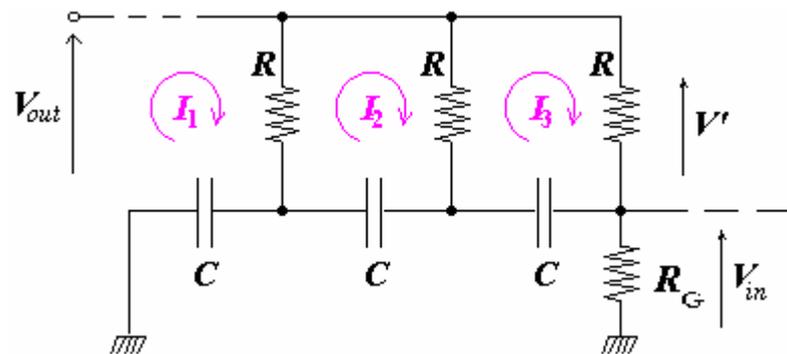
Reazione negativa parallelo di tensione

In questo caso risulta $A_{V_f} = \frac{A'_{V_f}}{1 + \beta A'_{V_f}}$ dove $A'_{V_f} = -\frac{R}{R} \frac{2}{1} = -29$

(con FET in config. CD)



$$A_v = \frac{\mu}{\mu + 1} < 1$$



Procedendo come nel caso precedente:

$$\frac{V'}{V_{out}} = \frac{1}{1 - 5\alpha^2 + j(\alpha^3 - 6\alpha)}$$

$$\Downarrow$$

$$V' = \frac{V_{out}}{1 - 5\alpha^2 + j(\alpha^3 - 6\alpha)}$$

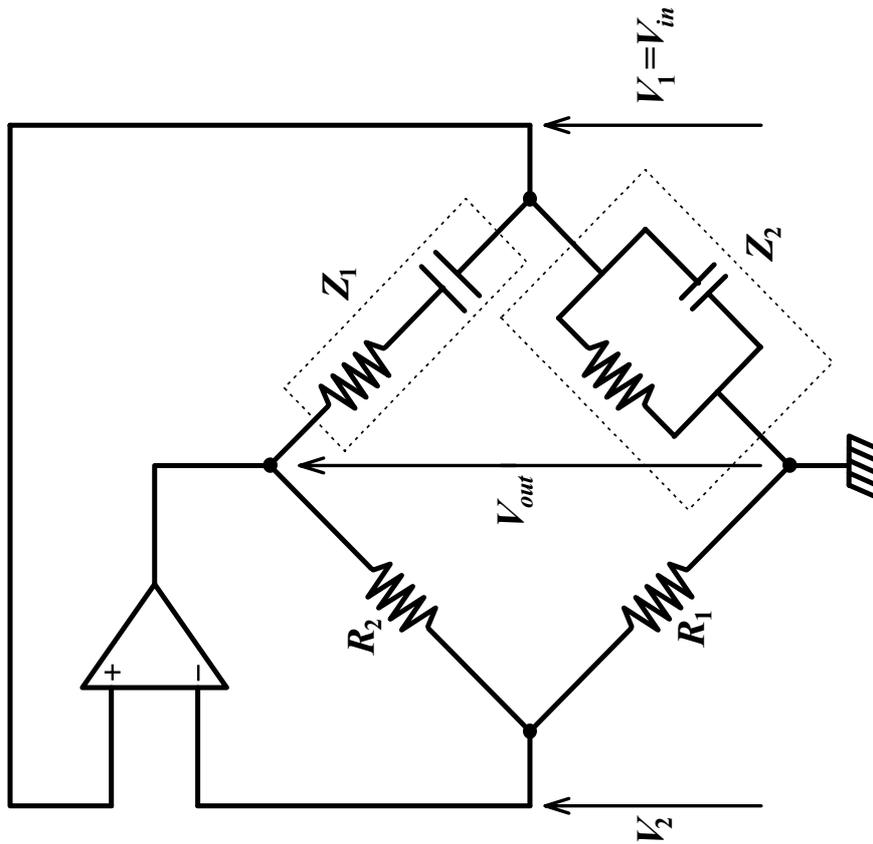
Quindi $\omega_{osc} = \frac{1}{RC\sqrt{6}}$. Essendo però $V_{out} = V_{in} + V'$, dividendo per V_{out} si ha:

$$\beta = \frac{V_{in}}{V_{out}} = 1 - \frac{V'}{V_{out}} = 1 - \left(-\frac{1}{29}\right) = 1 + \frac{1}{29} = \frac{30}{29} \cong 1,034$$

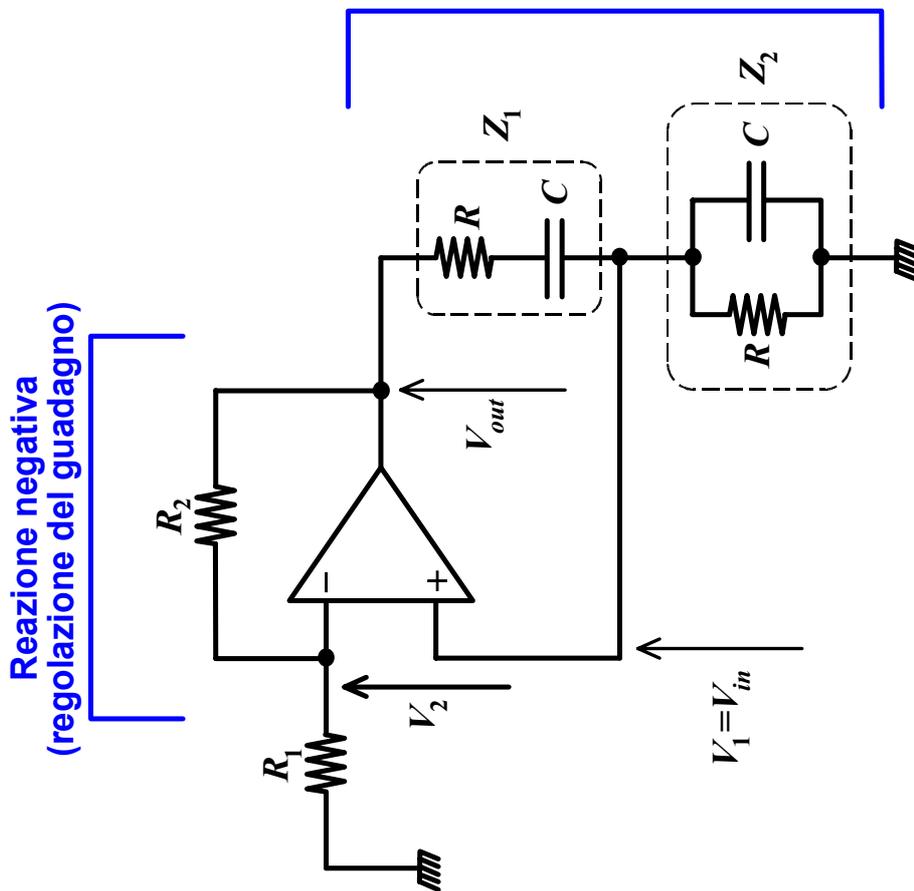
Pur essendo $A_v < 1$ si riesce ad avere $|\beta A_v| > 1$ per un valore di μ sufficientemente elevato.

Ad esempio, per $\mu = 50 \Rightarrow |\beta A_v| = 1,034 \cdot \frac{50}{50+1} \cong 1,014$.

Oscillatore a ponte di Wien



Reazione positiva (sfasamento e ampiezza)



$$V_{in} = V_1 = V_2 = \frac{R_1}{R_1 + R_2} V_{out} \Rightarrow V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

$$\text{Ma: } V_{in} = \left(\frac{Z_2}{Z_1 + Z_2}\right) V_{out} \Rightarrow V_{out} = \left(\frac{Z_2}{Z_1 + Z_2}\right) \left(1 + \frac{R_2}{R_1}\right) V_{out}$$

$$\Downarrow$$

$$\left(\frac{Z_2}{Z_1 + Z_2}\right) \left(1 + \frac{R_2}{R_1}\right) = 1$$

Posto $\alpha' = \omega RC$ si trova:

$$\frac{Z_2}{Z_1 + Z_2} = \frac{\frac{R}{1 + j\alpha'}}{\frac{1 + j\alpha'}{j\omega C} + \frac{R}{1 + j\alpha'}} = \frac{\frac{R}{1 + j\alpha'}}{\frac{(1 + j\alpha')^2 + j\alpha' R}{j\omega C (1 + j\alpha')}} = \frac{j\alpha' R}{1 - \alpha'^2 + 2j\alpha' R + j\alpha' R} =$$

$$= \frac{j\alpha' R}{1 - \alpha'^2 + 3j\alpha' R} \cdot \frac{j}{j} = \frac{-\alpha' R}{j - j\alpha'^2 - 3\alpha' R} = \frac{\alpha' R}{3\alpha' R + j(\alpha'^2 - 1)}$$

$$\Downarrow$$

$$\alpha'^2 - 1 = 0 \Rightarrow \alpha' = \omega RC = 1 \Rightarrow$$

$$\omega_{osc} = \frac{1}{RC}$$

$$\Downarrow$$

$$\frac{Z_2}{Z_1 + Z_2} = \frac{1}{3} \Rightarrow 1 + \frac{R_2}{R_1} = 3 \Rightarrow$$

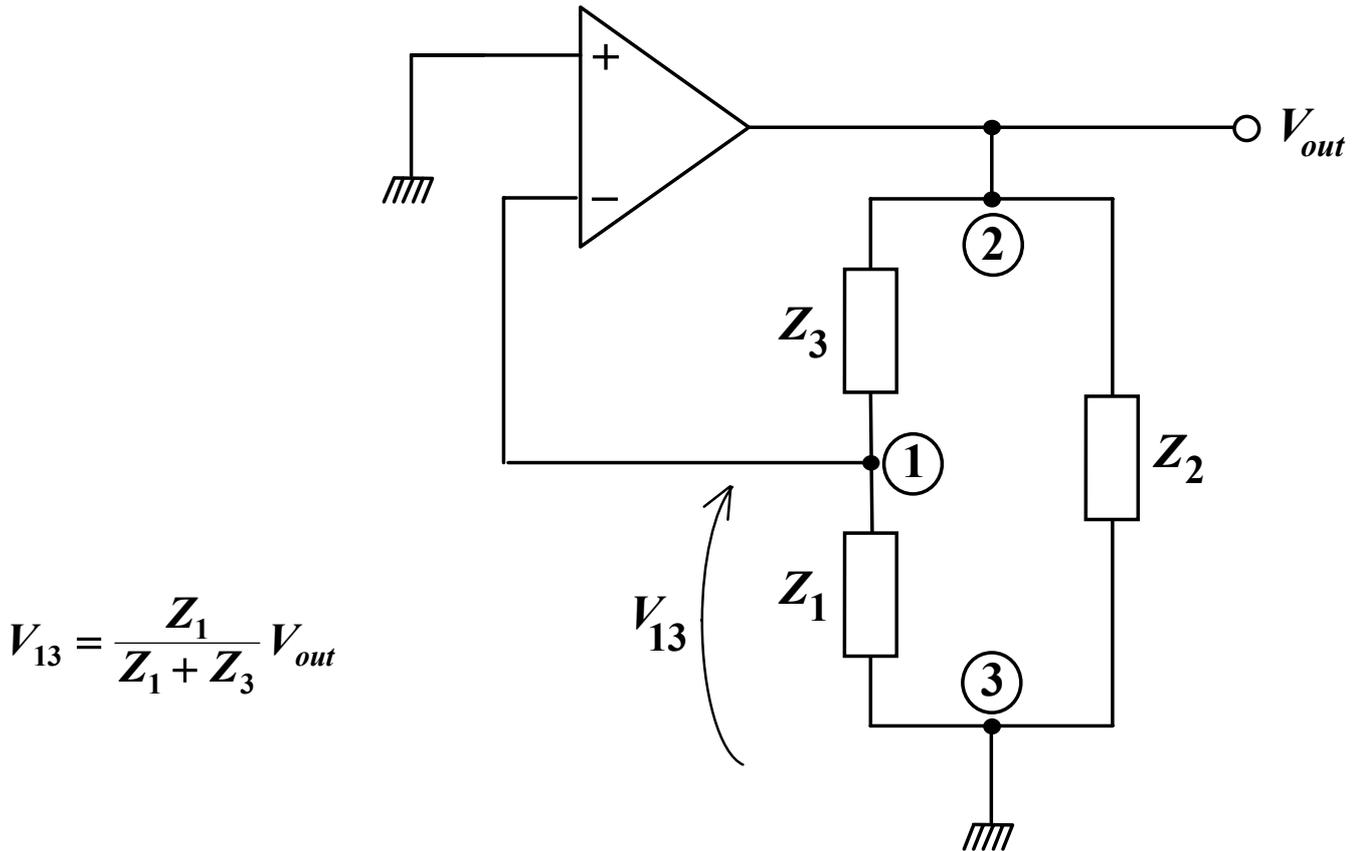
$$R_2 = 2R_1$$

Problema della stabilizzazione dell'ampiezza della tensione di uscita. Soluzioni:

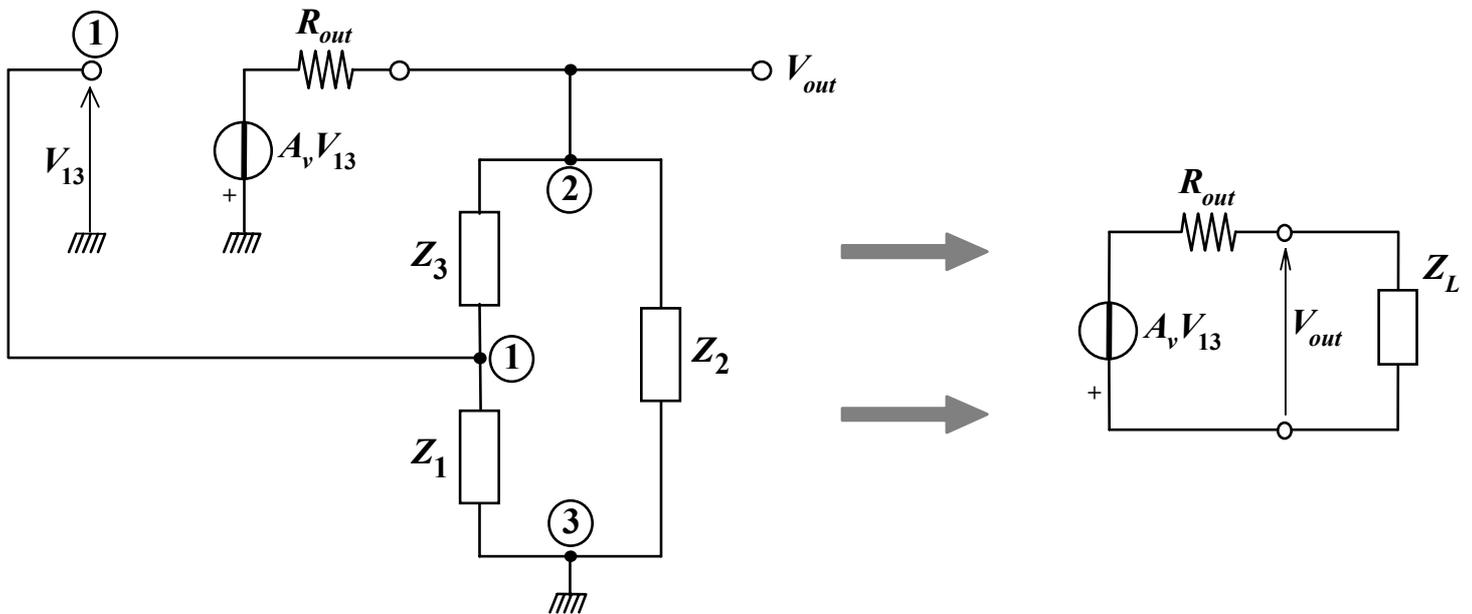
Al posto di R_1 si può inserire un sensistor (coefficiente termico positivo)

Al posto di R_2 si può inserire un termistor (coefficiente termico negativo)

Oscillatori a tre punti



Schematizzazione adottata per l'analisi del circuito



dove $Z_L = Z_2 \parallel (Z_1 + Z_3) = \frac{(Z_1 + Z_3) Z_2}{Z_1 + Z_2 + Z_3}$

$$V_{out} = ?$$

$$V_{out} = -A_v V_{13} \cdot \frac{Z_L}{R_{out} + Z_L} \Rightarrow V_{out} = -A_v \cdot \frac{Z_L}{R_{out} + Z_L} \cdot V_{out} \frac{Z_1}{Z_1 + Z_3}$$

⇓

$$-A_v \cdot \frac{Z_L}{R_{out} + Z_L} \cdot \frac{Z_1}{Z_1 + Z_3} = 1$$

⇓

$$-A_v \cdot \frac{(Z_1 + Z_3) \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3}}{R_{out} + (Z_1 + Z_3) \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3}} \cdot \frac{Z_1}{Z_1 + Z_3} = \frac{-A_v Z_1 Z_2}{R_{out}(Z_1 + Z_2 + Z_3) + Z_2(Z_1 + Z_3)} = 1$$

$$Z_i = jX_i \begin{cases} j\omega L \\ \frac{1}{j\omega C} \end{cases}$$

⇓

$$\begin{aligned} & \frac{-A_v jX_1 \cdot jX_2}{jR_{out}(X_1 + X_2 + X_3) + jX_2(jX_1 + jX_3)} = \\ & = \frac{A_v X_1 X_2}{jR_{out}(X_1 + X_2 + X_3) - X_2(X_1 + X_3)} = 1 \end{aligned}$$

⇓

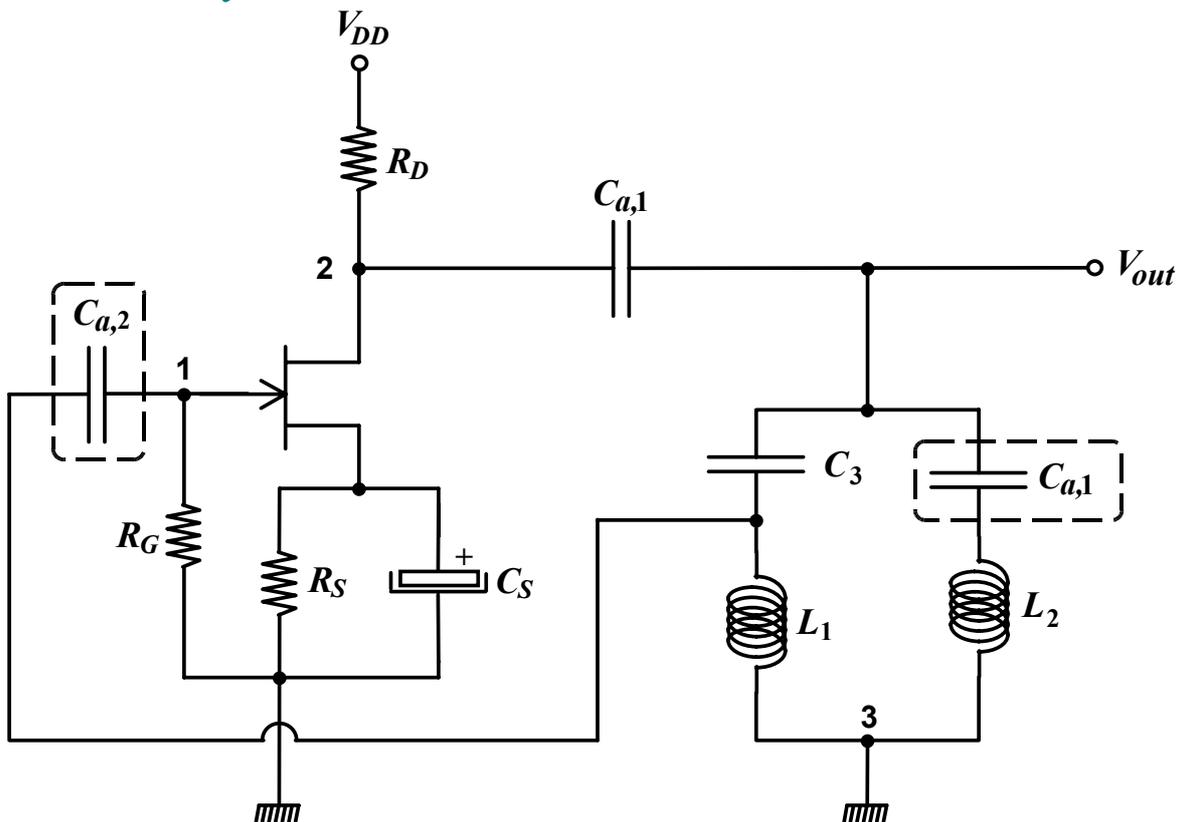
$$\boxed{X_1 + X_2 + X_3 = 0} \Rightarrow X_1 + X_3 = -X_2$$

⇓

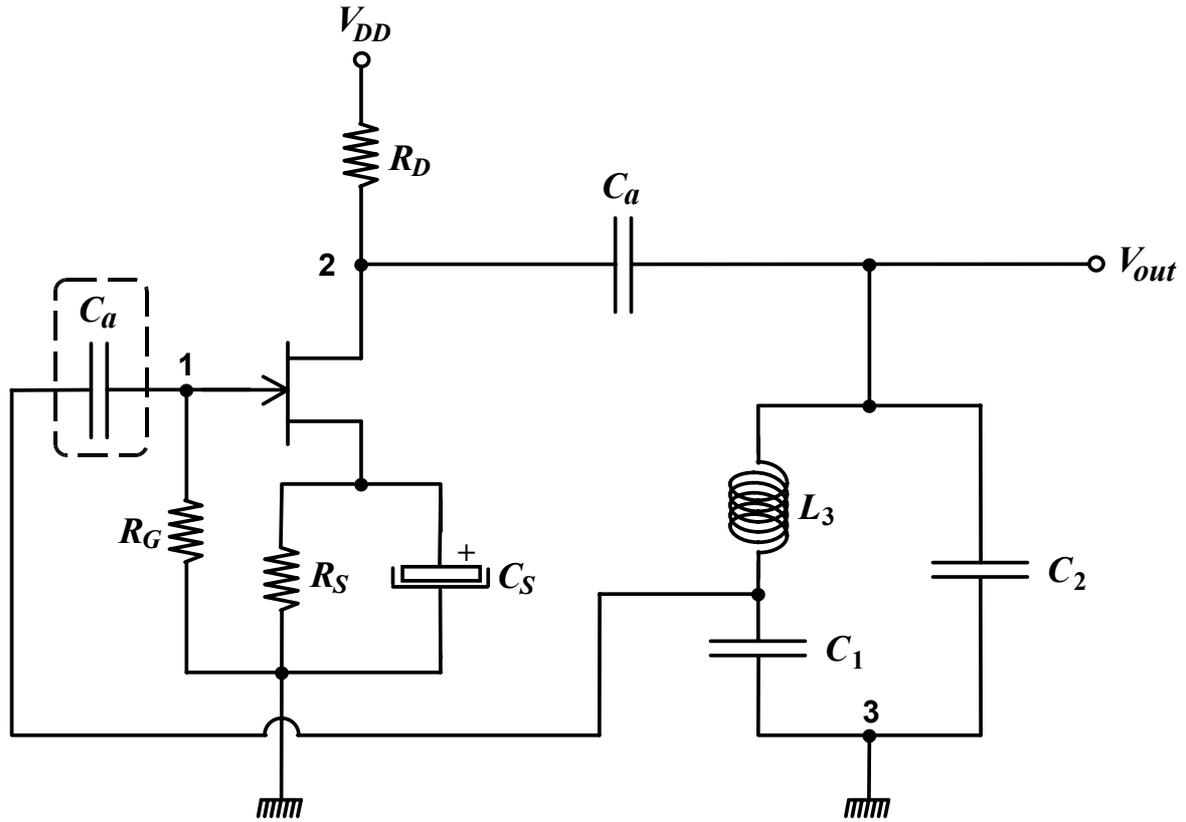
$$\frac{A_v X_1 X_2}{-X_2(-X_2)} = \frac{A_v X_1}{X_2} = 1 \Rightarrow \boxed{A_v = \frac{X_2}{X_1}} \quad \text{P } X_1 \text{ e } X_2 \text{ dello stesso segno}$$

