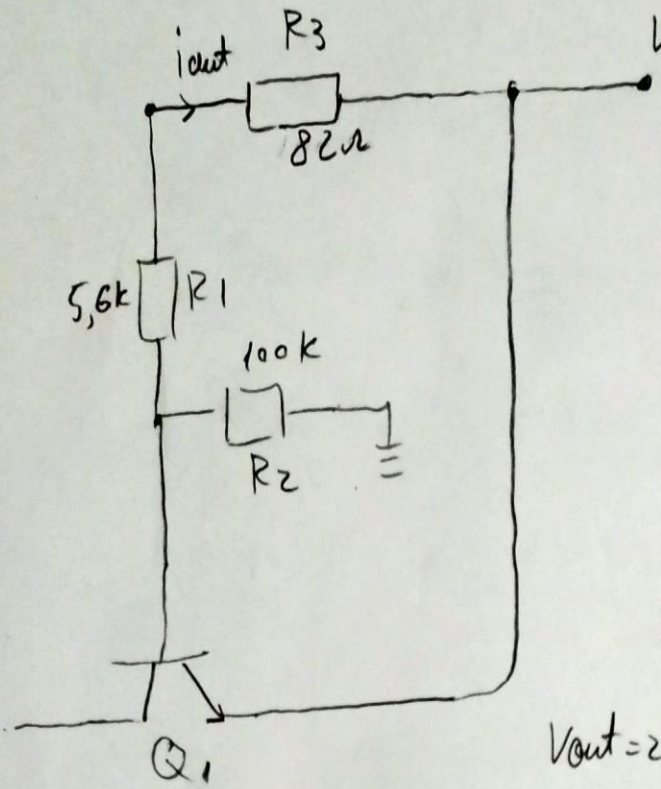
Over current Protection



Foldback

$V_{R3} < 2V$

$i_{out} = 21\ mA$

$$R_3 \cdot i_{out} = (V_{BE1} + V_{out}) \frac{R_1+R_2}{R_2} - V_{out}$$

$V_{out} = 23V$

$$R_3 = \frac{(0,6 + 23) \cdot \frac{5,6+100}{100} - 23}{i_{out}} =$$

$$R_3 = 23,6 \cdot 1,056 - 23 = \frac{1,9216}{0,021} = 91.5\ \Omega$$

$V_{out} = 25$

$$R_3 = \frac{(V_{BE1} + V_{out}) \cdot \frac{R_1+R_2}{R_2} - V_{out}}{i_{out}} = \frac{27,03 - 25}{0,021} = 97\ \Omega$$

choose $R_3 = 82\ \Omega$ SMD 0805 ± 1% 125 mW

$i_{out} = 21\,mA$ alog $R_1 = 5{,}6\,k\Omega$ $V_{out} = 23\,V$

$$i_{out} = \frac{1}{R_3}\left[\left(1 + \frac{R1}{R2}\right)\cdot V_{BE} + \frac{R1}{R2}\cdot V_{out}\right]$$

$$i_{out} = 12{,}2\left[\left(1 + \frac{5{,}6k}{R_2}\right)\cdot 0{,}6 + \frac{5{,}6\cdot 23}{R_2}\right] = 12{,}2\left[0{,}6 + \frac{3{,}36}{R_2} + \frac{128{,}8}{R_2}\right]$$

$$12{,}2\left[0{,}6 + \frac{132{,}16}{R_2}\right] = 21 \Rightarrow R_2 = \frac{1612{,}35}{13{,}68} = 117{,}86\,k\Omega$$

$$V_{out} = 25\,V \Rightarrow 18 = 10\left[\left(1 + \frac{5{,}6}{R_2}\right)\cdot 0{,}6 + \frac{5{,}6}{R_2}\cdot 25\right] \Rightarrow$$

$$12{,}2\left(0{,}6 + \frac{3{,}36}{R_2} + \frac{140}{R_2}\right) \Rightarrow 21 = 7{,}32 + \frac{1749}{R_2} = 13{,}68 = \frac{1749}{R_2} \Rightarrow$$

