University POLITEHNICA of Bucharest

Faculty of Electronics, Telecommunications and Information Technology

Project 1

Negative Voltage Regulator

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1. Project Requirements

It is required to design a positive linear voltage regulator with discrete components, with the following specifications:

N=2

- Supply voltage between (-13)÷(-10) [V];
- Programmable output voltage (-6)÷(-5) [V];
- The output current through the load between 0÷68 [mA];
- Short circuit protection of the output terminals with foldback current limiting circuit.
- Overvoltage protection of the output terminals.
- $S = \left.\frac{\Delta V_i}{\Delta V_o}\right|_{RL} \geq 79$
- The output impedance of the regulator $R_O \leq 2\Omega$.

2. The block diagram of the circuit

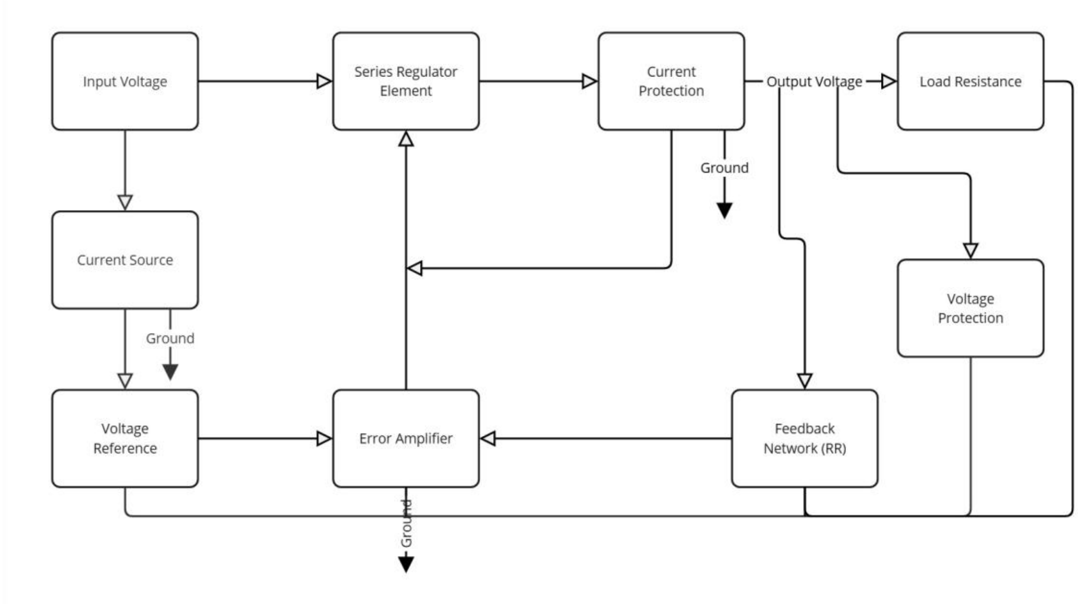


Fig 2.1. Block diagram of the electronic circuit

Voltage stabilizers, also known as voltage regulators, are devices designed to maintain a constant voltage level to electrical equipment, protecting them from voltage fluctuations that could cause damage or reduce performance. They are essential in ensuring the reliability and longevity of electronic devices and are widely used in power systems to provide stable voltage outputs despite variations in input voltage or load conditions. [22]

A reaction stabilizer scheme was used. The voltage reference for it is practically a parametric stabilizer. But it now works on a large load resistance that does not vary. The order is therefore made in tension on a constant load.

During normal operation the differential voltage at the input of the error amplifier is practically zero. Thus the amplifier must transform the voltage command into a current command (transimpedance amplifier). The voltage command is given by the feedback network (a voltage divider).[23]

The result of comparing the voltage reference with what is sampled from the output voltage is a current that is applied to the series regulator element. This will be an ideal transistor for which the collector current is proportional to the base current.

If the output voltage decreases compared to the equilibrium value, the voltage sampled by the feedback network will be lower than the reference voltage, so a positive differential voltage appears at the input of the error amplifier. The output current will be higher than normal and will command a higher current through the series regulator element. Thus the output voltage starts to increase.