Oscillatore Hartley	Oscillatore Colpitts
$X_1 = \omega L_1$	$X_1 = -\frac{1}{\omega C_1}$
$X_2 = \omega L_2$	$X_2 = -\frac{1}{\omega C_2}$
$X_3 = -\frac{1}{\omega C_3}$	$X_3 = \omega L_3$
$\omega L_1 + \omega L_2 - \frac{1}{\omega C_3} = 0 \Big _{\omega=\omega_{osc}}$	$-\frac{1}{\omega C_1} - \frac{1}{\omega C_2} + \omega L_3 = 0 \Big _{\omega=\omega_{osc}}$
$\omega_{osc} = \sqrt{\frac{1}{C_3} \left(\frac{1}{L_1 + L_2} \right)}$	$\omega_{osc} = \sqrt{\frac{1}{L_3} \left(\frac{1}{C_1} + \frac{1}{C_2} \right)}$
$A_V = \frac{L_2}{L_1}$	$A_V = \frac{C_1}{C_2}$

Oscillatore Hartley

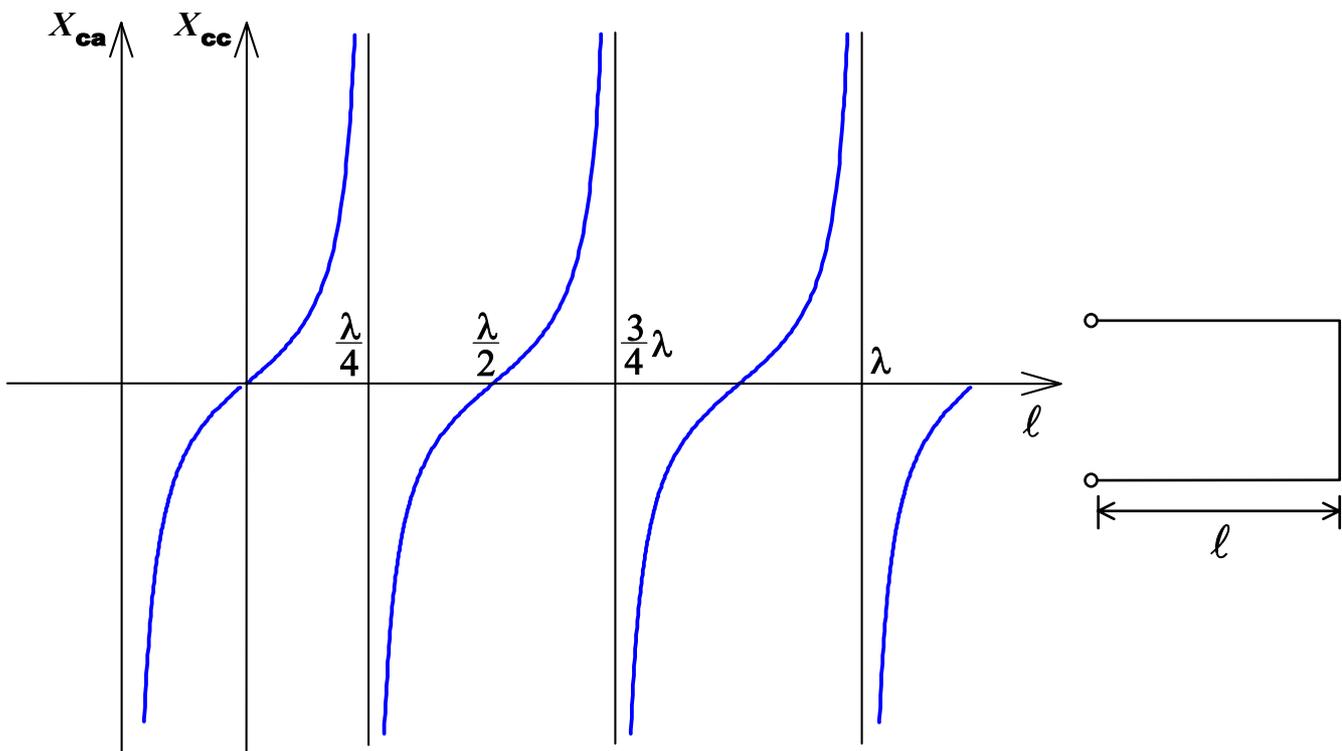


Oscillatore Colpitts

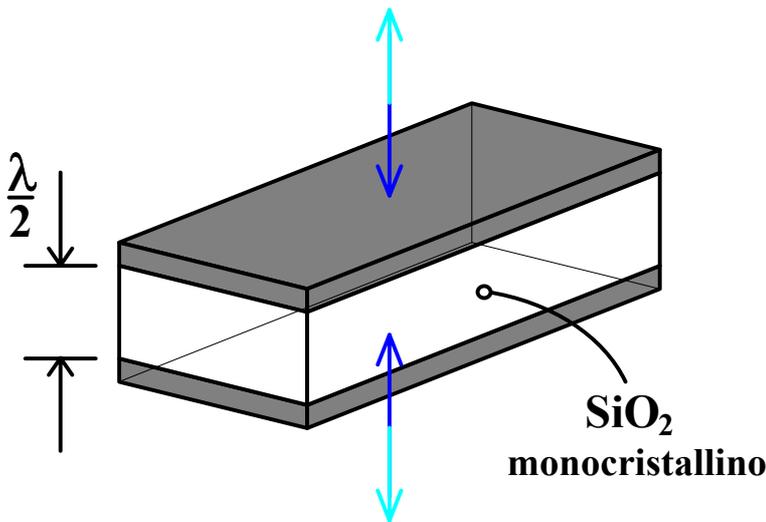


Utilizzo di stub alle alte frequenze

Parametri parassiti: tempo, temperatura, pressione, dispersione dei parametri, ecc.



Oscillatori a quarzo



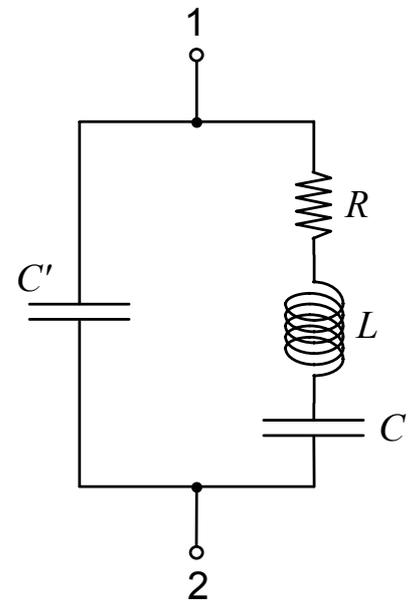
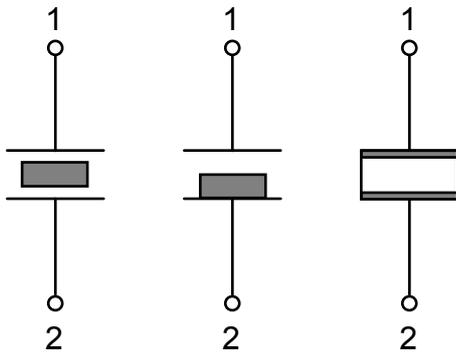
Piezolettricità (Curie, 1880)

$$X_2 + X_3 = -X_1$$

$$\Delta X_2 + \Delta X_3 = -\Delta X_1$$

$$\frac{\Delta X_1}{\Delta \omega} = S_f \Rightarrow \Delta \omega = \frac{\Delta X_1}{S_f}$$

Simboli circuitali e modello di un quarzo (Mason)



$$Z_{eq.} = \frac{\frac{1}{sC'} \left(R + sL + \frac{1}{sC} \right)}{\frac{1}{sC'} + R + sL + \frac{1}{sC}} =$$

$$= \frac{\frac{1}{s^2 C C'} (sRC + s^2 LC + 1)}{\frac{1}{s C C'} (C + sR C C' + s^2 L C C' + C')} \stackrel{s=j\omega}{=} \frac{1 - \omega^2 LC + j\omega R}{j\omega [(C + C') - \omega^2 L C C' - RC]}$$

Per $R \cong 0$ si ha:

$$Z_{eq.} = \frac{1 - \omega^2 LC}{j\omega[(C + C') - \omega^2 LCC']} = \frac{LC\left(\frac{1}{LC} - \omega^2\right)}{j\omega LCC'\left[\frac{C + C'}{LCC'} - \omega^2\right]} = \frac{\omega^2 - \frac{1}{LC}}{j\omega C'\left[\omega^2 - \frac{1}{L} \frac{C + C'}{CC'}\right]}$$

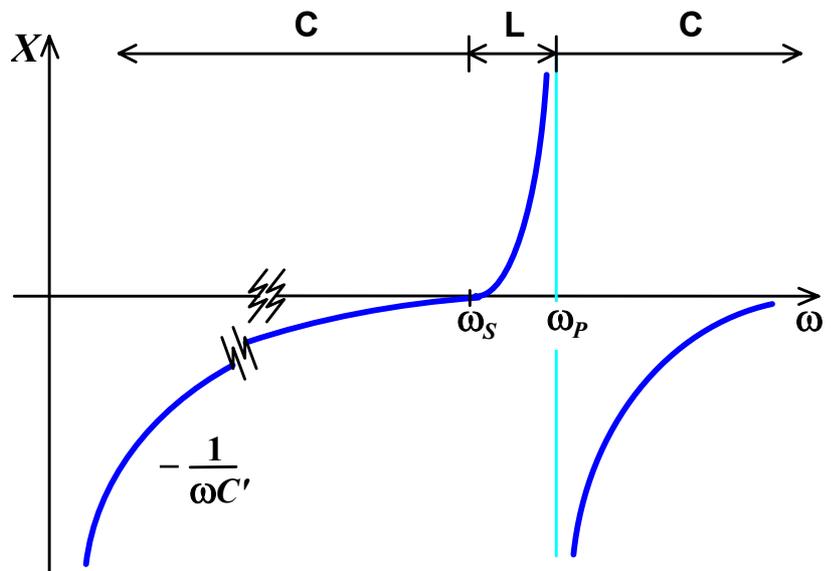
Posto $\omega_S = \frac{1}{\sqrt{LC}}$ e $\omega_P = \sqrt{\frac{1}{L} \left(\frac{C + C'}{CC'}\right)}$ si ottiene:

$$Z_{eq.} = \frac{1}{j\omega C'} \frac{\omega^2 - \omega_S^2}{\omega^2 - \omega_P^2}$$

$C' \gg C \Rightarrow \omega_S \cong \omega_P$

$Q = \frac{\omega_0}{\omega_P - \omega_S} = 1000 \div 10000$

con $\omega_0 = \frac{\omega_P + \omega_S}{2}$



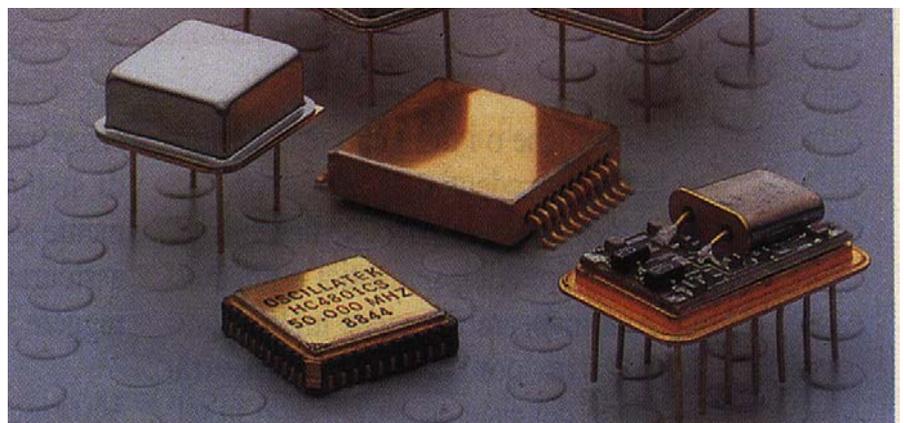
$f = \text{decine...di...MHz}$

⇓

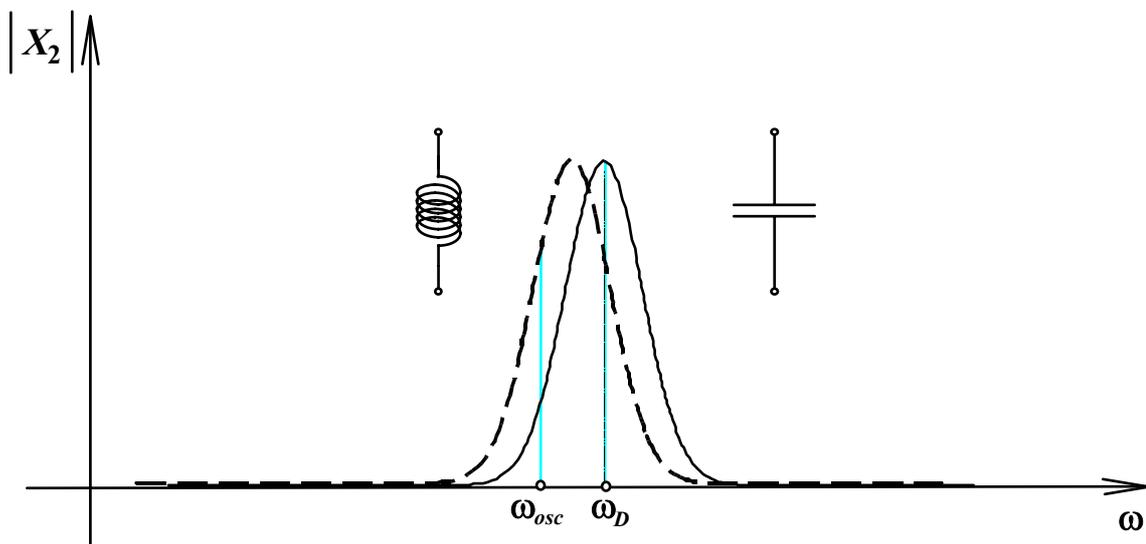
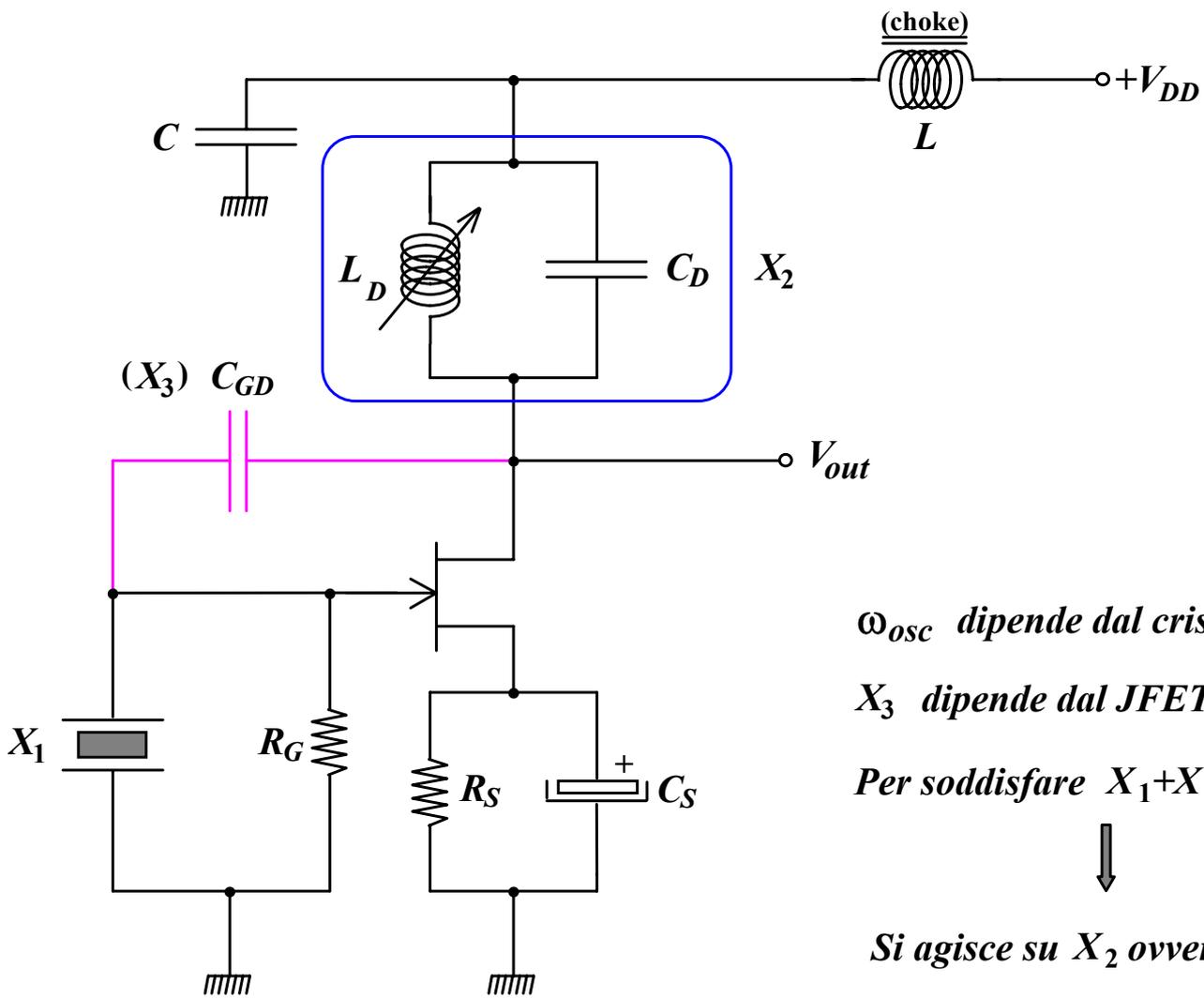
$d = \frac{\lambda}{2} = \text{decimi...di...mm}$

⇓

Quarzi.in.."overtone"

