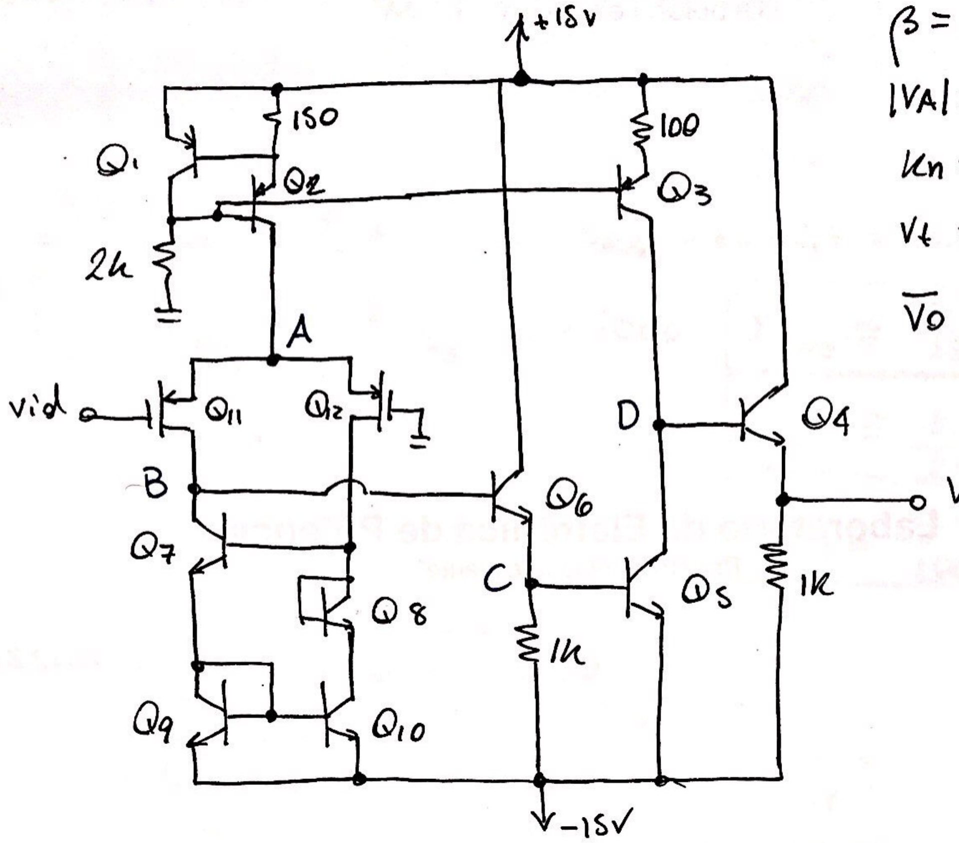
→ Resolução Exercício 6 - CEA

I



$\beta = 500$

$|V_A| = 50V$

$k_n = 2mA/V^2$

$V_t = 1V$

$\overline{V_O} = 0V$

a) Análise C.C. → calcular a corrente em todos os transistores e as tensões A, B, C e D.

→ Como $V_O = 0$, têm-se que

- $I_{EQ4} = \frac{V_O - (-15V)}{1k\Omega} = 15mA$ → como $\beta >> 1$ → $\boxed{I_{CQ4} \cong 15mA}$

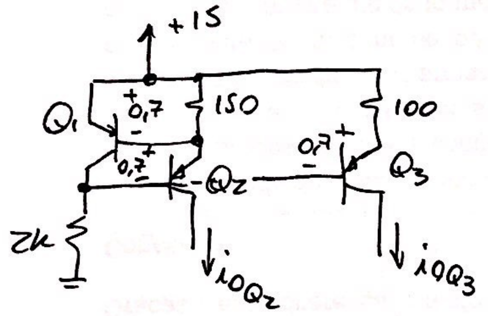
- $V_D = V_O + 0{,}7$ → $\boxed{V_D = 0{,}7V}$

- $V_C = -15V + 0{,}7$ → $\boxed{V_C = -14{,}3V}$

$$\boxed{I_{CQ6} \cong I_{EQ6} = \frac{V_C - (-15)}{1k} = 0{,}7mA}$$

- $V_B = V_C + 0{,}7$ ⇒ $\boxed{V_B = -13{,}6V}$

→ Para encontrar V_A e as demais correntes, deve-se analisar as fontes de corrente:



$V_{R150} = 0{,}7V$

$V_{R100} = 0{,}7V$

$V_{R2k} = 15 - 1{,}4 = 13{,}6\,V$

→ logo $\boxed{I_{CQ_2} \cong \frac{0{,}7V}{150} = 4{,}67mA}$

$\boxed{I_{CQ_1} \cong \frac{13{,}6}{2k} = 6{,}8mA}$

$\boxed{I_{CQ_3} \cong \frac{0{,}7}{100} = 7{,}0mA}$

→ Assim $\boxed{I_{CQ_5} = I_{CQ_3} = 7{,}0mA}$

$\boxed{I_{DQ_{11}} = I_{DQ_{12}} = \frac{I_{CQ_2}}{2} = 2{,}335mA}$

$\boxed{I_{CQ_7} = I_{CQ_9} = I_{DQ_{11}} = 2{,}335mA}$

$\boxed{I_{CQ_8} = I_{CQ_{10}} = I_{DQ_{12}} = 2{,}335mA}$

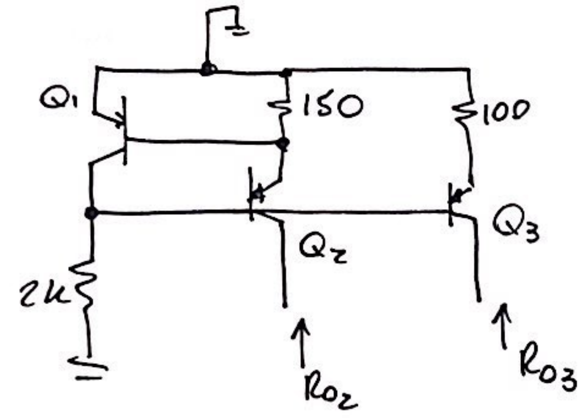
→ olhando Q_{11} → $I_D = \frac{1}{2} k_n V_{ov}^2$ → $V_{ov} = \sqrt{\frac{2 I_D}{k_n}} = 1{,}528V$

$$V_{SG_{11}} = \sqrt{\frac{2I_{DQ_{11}}}{k_n}} + 1 \Rightarrow V_{SG_{11}} = 2{,}52V$$

→ logo: $\boxed{V_A = 2{,}52V}$

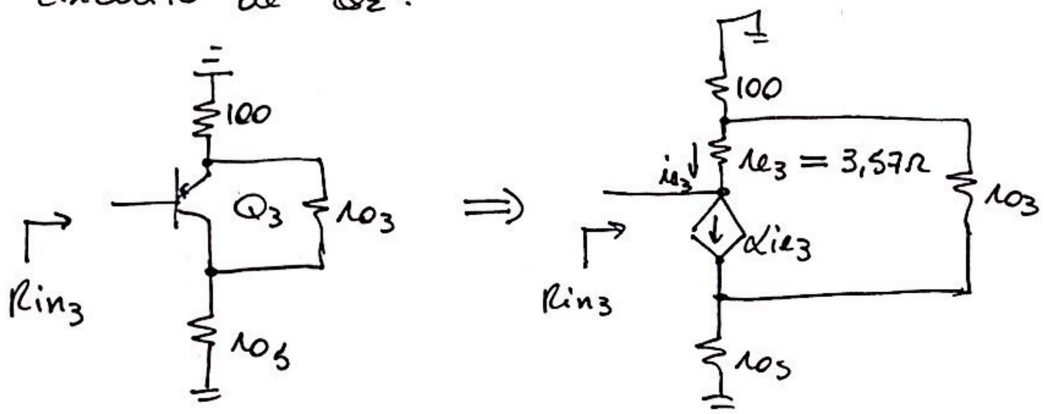
Scanned with CamScanner

b) Cálculo das resistências de saída das fontes de corrente:



