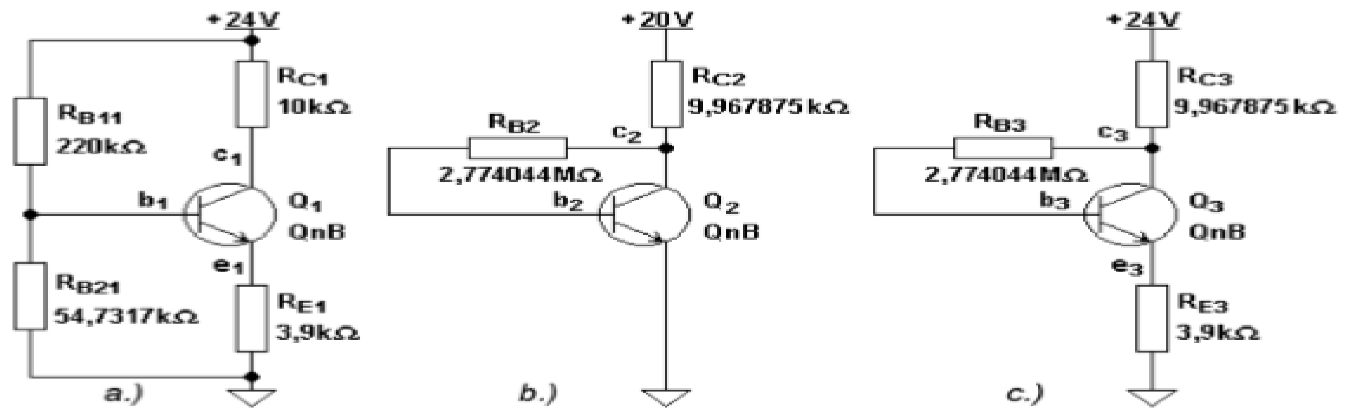
Estabilidade do Ponto Quiescente

Exercício

Os transistores da Figura 7 foram polarizados no mesmo ponto quiescente e, por isso, alguns resistores foram colocados com valores quebrados e com precisão de seis casas decimais. Estudar a estabilidade desses pontos quiescentes em três situações:

a) Variações de I_{CQ} em função dos ganhos de corrente dos transistores ($\Delta I_{CQ} / \Delta\beta$).
b) Variações de I_{CQ} em função da temperatura ($\Delta I_{CQ} / \Delta\theta$).
c) Variações de I_{CQ} em função das tensões de alimentação ($\Delta I_{CQ} / \Delta V_{CC}$).
d) Concluir qual dos três circuitos é mais estável estaticamente.

Considerar $\Delta\theta$ =50°C (0 ~50°C), ΔV_{CC}= ± 0,5V e $\Delta\beta=\beta_{max} - \beta_{min}$.



Dados do transistor Q_{nB} :

β_{tip} = 310,2984 e V_{BEtip} = 0,63685 V @ 27 ° C.
Espalhamento de fabricação ≡ β_{min} = 188,554 c/ V_{BEmax} = 0,637 V e β_{max} = 583,85 c/ V_{BEmin} = 0,63615 V @ 27 ° C.
Espalhamento térmico: β (50°C) = 316,7076; β (0°C) = 302,243; V_{BE}(50°C) = 0,58848 V ; V_{BE}(0°C) = 0,69254 V.

Equações de Polarização

Circuito A

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right) \times R_{B_1} \times \beta}{R_{B_1} + (\beta+1) \times R_{E_1}}$$

$$R_{B_1} = \frac{R_{B_{11}} \times R_{B_{21}}}{R_{B_{11}} + R_{B_{21}}}$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta} \times R_{E_1}\right) \times I_{C_1}$$

