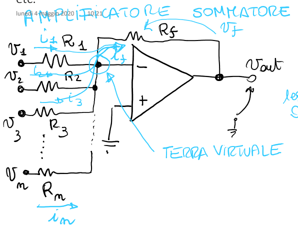
Lezione 14 e Lezione 15a: Amplificatore sommatore, amplificatore delle differenze, l'amplificatore operazionale reale: tensione di offset, correnti di bias, etc.

lunedì 4 maggio 2020 10:21

AMPLIFICATORE SOMMATORE (VOLTAGE ADDER, SUMMING AMPLIFIER, INVERTING ADDER)



legge di Ohm

$$i_i = \frac{v_i}{R_i} \quad i = 1 \dots n \qquad \begin{cases} i_1 = v_1/R_1 \\ i_2 = v_2/R_2 \\ i_3 = v_3/R_3 \end{cases}$$

$$i_f = i_1 + i_2 + i_3 + \dots i_n$$

bilancio di correnti al nodo ⊖

legge di ohm

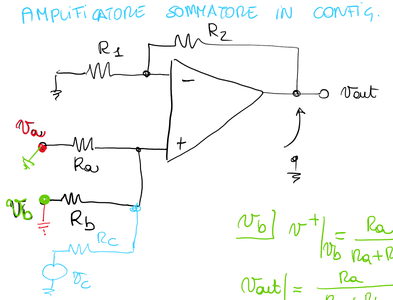
$$v_{out} = -v_f = -i_f R_f =$$

$$= -\left[\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} + \frac{v_n}{R_n}\right] * R_f$$

config. invertente

somma pesata delle tensioni in ingresso

AMPLIFICATORE SOMMATORE IN CONFIG. NON INVERTENTE



Princ. sovrapposiz. effetti

v_a]

$$v^+\big|_{v_a} = \frac{R_b /\!/ R_c}{R_b + R_a} v_a$$

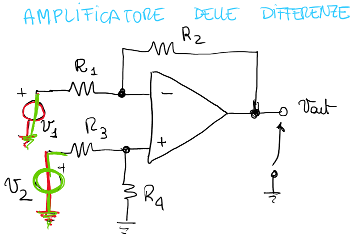
$$v_{out}\big|_{v_a} = \underbrace{\frac{R_b /\!/ R_c}{R_b + R_a} v_a}_{v^+|_{v_a}} \left(1 + \frac{R_2}{R_1}\right)$$

v_b] $$v^+\big|_{v_b} = \frac{R_a}{R_a + R_b} v_b$$

$$v_{out}\big|_{v_b} = \underbrace{\frac{R_a}{R_a + R_b} v_b}_{v^+|_{v_b}} \left(1 + R_2/R_1\right)$$

$$v_{out} = v_{out}\big|_{v_a} + v_{out}\big|_{v_b} = \left(1 + \frac{R_2}{R_1}\right)\left[\frac{R_b /\!/ R_c}{R_a + R_b /\!/ R_c} v_a + \frac{R_a /\!/ R_c}{R_a /\!/ R_c + R_b} v_b + \frac{R_a /\!/ R_b}{R_c + R_a /\!/ R_b} v_c\right]$$

AMPLIFICATORE DELLE DIFFERENZE



Princ. sovrapp. effetti

v_1] config. invertente

$$v_{out}\big|_{v_1} = -\frac{R_2}{R_1} v_1$$

v_2] $$v^+\big|_{v_2} = \frac{R_4}{R_3 + R_4} v_2$$

config. non invertente per v^+

$$v_{out} = \left(1 + \frac{R_2}{R_1}\right) v^+\big|_{v_2} = \left(1 + \frac{R_2}{R_1}\right) \frac{R_4}{R_3 + R_4} v_2$$

$$v_{out} = v_{out}\big|_{v_1} + v_{out}\big|_{v_2} = -\frac{R_2}{R_1} v_1 + \left(1 + \frac{R_2}{R_1}\right) \frac{R_4}{R_3 + R_4} v_2$$

Per amplificare la sola differenza tra le tensioni in ingresso

$$\frac{R_2}{R_1} = \left(1 + \frac{R_2}{R_1}\right) \frac{R_4}{R_3 + R_4}$$

$$\frac{R_2}{\cancel{R_1}} = \frac{(R_1 + R_2)}{\cancel{R_1}} \frac{R_4}{R_3 + R_4}$$