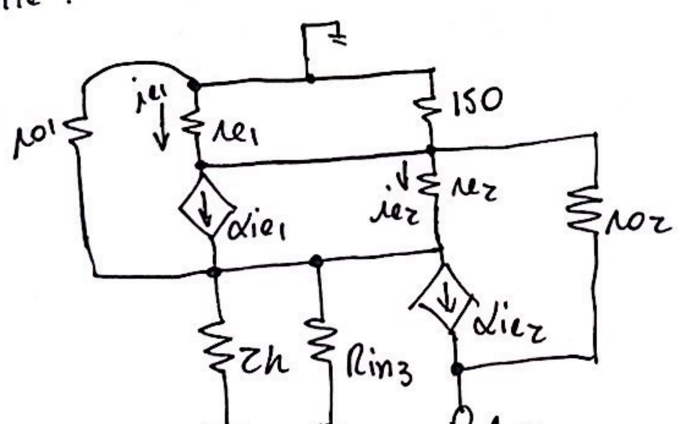
→ <u>Cálculo de R_{o2}</u>

→ Primeiramente, levantamos a influência de Q_3 no circuito de Q_2:



→ Sabemos que $R_{in3} \cong (\beta+1)(r_{e3}+100) \cong 52k\Omega$

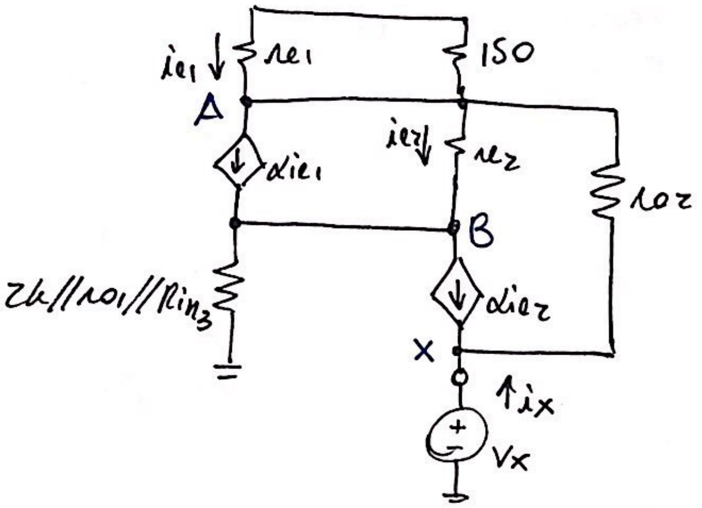
→ Agora levantamos o modelo de pequenos sinais do circuito da fonte:



onde:

$R_{in3} = 52k\Omega$
$r_{e1} = 3,68\Omega$
$r_{e2} = 5,35\Omega$
$r_{o1} = 7,35k\Omega$
$r_{o2} = 10,7k\Omega$
$\alpha = 0,998$

→ Redesenhando



$\rightarrow \ 2k // r_{o1} // R_{in3} = 1{,}53 K\Omega$

- $i_{e1} = -\dfrac{V_A}{r_{e1}}$
- $i_{e2} = \dfrac{V_A - V_B}{r_{e2}}$

→ Resolvendo por método dos nós:

Nó A →

$$\frac{V_A}{150} + \frac{V_A - V_B}{r_{e2}} + \frac{V_A - V_x}{r_{o2}} + \alpha\left(-\frac{V_A}{r_{e1}}\right) = \left(-\frac{V_A}{r_{e1}}\right)$$

$$V_A\left(\frac{1}{150} + \frac{1}{r_{e2}} + \frac{1}{r_{o2}} + \frac{1-\alpha}{r_{e1}}\right) = \frac{V_B}{r_{e2}} + \frac{V_x}{r_{o2}}$$

$$\rightarrow \ 1-\alpha = 1 - \frac{\beta}{\beta+1} = \frac{1}{\beta+1} \quad e \quad \underline{\underline{(\beta+1) r_{e1} = r_{\pi 1}}}$$

logo,

- $$V_A \underbrace{\left(\frac{1}{150} + \frac{1}{r_{e2}} + \frac{1}{r_{o2}} + \frac{1}{r_{\pi 1}}\right)}_{\sim \frac{1}{r_{e2}} \text{ (termo dominante)}} = \frac{V_B}{r_{e2}} + \frac{V_x}{r_{o2}}$$

$$\boxed{V_A \cong V_B + \frac{V_x r_{e2}}{r_{o2}}}$$

Nó B →

$$\frac{V_A - V_B}{r_{e2}} + \alpha\left(-\frac{V_A}{r_{e1}}\right) = \alpha\left(\frac{V_A - V_B}{r_{e2}}\right) + \frac{V_B}{1{,}53k}$$

$$V_A\left(\frac{1}{r_{e2}} - \frac{\alpha}{r_{e1}} - \frac{\alpha}{r_{e2}}\right) = V_B\left(\frac{1}{1{,}53k} - \frac{\alpha}{r_{e2}} + \frac{1}{r_{e2}}\right)$$

$$V_A\left(\frac{1}{r_{\pi 2}} - \frac{\alpha}{r_{e1}}\right) = V_B\left(\frac{1}{1{,}53k} + \frac{1}{r_{\pi 2}}\right)$$

V

$$\left(V_B + \frac{r_{e2}}{r_{o2}} V_x\right)\left(\frac{1}{r_{\pi 2}} - \frac{\alpha}{r_{e1}}\right) = V_B\left(\frac{1}{1{,}53k} + \frac{1}{r_{\pi 2}}\right)$$

$$V_B\left(\frac{1}{1{,}53k} + \cancel{\frac{1}{r_{\pi 2}}} - \cancel{\frac{1}{r_{\pi 2}}} + \frac{\alpha}{r_{e1}}\right) = \left[\frac{r_{e2}}{r_{o2} r_{\pi 2}} - \frac{\alpha r_{e2}}{r_{o2} r_{e1}}\right] V_x$$

$$V_B \, \frac{r_{e1} + \alpha\, 1{,}53k}{1{,}53k\, \cancel{r_{e1}}} = \frac{r_{e1} r_{e2} - \alpha r_{e2} r_{\pi 2}}{r_{o2} r_{\pi 2} \cancel{r_{e1}}} V_x$$

$$V_B = \frac{1{,}53k\left[r_{e1} \cancel{r_{e2}} - \alpha(\beta+1) r_{e2}^{\cancel{2}}\right]}{r_{o2} \cancel{r_{e2}} (\beta+1)(r_{e1} + \alpha\, 1{,}53k)} V_x$$

$$\boxed{V_B = \frac{1{,}53k\,(r_{e1} - \beta r_{e2})}{r_{o2}(r_{\pi 1} + \beta\, 1{,}53k)} V_x}$$

$$V_A = \left[\frac{1{,}53k\,(r_{e1} - \beta r_{e2})}{r_{o2}(r_{\pi 1} + \beta \cdot 1{,}53k)} + \frac{r_{e2}}{r_{o2}}\right] V_x$$

$$V_A = \frac{1{,}53k\, r_{e1} - \cancel{\beta\, 1{,}53k\, r_{e2}} + r_{e2} r_{\pi 1} + \cancel{\beta\, 1{,}53k\, r_{e2}}}{r_{o2}(r_{\pi 1} + \beta \cdot 1{,}53k)} \cdot V_x$$

$$\boxed{V_A = \frac{r_{e1}(1{,}53k + r_{\pi 2})}{r_{o2}(r_{\pi 1} + \beta\, 1{,}53k)} V_x}$$