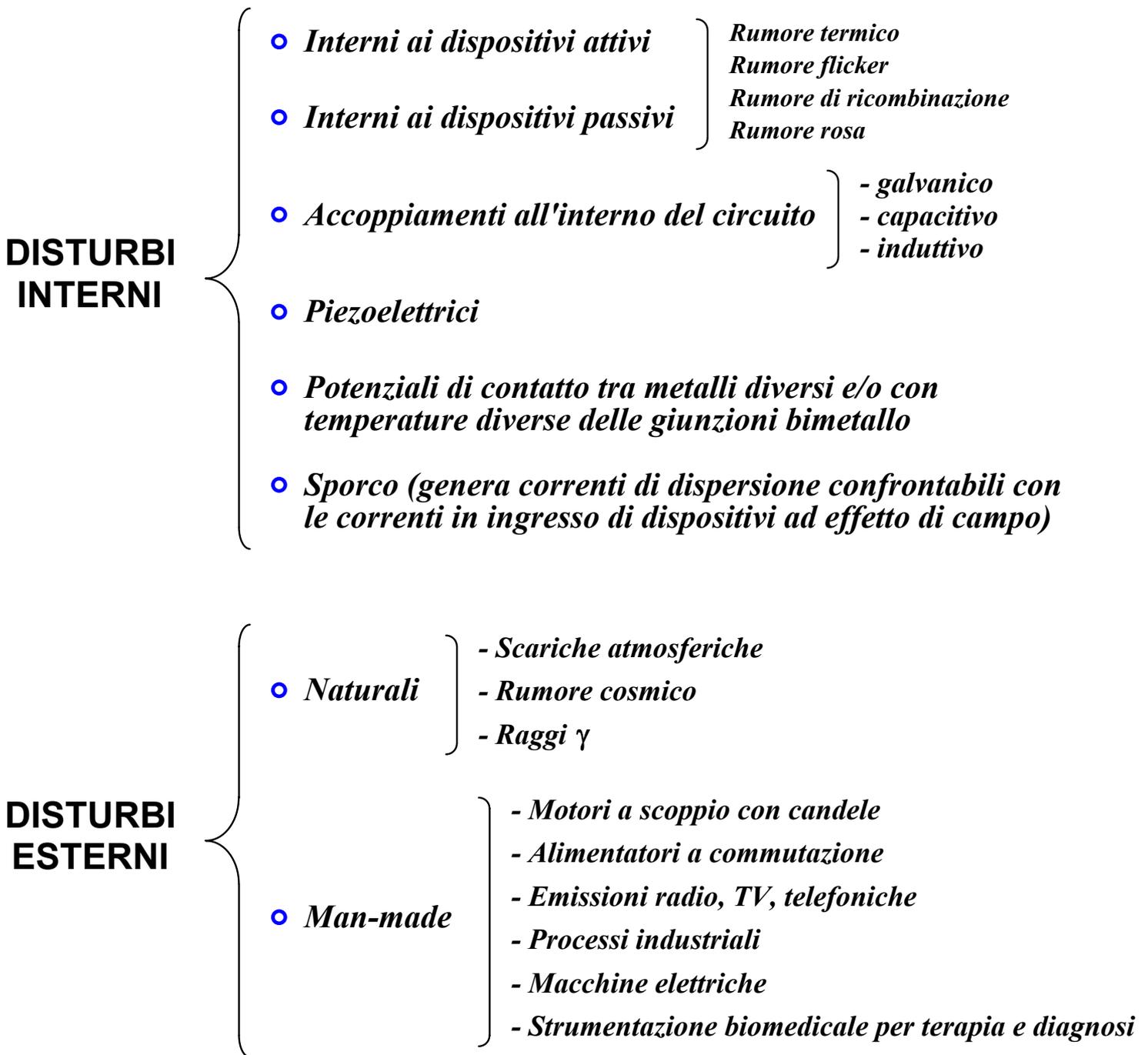


Oscillatore Hartley a quarzo



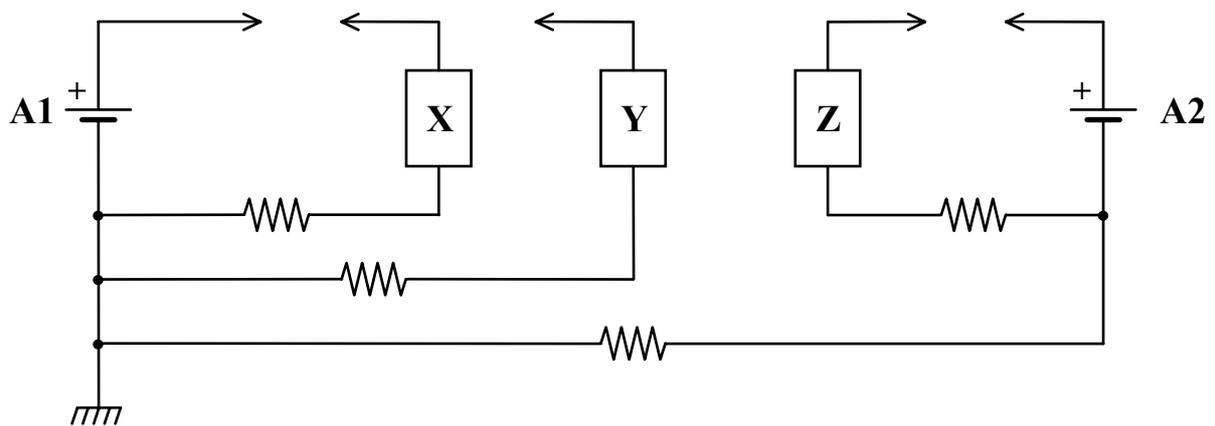
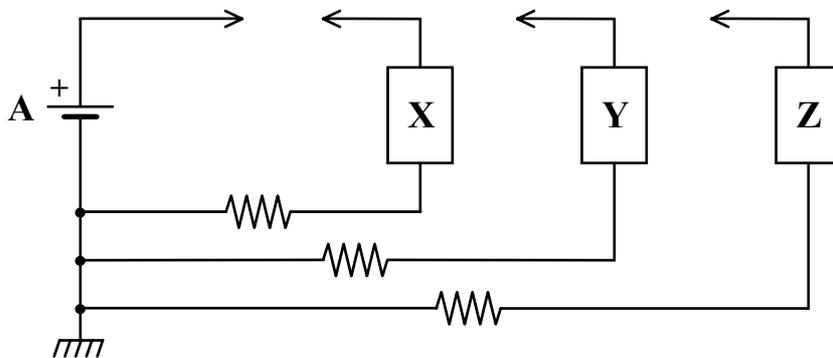
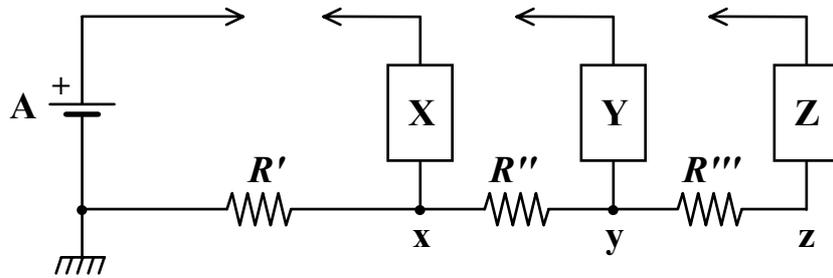
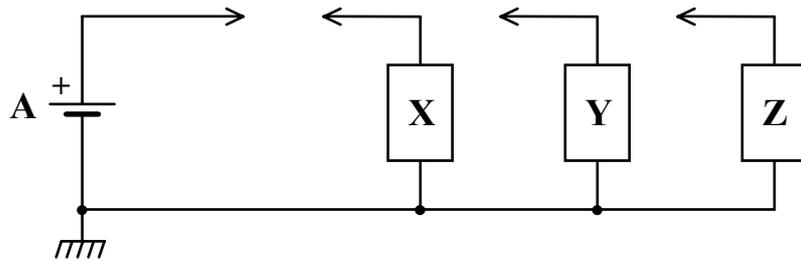
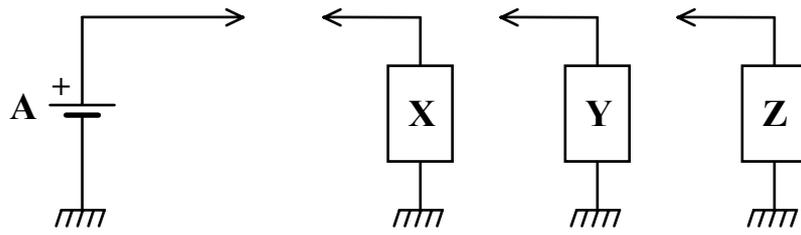
$$\omega_D = \frac{1}{\sqrt{L_D C_D}}$$

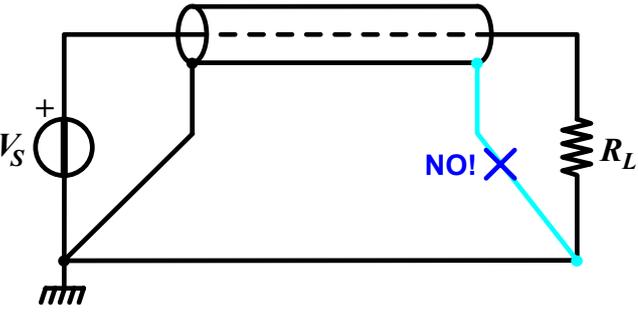
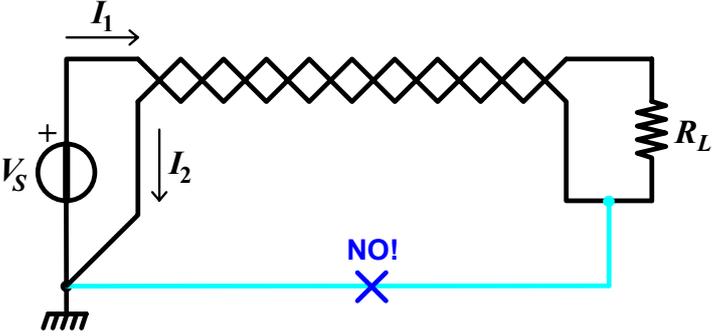
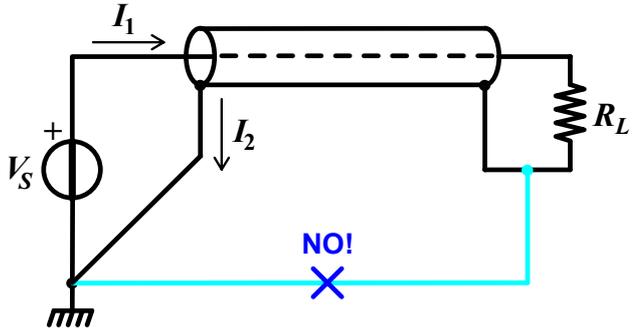
Tipi di disturbi e metodi per la loro riduzione



Problema della Compatibilità Elettromagnetica
(e.m.c.=electromagnetic compatibility)

Accoppiamento galvanico

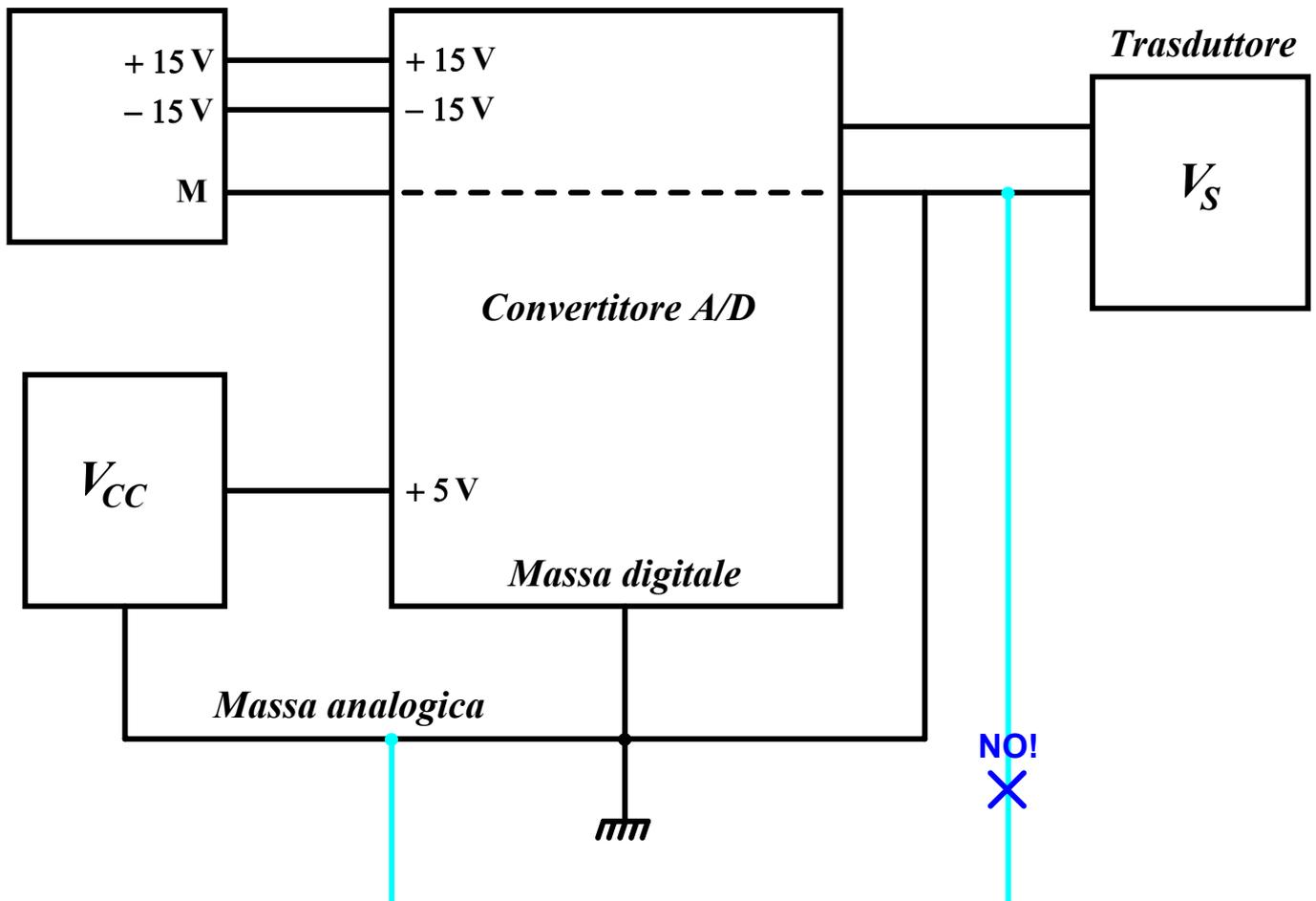
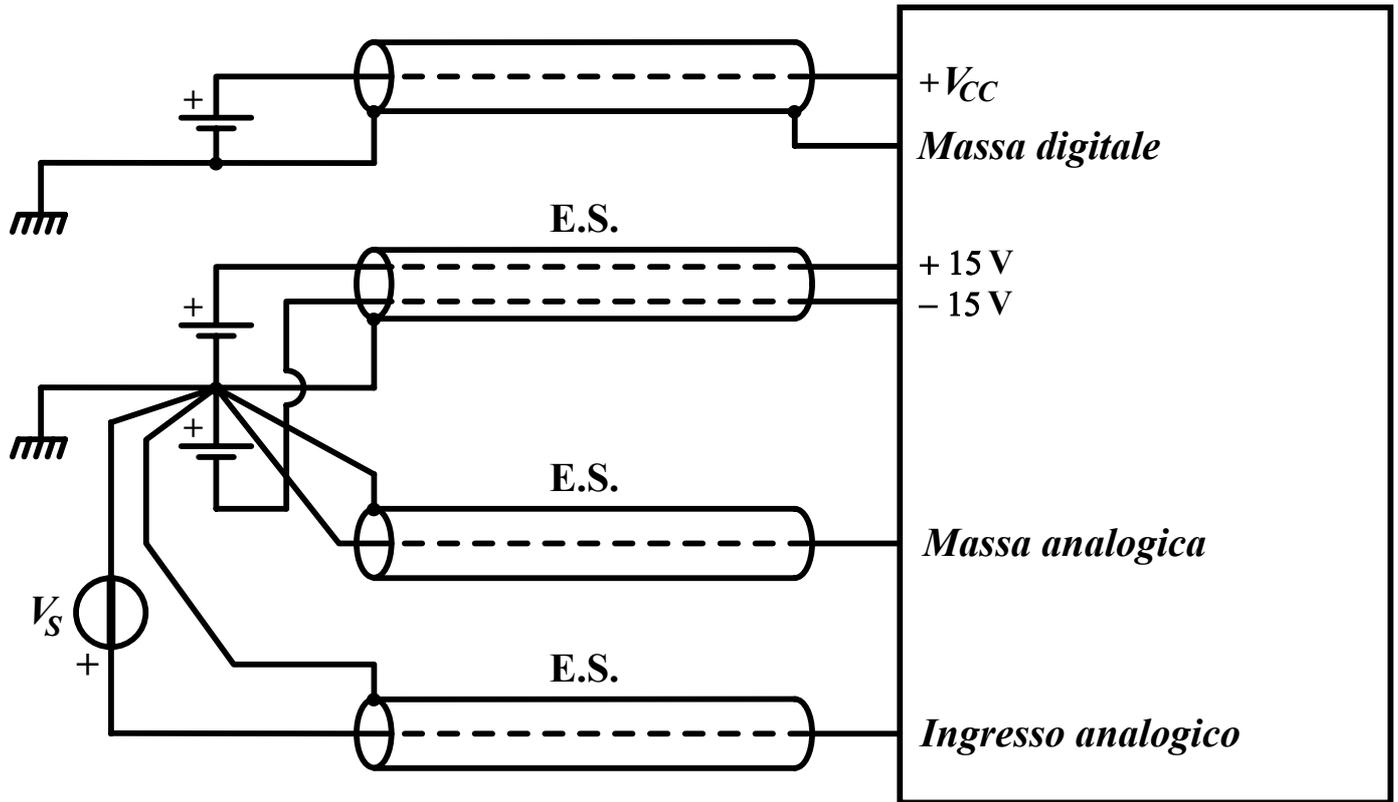


<i>Schermo elettrostatico (E.S.)</i>	<i>Sistemi per la riduzione della potenza irradiata</i>
	
	

Suggerimenti per la realizzazione di un circuito stampato

- Tutte le masse locali sono da connettersi ad un unico grande piano di massa;
- Le capacità di by-pass (10÷100nF) sono da collegarsi il più vicino possibile ai circuiti integrati;
- Le aree libere da componenti e piste vanno collegate al piano di massa;
- Si deve cercare di realizzare circuiti con minime dimensioni.

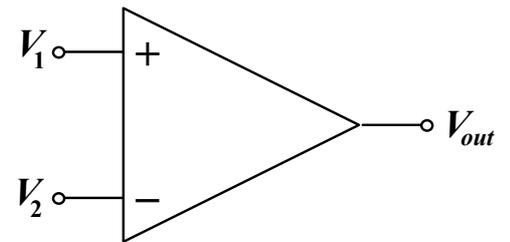
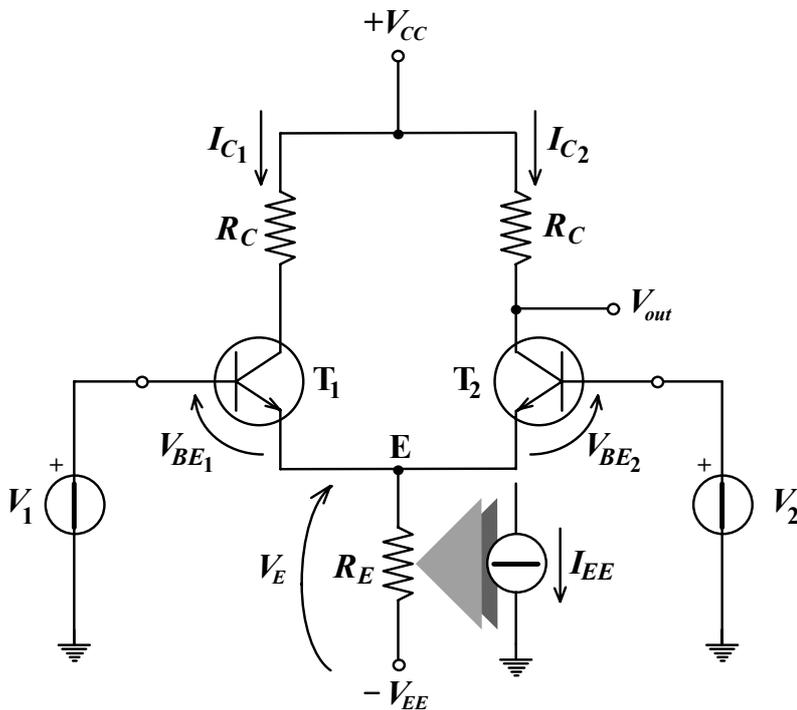
Esempi



Amplificatore differenziale

$$I_{C_1} \left(1 + \frac{I_{C_2}}{I_{C_1}} \right) = \alpha_F I_{EE} \Rightarrow I_{C_1} = \frac{\alpha_F I_{EE}}{1 + \frac{I_{C_2}}{I_{C_1}}}$$

$$I_{E_1} + I_{E_2} = I_{EE} \Rightarrow I_{C_2} \left(1 + \frac{I_{C_1}}{I_{C_2}} \right) = \alpha_F I_{EE} \Rightarrow I_{C_2} = \frac{\alpha_F I_{EE}}{1 + \frac{I_{C_1}}{I_{C_2}}}$$



$$V_1 = V_{BE_1} + V_E; \quad V_2 = V_{BE_2} + V_E \quad \Rightarrow \quad V_1 - V_2 = V_{BE_1} - V_{BE_2} = V_d$$

$$I_C = \alpha_F I_{E_S} \left(e^{-\frac{V_{BE}}{\eta V_T}} - 1 \right) - I_{C_S} \left(e^{-\frac{V_{CB}}{\eta V_T}} - 1 \right)$$

⇓ (regione attiva)

$$I_{C_1} = \alpha_F I_{E_S} e^{-\frac{V_{BE1}}{V_T}} \quad I_{C_2} = \alpha_F I_{E_S} e^{-\frac{V_{BE2}}{V_T}}$$

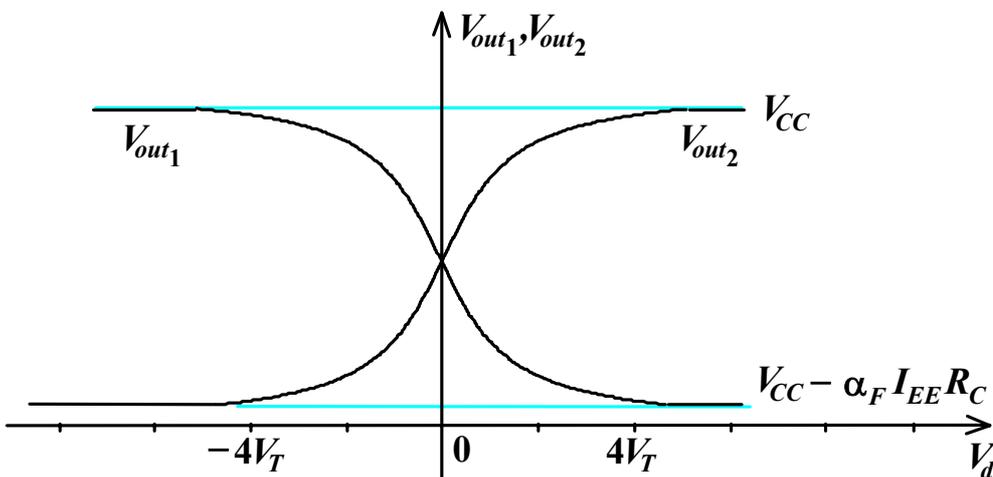
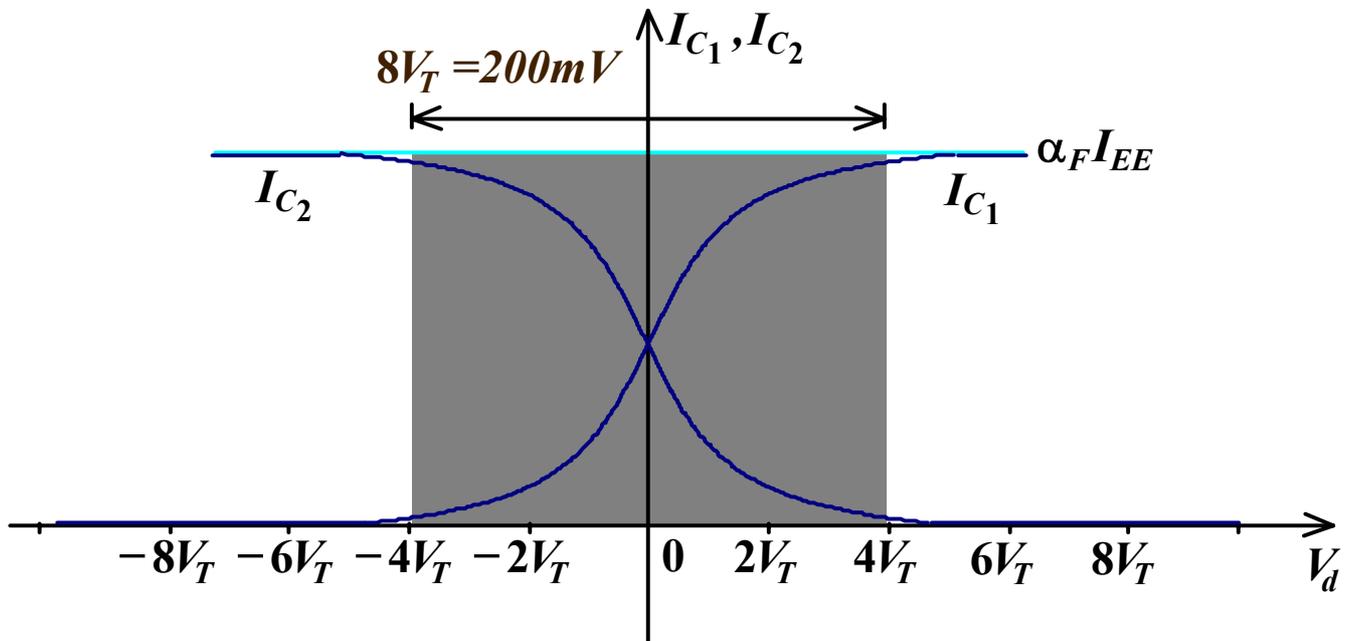
Supposti uguali i guadagni di corrente si ha:

$$\frac{I_{C1}}{I_{C2}} = e^{\frac{V_{BE1} - V_{BE2}}{V_T}} = e^{\frac{V_d}{V_T}} \Rightarrow \frac{I_{C2}}{I_{C1}} = e^{-\frac{V_d}{V_T}}$$