Circuito B

$$I_{C_2} = \frac{V_{CC_2} - V_{BE}}{R_{B_2} + (\beta+1) \times R_{C_2}} \times \beta$$

$$V_{CE_2} = V_{CC_2} - \frac{\beta+1}{\beta} \times R_{C_2} \times I_{C_2}$$

Circuito C

$$I_{C_3} = \frac{V_{CC} - V_{BE}}{R_{B3} + (\beta+1) \times (R_{C3} + R_{E3})} \times \beta$$

$$V_{CE_3} = V_{CC} - \frac{\beta+1}{\beta} \times (R_{C3} + R_{E3}) \times I_{C_3}$$

a) Variações de I_{CQ} em função dos ganhos de corrente dos transistores ($\Delta I_{CQ} / \Delta\beta$)

Circuito A

- Cálculo de $I_{C1(min)}$ e $V_{CE(max)}$ (β_{min} = 188,54 e V_{BEmax} = 0,637V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right) \times R_{B_1} \times \beta}{R_{B_1} + (\beta+1) \times R_{E_1}} \rightarrow I_{C_1(\min)} = \frac{\left(\frac{24}{220k} - \frac{0,637}{43,83k}\right) \times 43,83k \times 188,554}{43,83k + (188,554 + 1) \times 3,9k} = 997,882 \quad [\mu A]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta} \times R_{E_1}\right) \times I_{C_1} \rightarrow V_{CE_1(\max)} = 24 - \left(10k + \frac{188,554+1}{188,554} \times 3,9k\right) \times 997,882\mu = 10,109 \quad [V]$$

- Cálculo de $I_{C1(max)}$ e $V_{CE(min)}$ (β_{max} = 583,85 e V_{BEmin} = 0,63615V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right) \times R_{B_1} \times \beta}{R_{B_1} + (\beta+1) \times R_{E_1}} \rightarrow I_{C_1(\max)} = \frac{\left(\frac{24}{220k} - \frac{0,63615}{43,83k}\right) \times 43,83k \times 583,85}{43,83k + (583,85 + 1) \times 3,9k} = 1,04103 \quad [mA]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta} \times R_{E_1}\right) \times I_{C_1} \rightarrow V_{CE_1(\min)} = 24 - \left(10k + \frac{583,85+1}{583,85} \times 3,9k\right) \times 1,04103m = 9,5228 \quad [V]$$

Variação no ponto quiescente: 997,882 µA ≤ I_{CQ} ≤ 1,04103mA e 10,109V ≤ V_{CE} ≤9,5228V

Circuito B

- Cálculo de $I_{C1(min)}$ e $V_{CE(max)}$ (β_{min} = 188,54 e V_{BEmax} = 0,637V)

$$I_{C_2} = \frac{V_{CC_2} - V_{BE}}{R_{B_2} + (\beta + 1) \times R_{C_2}} \times \beta \rightarrow I_{C_2\,(\min)} = \frac{20 - 0{,}637}{2{,}774044M + (188{,}554 + 1) \times 9{,}967875k} \times 188{,}554 = 782{,}883 \quad [\mu A]$$

$$V_{CE_2} = V_{CC_2} - \frac{\beta + 1}{\beta} \times R_{C_2} \times I_{C_2} \rightarrow V_{CE_2\,(\max)} = 20 - \frac{188{,}554 + 1}{188{,}554} \times 9{,}967875k \times 782{,}883\mu = 12{,}155 \quad [V]$$

- Cálculo de $I_{C1(max)}$ e $V_{CE(min)}$ (β_{max} = 583,85 e V_{BEmin} = 0,63615V)

$$I_{C_2} = \frac{V_{CC_2} - V_{BE}}{R_{B_2} + (\beta + 1) \times R_{C_2}} \times \beta \rightarrow I_{C_2\,(\max)} = \frac{20 - 0{,}63615}{2{,}774044M + (583{,}85 + 1) \times 9{,}967875k} \times 583{,}85 = 1{,}314 \quad [mA]$$

$$V_{CE_2} = V_{CC_2} - \frac{\beta + 1}{\beta} \times R_{C_2} \times I_{C_2} \rightarrow V_{CE_2\,(\min)} = 20 - \frac{583{,}85 + 1}{583{,}85} \times 9{,}967875k \times 1{,}314m = 6{,}88 \quad [V]$$