If the output voltage tends to increase compared to the equilibrium value, a negative differential voltage will appear which will lead to a decrease in the current from the output of the error amplifier, thus to a decrease in the current through the series regulator element. Thus the output voltage will start to decrease.

If the temperature of the series regulator element increases too much or the current through it exceeds the limit value, the protection circuit takes the current charged by the error amplifier and the series regulator element closes and does not allow current to pass. [24], [25]

3. The detailed schematic diagram

Implementing multiple amplification stages in series enhances overall performance by increasing voltage gain and improving input and output impedance matching. In such multistage amplifier configurations, the initial differential stage typically exhibits a higher output impedance, which contributes to increased voltage gain. Differential stages serve the dual purpose of providing both voltage and current amplification; therefore, specific stages are designed to optimize each function. [26]

3.1. Voltage Reference

The voltage reference consists of a Zener diode fed from a constant current source, so the voltage on the diode will have a very small drift. I chose a BZX84-C2V7 type diode, as it has a constant breakdown voltage of approximately 2.7V when it is fed with a current of 4mA. The result is a power dissipated by the diode of about 12mW, power much lower than the maximum power of 300mW specified by the manufacturer in the data sheet.

A BC546 type NPN transistor, other passive components and an additional Zener diode are used as a constant current source.

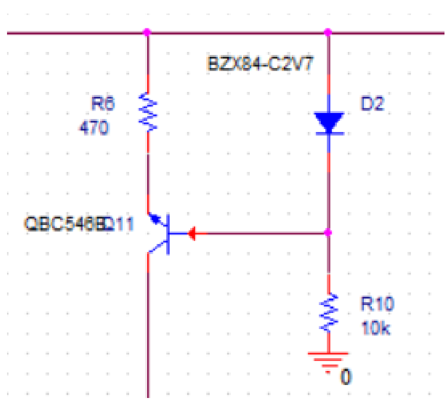


Fig 3.1.

The current source made with Q11 and R6 has the role of providing a current of a fixed value through the Zener diode D1 regardless of the value of the load or the supply voltage, thus the input stage is immune to variations in the supply voltage.

For this current source, a BC546 type NPN transistor is used. Diode D2 forms a voltage reference so as to provide Vz=2.7V for transistor Q6. The diode is kept in conduction at a current of about 1mA with the help of R10.

3.2. The Error Amplifier

In order to achieve the highest possible voltage amplification values, a scheme with a differential amplification stage and a voltage-current conversion stage (Q5) was chosen. Transistor Q5 works as an emitter degeneration, which involves adding a resistor to the emitter terminal of a bipolar junction transistor (BJT) in a common-emitter amplifier configuration. This technique introduces negative feedback, enhancing the amplifier's performance by improving stability, linearity, and input impedance, while reducing gain sensitivity to transistor parameter variations. [28]

The differential stage (Q1 and Q2) is made with bipolar transistors, in NPN configuration, type BC546. Such transistors were chosen to have a minimum current loading of the voltage reference and the feedback network. Also, this type of floor offers a high input impedance.

The differential stage is supplied with current through a current source made with a resistor R5. In order to obtain a good symmetry of the currents through the differential stage, I used a current mirror (Q3, Q4) made with BC556 type bipolar transistors.