• <u>Nó X</u> $\quad i_x + \alpha\left(\frac{V_A - V_B}{r_{e2}}\right) + \frac{V_A - V_x}{r_{o2}} = 0$

$$i_x + V_A\left(\frac{\alpha}{r_{e2}} + \frac{1}{r_{o2}}\right) - \frac{\alpha}{r_{e2}} V_B = \frac{V_x}{r_{o2}}$$

$$i_x + \left(\frac{\alpha r_{o2} + r_{e2}}{r_{e2} r_{o2}}\right)\frac{r_{e1}(1{,}53k + r_{\pi 2})}{r_{o2}(r_{\pi 1} + \beta\, 1{,}53k)} V_x - \frac{\alpha\, 1{,}53k\,(r_{e1} - \beta r_{e2})}{r_{o2} r_{e2}(r_{\pi 1} + \beta\, 1{,}53k)} V_x = \frac{V_x}{r_{o2}}$$

VI

$$\frac{i_x}{v_x} = \left[\frac{1}{r_{o2}} + \frac{\alpha\, 1{,}53k\,(r_{e1} - \beta r_{e2})}{r_{o2} r_{e2}\,(r_{\pi 1} + \beta\, 1{,}53k)} - \frac{r_{e1}\,(\alpha r_{o2} + r_{e2})(1{,}53k + r_{\pi 2})}{r_{o2}^2\, r_{e2}\,(r_{\pi 1} + \beta\, 1{,}53k)} \right]$$

$$= \frac{r_{o2} r_{e2}(r_{\pi 1} + \beta\, 1{,}53k) + \alpha\, 1{,}53k\,(r_{e1} - \beta r_{e2})\, r_{o2} - r_{e1}(\alpha r_{o2} + r_{e2})(1{,}53k + r_{\pi 2})}{r_{o2}^2\, r_{e2}\,(r_{\pi 1} + \beta\, 1{,}53k)}$$

$$\frac{i_x}{v_x} = \frac{1{,}53k\,(\beta r_{o2} r_{e2} + \cancel{\alpha r_{o2} r_{e1}} - \alpha\beta r_{o2} r_{e2} - \cancel{\alpha r_{o2} r_{e1}} - r_{e1} r_{e2})}{r_{o2}^2\, r_{e2}\,(r_{\pi 1} + \beta \cdot 1{,}53k)} +$$

$$\frac{r_{o2} r_{e2} r_{e1}\,(\beta + 1) - \overbrace{\alpha(\beta + 1)}^{\beta}\, r_{o2} r_{e1} r_{e2} - (\beta + 1)\, r_{e1} r_{e2}^2}{r_{o2}^2\, r_{e2}\,(r_{\pi 1} + \beta \cdot 1{,}53k)}$$

• Manipulando esta expressão, encontramos:

$$\frac{i_x}{v_x} = \frac{\cancel{r_{o2}}\,\cancel{r_{e2}}\left[1{,}53k\left(\alpha - r_{e1}/r_{o2}\right) + r_{e1}\left(1 - r_{\pi 2}/r_{o2}\right)\right]}{r_{o2}^{\cancel{2}}\,\cancel{r_{e2}}\,(r_{\pi 1} + \beta \cdot 1{,}53k)}$$

$$R_{o2} = \frac{v_x}{i_x} = \frac{r_{o2}\,(r_{\pi 1} + \beta \cdot 1{,}53k)}{1{,}53k\left(\alpha - r_{e1}/r_{o2}\right) + r_{e1}\left(1 - r_{\pi 2}/r_{o2}\right)} = \boxed{5{,}355\ M\Omega}$$

• mas, $\alpha - \frac{r_{e1}}{r_{o2}} = \frac{\alpha r_{o2} - r_{e1}}{r_{o2}} \simeq \alpha$, pois $r_{o2} >> r_{e1}$

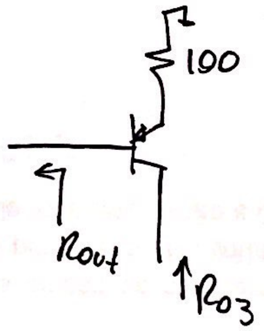
logo → $R_{o2} \cong \frac{r_{o2}\,(r_{\pi 1} + \beta \cdot 1{,}53k)}{\alpha\, 1{,}53k + r_{e1}\left(1 - r_{\pi 2}/r_{o2}\right)}$

→ novamente → $\alpha\, 1{,}53k >> r_{e1}\left(1 - r_{\pi 2}/r_{o2}\right)$, pois

$\frac{r_{\pi 2}}{r_{o2}} < 1$ e $1{,}53k\Omega >> r_{e1}$

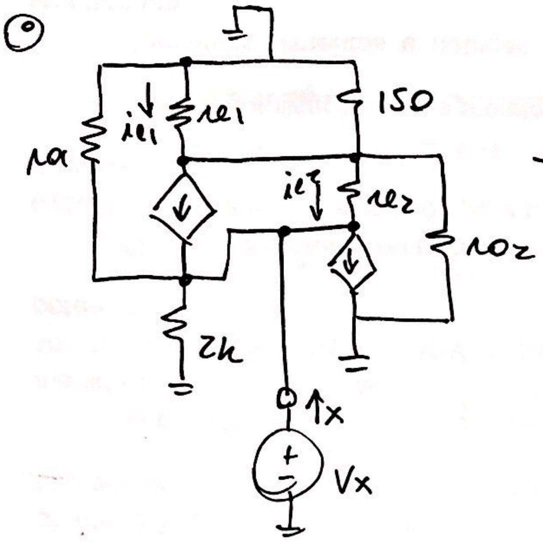
assim: $\boxed{R_{o2} \cong \frac{r_{o2}\,(r_{\pi 1} + \beta \cdot 1{,}53k)}{\alpha \cdot 1{,}53k}} = 5{,}37\ M\Omega$

- Cálculo de R_{o3}



→ Qual a influência de Q_2 em Q_3? → Calcular Rout

Calculando Rout



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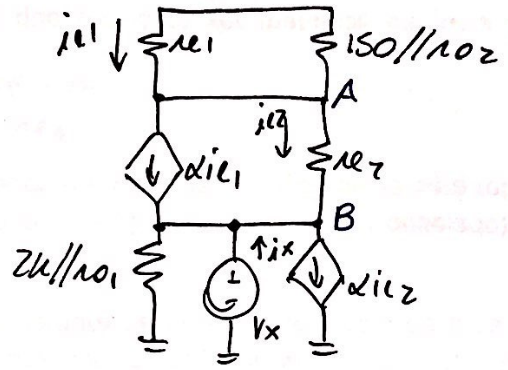


$$\boxed{V_B = V_x}$$

→ Nó A

$$\frac{V_A}{150//r_{o2}} + \frac{V_A - V_B}{r_{e2}} + \alpha\left(-\frac{V_A}{r_{e1}}\right) = \left(-\frac{V_A}{r_{e1}}\right)$$

$$V_A \underbrace{\left(\frac{1}{150//r_{o2}} + \frac{1}{r_{e2}} + \frac{1}{r_{\pi 1}}\right)}_{\sim 1/r_{e2}} = \frac{V_B}{r_{e2}}$$

$$\boxed{V_A \cong V_B}$$

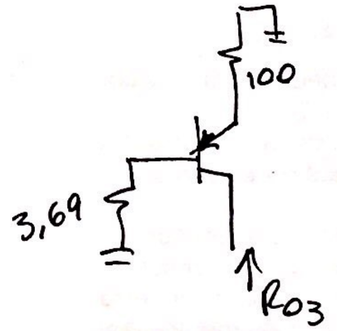
Nó B

$$i_x + \alpha\left(-\frac{V_A}{r_{e1}}\right) + \frac{V_A - V_B}{r_{e2}} = \alpha\left(\frac{V_A - V_B}{r_{e2}}\right) + \frac{V_B}{2k//r_{o1}}$$