⇓

$$I_{C1} = \frac{\alpha_F I_{EE}}{1 + e^{-\frac{V_d}{V_T}}} \quad I_{C2} = \frac{\alpha_F I_{EE}}{1 + e^{\frac{V_d}{V_T}}}$$

Graficamente

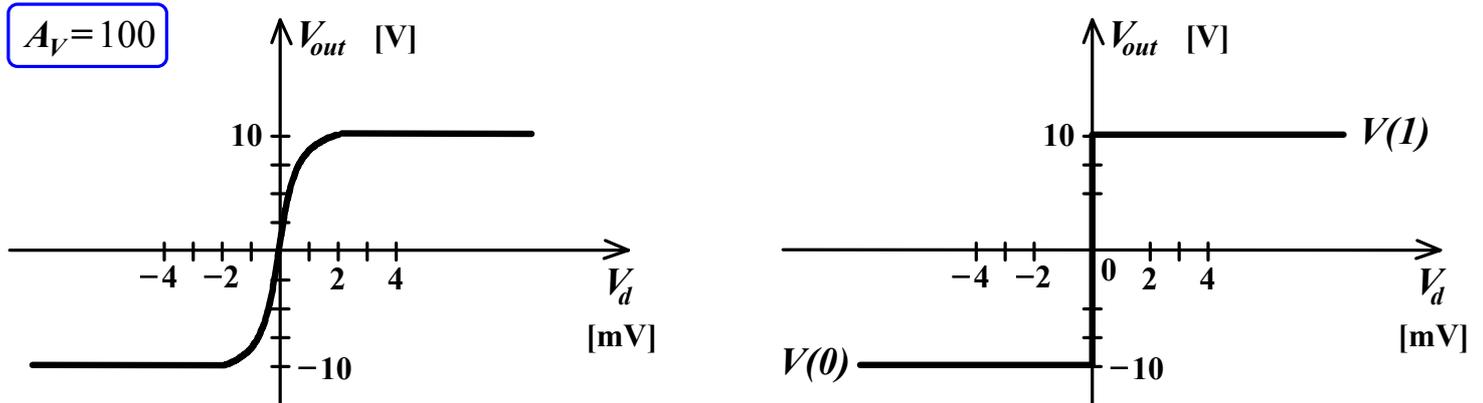


$$V_{out1} = V_{CC} - R_C I_{C1}$$

$$V_{out2} = V_{CC} - R_C I_{C2}$$

Comparatori

Caratteristiche a confronto



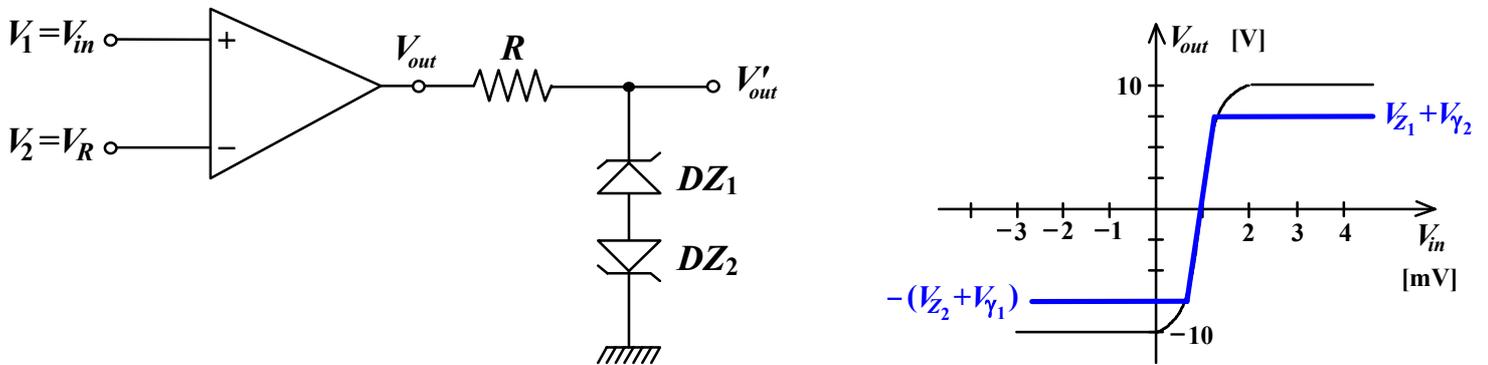
Modelli di comparatori (ΔV_i fino a $15\mu\text{V}$ e ritardi di $20 \div 200$ ns):

Fairchild $\mu\text{A}710$

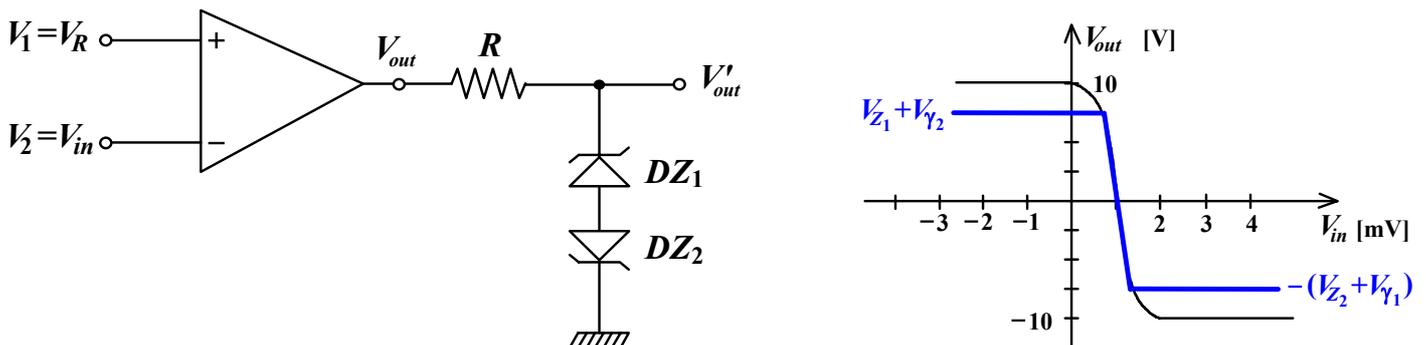
National LM111
Harris HA2111

Analog Devices AD604

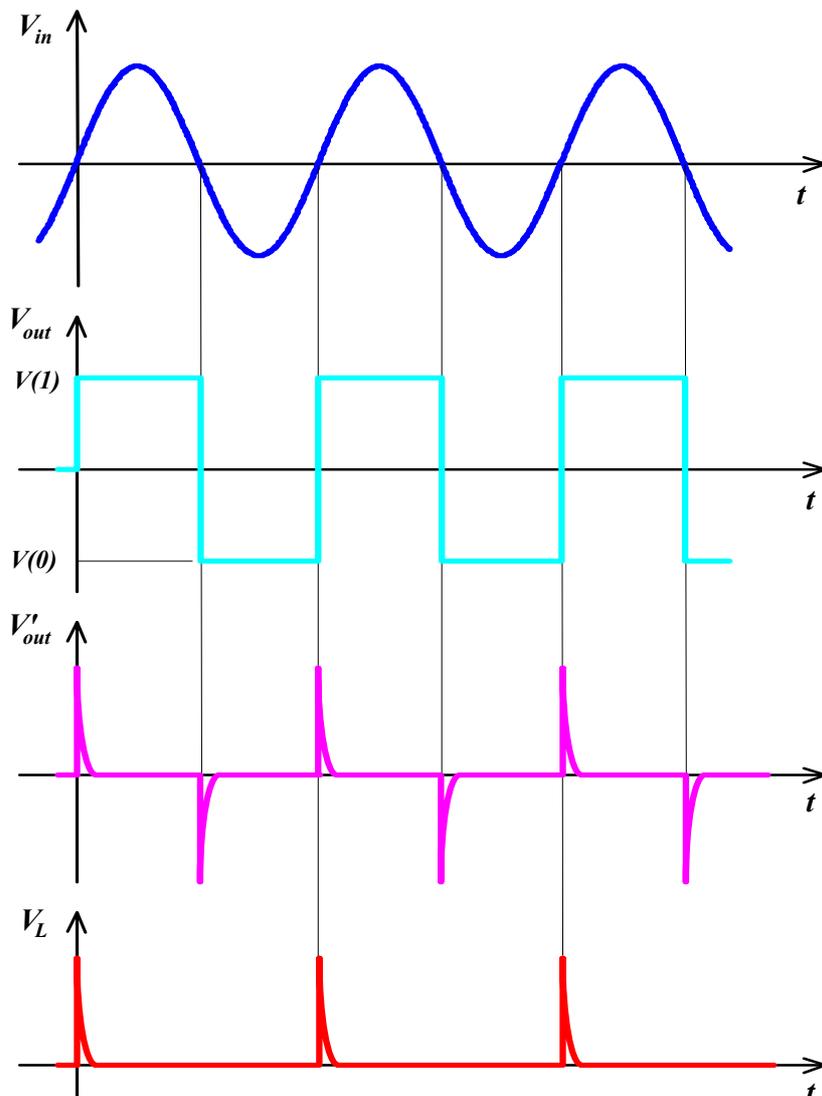
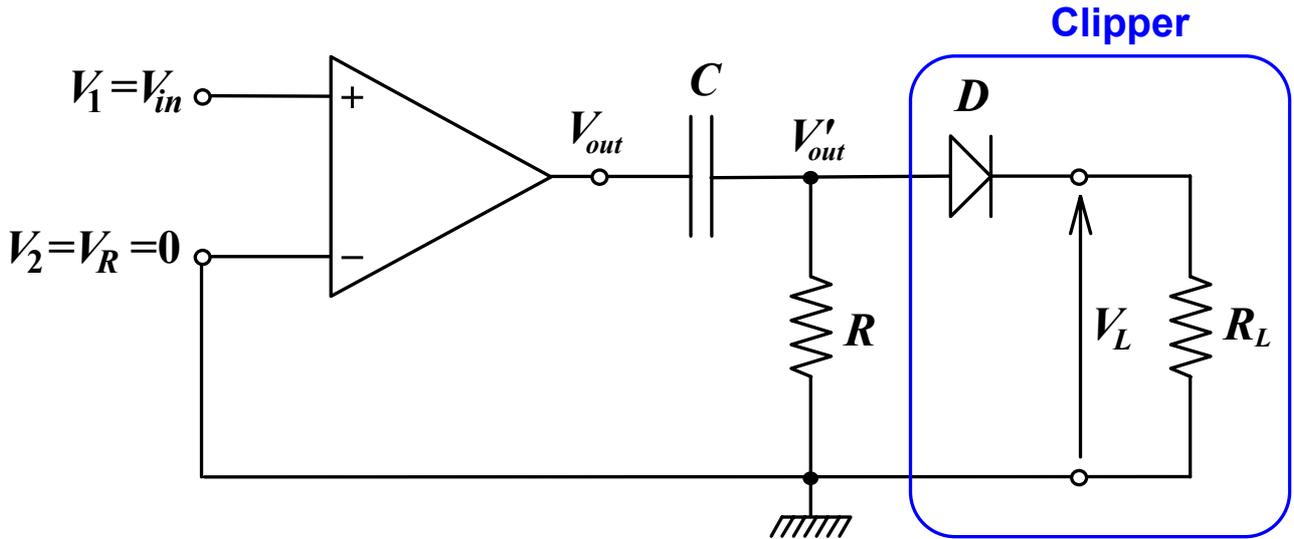
Funzionamento non invertente



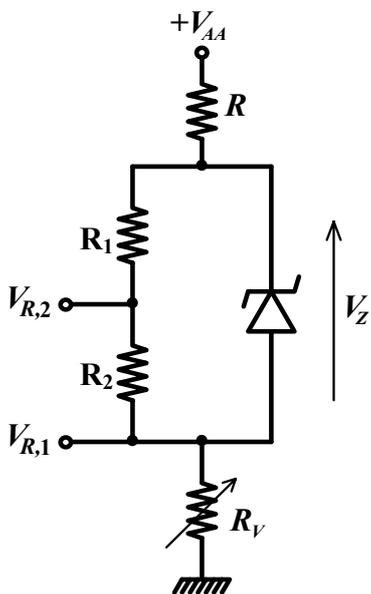
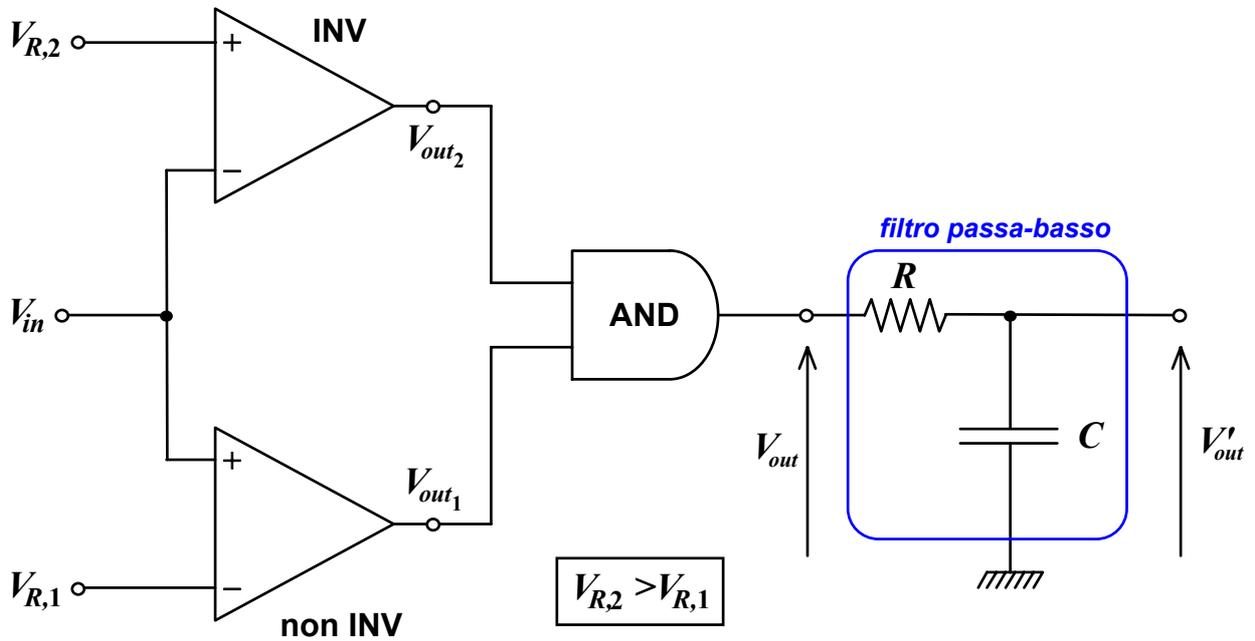
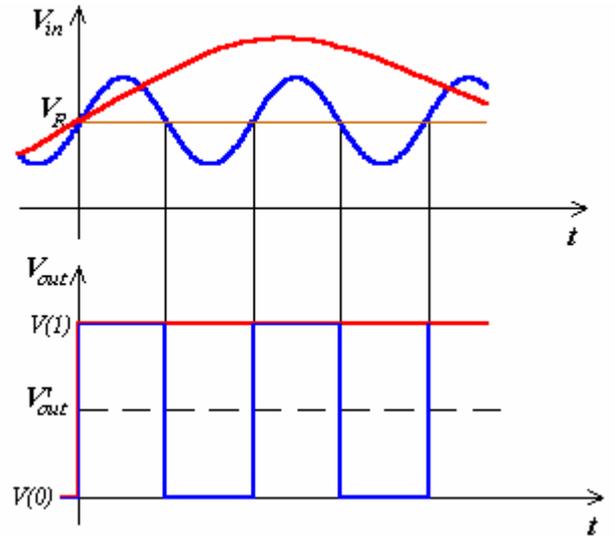
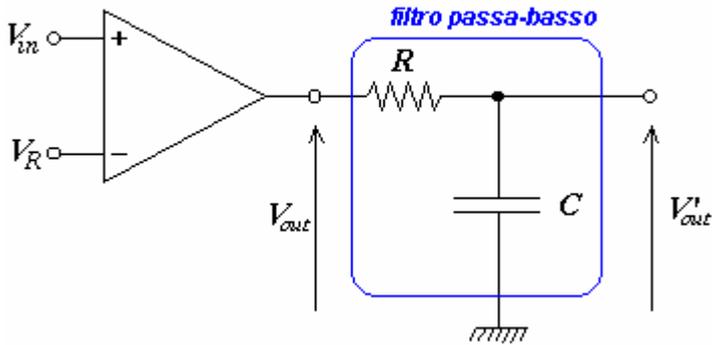
Funzionamento invertente



Zero crossing detector



Altri circuiti con comparatori

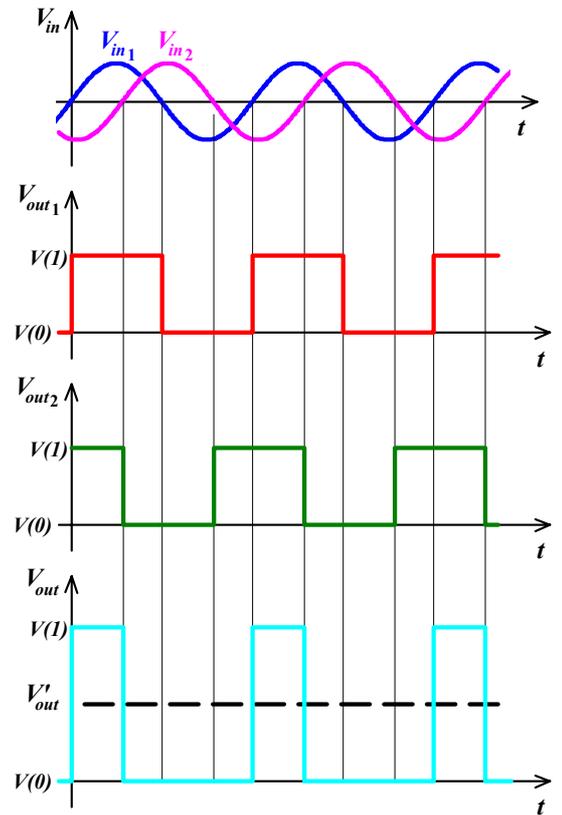
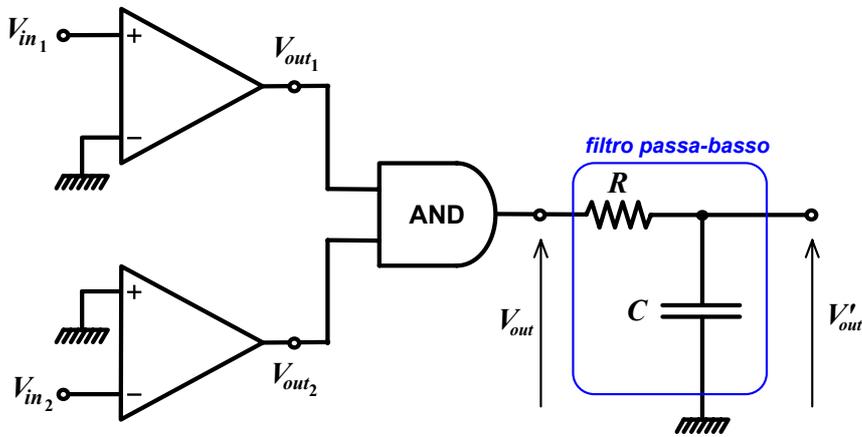
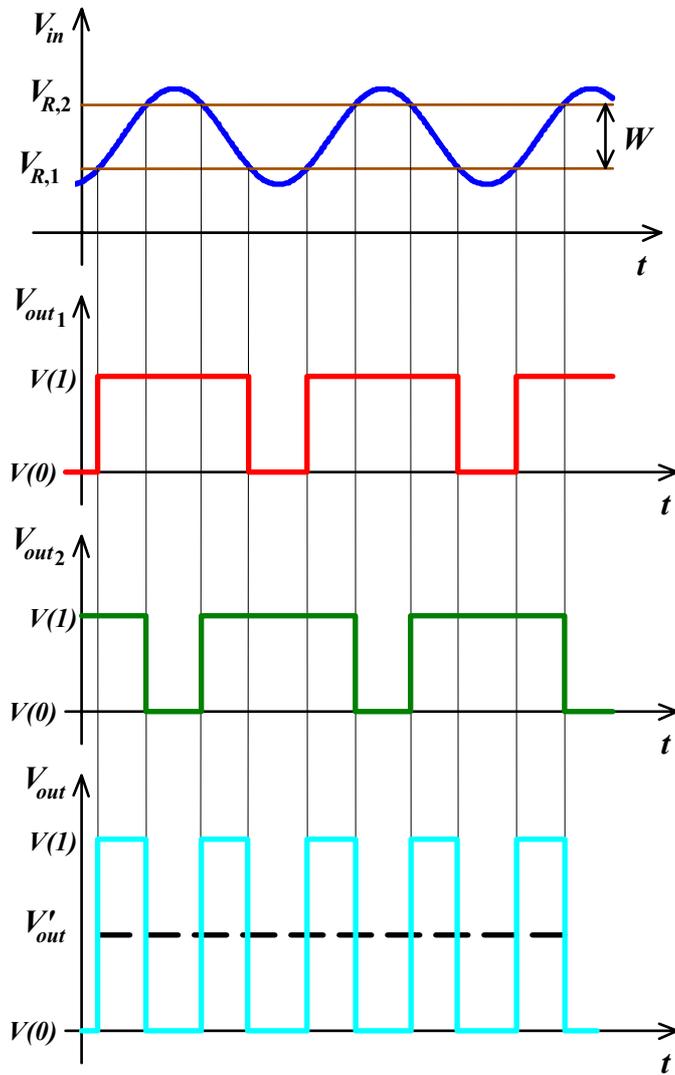