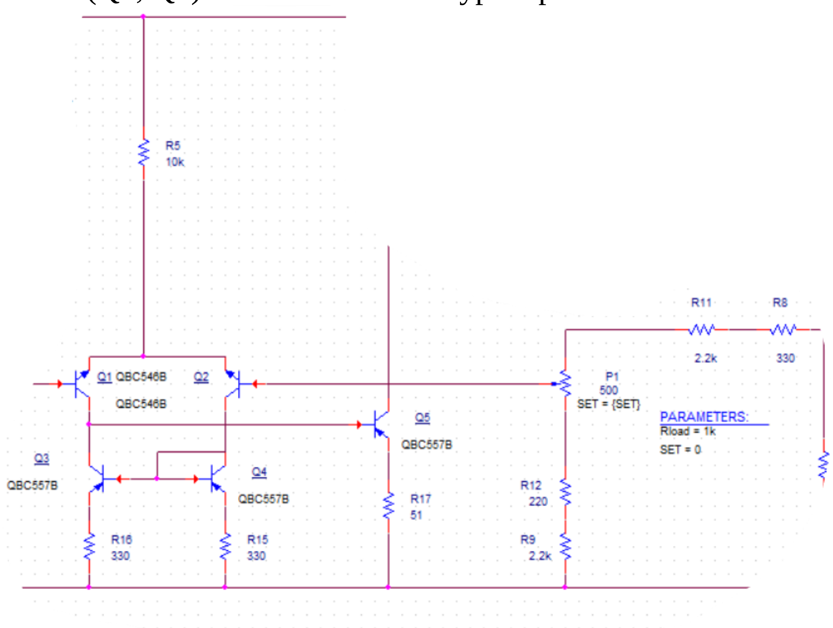


Fig. 3.2.

The currents through the differential floor follow the following relationship:

$$I_{C1} + I_{C2} = I_{R5}$$

Resistor R5 limits the current through the differential stage to a fixed value, which will depend on Vin, Vref and the value of R5 as follows:

$$I_{R5} = (V_{in} - V_{Z-Vbe})/R_5 = 0.7mA$$

This current is divided equally by Q1 and Q2 so it results:

$$Ic1=Ic2=0.35mA$$

These current values fall within the specifications of the transistors and will result in a power dissipated of very low values.

The voltage-current converter is a bipolar transistor that will work in common emitter connection Q_5. It has as its load a resistor R3, which realizes the limitation of the current to a value desired by us in the design.

Resistor R3 limits the current through the common emitter stage to a fixed value, which will depend on Vin, Vref and the value of R3 as follows:

$$I_{R5} = (V_{in} - V_{out-} V_{be})/R_3 = 2.5mA \text{ but depends on Vout}$$

For the calculation I chose the worst case scenario, where Vin=13V, Vout=5V.

3.3. The Series Regulator Element

The series regulator element is made with a $Q_{10 \text{ bipolar transistor}}$, it is connected in common collector connection (repeater on the emitter). Considering the factor $\beta \approx 100$ and a maximum current of 68mA, a command current of only 0.68mA will be required, which is accomplished with the help of the $Q_{10 \text{ transistor}}$.

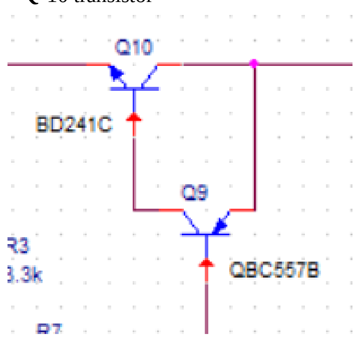


Fig. 3.3.

From the catalog sheet of the BD241 transistor, it supports a maximum collector current of 3A, has a current amplification of at least 100, voltage Vcemax =100V, and the maximum power dissipated at $25°C$ is 40W.

For the worst case where the output voltage takes the value of 5V and the input takes the value of 13V and the output current is 68mA, the following power will be dissipated on the series element :

$$P_d = (U_{in} - U_{out}) * I_{out}$$

This results in P_d =(13V-5V)*0.068A =544mW.

3.4. The Feedback Network

The network is made by means of a resistive voltage divider that returns to the inverting amplification of the error amplifier a part of the output voltage.

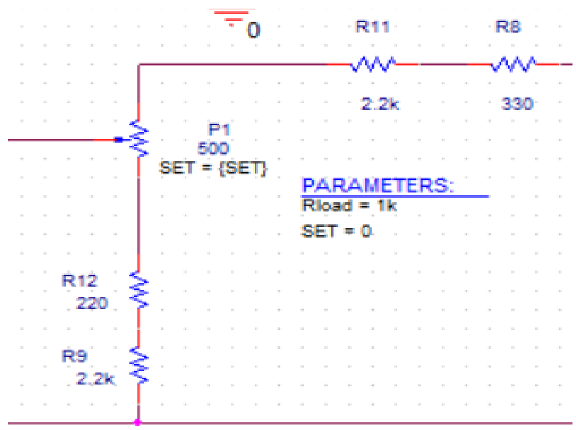


Fig. 3.4.