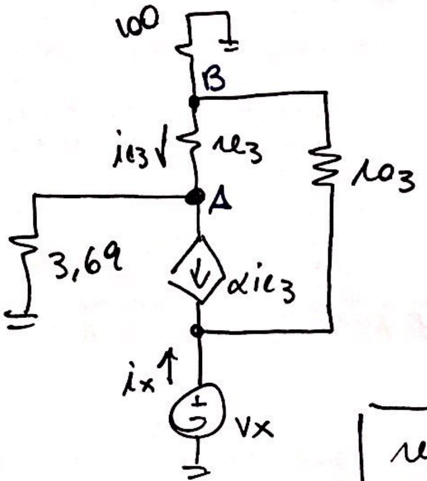
$$i_x = \frac{V_B}{2k//r_{o1}} + (\alpha - 1)\cancelto{0}{\left(\frac{V_A - V_B}{r_{e2}}\right)} + \frac{\alpha V_A}{r_{e1}}$$

$$i_x = V_B \underbrace{\left(\frac{1}{2k//r_{o1}} + \frac{\alpha}{r_{e1}}\right)}_{\sim \frac{\alpha}{r_{e1}}} \Longrightarrow \boxed{R_{out} = \frac{V_B}{i_x} \cong \frac{r_{e1}}{\alpha} = 3{,}69\,\Omega}$$

→ Continuando



→



$$\boxed{\begin{aligned} r_{e3} &= 3{,}57\,\Omega \\ r_{o3} &= 7{,}14\,k\Omega \end{aligned}}$$

• Nó A

$$\frac{V_B - V_A}{r_{e3}} = \frac{V_A}{3{,}69} + \alpha\left(\frac{V_B - V_A}{r_{e3}}\right)$$

$$V_A\left(\frac{1}{3{,}69} + \frac{1-\alpha}{r_{e3}}\right) = V_B\left(\frac{1-\alpha}{r_{e3}}\right)$$

$$V_A\left(\frac{1}{3{,}69} + \frac{1}{r_{\pi 3}}\right) = \frac{V_B}{r_{\pi 3}}$$

$$V_A \, \frac{r_{\pi 3} + 3{,}69}{3{,}69\, \cancel{r_{\pi 3}}} = \frac{V_B}{\cancel{r_{\pi 3}}} \rightarrow \boxed{V_A = \frac{3{,}69}{r_{\pi 3} + 3{,}69} V_B}$$

$$\boxed{V_A = 2 \times 10^{-3} \cdot V_B}$$

Nó B:

$$\frac{V_B}{100} + \frac{V_B - V_A}{r_{e3}} + \frac{V_B - V_x}{r_{o3}} = 0$$

$$\underbrace{V_B\left(\frac{1}{100} + \frac{0{,}998}{r_{e3}} + \frac{1}{r_{o3}}\right)}_{} = \frac{V_x}{r_{o3}}$$

$$V_B \, \frac{r_{e3} r_{o3} + 0{,}998 \cdot 100 r_{o3} + 100 r_{e3}}{100\, r_{e3}\, \cancel{r_{o3}}} = \frac{V_x}{\cancel{r_{o3}}}$$

$$V_B = \frac{100 \cdot r_{e3}}{99{,}8 r_{o3} + 100 r_{e3} + r_{e3} r_{o3}} \cdot V_x$$

Nó X

$$i_x + \alpha\left(\frac{V_B - V_A}{r_{e3}}\right) + \frac{V_B - V_x}{r_{o3}} = 0$$

$$i_x + \frac{\alpha \cdot 0{,}998\, V_B}{r_{e3}} + \frac{V_B}{r_{o3}} = \frac{V_x}{r_{o3}}$$

$$i_x = \frac{V_x}{r_{o3}} - \left(\frac{1}{r_{o3}} + \frac{\alpha\, 0{,}998}{r_{e3}}\right)\cdot\left(\frac{100\cdot r_{e3}}{99{,}8\, r_{o3} + 100\, r_{e3} + r_{e3}\, r_{o3}}\right) V_x$$

$$i_x = \frac{V_x}{r_{o3}} - \frac{r_{e3} + \alpha\cdot 0{,}998\, r_{o3}}{\cancel{r_{e3}}\, r_{o3}} \cdot \frac{100\, \cancel{r_{e3}}}{99{,}8\, r_{o3} + 100\, r_{e3} + r_{e3}\, r_{o3}}\; V_x$$

$$\frac{i_x}{V_x} = \frac{99{,}8\, r_{o3} + \cancel{100\, r_{e3}} + r_{e3}\, r_{o3} - \cancel{100\, r_{e3}} - \alpha\cdot 0{,}998\cdot 100\, r_{o3}}{r_{o3}\,(99{,}8\, r_{o3} + 100\, r_{e3} + r_{e3}\, r_{o3})}$$

$$= \frac{99{,}8\, \cancel{r_{o3}}\,(1-\alpha) + r_{e3}\, \cancel{r_{o3}}}{\cancel{r_{o3}}\,(99{,}8\, r_{o3} + 100\, r_{e3} + r_{e3}\, r_{o3})}\; \frac{(\beta+1)}{(\beta+1)}$$

$$\frac{i_x}{V_x} = \frac{99{,}8 + r_{\pi 3}}{(\beta+1)\, 99{,}8\, r_{o3} + 100\, r_{\pi 3} + r_{\pi 3}\, r_{o3}}$$

$$\boxed{R_{o3} = \frac{(\beta+1)\, 99{,}8\, r_{o3} + (100 + r_{o3})\, r_{\pi 3}}{99{,}8 + r_{\pi 3}} = 196{,}28\, k\Omega}$$

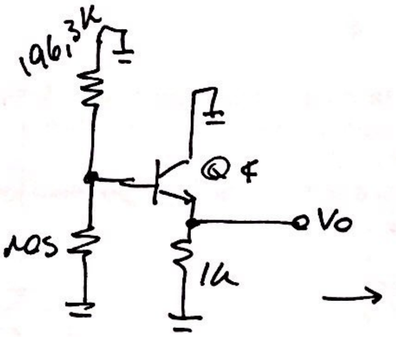
→ Compilando

$$\boxed{\begin{aligned} \rightarrow R_{o2} &= 5{,}36\, M\Omega \\ R_{o3} &= 196{,}3\, k\Omega \end{aligned}}$$

c) Cálculo de Ad e Ro

→ Iniciando com o cálculo de Ro

→ fazendo vid=0, o estágio de saída se torna:



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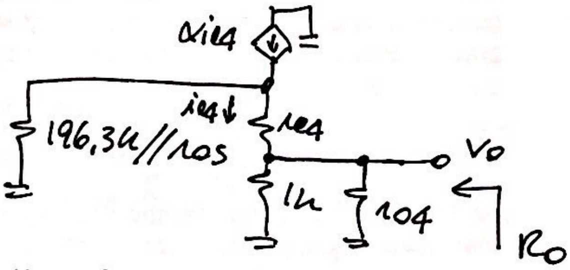


$$\rightarrow Ro = (ro4 // 1k) // \left(re4 + \frac{196{,}3k // ro5}{\beta + 1}\right)$$