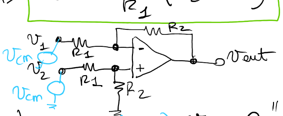
$$R_2 R_3 + \cancel{R_2 R_4} = R_1 R_4 + \cancel{R_2 R_4}$$

$$R_2 R_3 = R_1 R_4$$

$$\boxed{\frac{R_1}{R_2} = \frac{R_3}{R_4}} \Rightarrow \boxed{v_{out} = \frac{R_2}{R_1}(v_2 - v_1)} \Rightarrow \boxed{G_{diff} = \frac{R_2}{R_1}}$$

$R_1 = R_3$

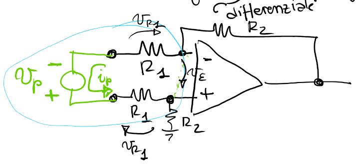
$R_2 = R_4$



Su segnale di modo comune (v_{cm}) $v_{out} = 0$!!

$$G_{cm} \triangleq \frac{v_{out}}{v_{cm}} = 0 \Rightarrow CMRR = \left|\frac{G_{diff}}{G_{cm}}\right| = \infty$$

Resistenza di $\underbrace{\text{ingresso}}_{\text{differenziale}}$ dell'amplificatore delle differenze:



$$R_{in\,diff} \triangleq \frac{v_p}{i_p}$$

$$v_p = v_{R_1} + v_\varepsilon + v_{R_1} =$$

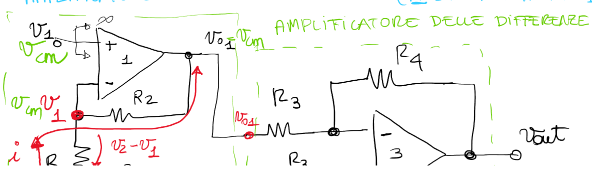
=0 grazie alla retroaz. ideale

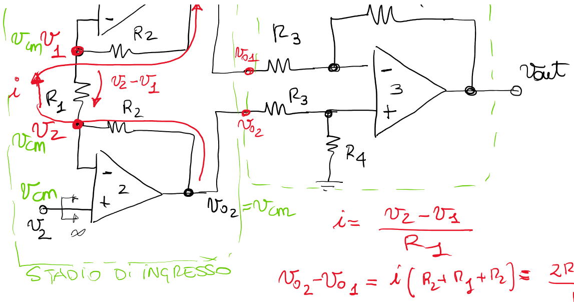
$$= i_p R_1 + 0 + i_p R_1 =$$

$$= 2 R_1 i_p$$

$$\Rightarrow R_{in\,diff} = 2 R_1$$

AMPLIFICATORE PER STRUMENTAZIONE (INSTRUMENTATION AMPLIFIER - INA)





$$i = \frac{v_2 - v_1}{R_1}$$

$$v_{o2} - v_{o1} = i\left(R_2 + R_1 + R_2\right) = \frac{2R_2 + R_1}{R_1}\left(v_2 - v_1\right)$$

$$v_{out} = \frac{R_4}{R_3}\left(v_{o2} - v_{o1}\right) = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)\left(v_2 - v_1\right)$$

$$G_{diff} = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)$$

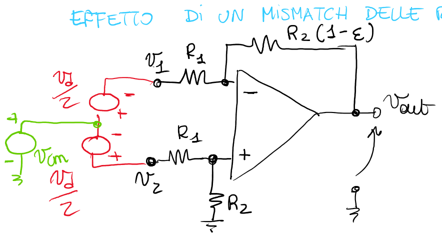
in un INA commerciale R_1 aggiunta dall'utilizzatore del valore appropriato

Segnale di modo comune v_{cm}:
- differenza di potenziale ai capi di R_1 è zero
- $i = 0$
- $v_{o2} = v_{o1} = v_{cm}$, cioè lo stadio di ingresso è un buffer

$$\Downarrow$$

$$v_{out}\Big|_{v_{cm}} = 0 \implies G_{cm} = 0$$

EFFETTO DI UN MISMATCH DELLE RESISTENZE IN UN AMPLIFICATORE DELLE DIFFERENZE



$$v_1 = v_{cm} - v_d/2$$

$$v_2 = v_{cm} + v_d/2$$

$$\begin{cases} v_2 - v_1 = v_d \\ \dfrac{v_2 + v_1}{2} = v_{cm} \end{cases}$$

Princ. di sovrapposizione degli effetti

$$v_{out} = \frac{R_2}{R_1 + R_2} \cdot \left[1 + \frac{R_2(1-\varepsilon)}{R_1}\right]\left(v_{cm} + \frac{v_d}{2}\right) +$$