Variação no ponto quiescente: 782,883µA ≤ I_{CQ} ≤ 1,314mA e 12,155V ≤ V_{CE} ≤6,88V

Circuito C

- Cálculo de $I_{C1(min)}$ e $V_{CE(max)}$ (β_{min} = 188,54 e V_{BEmax} = 0,637V)

$$I_{C_3} = \frac{V_{CC} - V_{BE}}{R_{B3} + (\beta + 1) \times (R_{C3} + R_{E3})} \times \beta \rightarrow I_{C_2(\min)} = \frac{24 - 0{,}637}{2{,}774044M + (188{,}554 + 1) \times (9{,}967875k + 3{,}9k)} \times 188{,}554 = 815{,}36 \quad [\mu A]$$

$$V_{CE_3} = V_{CC} - \frac{\beta + 1}{\beta} \times (R_{C3} + R_{E3}) \times I_{C_3} \rightarrow V_{CE_2(\max)} = 24 - \frac{188{,}554 + 1}{188{,}554} \times (9{,}967875k + 3{,}9k) \times 815{,}36\mu = 12{,}633 \quad [V]$$

- Cálculo de $I_{C1(max)}$ e $V_{CE(min)}$ (β_{max} = 583,85 e V_{BEmin} = 0,63615V)

$$I_{C_3} = \frac{V_{CC} - V_{BE}}{R_{B3} + (\beta + 1) \times (R_{C3} + R_{E3})} \times \beta \rightarrow I_{C_2(\max)} = \frac{24 - 0{,}63615}{2{,}774044M + (583{,}85 + 1) \times (9{,}967875k + 3{,}9k)} \times 583{,}85 = 1{,}2532 \quad [mA]$$

$$V_{CE_3} = V_{CC} - \frac{\beta + 1}{\beta} \times (R_{C3} + R_{E3}) \times I_{C_3} \rightarrow V_{CE_2(\min)} = 24 - \frac{583{,}85 + 1}{583{,}85} \times (9{,}967875k + 3{,}9k) \times 1{,}2532m = 6{,}591 \quad [V]$$

Variação no ponto quiescente: 815,36μA ≤ I_{CQ} ≤ 1,2532mA e 12,633V ≤ V_{CE} ≤6,591V

➡ **O circuito A tem a maior estabilidade !**

b) Variações de I_{CQ} em função da temperatura ($\Delta I_C Q$ / $\Delta\theta$):

Circuito A

- Caso típico @ 27°C (β_{tip} = 310,2984, V_{BEtip} = 0,63685V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right)\times R_{B_1}\times\beta}{R_{B_1} + (\beta+1)\times R_{E_1}} \rightarrow I_{C_1(tip)} = \frac{\left(\frac{24}{220k} - \frac{0,63685}{43,83k}\right)\times 43,83k \times 310,2984}{43,83k + (310,2984+1)\times 3,9k} = 1,02235 \quad [\text{mA}]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta}\times R_{E_1}\right)\times I_{C_1} \rightarrow V_{CE_1(tip)} = 24 - \left(10k + \frac{310,2984+1}{310,2984}\times 3,9k\right)\times 1,02252m = 9,7765 \quad [\text{V}]$$

- Caso típico @ 50°C (β_{50oC} = 316,7076, V_{50oC} = 0,58848V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right)\times R_{B_1}\times\beta}{R_{B_1} + (\beta+1)\times R_{E_1}} \rightarrow I_{C_1(50°C)} = \frac{\left(\frac{24}{220k} - \frac{0,58848}{43,83k}\right)\times 43,83k \times 316,7076}{43,83k + (316,7076+1)\times 3,9k} = 1,03507 \quad [\text{mA}]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta}\times R_{E_1}\right)\times I_{C_1} \rightarrow V_{CE_1(50°C)} = 24 - \left(10k + \frac{316,7076+1}{316,7076}\times 3,9k\right)\times 1,03507m = 9,6 \quad [\text{V}]$$