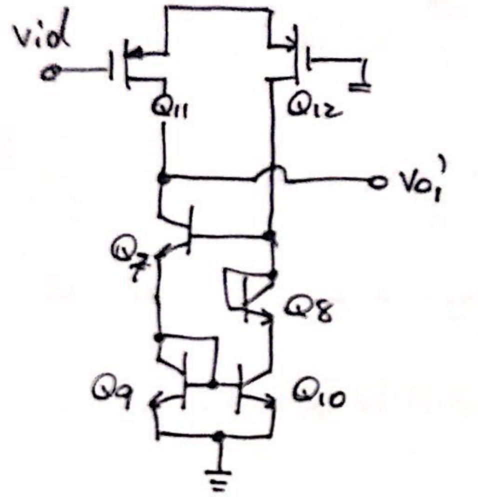
- $ro5 = \frac{50}{7mA} = 7{,}14k\Omega$
- $ro4 = \frac{50}{15mA} = 3{,}33k\Omega$
- $re4 = \frac{28mV}{15mA} = 1{,}7\Omega$

$$\boxed{Ro = 15{,}15\Omega}$$

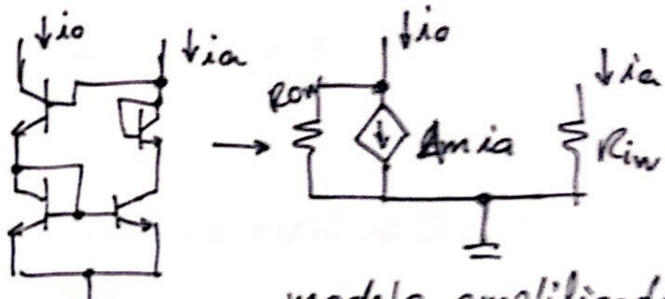
→ Cálculo de Ad

↳ P/ realizar o cálculo do ganho diferencial é interessante analisar os múltiplos estágios do amplificador e em seguida multiplicar os ganhos individuais de cada estágio p/ encontrar o ganho total.

→ Analisando o par diferencial com carga ativa:



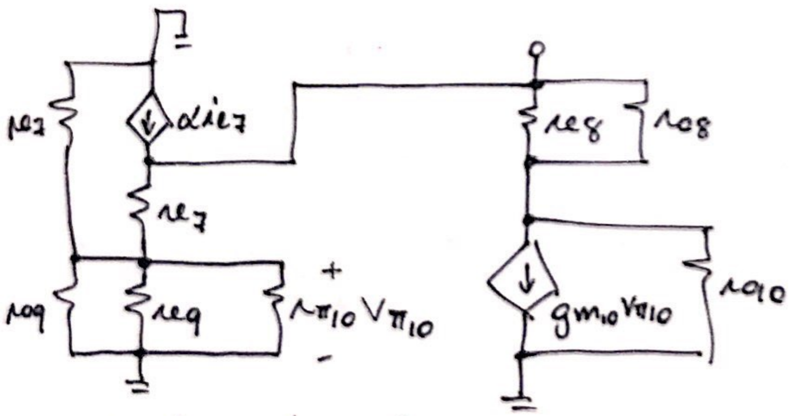
→ Um boa estratégia é fazer um modelo do espelho de wilson:



modelo amplificador de corrente.

→ Em função das análises feitas em sala, sabe-se que $\boxed{R_{ow} \cong \frac{\beta \cdot r_{o7}}{2}}$; sendo que nos resta calcular R_{iw} e A_m.

→ cálculo de R_{iw}



→ $r_{o7} = r_{o8} = r_{o9} = r_{o10} = r_o = \frac{50V}{2{,}335mA}$

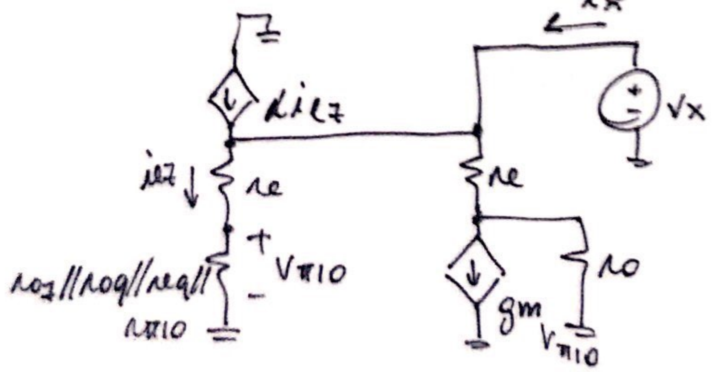
• $r_o = 21{,}4k\Omega$

• $r_{e7} - r_{e10} = r_e = \frac{25mV}{2{,}335mA} = 10{,}7\Omega$

→ $r_e // r_o \approx r_e$

• $g_{m10} = \frac{2{,}335mA}{25mV} = 0{,}093 A/V$

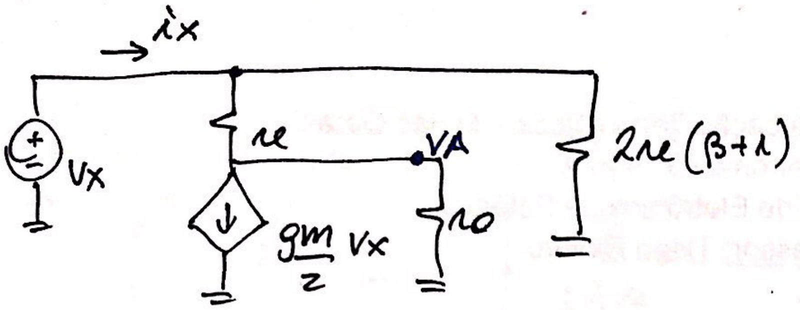
→ Redesenhando



→ $r_{o7}//r_{o9}//r_{e9}//r_{\pi10} \approx r_e$

• Assim:

$$V_{\pi10} \cong \frac{Vx \cdot \cancel{r_e}}{2\cancel{r_e}} \cong \frac{Vx}{2}$$



Nó A

$$\frac{V_x - V_A}{r_e} = \frac{V_A}{r_o} + \frac{g_m V_x}{2}$$

$$V_x - V_A = \frac{r_e}{r_o} V_A + \frac{g_m r_e}{2} V_x \quad \longrightarrow \quad g_m = \frac{\alpha}{r_e}$$

$$V_x - V_A = \frac{r_e}{r_o} V_A + \frac{\alpha}{2} V_x$$

$$V_x \left(1 - \frac{\alpha}{2}\right) = V_A \frac{r_o + r_e}{r_o}$$

$$\boxed{V_A = \frac{r_o\left(1 - \alpha/2\right)}{r_o + r_e} V_x} \longrightarrow \begin{matrix} \alpha \cong 1 \\ r_o >> r_e \end{matrix} \Rightarrow \boxed{V_A \cong \frac{V_x}{2}} //$$