$R_2 = 127{,}85\,k\Omega$

I choose $R_2 = 100\,k\Omega$ SMD 0805 ±1 0,125W

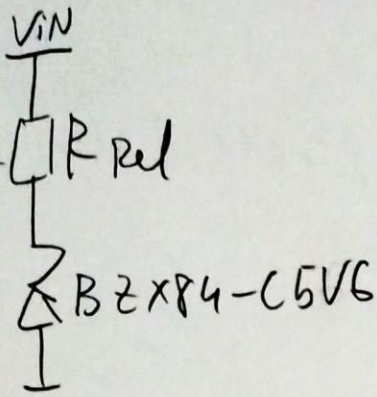
For $R_2 = 100\,k\Omega$ $R_1 = 5{,}6\,k\Omega$ $R_3 = 82\,\Omega$ ⇒

$V_{o\,min} = 23\,V \Rightarrow i_{out} = 12{,}2\left[\left(1 + \frac{5{,}6}{100}\right)\cdot 0{,}6 + \frac{5{,}6}{100}\cdot 23\right] = 23{,}44\,mA$

$V_{o\,max} = 25\,V \Rightarrow i_{out} = 12{,}2\left[\left(1 + \frac{5{,}6}{100}\right)\cdot 0{,}6 + \frac{5{,}6}{100}\cdot 25\right] = 24{,}8\,mA$

$$i_{SC} = \frac{1}{R_3}\left(1 + \frac{R1}{R2}\right)\cdot V_{BE} = 12{,}2\left(1 + \frac{5{,}6}{100}\right)\cdot 0{,}6 = 7{,}73\,mA$$

Voltage Referance



From the data sheet $iz_{min} = 5mA$

i choosed $iz = 6mA$

$$iz = \frac{V_{in} - Vz}{R_{Rel}} \Rightarrow R_{Rel} = \frac{V_{IN} - Vz}{iz} = \frac{30 - 5,6}{6} = 4,06k\Omega$$

$$\frac{33 - 5,6}{6} = 4,56k\Omega$$

i choose $R_{Rel} = 4,5k\Omega$

R_{Rel} = 2 x 5,10Ω SMD 0805 ± 1% 0,125W

2 x 1kΩ SMD 0805 ± 1% 0,125W

1 x 1,5kΩ SMD 0805 ± 1% 0,125W

To limit the power to an ok value and respect.

$i_Z > 5\,mA$ i chosed $R_{Ref} = 4{,}5\,k\Omega$

R_{Ref} = $2 \times 510\,\Omega$ SMD 0805 ± 1% 0,125 W

$2 \times 1\,k\Omega$ SMD 0805 ± 1% 0,125 W

$1 \times 1{,}5\,k\Omega$ SMD 0805 ± 1% 0,125 W

$$i_{Z\,min} = \frac{V_{IN\,min} - V_Z}{R_{Ref}} = \frac{30 - 5{,}6}{4500} = 5{,}42\,mA > 5\,mA.$$

$$i_{Z\,max} = \frac{V_{IN\,max} - V_Z}{R_{Ref}} = \frac{33 - 5{,}6}{4500} \simeq 6\,mA > 5\,mA$$

$$P_{Max\,R17} = i_{Z\,max}^2 \cdot R_{17} = 6^2\,mA \cdot 1{,}5\,k\Omega = 54\,mW < 125\,mW$$

Series Pass Element

$P_D = V_{out\,max} \cdot i_{out\,max} = 25 \cdot 0{,}018 = 450\,mW < 15W$

The series element is a transistor MJD31C SMD

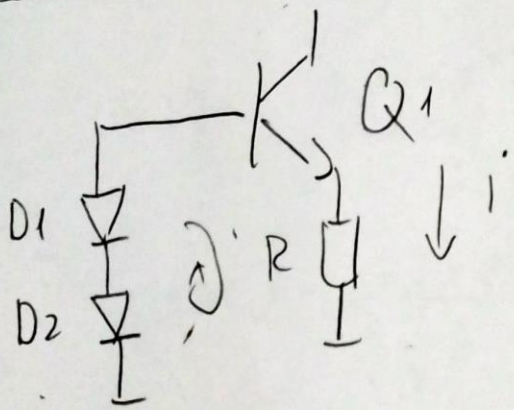
D-PACK NPN 100V 3A 15W

$V_{CE} > V_{in\,max} = 33V$

$R_L = \frac{i_{out\,Max}}{i_{out\,max}} = \frac{25}{0{,}018} = 1388\,\Omega$

$\underline{\sim} 1{,}2\,k\Omega \Rightarrow$

Transistor current source



$V_{BE1} + R\,i = 2\,V_{D1,2} \Rightarrow R = \frac{V_{BE1}}{i} = \frac{0{,}65}{0{,}004} = 162{,}5\,\Omega$