$$V_{R,1} = \frac{R_V}{R + R_V} (V_{AA} - V_Z)$$

$$V_{R,2} = \frac{R_V}{R + R_V} (V_{AA} - V_Z) + \frac{R_2}{R_1 + R_2} V_Z$$

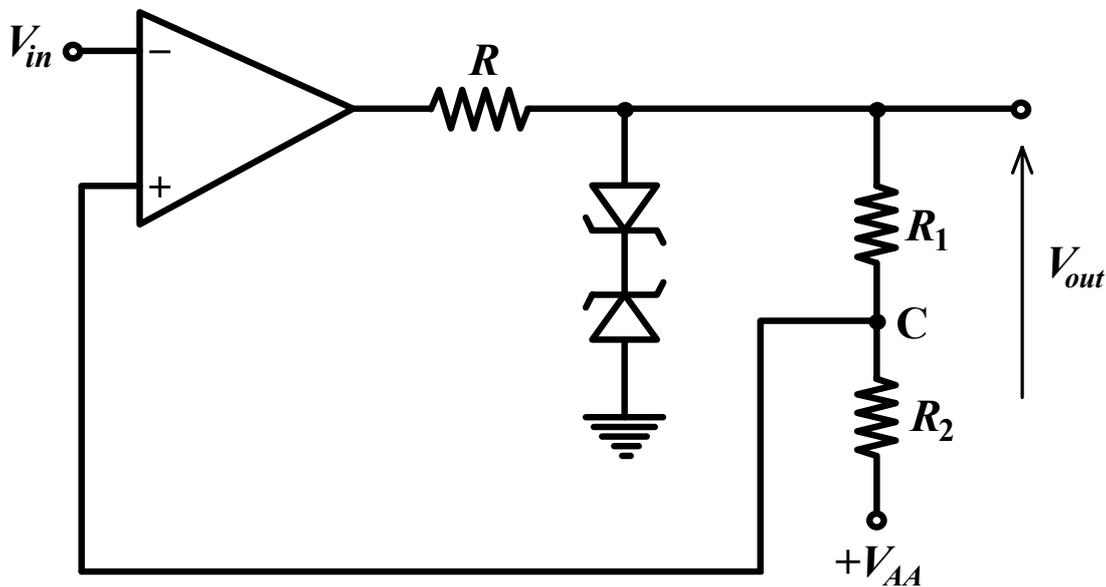
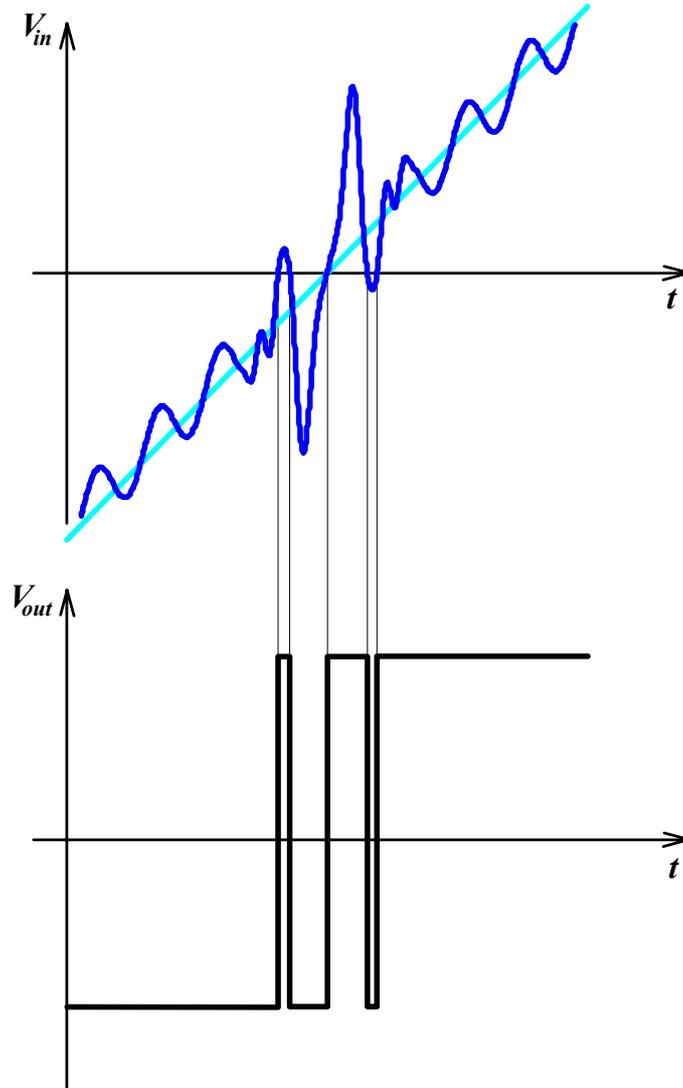
$$W = V_{R,2} - V_{R,1} = \frac{R_2}{R_1 + R_2} \cdot V_Z$$

$$\bar{V}_R = \frac{2 \left[\frac{R_V}{R + R_V} (V_{AA} - V_Z) \right] + \frac{R_2}{R_1 + R_2} V_Z}{2} = V_{R,1} + \frac{W}{2}$$



Trigger di Schmitt

Fenomeno del chattering



$$V(1) = 5V$$

$$V(0) = -5V$$

$$A = 10.000$$

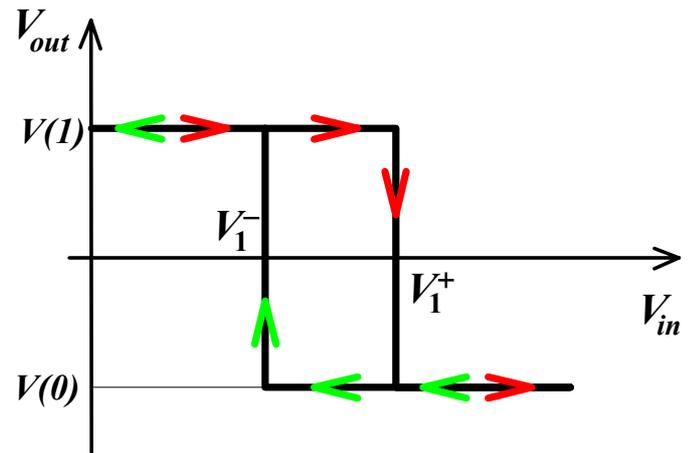
$$|\beta A| > 1$$

$$V_1^+ = \frac{R_2}{R_1 + R_2} V_{out} + \frac{R_1}{R_1 + R_2} V_{AA}$$

$$V_1^- = -\frac{R_2}{R_1 + R_2} V_{out} + \frac{R_1}{R_1 + R_2} V_{AA}$$

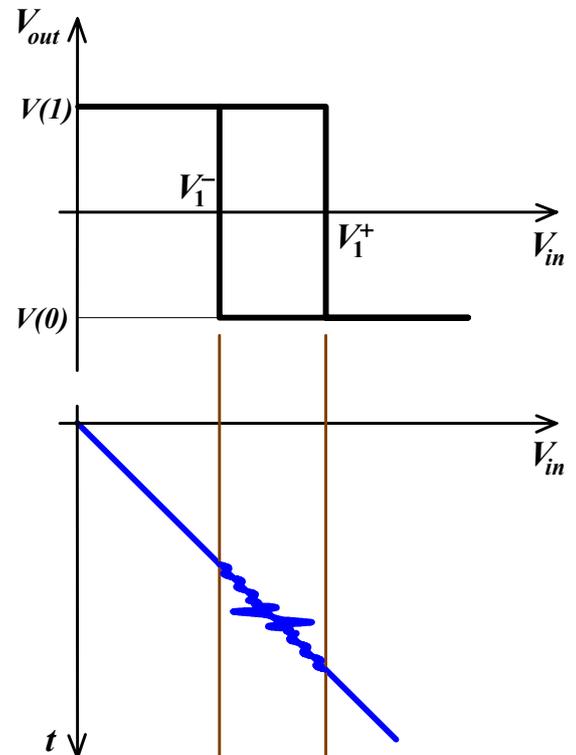
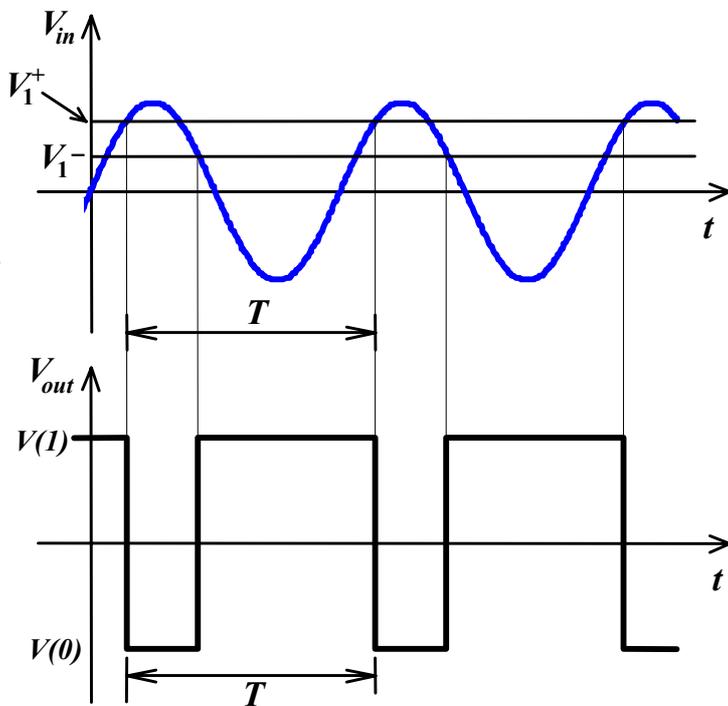
$$\Downarrow$$

$$V_1^- < V_1^+$$

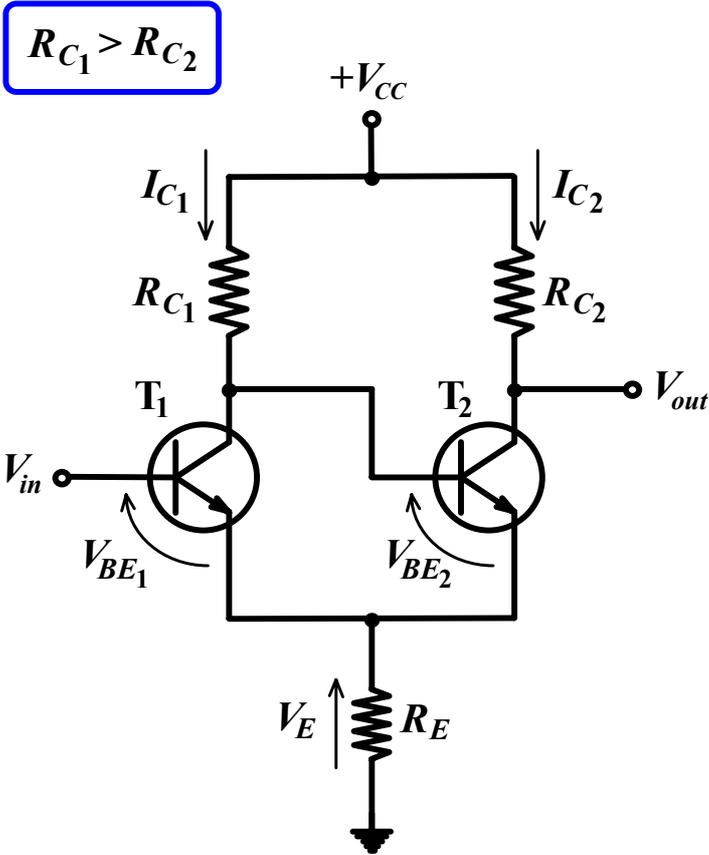


$$V_1^+ - V_1^- = \frac{2R_2}{R_1 + R_2} V_{out} \Rightarrow \text{se } R_2 \rightarrow 0 \Rightarrow V_1^+ - V_1^- \rightarrow 0$$

$$\frac{V_1^+ - V_1^-}{2} = \frac{R_1}{R_1 + R_2} V_{AA} \Rightarrow \text{se } V_{AA} = 0 \text{ la curva di isteresi si pone a cavallo dello } 0$$



Trigger di Schmitt realizzato a BJT



T₁ interdetto, T₂ saturo

$$\left(I_{C1} = I_{B2} \geq \frac{I_{C2,sat}}{h_{fe2}} \right)$$

⇓

$$V_{out} = V_{CC} - R_{C2} I_{C2,sat} \quad \text{(bassa)}$$

Quando

$$V_{in}^+ = V_E + V_{BE1,ON} = R_E I_{C2,sat} + V_{BE1,ON}$$

⇓

$$V_{out} \cong V_{CC} \quad \text{(alta)}$$

⇓

Quando

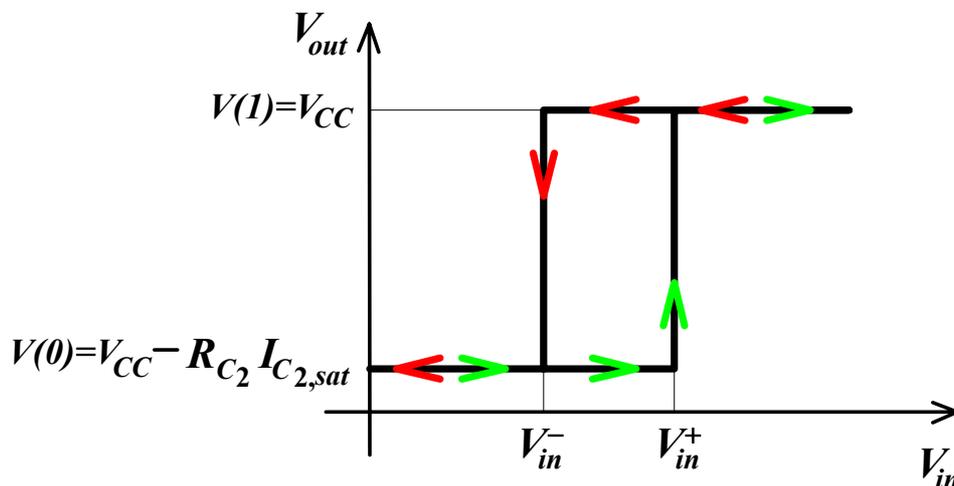
$$V_{in}^- = V_E + V_{BE2,ON} = R_E I_{C1,sat} + V_{BE2,ON}$$

⇓

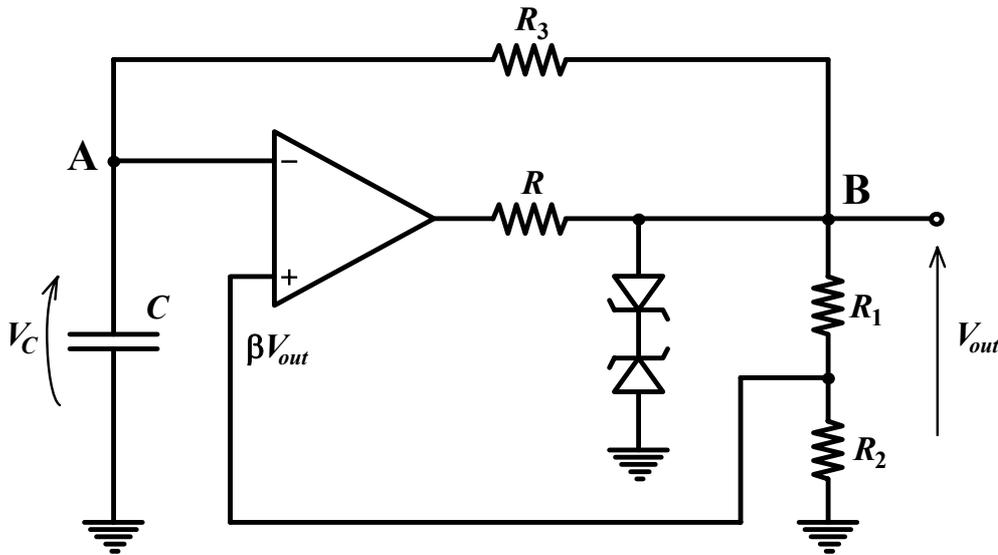
$$V_{out} = V_{CC} - R_{C2} I_{C2,sat}$$

(bassa)

$$V_H = V_{in}^+ - V_{in}^- = R_E (I_{C2,sat} - I_{C1,sat})$$



Generatori di onda quadra e triangolare (10÷10⁴ Hz)



$$V(1) = V_\gamma + V_Z$$

$$V(0) = -V_\gamma - V_Z$$

$$\beta = \frac{R_2}{R_1 + R_2}$$

$$V_d = V_C - \beta V_{out}$$

$$V_C(t) = A + B e^{-\frac{t}{\tau}} \quad \tau = R_3 C$$

$$V_C(0) = -\beta V_{out} = A + B$$

$$V_C(+\infty) = V_{out} = A$$

$$V_C(t) = V_{out} - V_{out}(1 + \beta) e^{-\frac{t}{\tau}}$$

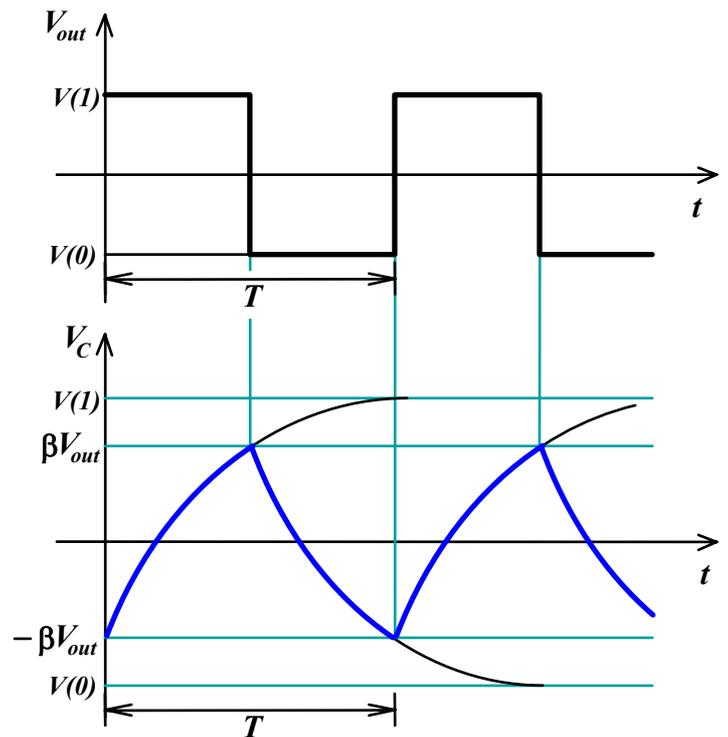
Poichè

$$V_C\left(\frac{T}{2}\right) = \beta V_{out} = V_{out} \left[1 - (1 + \beta) e^{-\frac{T}{2\tau}} \right]$$

dividendo per V_{out} si trova:

$$(1 + \beta) e^{-\frac{T}{2\tau}} = 1 - \beta \Rightarrow$$

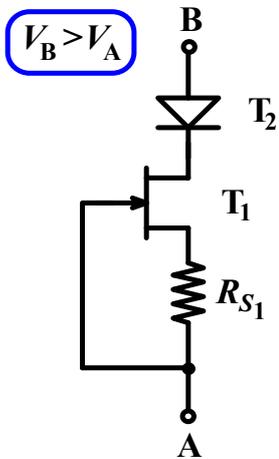
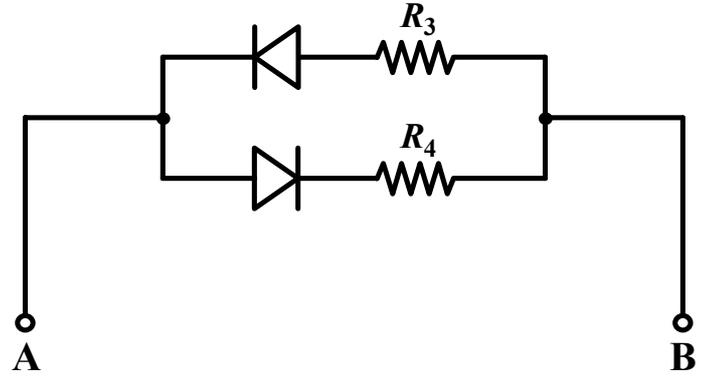
$$T = 2\tau \left[\ln\left(\frac{1 + \beta}{1 - \beta}\right) \right] = 2\tau \ln\left(1 + \frac{2R_1}{R_2}\right)$$



In generale $T = T_1 + T_2$ dove:

$$T_1 = R_3 C \ln \left(\frac{V(1) + \beta V(0)}{V(1) - \beta V(1)} \right)$$

$$T_2 = R_4 C \ln \left(\frac{V(0) + \beta V(1)}{V(0) - \beta V(0)} \right)$$



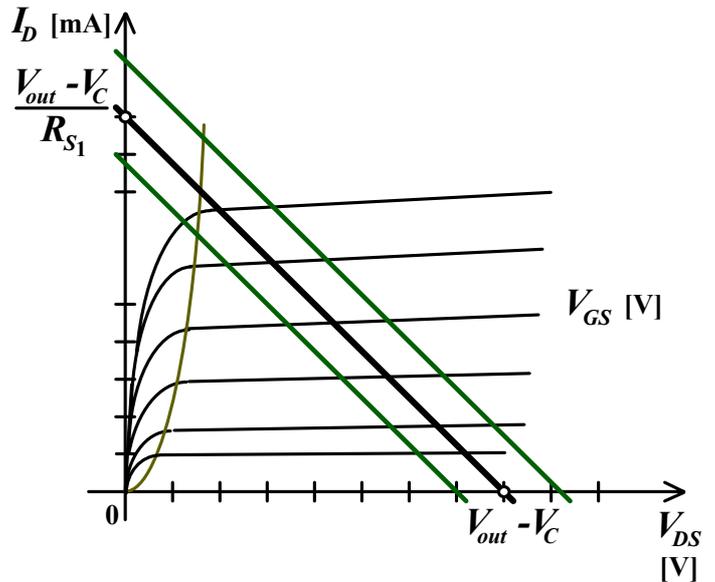
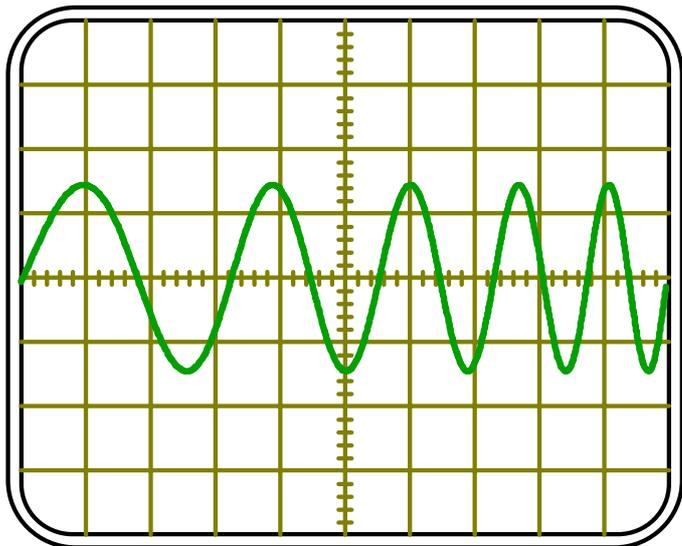
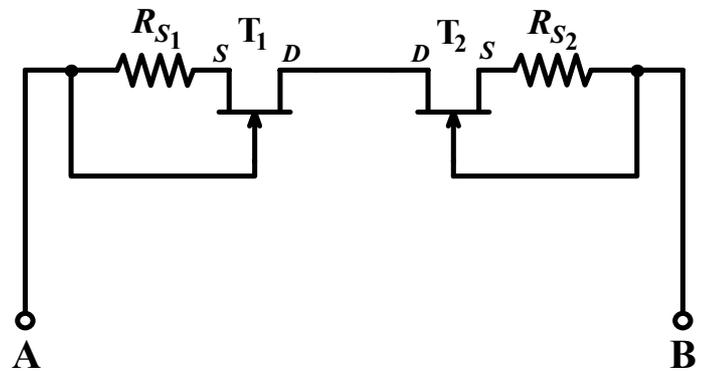
$$v_C = \frac{1}{C} \int i_C dt$$