$$- \frac{R_2(1-\varepsilon)}{R_1}\left[v_{cm} - \frac{v_d}{2}\right] =$$

$$= \left\{\frac{R_2}{R_1 + R_2}\left[1 + \frac{R_2(1-\varepsilon)}{R_1}\right] - \frac{R_2(1-\varepsilon)}{R_1}\right\} v_{cm} +$$

$$+ \left\{\frac{R_2}{R_1 + R_2}\left[1 + \frac{R_2(1-\varepsilon)}{R_1}\right] + \frac{R_2(1-\varepsilon)}{R_1}\right\}\frac{v_d}{2} =$$

$$= G_{cm}\, v_{cm} + G_{diff}\, v_d$$

$$G_{cm} = \frac{R_2}{R_1 + R_2} + \frac{R_2}{R_1 + R_2}\,\frac{R_2}{R_1}(1-\varepsilon) - \frac{R_2}{R_1}(1-\varepsilon) =$$

$$= \frac{R_2}{R_1 + R_2} + \frac{R_2}{R_1}(1-\varepsilon)\left[\frac{R_2}{R_1 + R_2} - 1\right] = \frac{R_2}{R_1 + R_2} + \frac{R_2}{\cancel{R_1}}(1-\varepsilon)\,\frac{\cancel{R_2} - R_1 - \cancel{R_2}}{R_1 + R_2} =$$

$$= \frac{R_2}{R_1 + R_2} - \frac{R_2}{R_1 + R_2}(1-\varepsilon) = \frac{R_2}{R_1 + R_2}\,\varepsilon \xrightarrow[\varepsilon \to 0]{} 0 \leftarrow \text{perfetto matching}$$

$$G_{diff} = \left\{\frac{R_2}{R_1 + R_2}\left[1 + \frac{R_2(1-\varepsilon)}{R_1}\right] + \frac{R_2(1-\varepsilon)}{R_1}\right\}\frac{1}{2} = \frac{R_2}{R_1}\left[1 - \frac{\varepsilon}{2}\,\frac{R_1 + 2R_2}{R_1 + R_2}\right]$$

$$\simeq \frac{R_2}{R_1}$$

$$CMRR = \left|\frac{G_{diff}}{G_{cm}}\right| = \frac{\cancel{R_2}/R_1\left[1 - \dfrac{\varepsilon}{2}\,\dfrac{R_1 + 2R_2}{R_1 + R_2}\right]}{\dfrac{\cancel{R_2}}{R_1 + R_2}\,\varepsilon} \simeq \frac{1 + \dfrac{R_2}{R_1}}{\varepsilon}$$

$$\varepsilon \to 0 \implies CMRR \to \infty$$

STRUTTURA INTERNA SEMPLIFICATA DI UN AMPLIFICATORE OPERAZIONALE

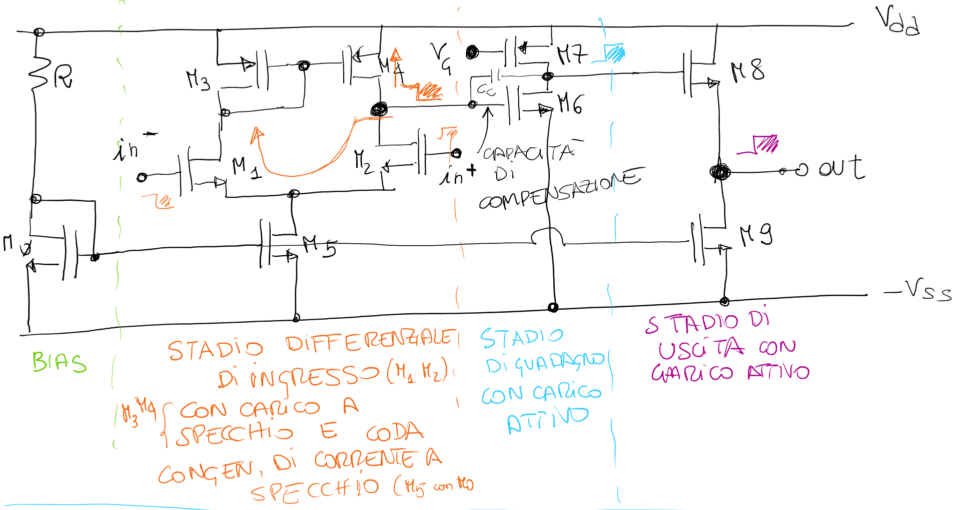
| 4cm |

$\frac{\cancel{R_2}}{R_1+R_2}\ \varepsilon$

ε

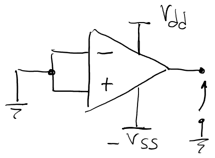
$\varepsilon \to 0 \Rightarrow CMRR \to \infty$