I chose $i = 4\,mA$

R = 150 Ω SMD 0805 ±1% 0,125 W

D1, D2 ales 1N4148 SMD, 0805, 300 mA 100V

Current Mirror

For improved characteristics of the error amplifier I chosed Q_2 Q_3 transistors PNP BC807 SMD SOT23 45V 800 mA

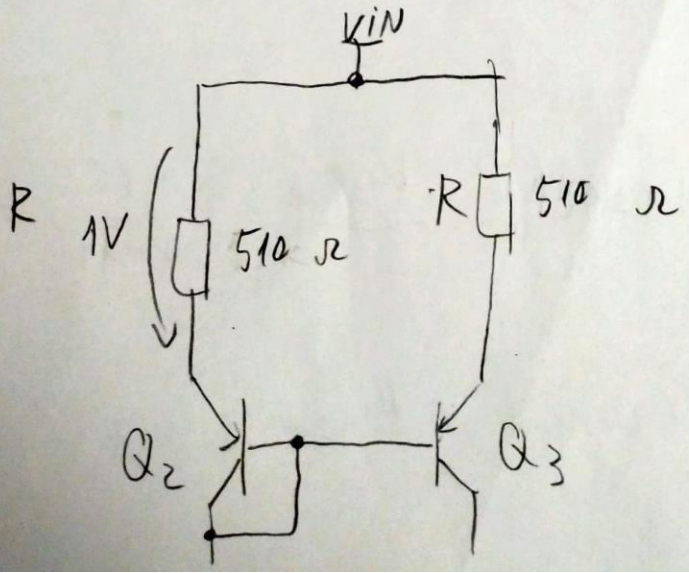
Biasing Resistors

$V_R \geq 0.7V$

$$V_R = R \cdot i_R \Rightarrow R = \frac{V_1}{i_R} = \frac{1}{0,002} = 500\ \Omega$$

$$i_R = 2mA = \frac{1}{2} \cdot i_{current\ source}$$

Ales 510 Ω SMD 0805 ± 1% 0,125 W



Negative FeedBack Network

$$V_{ref} = \frac{R_2}{R_1+P+R_2} \cdot V_{o\,max}$$

$$\Rightarrow V_{ref} = \frac{R_2 \cdot V_{o\,max}}{R_1+P+R_2} \Rightarrow R_2 V_{o\,max} = V_{Ref}(R_1+P+R_2)$$

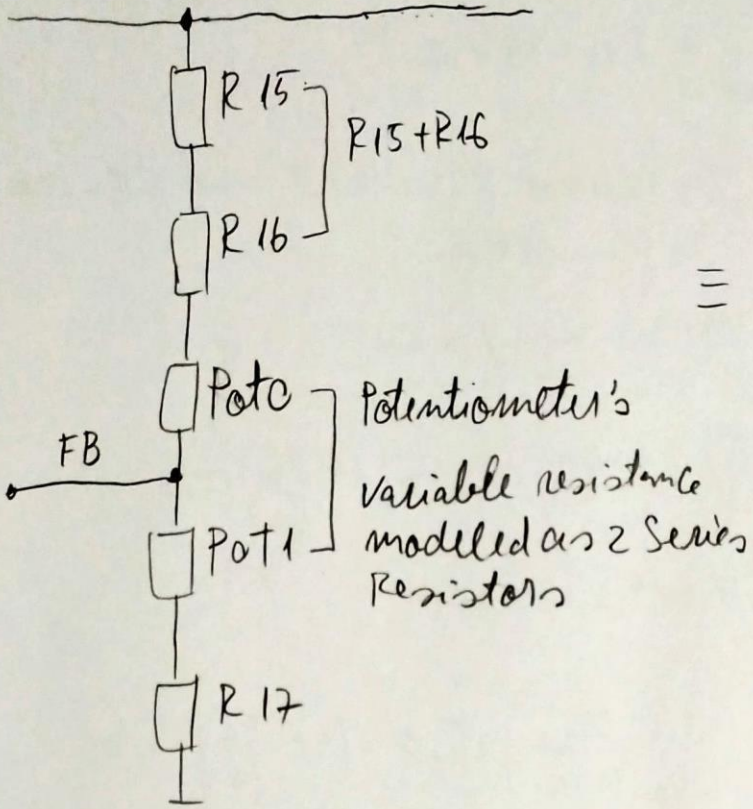
$$\Rightarrow V_{o\,max} = V_{Ref} \cdot \frac{R_1+P+R_2}{R_2}$$