\Downarrow

i_C costante

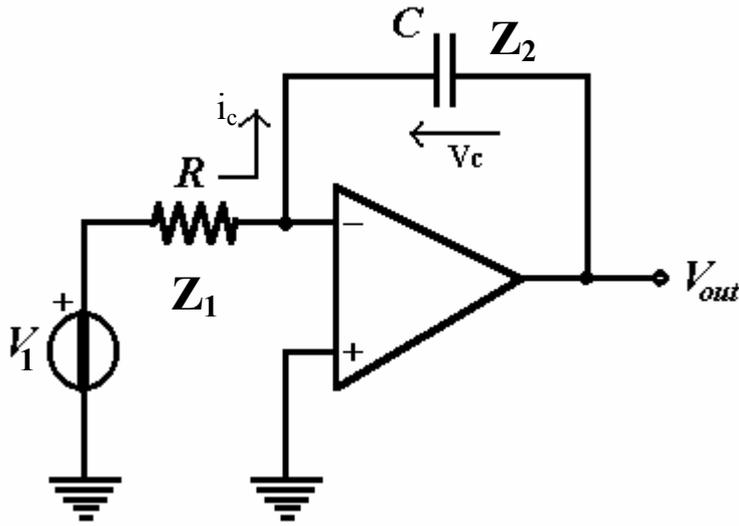
\Downarrow

$$v_C(t) = \frac{I_C}{C} t$$



$$I_D \uparrow \Rightarrow V_{R_{S1}} \uparrow \Rightarrow V_{SG1} \uparrow \Rightarrow I_D \downarrow$$

Utilizzo di un integratore di Miller



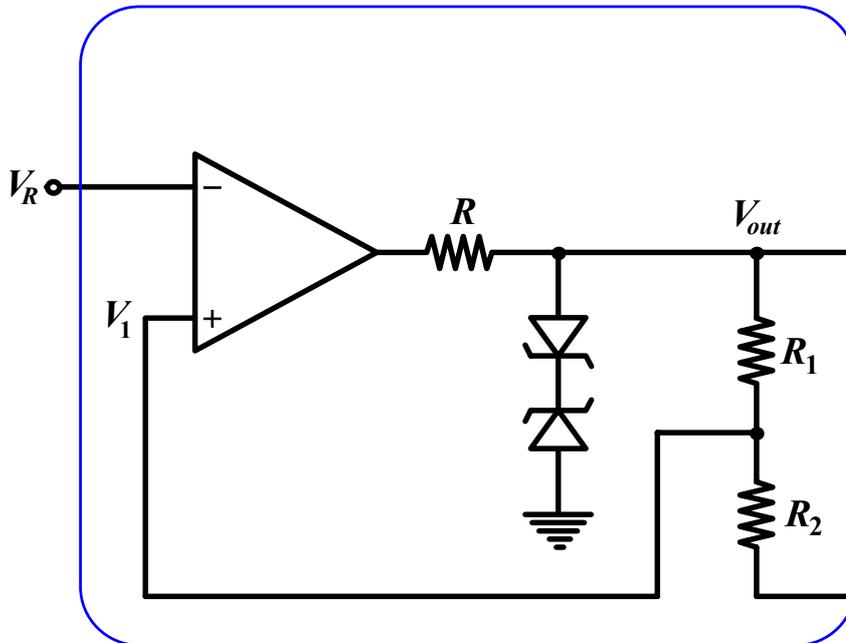
$$A_V = \frac{V_{out}}{V_1} = -\frac{Z_2}{Z_1} = -\frac{1}{j\omega RC}$$

$$\frac{V_1}{R} = I_1 = i_C$$

$$i_C = C \frac{dV_C}{dt} = -C \frac{dV_{out}}{dt} = \frac{V_1}{R}$$

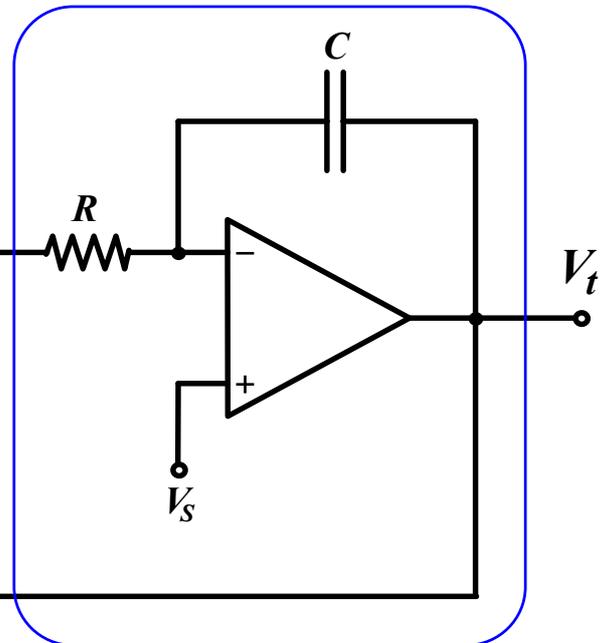
$$V_{out} = -\frac{1}{RC} \int_0^t V_1 dt + V_{out}(0)$$

trigger di Schmitt



$$V(1) = V_\gamma + V_Z$$

integratore di Miller

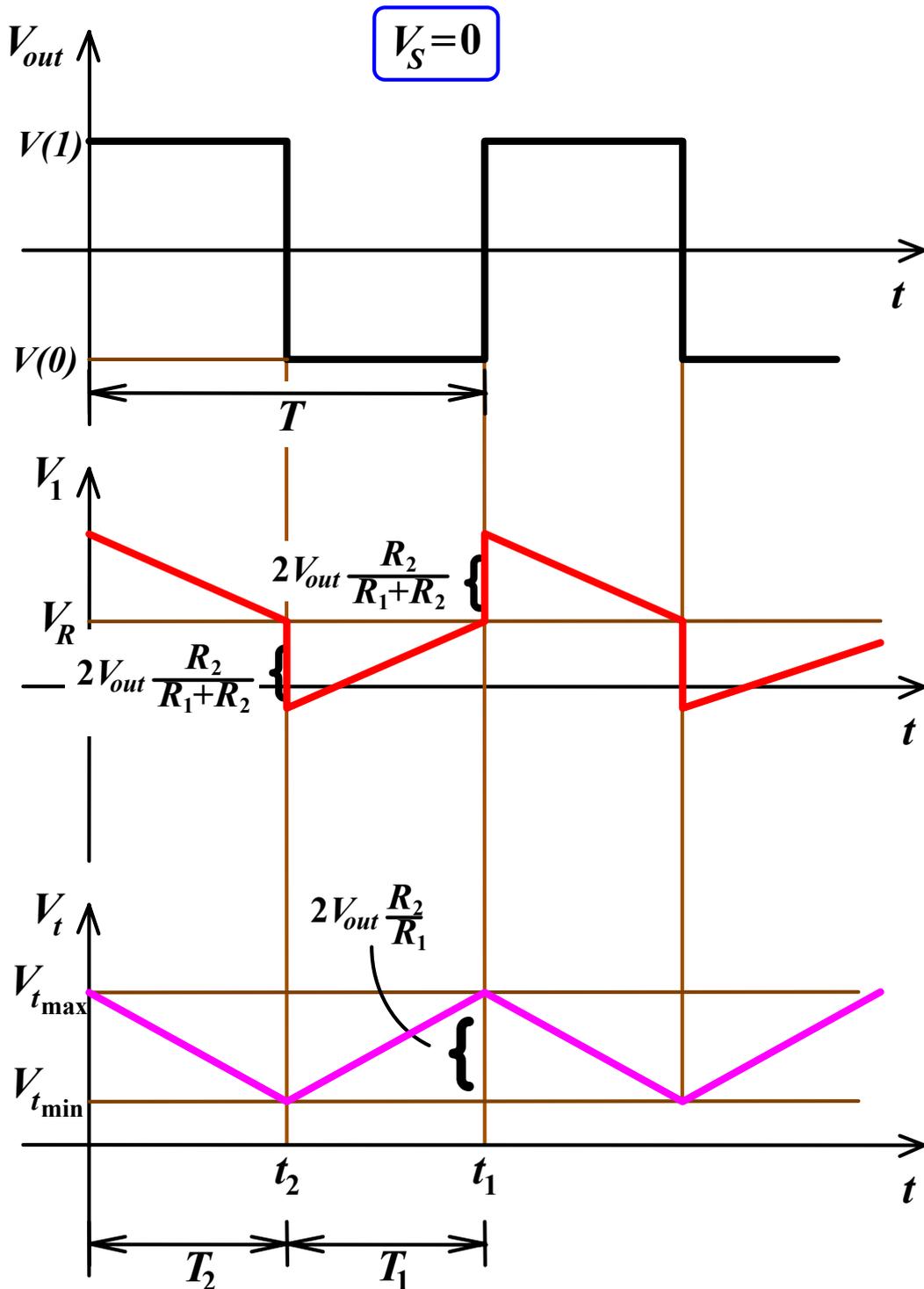


$$V(0) = -V_\gamma - V_Z$$

$$Hp: V_S = 0 \Rightarrow T_1 = T_2 = \frac{T}{2}$$

$$I_C = \frac{V_{out}}{R} \quad V_1 = \frac{R_1}{R_1 + R_2} V_t + \frac{R_2}{R_1 + R_2} V_{out}$$

$$V_C = \frac{I_C}{C} t + K = \frac{V_{out}}{R_C} t + K$$



$$V_1(t_2) = \frac{R_1}{R_1 + R_2} V_{t_{\min}} + \frac{R_2}{R_1 + R_2} V_{out} = V_R \Rightarrow V_{t_{\min}} = \frac{R_1 + R_2}{R_1} V_R - \frac{R_2}{R_1} V_{out}$$

$$V_1(t_1) = \frac{R_1}{R_1 + R_2} V_{t_{\max}} - \frac{R_2}{R_1 + R_2} V_{out} = V_R \Rightarrow V_{t_{\max}} = \frac{R_1 + R_2}{R_1} V_R + \frac{R_2}{R_1} V_{out}$$

$$\Delta V_t = V_{t_{\max}} - V_{t_{\min}} = 2 V_{out} \frac{R_2}{R_1} \qquad \frac{V_{t_{\max}} + V_{t_{\min}}}{2} = \frac{R_1 + R_2}{R_1} V_R$$

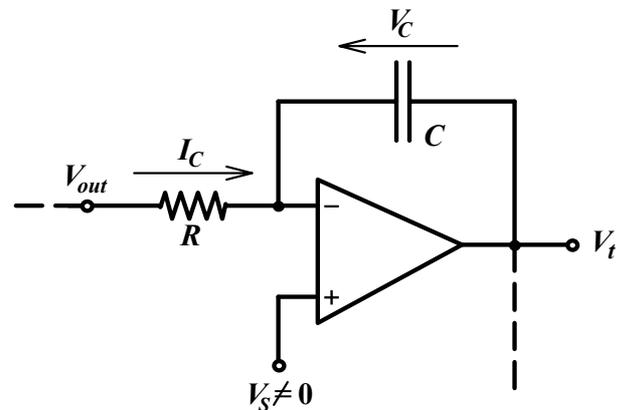
$$\frac{V_{t_{\max}} - V_{t_{\min}}}{T/2} = \left| \frac{dV_C}{dt} \right| = \frac{V_{out}}{RC} \Rightarrow 2 V_{out} \frac{R_2}{R_1} = \frac{V_{out}}{RC} \frac{T}{2} \Rightarrow$$

$$T = 4RC \frac{R_2}{R_1}$$

$$V_S \neq 0 \Rightarrow T_1 \neq T_2$$

$$I_R = I_C = \frac{V_{out} - V_S}{R} \Rightarrow V_t \downarrow \Rightarrow T_2$$

$$I_R = I_C^* = \frac{-V_{out} - V_S}{R} \Rightarrow V_t \uparrow \Rightarrow T_1$$



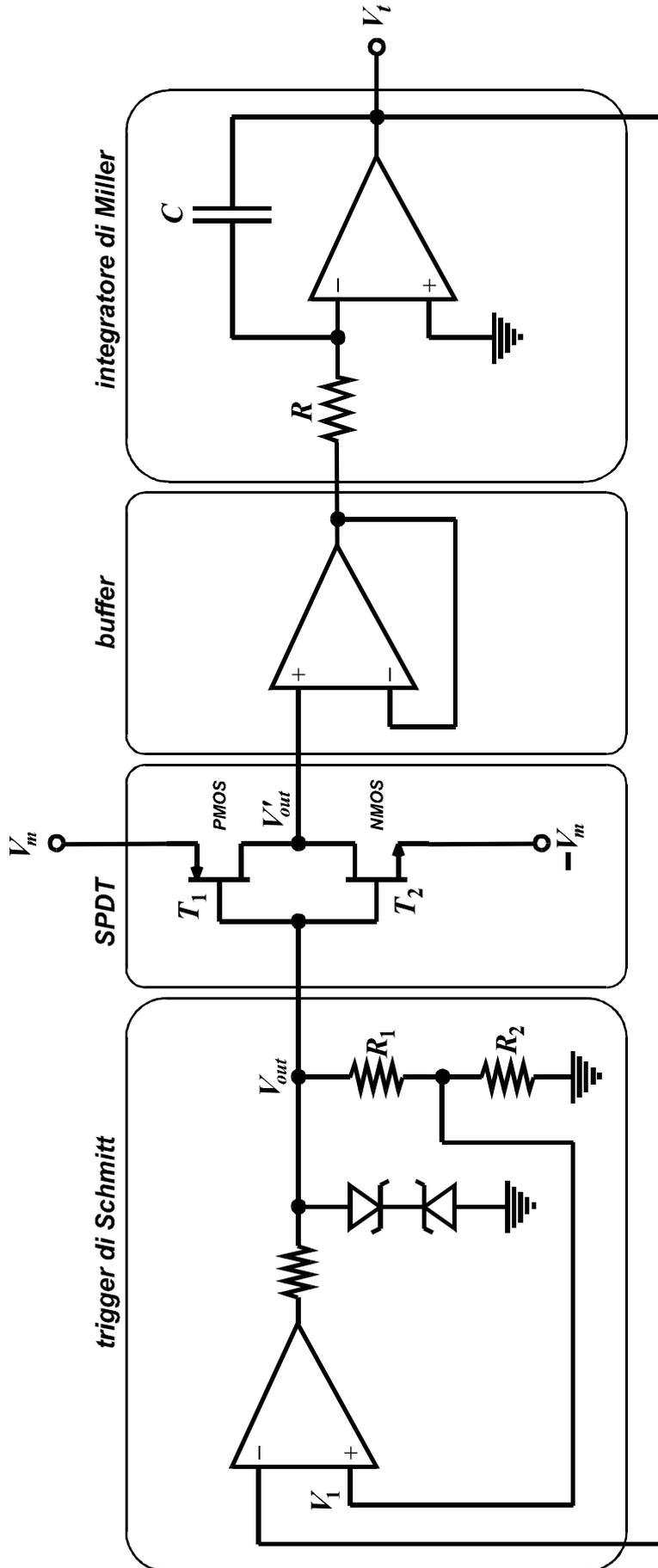
$$T_1 = 2V_{out} \frac{RC}{V_{out} + V_S} \frac{R_2}{R_1} \qquad T_2 = 2V_{out} \frac{RC}{V_{out} - V_S} \frac{R_2}{R_1}$$

$$T = T_1 + T_2 = 2V_{out} RC \frac{R_2}{R_1} \left[\frac{1}{V_{out} + V_S} + \frac{1}{V_{out} - V_S} \right] = 4RC \frac{R_2}{R_1} \frac{1}{1 - \left(\frac{V_S}{V_{out}} \right)^2}$$

$$f = \frac{R_1}{4RCR_2} \left(1 - \left(\frac{V_S}{V_{out}} \right)^2 \right) \qquad \frac{T_1}{T_1 + T_2} = \delta = \dots = \frac{1}{2} \left(1 - \frac{V_S}{V_{out}} \right)$$

$$V_S = 0 \Rightarrow \delta = 0,5 \qquad V_S = V_{out} \Rightarrow \delta = 0 \qquad V_S = -V_{out} \Rightarrow \delta = 1$$

V.C.O. (Voltage Controlled Oscillator)



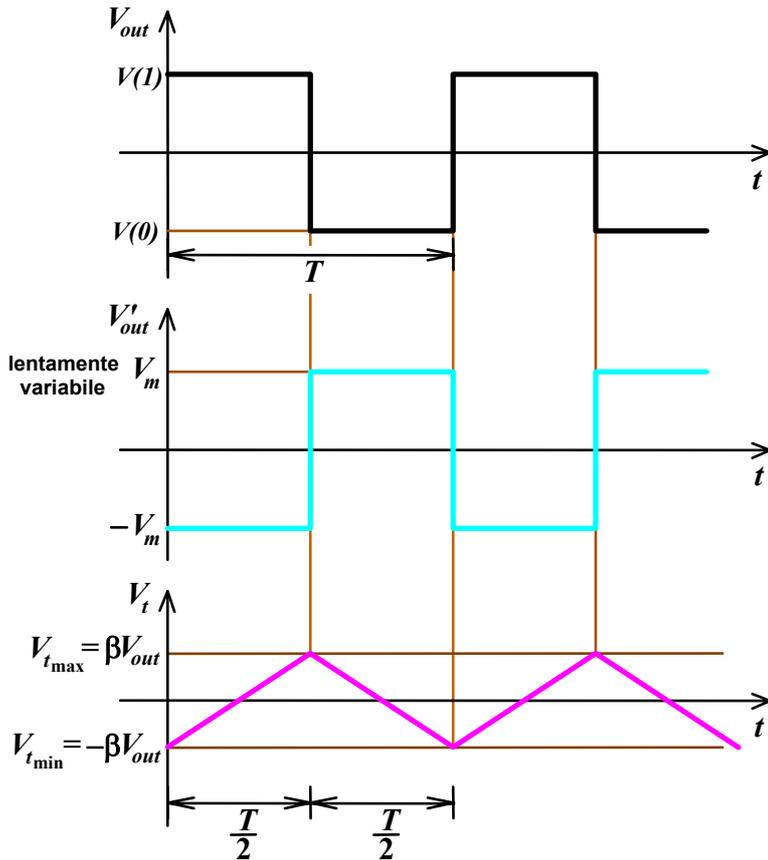
S.P.D.T. = Single Pole Double Throw

Ipotesi: $|V_{out}| > |V_m|$

V_m lentamente variabile \Rightarrow P.F.M. (Pulse Frequency Modulation)

$$V_{out} = V(1) \Rightarrow V'_{out} = -V_m \Rightarrow V_t \text{ sale}$$

$$V_{out} = V(0) \Rightarrow V'_{out} = V_m \Rightarrow V_t \text{ scende}$$

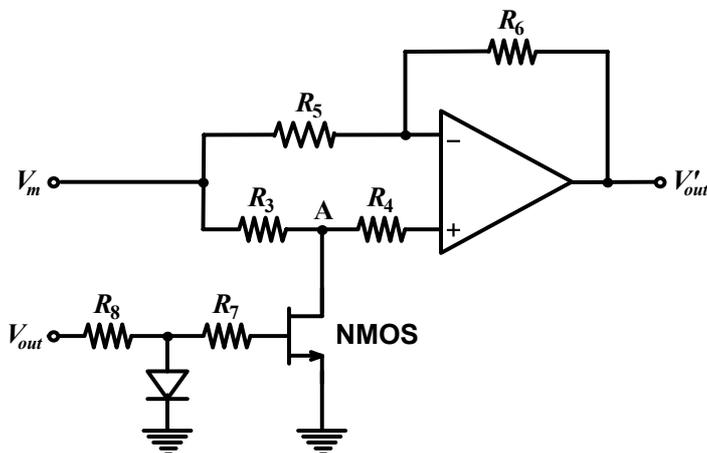


$$\frac{2\beta V_{out}}{T/2} = \frac{V_m}{RC}$$

\Downarrow

$$f_{osc} = \frac{1}{4\beta V_{out} RC} V_m$$

Amplificatore bifase



$$V_{out} > 0 \Rightarrow V'_{out} = -V_m \frac{R_6}{R_5}$$

$$\Downarrow R_5 = R_6 \Downarrow$$

$$V'_{out} = -V_m$$

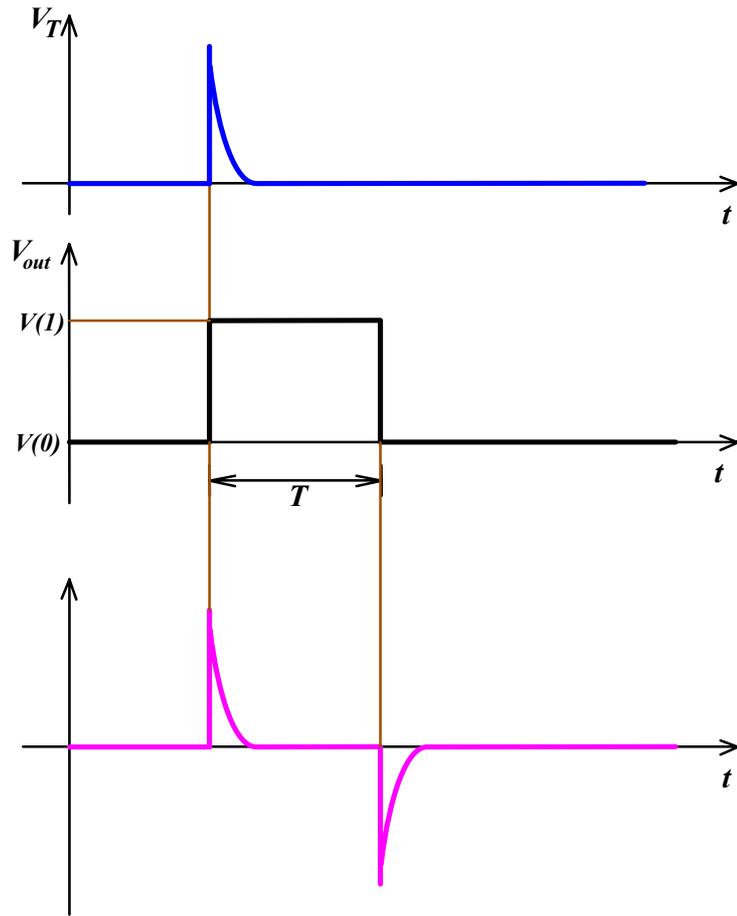
$$V_{out} < 0 \Rightarrow V'_{out} = -V_m \frac{R_6}{R_5} + V_m \left(1 + \frac{R_6}{R_5} \right)$$