Nó Vx $\rightarrow$

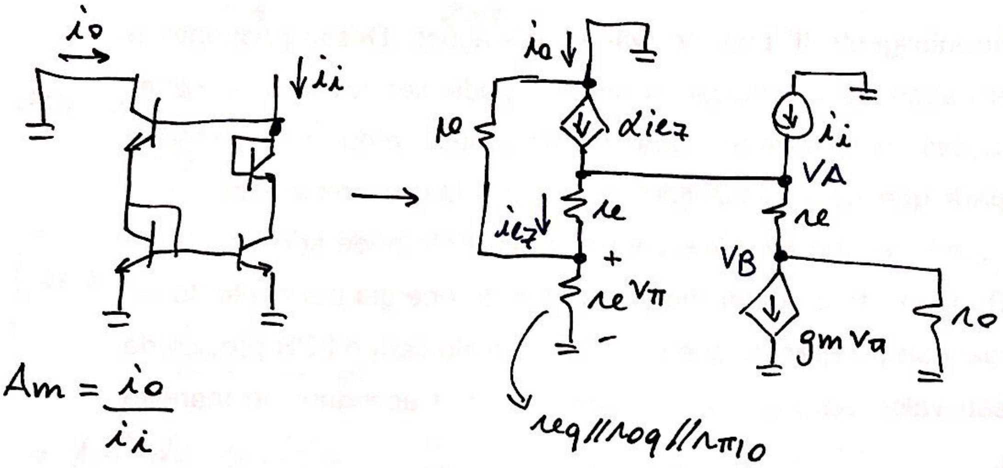
$$i_x = \frac{V_x - V_A}{r_e} + \frac{V_x}{2r_e(\beta+1)}$$

$$i_x = \frac{1}{2r_e} \cdot V_x + \frac{V_x}{2r_e(\beta+1)}$$

$$\frac{i_x}{V_x} = \frac{\beta+1+1}{2r_e(\beta+1)} = \frac{\beta+2}{2r_e(\beta+1)}$$

$$\boxed{R_{iw} = \frac{2r_e(\beta+1)}{\beta+2} = 21{,}36\,\Omega} //$$

→ Cálculo de Am



$$A_m = \frac{i_o}{i_i}$$

→ $V_\pi = V_A \cdot \dfrac{r_e // r_o}{r_e + r_e // r_o} \cong \dfrac{V_A}{2}$

Nó A

$$i_i = \frac{V_A - V_\pi}{r_e} + \frac{V_A - V_B}{r_e} - \alpha\left(\frac{V_A - V_\pi}{r_e}\right)$$

$$i_i = \frac{\cancel{V}_A(1-\alpha)}{2r_e} + \frac{V_A}{r_e} - \frac{V_B}{r_e} \cong$$

$$i_i = V_A\left(\frac{1}{2r_\pi} + \frac{1}{r_e}\right) - \frac{V_B}{r_e}$$

Nó B

$$\frac{V_A - V_B}{r_e} = \frac{V_B}{r_o} + g_m \frac{V_A}{2}$$

$$V_A - V_B = \frac{r_e}{r_o} V_B + \frac{g_m r_e}{2} V_A$$

$$V_A\left(1 - \frac{g_m r_e}{2}\right) = V_B\left(1 + \frac{r_e}{r_o}\right)$$

$$V_A\left(1 - \frac{\alpha}{2}\right) = V_B\left(\frac{r_o + r_e}{r_o}\right)$$

aproximando $\alpha \cong 1$, $r_o >> r_e$ → $\dfrac{V_A}{2} = V_B$ → $\boxed{V_B = \dfrac{V_A}{2}}$

logo → $i_i = V_A \dfrac{1 + 2(\beta+1)}{2r_\pi} - \dfrac{V_A}{2r_e}$

$$i_i = V_A \frac{\cancel{1} + 2\beta + 2 - \beta - \cancel{1}}{2r_\pi} \rightarrow \boxed{V_A = \frac{2r_\pi}{\beta+2} i_i}$$

$$i_{e7} = \frac{V_A - V_\pi}{r_e} = \frac{V_A}{2r_e}$$

$$i_{e7} = \frac{2r_\pi}{2r_e(\beta+2)} \cdot i_i = \frac{\cancel{2r_e}(\beta+1)}{\cancel{2r_e}(\beta+2)}\, i_i$$

$$\boxed{i_{e7} = \frac{\beta+1}{\beta+2}\, i_i}$$

→ Nó de saída $\quad i_o = \alpha i_{e7} + \frac{0 - V_\pi}{r_o}$

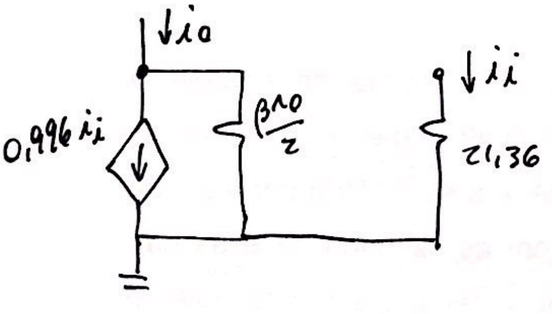
$$i_o = \frac{\beta}{\cancel{\beta+1}} \cdot \frac{\cancel{\beta+1}}{\beta+2}\, i_i - \frac{V_A}{2r_o}$$

$$i_o = \frac{\beta}{\beta+2}\, i_i - \frac{\cancel{2}r_\pi}{\cancel{2}r_o(\beta+2)}\, i_i$$

$$\frac{i_o}{i_i} = \frac{\beta r_o - r_\pi}{r_o(\beta+2)} \rightarrow \text{como } \beta r_o \gg r_\pi$$

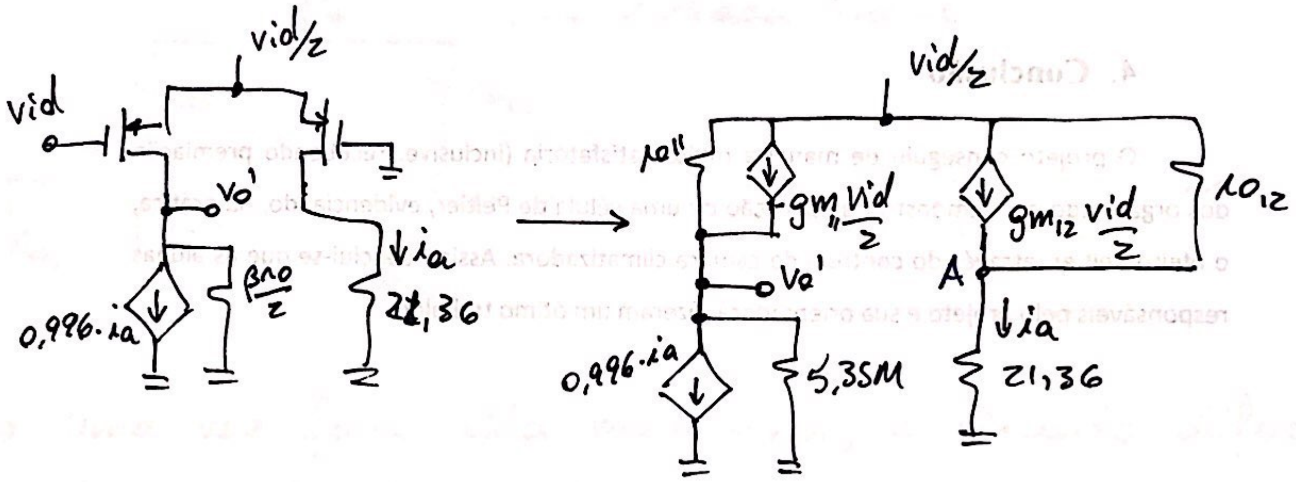
$$\boxed{A_m = \frac{i_o}{i_i} \cong \frac{\beta}{\beta+2} = 0{,}996}$$

→ Assim, o modelo do espelho de Wilson se torna



$$\rightarrow \boxed{\frac{\beta r_o}{2} = 5{,}35\, M\Omega}$$

→ Uma vez definido o modelo de espelho, voltamos ao circuito do par diferencial



- $\bullet\ gm_{11} = gm_{12} = \dfrac{2 I_{D11}}{V_{ov}} = 3{,}06\,mA/V^2$
- $\bullet\ ro_{11} = ro_{12} = \dfrac{50}{I_{D11}} = 21{,}4k\Omega$