STRUTTURA INTERNA SEMPLIFICATA DI UN AMPLIFICATORE OPERAZIONALE

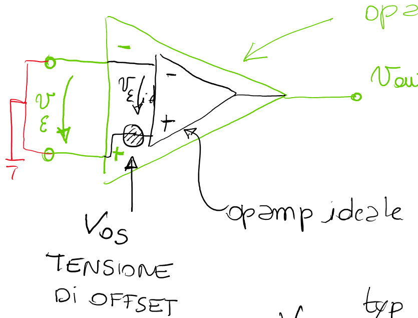


L'AMPLIFICATORE OPERAZIONALE REALE

* TENSIONE DI OFFSET



$v_{out} \neq 0$ in un opamp reale

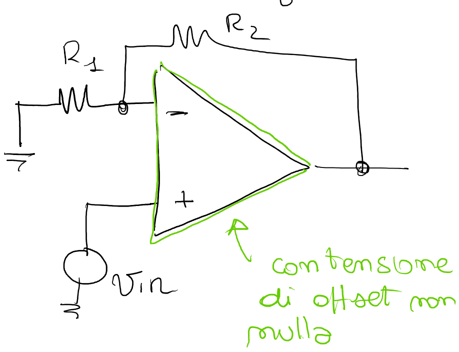


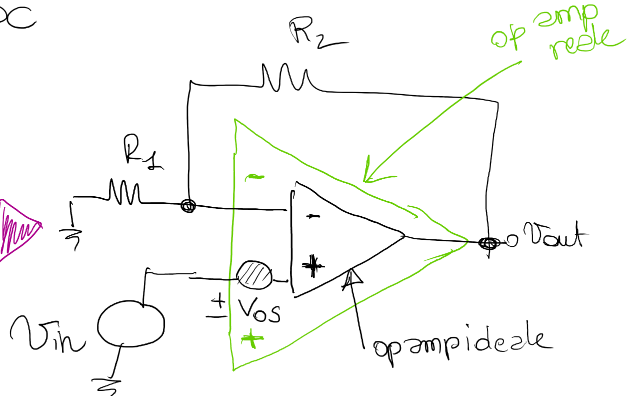
$$v_\varepsilon\Big|_{reale} = v_{\varepsilon_{ideale}} \pm V_{OS}$$

$$v_{out} = A_0\left(v_{\varepsilon_{ideale}} \pm V_{OS}\right)$$

$$V_{OS} \overset{typ}{=} 100\mu V \div 5mV$$

V_{OS} è una grandezza DC



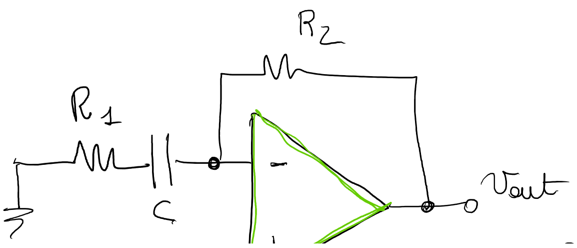


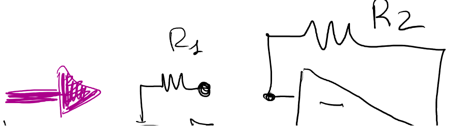
$$v^+ = v_{in} \pm V_{OS}$$

$$v_{out} = \left(1+\frac{R_2}{R_1}\right)\left(v_{in} \pm V_{OS}\right)$$

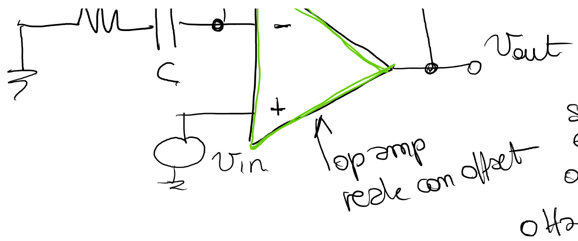
⇓ effetto della tensione di offset

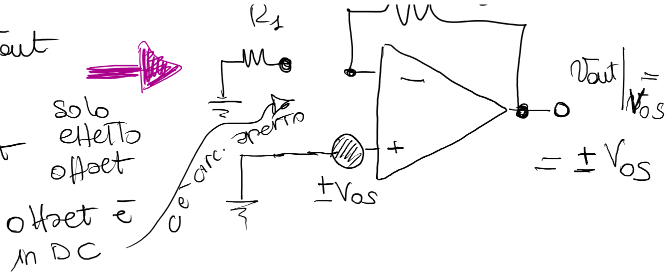
$$\Delta V_{out} = \pm\left(1+\frac{R_2}{R_1}\right)V_{OS}$$