$$\Downarrow R_5 = R_6 \Downarrow$$

$$V'_{out} = V_m$$

Multivibratori monostabili

Funzionamento

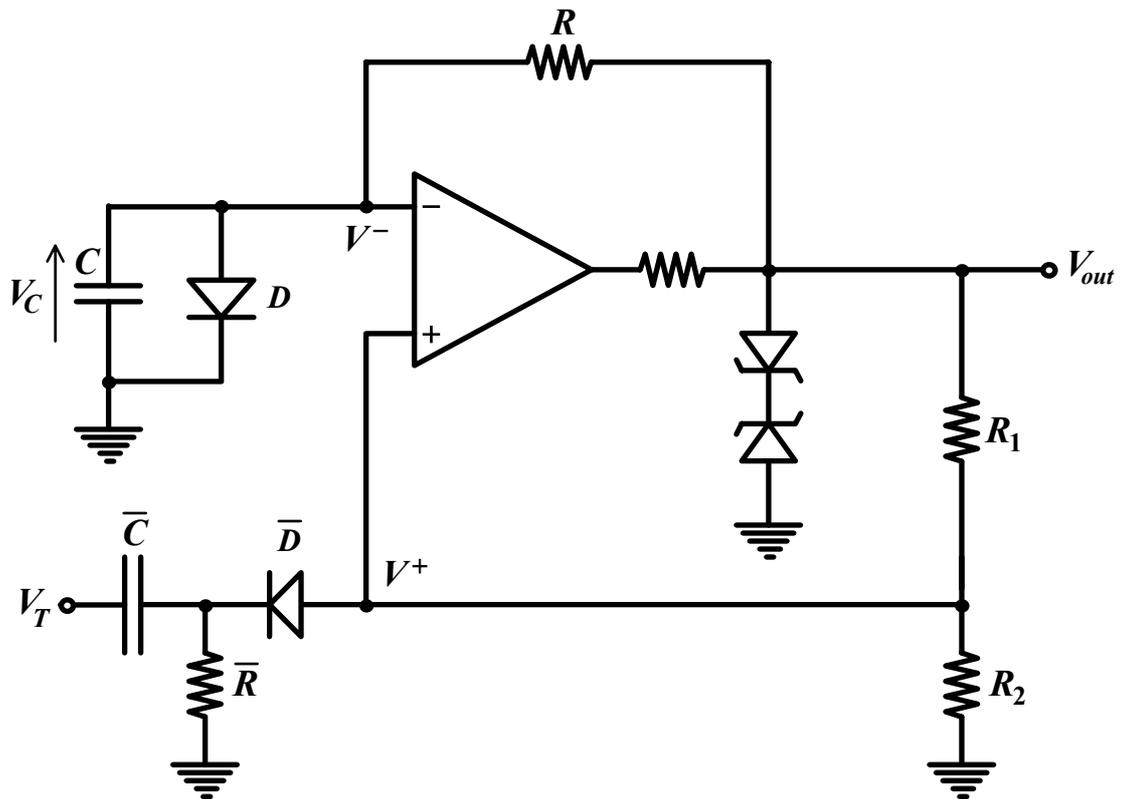


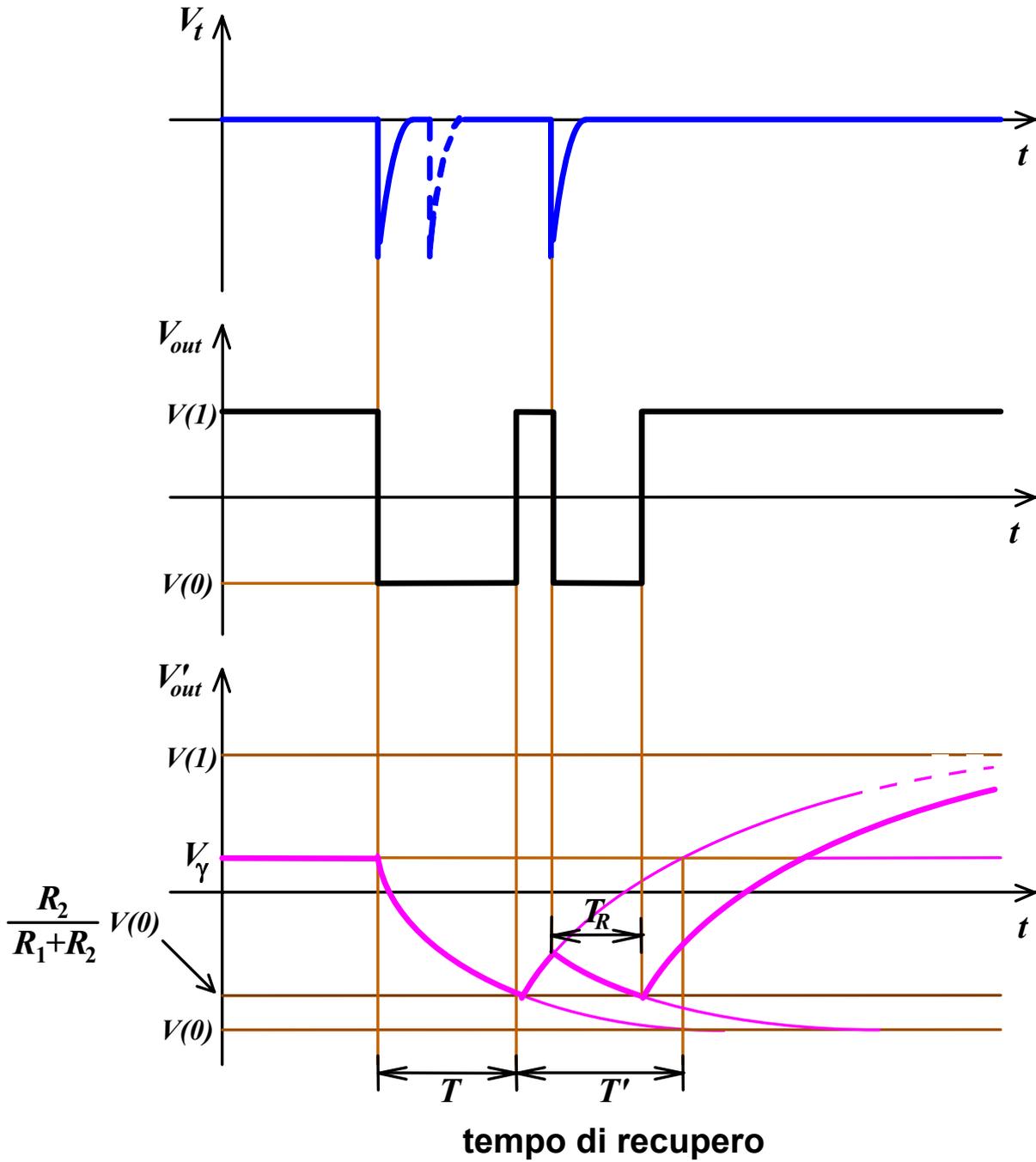
**Monostabile
non
risincronizzabile**

Ipotesi:

$$V_\gamma \ll \frac{R_2}{R_1 + R_2} V(1)$$

$$|V_T| > |\beta V_{out} - V_\gamma|$$





$R, C = ?$

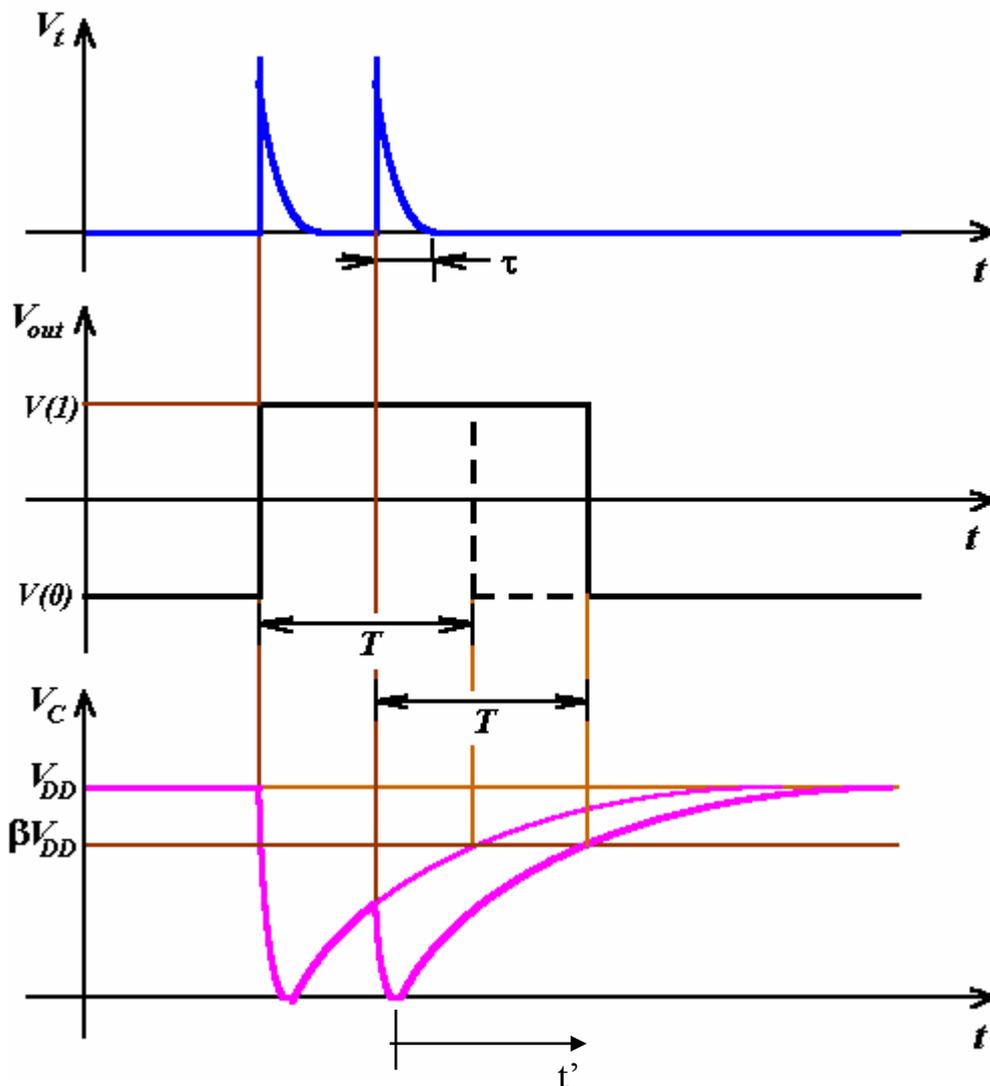
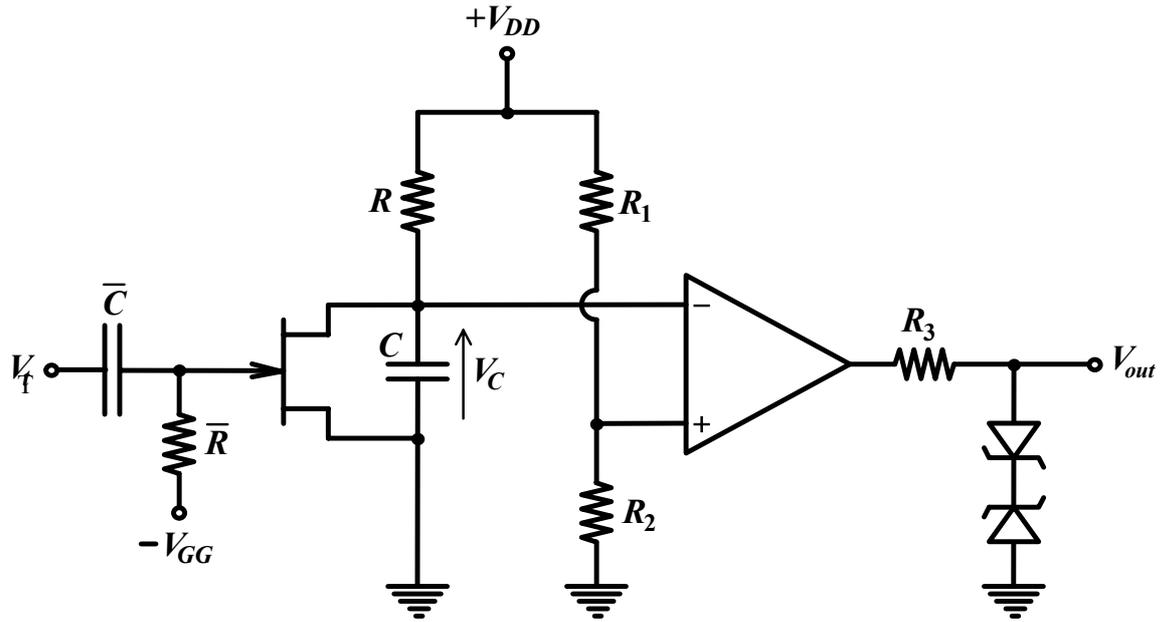
$$V_c(t) = -V_o + (V_\gamma + V_o)e^{-\frac{t}{RC}} \quad V_c(t) = -\beta V_o$$

$$T = RC \ln \frac{1 + \frac{V_\gamma}{V_{out}}}{1 - \beta} \quad \text{con} \quad \beta = \frac{R_2}{R_1 + R_2}$$

$$R_1 = R_2 \Rightarrow \beta = \frac{1}{2}; \quad V_\gamma \ll V_{out} \Rightarrow$$

$$T = RC \ln 2 = 0,69 RC$$

**Monostabile
risincronizzabile**



$$V_C = V_{DD} \left(1 - e^{-\frac{t'}{RC}} \right)$$

Carica di C:

$$\tau = CR$$

Scarica di C:

$$\tau = C \cdot r_{dON}$$

$$T = RC \ln \left(\frac{1}{1 - \beta} \right) =$$

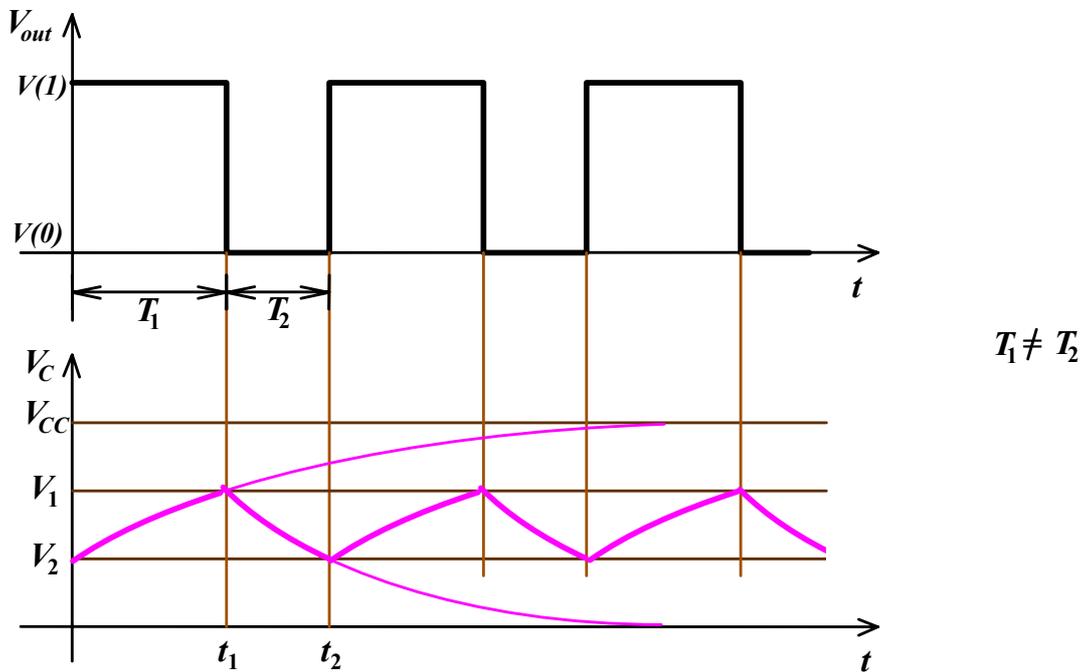
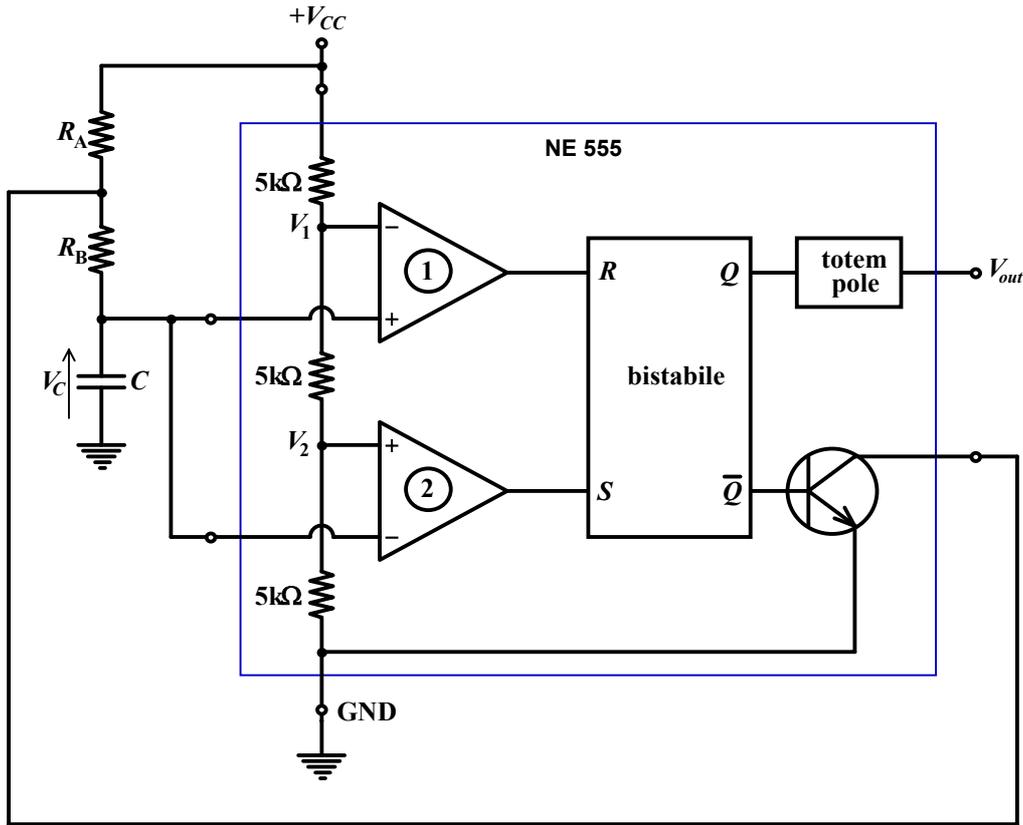
$$= RC \ln \left(1 + \frac{R_2}{R_1} \right)$$

$$R_1 = R_2$$



$$T = 0,69 RC$$

Astabile con NE555



$$V_C(t) = V_{CC} - \left[(V_{CC} - V_2) \exp\left(\frac{-t}{(R_A + R_B)C}\right) \right] = V_{CC} - (V_2 - V_{CC}) \exp\left(\frac{-t}{(R_A + R_B)C}\right)$$

$$V_C(t_1) = V_C(T_1) = V_1 \Rightarrow \dots \Rightarrow T_1 = (R_A + R_B) C \ln 2; \quad T_2 = R_B C \ln 2$$

Tecniche di modulazione con portante armonica

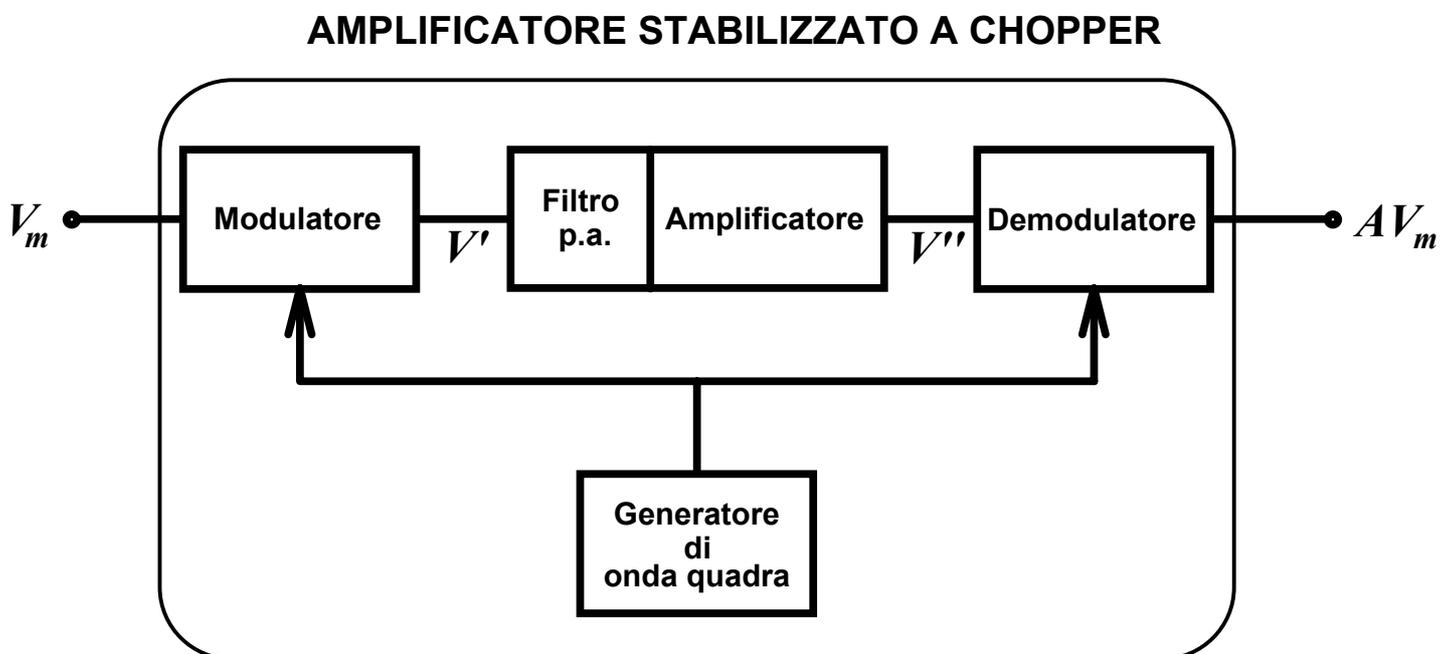
Con portante sinusoidale

- Modulazione di ampiezza o **AM** (Amplitude Modulation)
- Modulazione di frequenza o **FM** (Frequency Modulation)
- Modulazione di fase o **PM** (Phase Modulation)