Caso típico @ 0°C (β_{0oC} = 302,243, V_{OoC} = 0,69254V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right)\times R_{B_1}\times\beta}{R_{B_1}+(\beta+1)\times R_{E_1}} \rightarrow I_{C_1(0°C)} = \frac{\left(\frac{24}{220k} - \frac{0,69254}{43,83k}\right)\times 43,83k\times 302,243}{43,83k+(302,243+1)\times 3,9k} = 1,00759 \quad [mA]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta}\times R_{E_1}\right)\times I_{C_1} \rightarrow V_{CE_1(0°C)} = 24 - \left(10k + \frac{302,243+1}{302,243}\times 3,9k\right)\times 1,00759m = 9,9815 \quad [V]$$

Variação no ponto quiescente: 1,00759mA ≤ I_{CQ} ≤ 1,03507mA e 9,6V ≤ V_{CE} ≤ 9,9815V

Circuito B

Caso típico @ 27°C (β_{tip} = 310,2984, V_{BEtip} = 0,63685V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right)\times R_{B_1}\times\beta}{R_{B_1}+(\beta+1)\times R_{E_1}} \rightarrow I_{C_2(tip)} = \frac{20-0,63685\text{ V}}{2,774044M+(310,2984+1)\times 9,967875k}\times 310,2984 = 1,02235 \quad [mA]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta}\times R_{E_1}\right)\times I_{C_1} \rightarrow V_{CE_2(tip)} = 20 - \frac{310,2984+1}{310,2984}\times 9,967875k\times 1,02235m = 9,7765 \quad [V]$$

- Caso típico @ 50°C (β_{50oC} = 316,7076, V_{50oC} = 0,58848V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right) \times R_{B_1} \times \beta}{R_{B_1} + (\beta+1) \times R_{E_1}} \rightarrow I_{C_2(50°C)} = \frac{20 - 0,58848\ \text{V}}{2,774044M + (316,7076+1) \times 9,967875k} \times 316,7076 = 1,03482 \quad [\text{mA}]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta} \times R_{E_1}\right) \times I_{C_1} \rightarrow V_{CE_2(50°C)} = 20 - \frac{316,7076+1}{316,7076} \times 9,967875k \times 1,03482m = 9,6525 \quad [\text{V}]$$

- Caso típico @ 0°C (β_{0oC} = 302,243, V_{0oC} = 0,69254V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right) \times R_{B_1} \times \beta}{R_{B_1} + (\beta+1) \times R_{E_1}} \rightarrow I_{C_2(0°C)} = \frac{20 - 0,69254\ \text{V}}{2,774044M + (302,243+1) \times 9,967875k} \times 302,243 = 1,0067 \quad [\text{mA}]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta} \times R_{E_1}\right) \times I_{C_1} \rightarrow V_{CE_2(0°C)} = 20 - \frac{302,243+1}{302,243} \times 9,967875k \times 1,0067m = 9,9322 \quad [\text{V}]$$

Variação no ponto quiescente: 1,00670mA ≤ I_{CQ} ≤ 1,03482mA e 9,6525V ≤ V_{CE} ≤ 9,9322V

Circuito C

- Caso típico @ 27°C (β_{tip} = 310,2984, V_{BEtip} = 0,63685V)

$$I_{C_3} = \frac{V_{CC} - V_{BE}}{R_{B3} + (\beta+1)\times(R_{C3}+R_{E3})}\times\beta \rightarrow I_{C_3(tip)} = \frac{24-0{,}63685\ \text{V}}{2{,}774044M + (310{,}2984+1)\times(9{,}967875k+3{,}9k)}\times 310{,}2984 = 1{,}02235 \quad [\text{mA}]$$

$$V_{CE_3} = V_{CC} - \frac{\beta+1}{\beta}\times(R_{C3}+R_{E3})\times I_{C_3} \rightarrow V_{CE_3(tip)} = 24 - \frac{310{,}2984+1}{310{,}2984}\times(9{,}967875k+3900)\times 1{,}02235m = 9{,}7765 \quad [\text{V}]$$