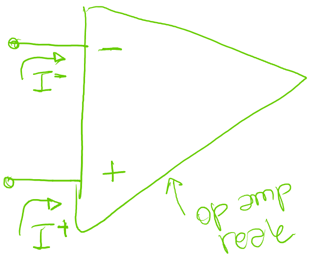


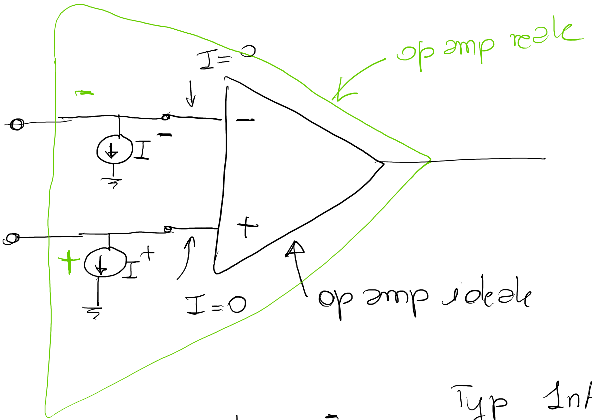
$v_{out}\Big|_{At} =$





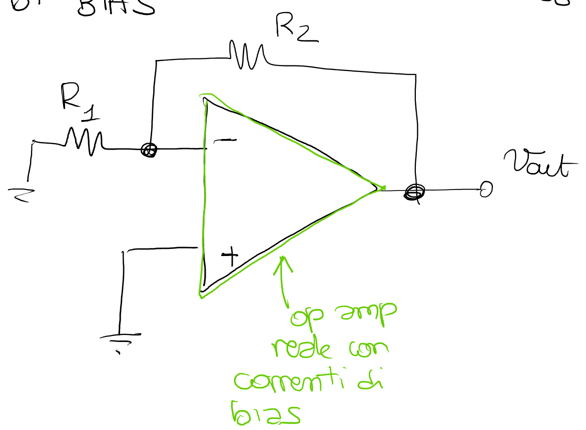
* CORRENTI DI BIAS

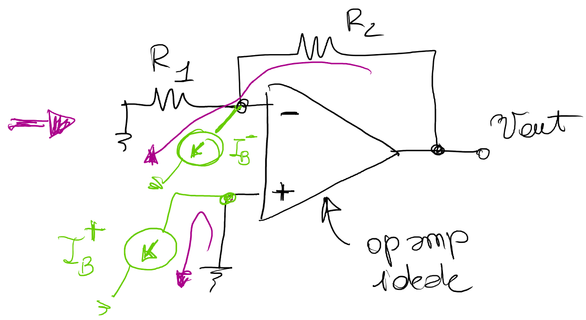




CORRENTI DI BIAS $\quad I_B = \dfrac{I^+ + I^-}{2}$ ← Typ $1nA \div 10\mu A$

OFFSET della CORRENTE DI BIAS $\quad I_{OS} = |I^+ - I^-|$ ← 2 ordini di grandezza più piccolo di I_B



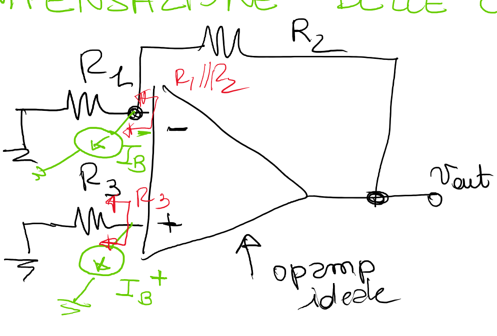


I_B^+ non dà contributo

$I_B^- \Rightarrow V_{out} = I_B^- R_2 \simeq I_B R_2$

↑ trascurando offset correnti di bias

COMPENSAZIONE DELLE CORRENTI DI BIAS



I_B^+ | $v^+ = -I_B^+ R_3$

$$V_{out}\big|_{I_B^+} = \left(1 + \frac{R_2}{R_1}\right) v^+ = \left(1 + R_2/R_1\right)\left(-I_B^+ R_3\right)$$