$$\Rightarrow \boxed{V_{o\,max} = \left(1+\frac{R_1+P}{R_2}\right) \cdot V_{Ref} \;;\; P=0}$$

$$V_{Ref} = \frac{R_2+P}{R_1+P+R_2} \cdot V_{o\,min} \Rightarrow \frac{V_{o\,min} = R_1+P+R_2}{R_2+P} \cdot V_{Ref}$$

$$\Rightarrow \boxed{V_{o\,min} = \left(1+\frac{R_1}{R_2+P}\right) \cdot V_{Ref} \;;\; P=0} \Rightarrow V_{o\,min} = \left(1+\frac{R_1}{R_2}\right) V_{ref}$$

Negative feedback network



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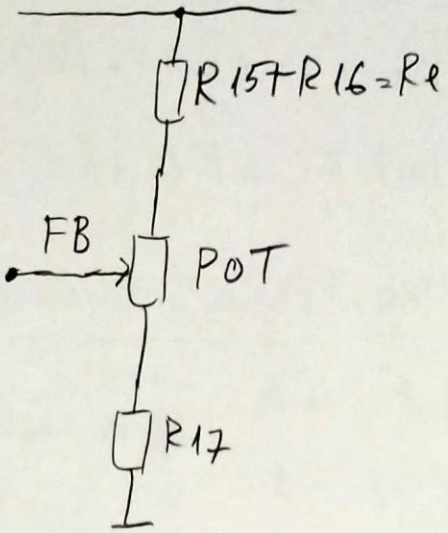


i chose $V_{ref} = 5,6V$

POT = 5 kΩ

$$V_{o\,min} = \left(1 + \frac{R_e}{R_{17}}\right) \cdot V_{Ref} \Rightarrow \frac{V_{o\,min}}{V_{Ref}} = 1 + \frac{R_e}{R_{17}} = \frac{23}{5,6} = 1 + \frac{R_e}{R_{17}}$$

$$4,10 = 1 + \frac{R_e}{R_{17}} \Rightarrow \frac{R_e}{R_{17}} = \frac{3,10}{1} \Rightarrow \boxed{R_e = 3,10 \cdot R_{17}}$$

$$V_{o\,max} = \left(1 + \frac{R_e}{R_{17}}\right) \cdot V_{Ref} \Rightarrow \frac{V_{e\,max}}{V_{Ref}} = 1 + \frac{R_e}{R_{17}} \Rightarrow 4,46 - 1 = \frac{R_e}{R_{17}}$$

$$\Rightarrow \boxed{R_e = 3,46\, R_{17}}$$

i chose $R17 = 10k\Omega$:

$Re = 31k\Omega \rightarrow Vo\ min$
$Re = 54,6k\Omega \rightarrow Vo\ max$
$\Big\} Re = 33k\Omega$

but $Re = R15 + R16$ So i chose $R15 = 10k\Omega$ and $R16 = 22k\Omega$
So $Re = 32k\Omega$

Worst Case Scenario for Vo min / max

$Pot = 4k\Omega$
$VRef = 5,2V$
$\Big\} \Rightarrow Vo\ max = \left(1 + \frac{32+4}{10}\right) \cdot 5,2 = \left(1 + \frac{36}{10}\right) \cdot 5,2$

$Vo\ max = 4,6 \cdot 5,2 = 23,92V$

$Vo\ min = \left(1 + \frac{32}{10+4}\right) \cdot 5,2 = \left(1 + \frac{32}{14}\right) \cdot 5,2$