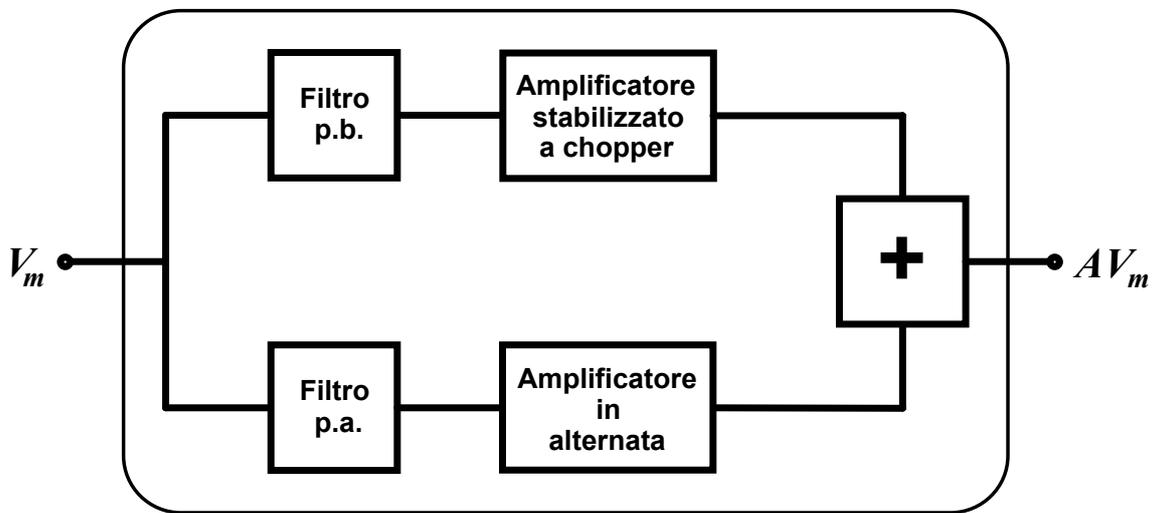
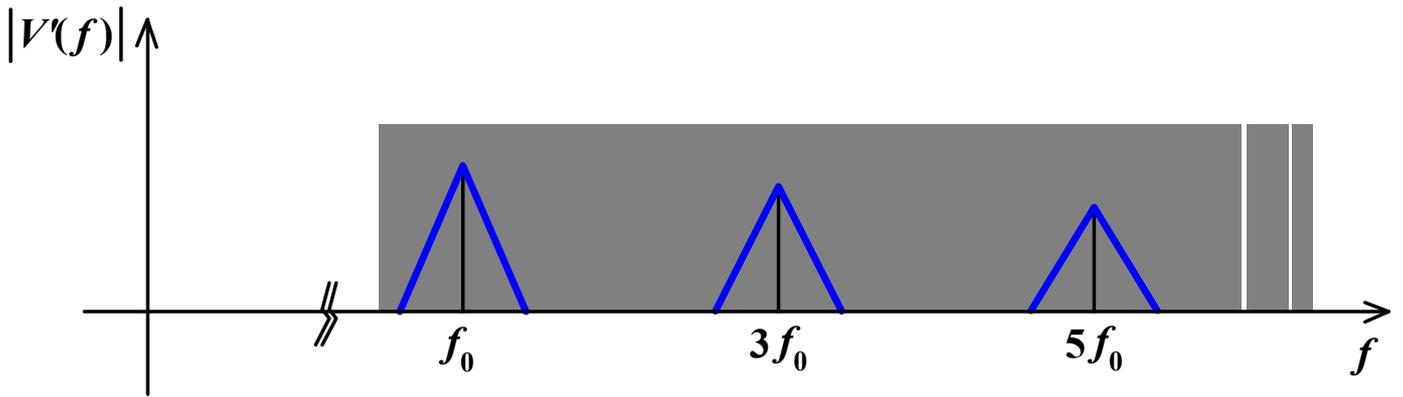
Con portante ad impulsi

- Modulazione di ampiezza di impulsi o **PAM** (Pulse Amplitude Modulation)
- Modulazione di larghezza di impulsi o **PWM** (Pulse Width Modulation)
- Modulazione di posizione di impulsi o **PPM** (Pulse Position Modulation)
- Modulazione di frequenza di impulsi o **PFM** (Pulse Frequency Modulation)

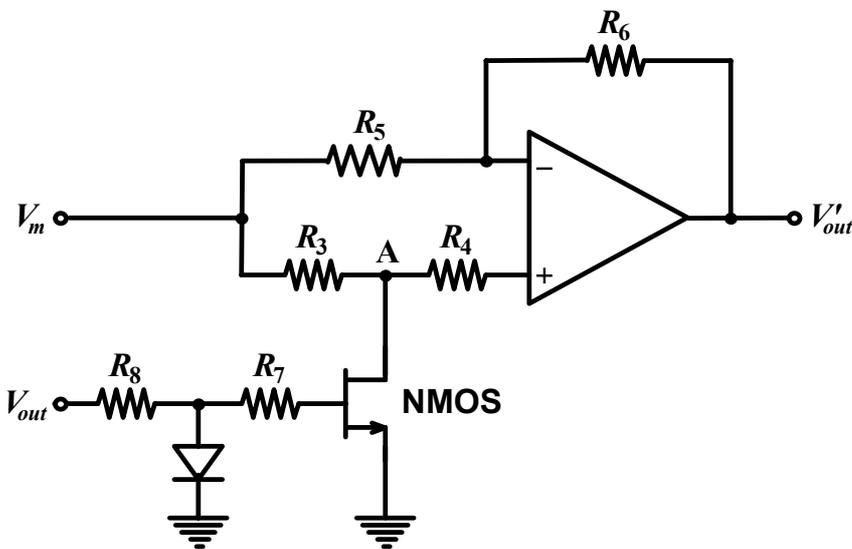
Amplificatore stabilizzato a chopper



Modulazione PAM

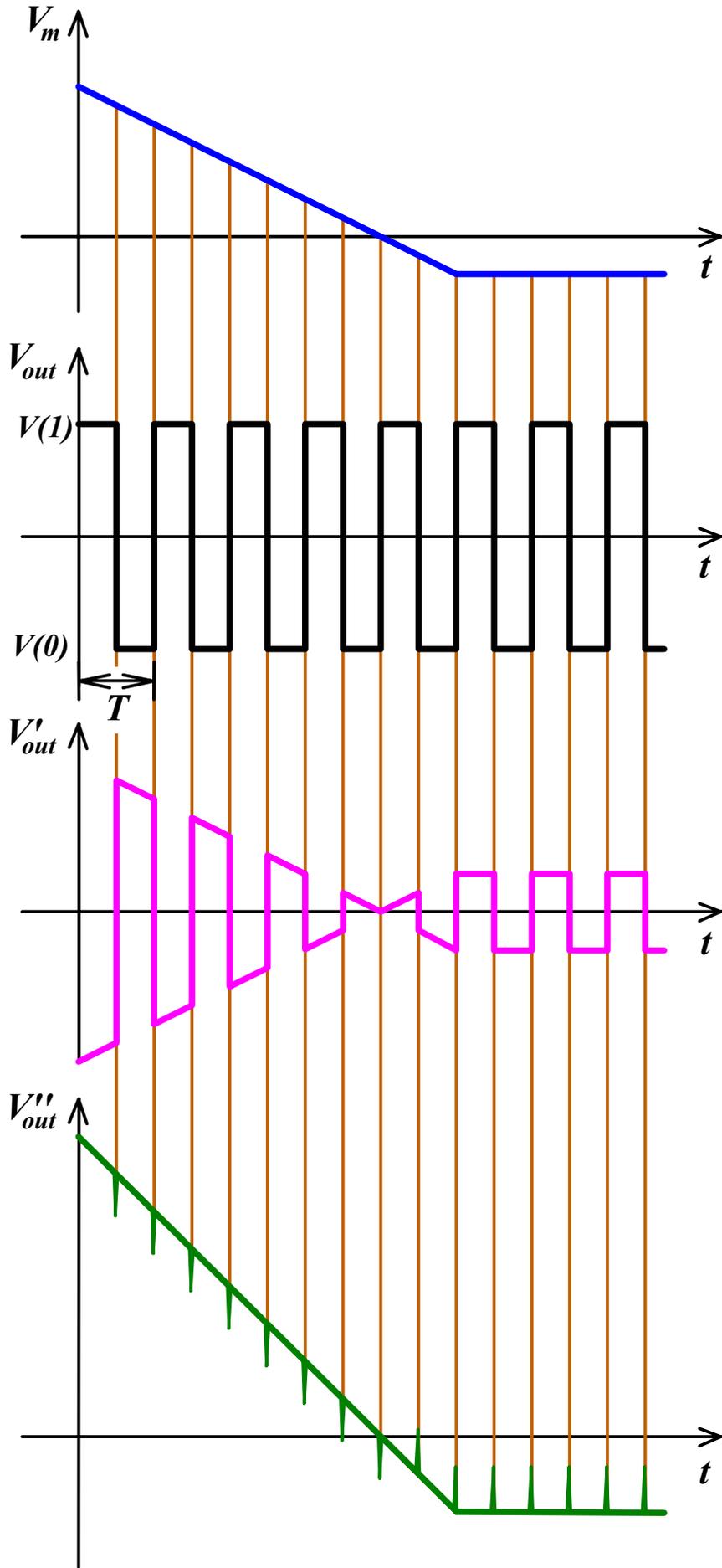


Modulatori e demodulatori

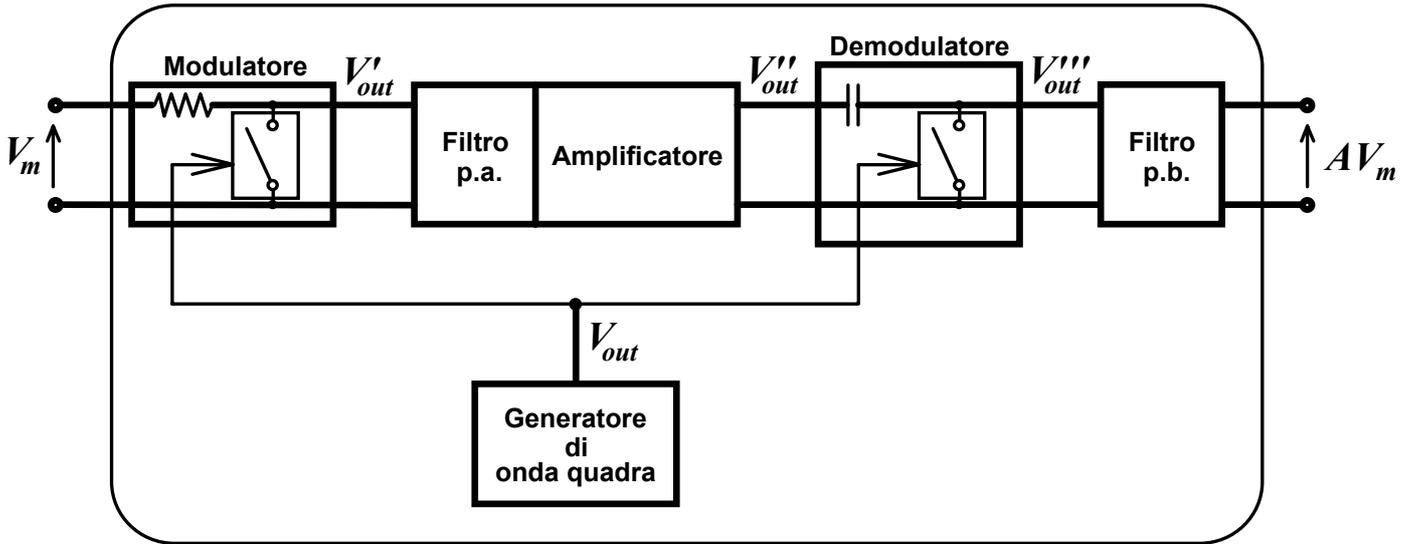


$$V_{out} = V(1) \Rightarrow V'_{out} = V_m$$

$$V_{out} = V(0) \Rightarrow V'_{out} = -V_m$$



AMPLIFICATORE STABILIZZATO A CHOPPER

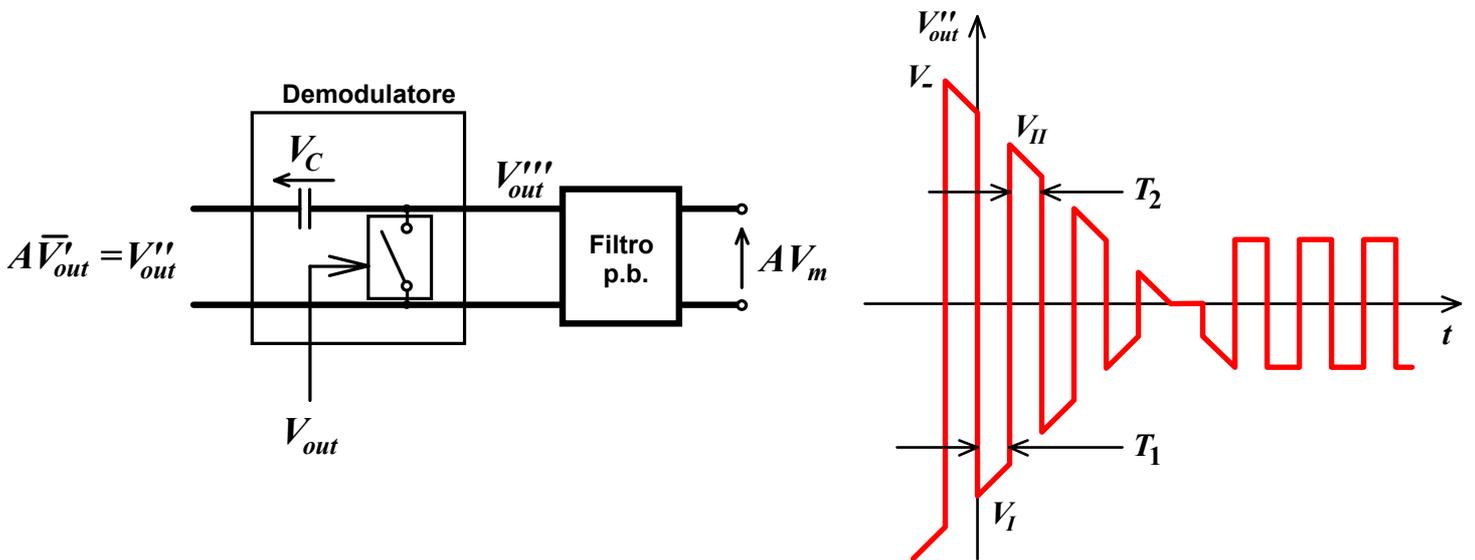


Ricostruzione del segnale modulato:

$$V_{out} = V(1) \Rightarrow JFET = ON \Rightarrow V'_{out} \approx 0$$

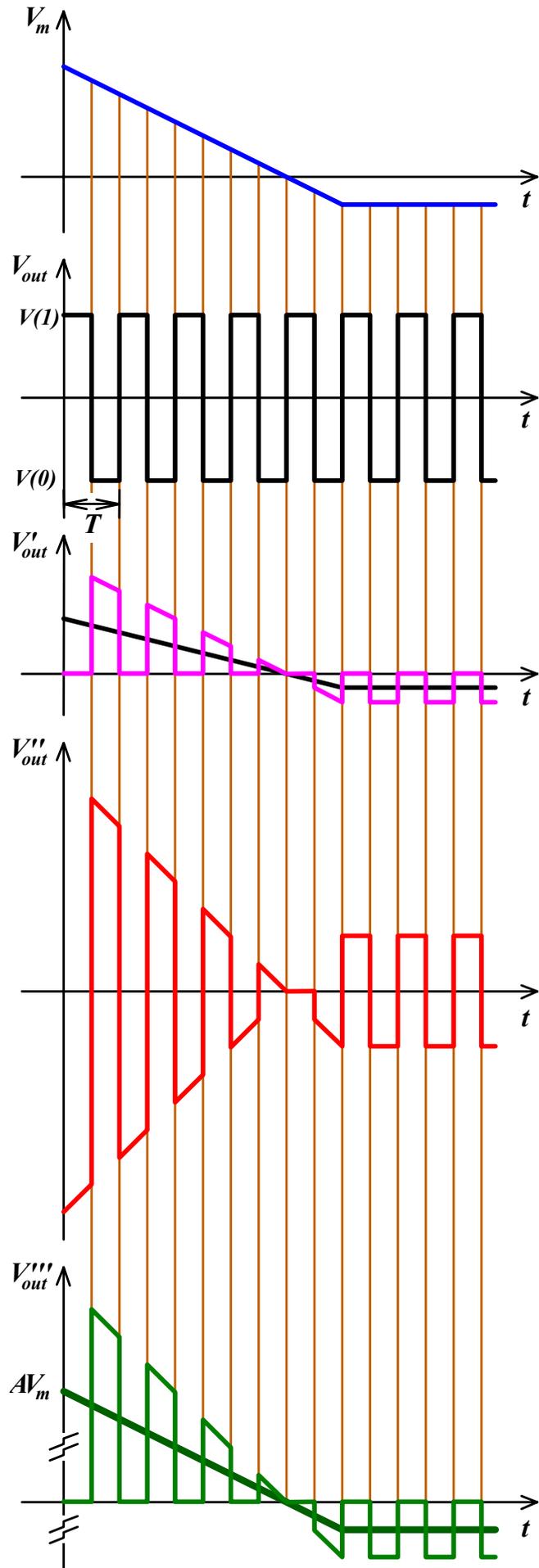
Ipotesi: Interruttore = JFET a canale n \Rightarrow

$$V_{out} = V(0) \Rightarrow JFET = OFF \Rightarrow V'_{out} \approx V_m$$

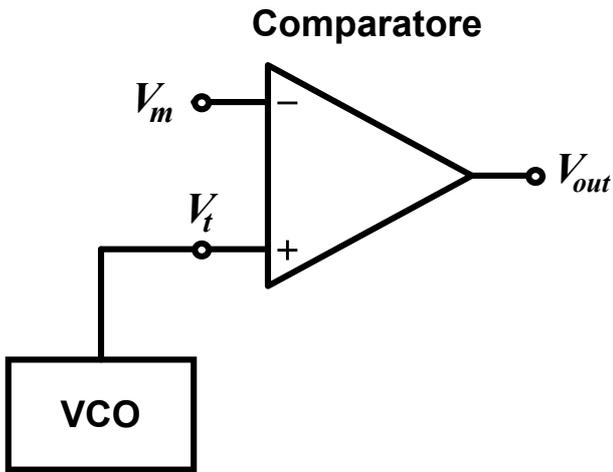


durante $T_1 \Rightarrow JFET = ON \Rightarrow V'''_{out} \Rightarrow V_I = V_C$

durante $T_2 \Rightarrow JFET = OFF \Rightarrow V'''_{out} \Rightarrow V_{II} = V_C$



Modulatore PWM



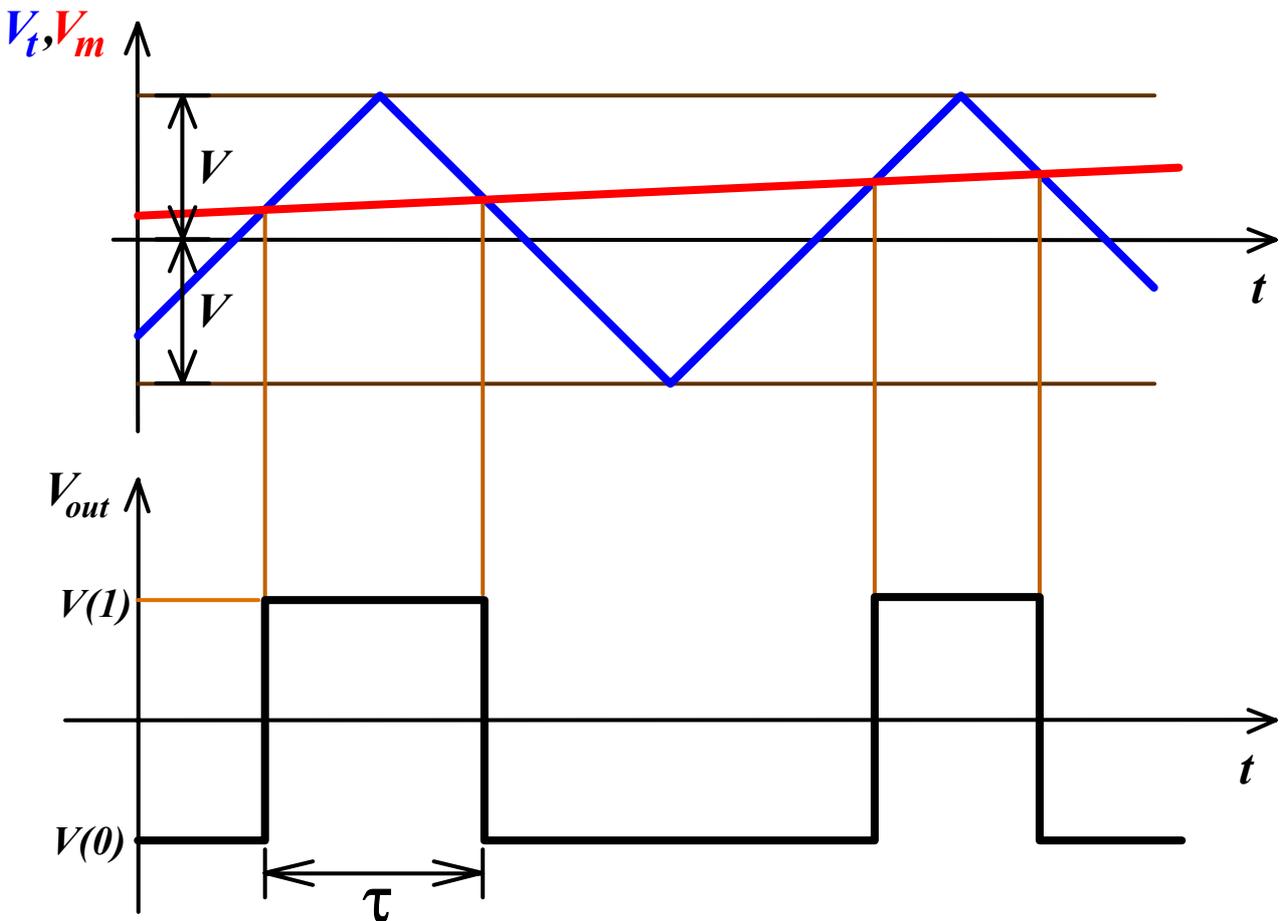
Ipotesi: V_m varia lentamente rispetto a V_t ;

$$|V| > |V_m|$$

$$|V_{t_{\min}}| = |V_{t_{\max}}| = V \Rightarrow \frac{2V}{T} = \frac{V - V_m}{\frac{\tau}{2}}$$

↓

$$\delta = \frac{\tau}{T} = \frac{1}{2} \left(1 - \frac{V_m}{V_{t_{\max}}} \right)$$



$$V_m = 0 \Rightarrow \delta = 0,5; \quad V_m = V_{out} \Rightarrow \delta = 0; \quad V_m = -V_{out} \Rightarrow \delta = 1$$