I_B^- | $v^+ = 0 \Rightarrow v^-$ terra virtuale

$$V_{out}\big|_{I_B^-} = R_2 I_B^-$$

Effetto correnti di bias:

$$V_{out} = V_{out}\big| + V_{out}\big| = -\left(1 + \frac{R_2}{}\right) I_B^+ R_3 + R_2 I_B^-$$

Effetto correnti di bias:

$$V_{out} = V_{out}\Big|_{I_B^+} + V_{out}\Big|_{I_B^-} = -\left(1+\frac{R_2}{R_1}\right) I_B^+ R_3 + R_2 I_B^-$$

Considerando solo le correnti di bias e non il loro offset:

$$V_{out} = -\left(1+\frac{R_2}{R_1}\right) I_B R_3 + R_2 I_B = I_B\left[R_2 - R_3\left(1+\frac{R_2}{R_1}\right)\right]$$

$$R_2 - R_3\left(1+\frac{R_2}{R_1}\right) = 0$$

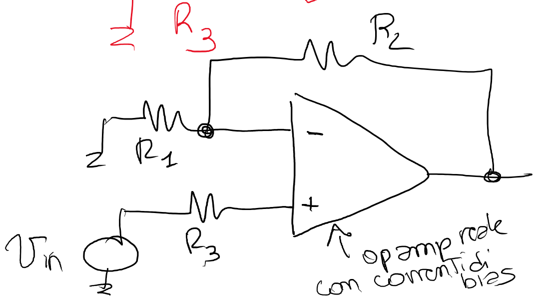
$$R_3\left(\frac{R_1+R_2}{R_1}\right) = R_2 \Rightarrow \boxed{R_3 = R_1 \| R_2}$$

$V_{out}\Big|_{I_B} = 0$ HO COMPENSATO L'EFFETTO DELLE CORRENTI DI BIAS NON IL LORO OFFSET

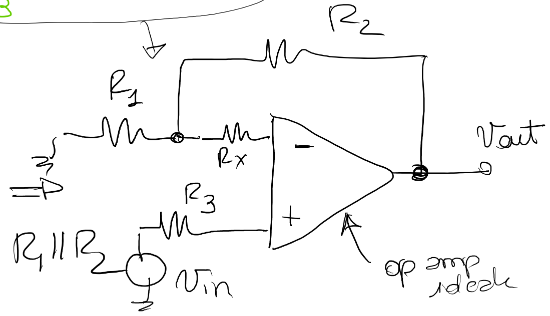
Se $R_3 > R_1 \| R_2$

R_x non modifica il trasferimento dello stadio

$$R_3 = R_x + R_1 \| R_2$$

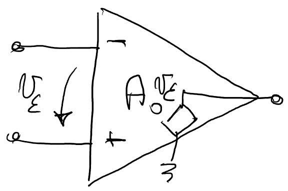


$R_3 > R_1 \| R_2$ ⟹



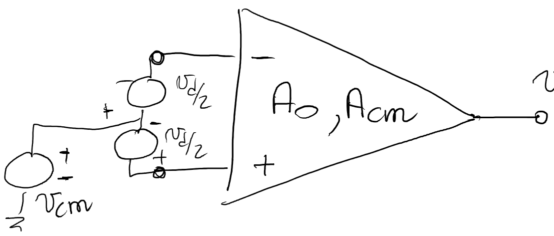
* RAPPORTO DI REIEZIONE DEL MODO COMUNE FINITO

JAEGER



$V_{out} = A_0 V_\varepsilon$

CASO REALE:



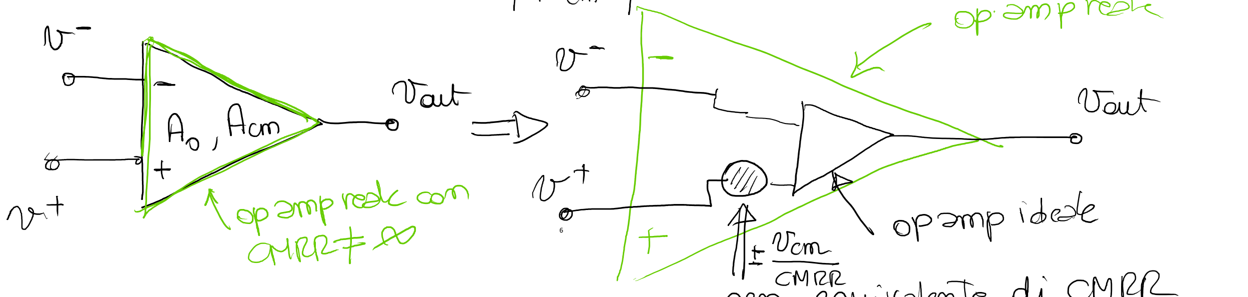
$$V_{out} = A_0\left(v^+ - v^-\right) + A_{cm}\left(\frac{v^+ + v^-}{2}\right) =$$