$Vo\ min = 17,08V$

$\Delta V = 23,92 - 17,08 = 6,84V$

Error for Vo max

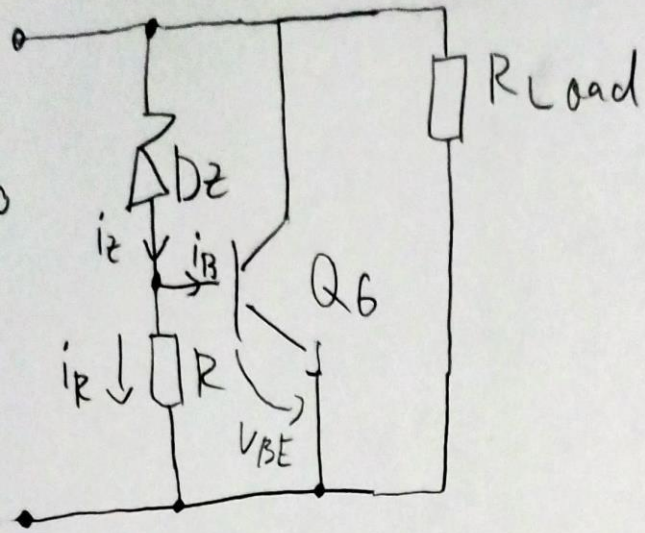
$\xi = \frac{24,38 - 25}{25} \cdot 100 = -4,32\ \%$

For optim conditions

$VRef = 5,6$
$Pot = 5k\Omega$
$\Big\} \Rightarrow Vo\ max = 26,32V$
$Vo\ min = 17,54V$

For $VRef: 5,6V$
$Pot = 4k\Omega$
$\Big\} \Rightarrow Vo\ max = 25,76V$
$Vo\ min = 18,4V$

Over Voltage Protection



$V_{o\,max} = 25V$

i chosed $V_{Dz} = 26,3V$

Dz : series of zener diodes

2 x BZX84-C5V6

1 x BZX84-C10

1 x BZX84-C6V8

$i_z = 5mA \Rightarrow i_R = 5mA$ $\quad V_{BE_6} \cong 0,6V$

$$R = \frac{V_{BE6}}{i_z} = \frac{0,6}{0,005} = 120\Omega$$ i chosed R = 100Ω SMD 0805 ±1% 125mW

For $i_z \geq 5mA$

$i_z = i_B + i_R$ if $i_R \geq 5mA \Rightarrow i_z \geq 5mA$

The overvoltage protection clamps the voltage at $V_{BE} + V_{Dz} \Rightarrow$ $\Rightarrow 28,6V$

Q6 is a power transistor.

DPACK 100V 15W NPN MJD31C SMD

in worst case the protection activate at $= (5,2 \times 2) + 9,4 + 6,4$

$\Rightarrow 26,2 + V_{BE_6} = 26,8V$

DC POWER and CURRENT CALCULATIONS

$$V_i = (R_1 + R_2 + R_{19} + R_{20} + R_3) \cdot i_1 + 2V_D$$

$$\Rightarrow i_1 = \frac{V_i - 2V_D}{R_1 + R_2 + R_{19} + R_{20} + R_3} \Rightarrow i_1 = \frac{30 - 1,2}{5000} = 5,72\ mA$$

PP $i_{B_2} << i_2$: $V_i = (R_4 + R_5 + R_6 + R_7 + R_8) \cdot i_{Z_3} + V_{Z_3} \Rightarrow$

$$i_{Z_3} = \frac{V_i - V_{Z_3}}{R_4 + R_5 + R_6 + R_7 + R_8} = \frac{30 - 5,6}{4500} = 5,42\ mA$$

$V_{BE_4} + R_{11} \cdot i_{C_4} = 2 \cdot V_D$; PP $i_{C_4} \simeq i_{E_4}$; $\beta >> 1$

$$\Rightarrow i_{C_4} = \frac{V_{BE_4}}{R_{11}} = \frac{0,7}{150} = 4,66\ mA$$

$i_{e_4} = i_{E_2} + i_{E_3} \Rightarrow i_{C_4} = i_{C_2} + i_{C_3}$ (1)