- Nó A:

$$gm_{12}\frac{vid}{2} + \frac{\frac{vid}{2} - VA}{ro_{12}} = \frac{VA}{21{,}36}$$

$$\left(gm_{12} + \frac{1}{ro_{12}}\right)\frac{vid}{2} = VA\underbrace{\left(\frac{1}{21{,}36} + \frac{1}{ro_{12}}\right)}_{\sim 1/21{,}36}$$

$$\boxed{VA = \frac{21{,}36}{2}\cdot\left(\frac{1 + gm_{12}ro_{12}}{ro_{12}}\right) vid}$$

$$ia = \frac{VA}{21{,}36} \longrightarrow \boxed{ia = \frac{1 + gm_{12}ro_{12}}{2ro_{12}}\ vid}$$

- Nó Vo':

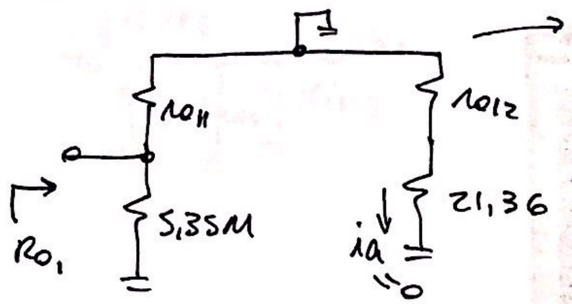
$$0{,}996\,ia + \frac{Vo'}{5{,}35M} + \frac{Vo' - vid/2}{ro_{11}} = -gm_{11}\frac{vid}{2}$$

$$Vo'\left(\frac{1}{5{,}35M} + \frac{1}{ro_{11}}\right) = vid\left(-\frac{gm_{11}}{2} + \frac{1}{2ro_{11}} - \frac{0{,}996(1 + gm_{12}ro_{12})}{2ro_{12}}\right)$$

$$Vo' = \left(\frac{5{,}35M\cdot\cancel{ro_{11}}}{5{,}35M + ro_{11}}\cdot\frac{-gm_{11}ro_{11} + 1 - 0{,}996 - gm_{12}ro_{12}\,0{,}996}{2\cancel{ro_{11}}}\right) vid$$

$$\boxed{\frac{Vo'}{vid} = -65{,}09\ V/V}$$

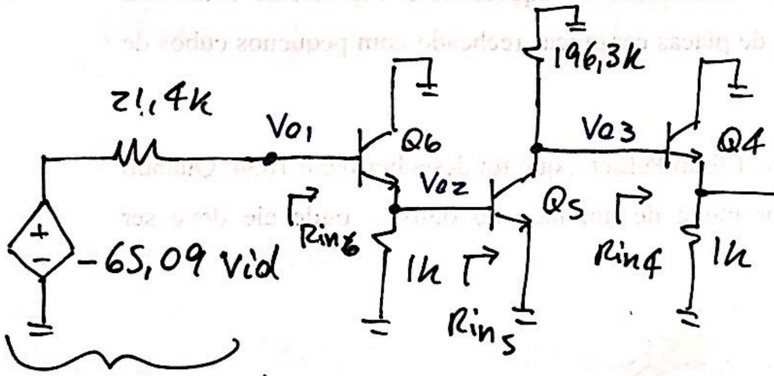
→ Podemos também calcular a resistência de saída do par:



$$\rightarrow R_{o1} = r_{o11} // 5{,}35M \approx r_{o11}$$

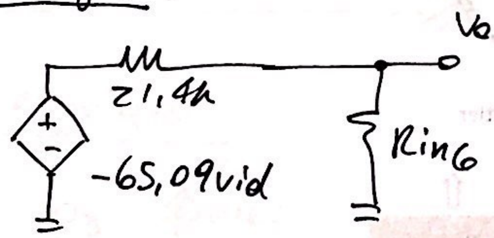
$$\boxed{R_{o1} = 21{,}4k\Omega}$$

→ Uma vez feita esta modelagem, o circuito diferencial do amplificador se torna:



→ calculando os ganhos:

1º estágio:



$$A_{v1} = \frac{V_{o1}}{V_{id}} = \frac{R_{in6}}{R_{in6} + 21{,}4k} \cdot -65{,}09$$

$$\boxed{A_{v1} = -61{,}11 \ V/V}$$

$$R_{in6} = (\beta+1)\left[\overset{r_{e6}}{1k} // R_{in5}\right]$$

$$R_{in5} = (\beta+1)\, r_{e5}$$

$$\rightarrow r_{e5} = \frac{25mV}{7mA} = 3{,}57\Omega$$

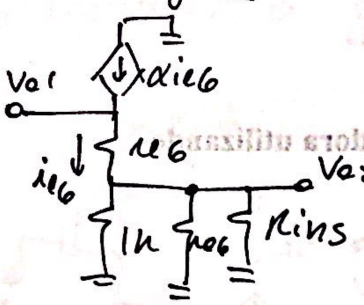
$$r_{e6} = \frac{25mV}{0{,}7mA} = 35{,}7\Omega$$

∘ logo → $R_{in5} = 1{,}79k\Omega$

$$\boxed{R_{in6} = 328{,}7k\Omega}$$

XVII

2º estágio



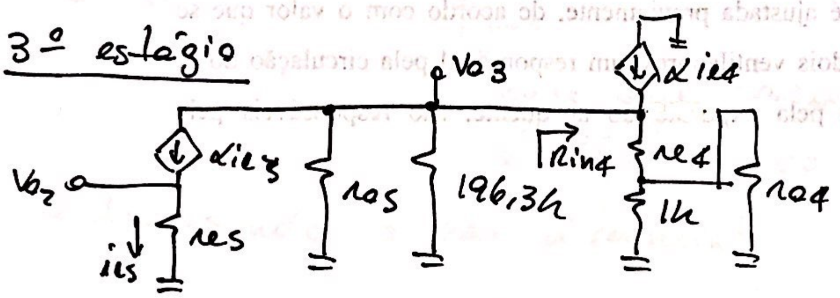
$r_{o6} = 71{,}4k\Omega$

$1k // r_{e6} // R_{ins} = 635{,}9\Omega$

$$V_{o2} = V_{o1} \cdot \frac{635{,}9}{635{,}9 + 35{,}7}$$

$$\boxed{A_{v2} = \frac{V_{o2}}{V_{o1}} = 0{,}947\ V/V}$$

3º estágio



- $r_{e5} = 3{,}57\Omega$
- $r_{o5} = 7{,}14k\Omega$
- $r_{e4} = 1{,}7\Omega$
- $r_{o4} = 3{,}33k\Omega$

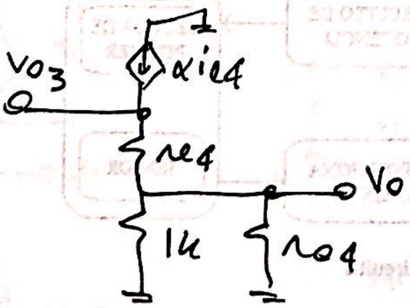
$R_{in4} = (r_{e4} + 1k // r_{o4})(\beta + 1)$