$$= A_0 v_d + A_{cm} v_{cm}$$

$$V_{out} = A_0\left[v_d + \frac{A_{cm}}{A_0} v_{cm}\right] = A_0\left[v_d \pm \frac{v_{cm}}{CMRR_{typ}}\right]_{typ}$$

$$v_{out} = A_0 \left[v_d + \frac{A_{cm}}{A_0} v_{cm} \right] = A_0 \left[v_d \pm \frac{v_{cm}}{CMRR} \right]$$

$$CMRR = \left| \frac{A_0}{A_{cm}} \right| \neq \infty \qquad \underset{typ}{60\,dB} \leq CMRR \leq \underset{typ}{120\,dB}$$



gen. equivalente di CMRR

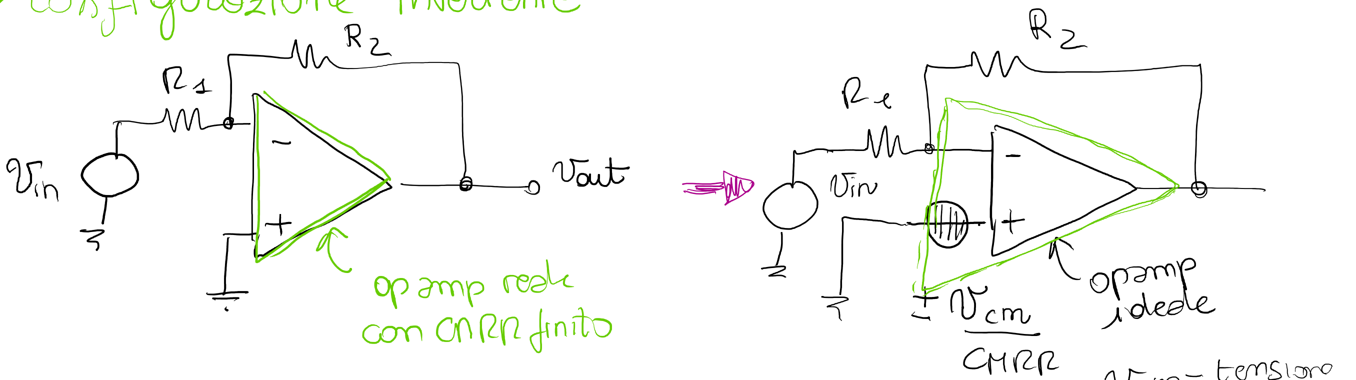
1. non ne conosciamo la polarità
2. dipende dal segnale!!!

$$v_{cm} = \frac{v^+ + v^-}{2}$$

CMRR finito
- config. invertente
- non invertente
- ampl. differenze / strumentazione

5 maggio 2020

→ configurazione invertente



$$v_{cm} \triangleq \frac{v^+ + v^-}{2} \qquad \begin{cases} v^+ = 0 \\ v^- = v^+ = 0 \end{cases} \Rightarrow v_{cm} = 0 \;!!$$

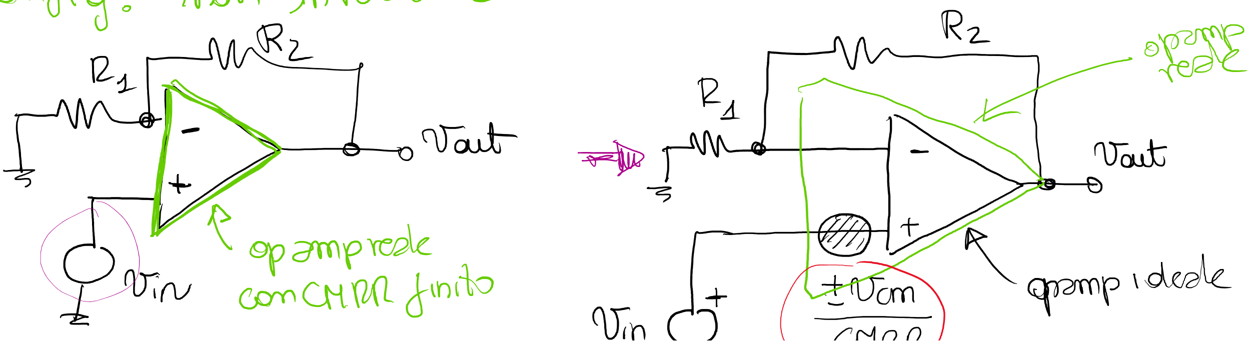
v_{cm} = tensione di modo comune ai morsetti dell'op amp.