$i_{R_9} = i_{R_{10}}$ ($R_9 = R_{10}$) $= i_{C_8} = i_{C_9}$ * (current mirror) (2)

$= i_{C_2} = i_{C_3}$ (Differential amplifier)

From (1) and (2) $\Rightarrow i_{C_2} = i_{C_3} = \frac{i_{C_4}}{2} = 2,3\ mA$

* In practice $i_{C_2} > i_{C_3}$ because a part of i_{C_3}'s current is supplied to the Series pass transistor

$i_{C3} = i_{C9} - i_{B1}$

$i_{C2} = i_{C8}$

$V_i = V_{CE1} + V_o + V_{BE1} + V_{BE8} + V_{BE3}$

$V_{CE1} = V_i - V_o - V_{BE1} - V_{BE8} - V_{BE3} = 30 - 25 - 2,1 \simeq 3V$

Q_5 and Q_6 are blocked $\Rightarrow V_{BE} < 0,3V$

$i_4 \cdot (R_{15} + R_{16} + POT + R_{17}) = V_{out} \Rightarrow i_4 = \frac{V_{out}}{R_{15} + R_{16} + R_{17} + POT}$

$\Rightarrow \frac{25}{47.000} = 531\mu A$

$R_9 i_{C7} + V_{EC7} + V_{BE7} - V_{BE7} - R_{10} i_{C8} - V_{EC8} = 0 \Rightarrow V_{EC7} = V_{EC8} = 1$

in Practice $V_{EC7} < V_{EC8}$ again because of the base current of

Q1

$V_i = R_9 i_{C7} + V_{EC7} + V_{CE2} + V_{Ref} \Rightarrow V_{CE2} = V_i - V_{EC7} - R_9 \cdot i_{C7}$

$\Rightarrow V_{CE2} = 22,8V$

$V_{CE2} = V_{CE3} = 22,8V$

$V_i = V_{EC7} + V_{CE2} + i_{C2} \cdot R_9 + V_{BE4} + V_{CE4} \Rightarrow V_{CE4} = 30 - 25,1$

$V_{CE4} = 4,9V$

Power dissipation

$P_{Q1} = V_{CE1} \cdot i_{C1} = 66\ mW$

$P_{Q2} = V_{CE2} \cdot i_{C2} = 52,44\ mW$

$P_{Q3} = V_{CE3} \cdot i_{C3} = 52,44\ mW$

$P_{Q4} = V_{CE4} \cdot i_{C4} = 23\ mW$

$P_{Q5} = V_{CE5} \cdot i_{C5} = 36\ mW$] – Protections are off

$P_{Q6} = V_{CE6} \cdot i_{C6} = 35\ mW$

$P_{R1} = P_{R2} = P_{R19} = P_{R20} = P_{R3} = i_1^2 \cdot R_2 = 32,7\ mW$

$P_{R4} = i_{Z3}^2 \cdot R_4 = 15\ mW$

$P_{R5} = i_{Z3}^2 \cdot R_5 = 44\ mW$

$P_{R6} = i_{Z3}^2 \cdot R_6 = 15\ mW$

$P_{R7} = P_{R8} = i_{Z3}^2 \cdot R_7 = 29,37\ mW$

$P_{R9} = P_{R10} = i_{C2}^2 \cdot R_{10} = 2,7\ mW$

$P_{R11} = i_{C4}^2 \cdot R_{11} = 3,25\ mW$

$P_{R14} = i_{out}^2 \cdot R_{14} = 36\ mW$

$P_{R12} = i_{R12}^2 \cdot R_{12} = 365\ \mu W$

$P_{R13} = i_{R13}^2 \cdot R_{13} = 6,5\ mW$

$P_{R15} = i_4^2 \cdot R_{15} = 2,81\ mW$

$P_{R16} = i_4^2 \cdot R_{16} = 6,2\ mW$

$P_{POT} = i_4^2 \cdot R_{POT} = 1,41\ mW$

$P_{17} = i_4^2 \cdot R_{17} = 2,81\ mW$

$P_{18} = i_{R18}^2 \cdot R_{18} = 1,3\ fW$

$P_{RL} = i_{out}^2 \cdot R_L = 529,2\ mW$