$R_{in4} = 386{,}1K\Omega$

$$\boxed{\frac{V_{o3}}{V_{o2}} = -\frac{\alpha\,(r_{o5} // 196{,}3k // R_{in4})}{r_{e5}} = -1{,}896\ kV/V}$$

$$\boxed{A_{v3} = -1{,}896\ kV/V}$$

4º estágio



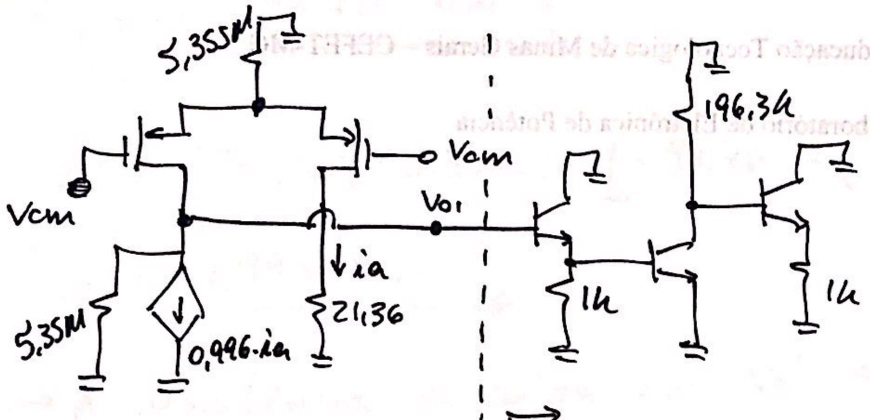
$$V_o = V_{o3} \cdot \frac{1k // r_{o4}}{1k // r_{o4} + r_{e4}}$$

$$\boxed{A_{v4} = \frac{V_o}{V_{o3}} = 0{,}998\ V/V}$$

- Assim, $A_d = A_{v1} \cdot A_{v2} \cdot A_{v3} \cdot A_{v4}$

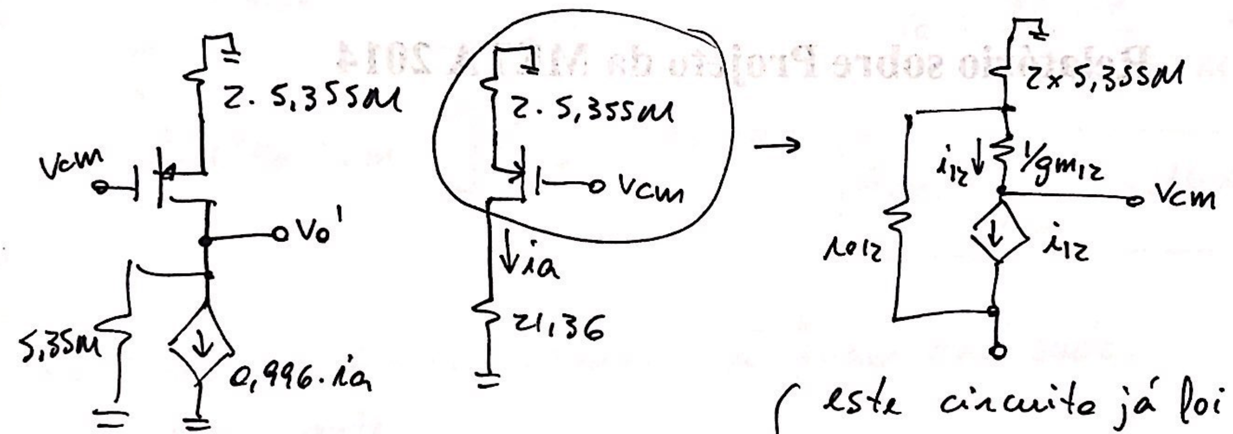
$$\boxed{A_d = 109{,}5\ kV/V}$$

d) Calcular o ganho de modo-comum XVIII

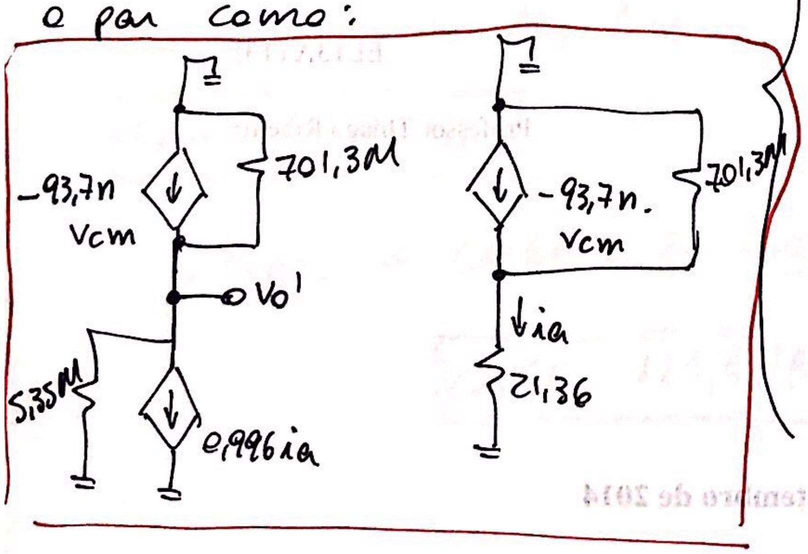


note que daqui p/ frente a análise é idêntica ao modo diferencial.

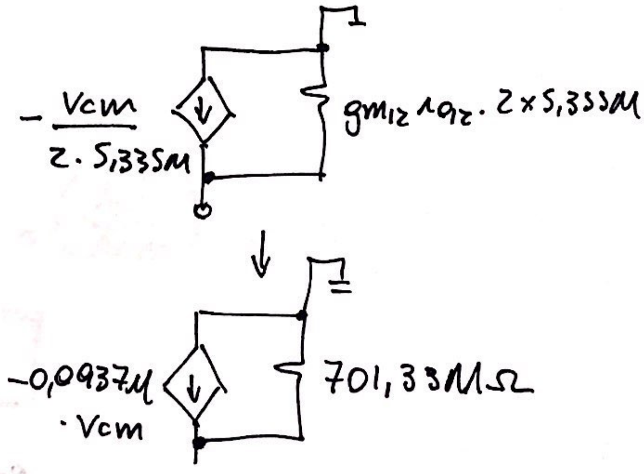
→ Analisando o par diferencial



Assim, pode-se redesenhar o par como:



este circuito já foi analisado nas aulas. Gerou-se o seguinte modelo:



XIX

$\rightarrow \boxed{i_a \cong -93{,}7n \cdot V_{cm}}$

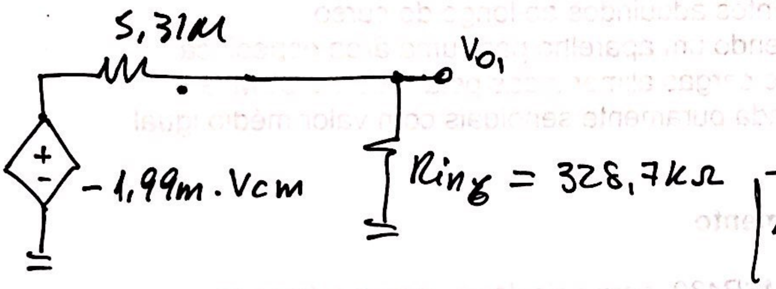
$$V_o' = (701{,}3M // 5{,}35M) \cdot \left[-93{,}7n - (-93{,}7n \cdot 0{,}996)\right] V_{cm}$$

$$\boxed{V_o' = -1{,}99\,m\ V_{cm}}$$

$\rightarrow$ A resistência de saída em V_o' se torna

$$\boxed{R_o' = 701{,}3M // 5{,}35M = 5{,}31M\Omega}$$

$\rightarrow$ Assim o ganho do 1º estágio se torna:



$$V_{o1} = \frac{328{,}7k}{328{,}7k + 5{,}31M} \cdot -1{,}99m\ V_{cm}$$

$$\boxed{A_{cm_1} = \frac{V_{o1}}{V_{cm}} = -116\,\mu\,V/V}$$

$\rightarrow$ Como os demais estágios já foram analisados anteriormente

$$A_{cm} = A_{cm_1} \cdot A_{v2} \cdot A_{v3} \cdot A_{v4}$$

$$\boxed{A_{cm} = 0{,}208\ V/V}$$

. logo. $\rightarrow$ $CMRR = 20 \log_{10}\left(\frac{A_d}{A_{cm}}\right)$

$$\boxed{CMRR = 114{,}4\ dB}$$