APPROSSIMAZ.

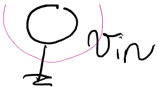
ASSUMO UN OPAMP IDEALE, CIOÈ CARATTERIZZATO SOLO DA GUADAGNO AD ANELLO APERTO A_0 DIFFERENZIALE E $A_0 \to \infty$.

↳ config. invertente è immune dagli effetti di CMRR finito

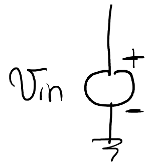
→ config. non invertente



opamp ideale con CMRR finito



opamp ideale



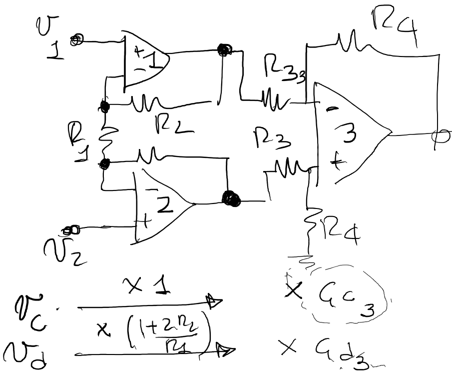
$$v_{cm} \triangleq \frac{v^+ + v^-}{2} \quad \begin{cases} v^+ = v_{in} \\ v^- = v^+ = v_{in} \end{cases} \Rightarrow v_{cm} = v_{in} \pm \frac{v_{in}}{CMRR}$$

APPROSSIMAZ. OPAMP IDEALE!

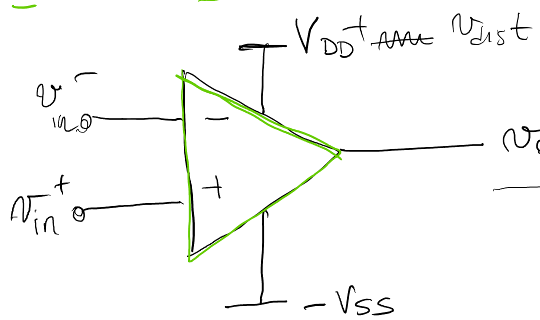
$$v_{out} = \underbrace{\left(v_{in} \pm \frac{v_{in}}{CMRR}\right)}_{v^+}\left(1 + \frac{R_2}{R_1}\right) = v_{in}\left(1 \pm \frac{1}{CMRR}\right)\left(1 + \dots\right)$$

note sul CMRR dell'INA

$$CMRR_{TOT} = \left(1 + \frac{2R_2}{R_1}\right)_{iNA} \underbrace{CMRR_{\text{ampl. delle diff.}}}_{= CMRR_3}$$



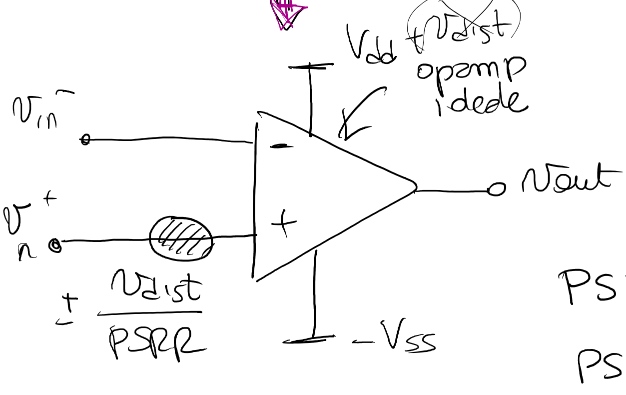
* RAPPORTO DI REIEZIONE DELLA TENSIONE DI ALIMENTAZIONE (POWER SUPPLY REJECTION RATIO – PSRR)



$$v_{out} = A_0 v_\varepsilon + A_{\text{power supply}} v_{dist} =$$

$$= A_0 \left[v_\varepsilon + \frac{A_{\text{power supply}}}{A_0} v_{dist} \right]$$

$$= A_0 \left[v_\varepsilon \pm \frac{v_{dist}}{PSRR} \right]$$



$$PSRR = \left| \frac{A_0}{A_{\text{power supply}}} \right|$$

fornito dal data sheet

$PSRR^+$ (relativo a V_{dd})

$PSRR^-$ (relativo a $-V_{ss}$)

$\frac{z_2}{z_1}$

=