- Caso típico @ 50°C (β_{50oC} = 316,7076, V_{50oC} = 0,58848V)

$$I_{C_3} = \frac{V_{CC} - V_{BE}}{R_{B3} + (\beta+1)\times(R_{C3}+R_{E3})}\times\beta \rightarrow I_{C_3(50°C)} = \frac{24-0{,}58848\ \text{V}}{2{,}774044M + (316{,}7076+1)\times(9{,}967875k+3{,}9k)}\times 316{,}7076 = 1{,}03268 \quad [\text{mA}]$$

$$V_{CE_3} = V_{CC} - \frac{\beta+1}{\beta}\times(R_{C3}+R_{E3})\times I_{C_3} \rightarrow V_{CE_3(50°C)} = 24 - \frac{316{,}7076+1}{316{,}7076}\times(9{,}967875k+3{,}9k)\times 1{,}03268m = 9{,}6337 \quad [\text{V}]$$

- Caso típico @ 0°C (β_{0oC} = 302,243, V_{0oC} = 0,69254V)

$$I_{C_3} = \frac{V_{CC} - V_{BE}}{R_{B3} + (\beta+1)\times(R_{C3}+R_{E3})}\times\beta \rightarrow I_{C_3(0°C)} = \frac{24-0{,}69254\ \text{V}}{2{,}774044M + (302{,}243+1)\times(9{,}967875k+3{,}9k)}\times 302{,}243 = 1{,}0093 \quad [\text{mA}]$$

$$V_{CE_3} = V_{CC} - \frac{\beta+1}{\beta}\times(R_{C3}+R_{E3})\times I_{C_3} \rightarrow V_{CE_3(0°C)} = 24 - \frac{302{,}243+1}{302{,}243}\times(9{,}967875k+3{,}9k)\times 1{,}0093m = 9{,}9564 \quad [\text{V}]$$

Variação no ponto quiescente: 1,00930mA $\leq I_{CQ} \leq$ 1,03268mA e 9,6337V $\leq V_{CE} \leq$ 9,9564V

➡ **Os circuitos tem estabilidade muito próxima com relação a variação de temperatura . O circuito B é um pouco mais estável!**

C) Variações de I_{CQ} em função da tensão de alimentação ($\Delta I_C Q$ / ΔV_{CC}):

Circuito A

- V_{CC} = 24,5 V (β_{tip} = 310,2984, V_{BEtip} = 0,63685V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right) \times R_{B_1} \times \beta}{R_{B_1} + (\beta+1) \times R_{E_1}} \rightarrow I_{C_1(24,5V)} = \frac{\left(\frac{24,5}{220k} - \frac{0,63685}{43,83k}\right) \times 43,83k \times 310,2984}{43,83k + (310,2984+1) \times 3,9k} = 1,047 \quad [mA]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta} \times R_{E_1}\right) \times I_{C_1} \rightarrow V_{CE_1(24,5V)} = 24,5 - \left(10k + \frac{310,2984+1}{310,2984} \times 3,9k\right) \times 1,047m = 9,9347 \quad [V]$$

- V_{CC} = 23,5 V (β_{tip} = 310,2984, V_{BEtip} = 0,63685V)

$$I_{C_1} = \frac{\left(\frac{V_{CC}}{R_{B_{11}}} - \frac{V_{BE}}{R_{B_1}}\right) \times R_{B_1} \times \beta}{R_{B_1} + (\beta+1) \times R_{E_1}} \rightarrow I_{C_1(23,5V)} = \frac{\left(\frac{23,5}{220k} - \frac{0,63685}{43,83k}\right) \times 43,83k \times 310,2984}{43,83k + (310,2984+1) \times 3,9k} = 997,774 \quad [A]$$

$$V_{CE_1} = V_{CC} - \left(R_{C_1} + \frac{\beta+1}{\beta} \times R_{E_1}\right) \times I_{C_1} \rightarrow V_{CE_1(23,5V)} = 23,5 - \left(10k + \frac{310,2984+1}{310,2984} \times 3,9k\right) \times 997,774\mu = 9,6184 \quad [V]$$

Variação no ponto quiescente: 997,774µA ≤ I_{CQ} ≤ 1,047mA e 9,9347V ≤ V_{CE} ≤ 9,6184V

Circuito B

- V_{CC} = 20,5 V (β_{tip} = 310,2984, V_{BEtip} = 0,63685V)

$$I_{C_2} = \frac{V_{CC_2} - V_{BE}}{R_{B_2} + (\beta+1) \times R_{C_2}} \times \beta \rightarrow I_{C_2(20,5V)} = \frac{20,5 - 0,63685\ \text{V}}{2,774044M + (310,2984+1) \times 9,967875k} \times 310,2984 = 1,04875 \quad [\text{mA}]$$

$$V_{CE_2} = V_{CC_2} - \frac{\beta+1}{\beta} \times R_{C_2} \times I_{C_2} \rightarrow V_{CE_2(20,5V)} = 20,5 - \frac{310,2984+1}{310,2984} \times 9,967875k \times 1,04875m = 10,0126 \quad [\text{V}]$$

- V_{CC} = 19,5 V (β_{tip} = 310,2984, V_{BEtip} = 0,63685V)

$$I_{C_2} = \frac{V_{CC_2} - V_{BE}}{R_{B_2} + (\beta+1) \times R_{C_2}} \times \beta \rightarrow I_{C_2(19,5V)} = \frac{19,5 - 0,63685\ \text{V}}{2,774044M + (310,2984+1) \times 9,967875k} \times 310,2984 = 995,9465 \quad [\mu\text{A}]$$

$$V_{CE_2} = V_{CC_2} - \frac{\beta+1}{\beta} \times R_{C_2} \times I_{C_2} \rightarrow V_{CE_2(19,5V)} = 19,5 - \frac{310,2984+1}{310,2984} \times 9,967875k \times 995,9465\mu = 9,5405 \quad [\text{V}]$$

Variação no ponto quiescente: 995,9465μA ≤ I_{CQ} ≤ 1,04875mA e 9,5405V ≤ V_{CE} ≤ 10,0126V

Circuito C

- V_{CC} = 24,5 V:

$$I_{C_3} = \frac{V_{CC} - V_{BE}}{R_{B3} + (\beta+1)\times(R_{C3} + R_{E3})} \times \beta \rightarrow I_{C_3(24,5V)} = \frac{24,5 - 0,63685\text{ V}}{2,774044M + (310,2984+1)\times(9,967875k + 3,9k)} \times 310,2984 = 1,04423 \quad [\text{mA}]$$

$$V_{CE_3} = V_{CC} - \frac{\beta+1}{\beta}\times(R_{C3} + R_{E3})\times I_{C_3} \rightarrow V_{CE_3(24,5V)} = 24,5 - \frac{310,2984+1}{310,2984}\times(9,967875k + 3,9k)\times 1,04423m = 9,9721 \quad [\text{V}]$$

- V_{CC} = 23,5 V:

$$I_{C_3} = \frac{V_{CC} - V_{BE}}{R_{B3} + (\beta+1)\times(R_{C3} + R_{E3})} \times \beta \rightarrow I_{C_3(23,5V)} = \frac{23,5 - 0,63685\text{ V}}{2,774044M + (310,2984+1)\times(9,967875k + 3,9k)} \times 310,2984 = 1,0005 \quad [\text{mA}]$$

$$V_{CE_3} = V_{CC} - \frac{\beta+1}{\beta}\times(R_{C3} + R_{E3})\times I_{C_3} \rightarrow V_{CE_3(23,5V)} = 23,5 - \frac{310,2984+1}{310,2984}\times(9,967875k + 3,9k)\times 1,0005m = 9,5809 \quad [\text{V}]$$

Variação no ponto quiescente: 1,0005mA ≤ I_{CQ} ≤ 1,04423mA e 9,5809V ≤ V_{CE} ≤ 9.9721V

Os circuitos tem estabilidade muito próxima com relação a variação de tensão de alimentação . O circuito C é um pouco mais estável!