This fraction of the output voltage is compared with the reference voltage given by the Zener diode and the error voltage is generated.

$$Vin- = \frac{R9 + P1}{P1 + R9 + R11} Vout = Vref$$

V_{ref} =2.7V

To obtain a minimum output voltage of Vmin = 5V:

$$\frac{R9 + P1}{P1 + R9 + R11} = Vref/Vmin$$

To obtain a maximum output voltage of Vmax = 6V:

$$\frac{R9 + P1}{P1 + R9 + R11} = \text{Vref/Vmax but P1=0 in this case}$$

This results in the values of the resistors in the reaction network:

R11=2.5k and R9= 2.4k

And the resistor R11 will be made by connecting two resistors of different values, so that the calculated value can be precisely obtained.

R11=2.2k+330 and R9 = 2.2k +220

3.5. Protection Circuits

3.5.1. Overcurrent Protection [27]

The resistance R $_1$ +R13 works as a current-voltage converter, so that at a current of 82mA at the output it must give a voltage drop that will open the transistor Q6.

In order for the protection to also take into account the voltage level at the output, a voltage divider was made with R2/R4 as follows

Vbe' =Vout* R2/(R2+R4) and a value of approximately 300mV will result.

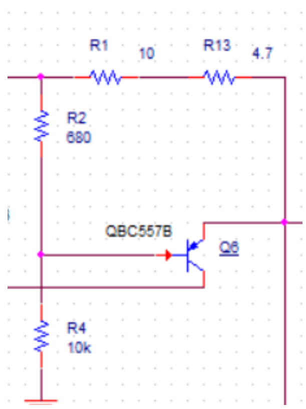


Fig. 3.5.1.

3.5.2. Overvoltage Protection

Overvoltage protection is provided by Q12, it will enter conduction through the base current provided by diodes D2 and D4 when the voltage Vz is exceeded.

Vmax = Vbe + Vd3 = 0.6V+6.8V = 7.4V

Resistor R14 cancels the residual current of diode D3, so that the protection comes into operation when the diode reach the Zener region, otherwise a premature activation of the protection would occur.

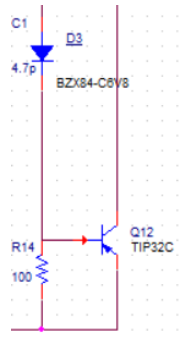


Fig. 3.5.2.

3.6. Final scheme of the voltage regulator

The voltage regulator has the following final scheme after all necessary parts and circuit subblocks have been set up:

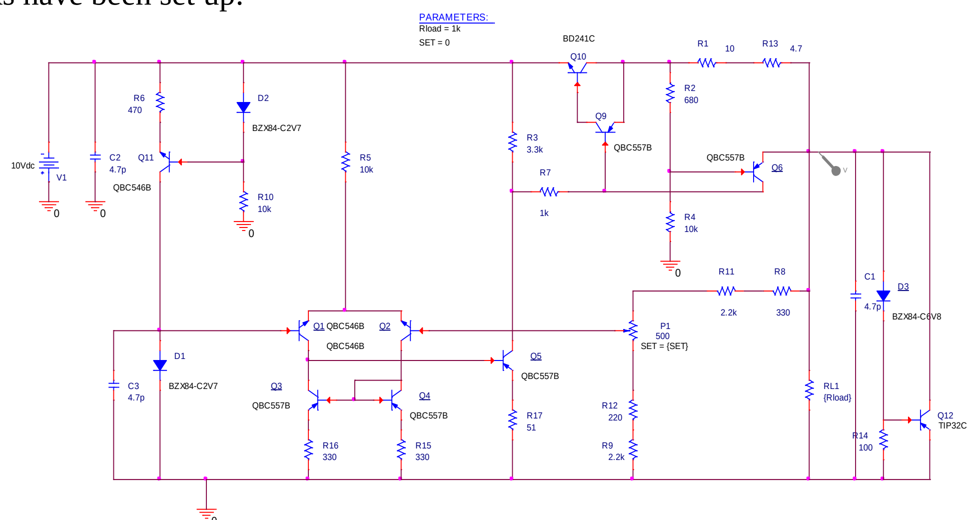


Fig. 3.6.1.

Vin $_{min}$=10V, Vout $_{min}$=5V, SET=1

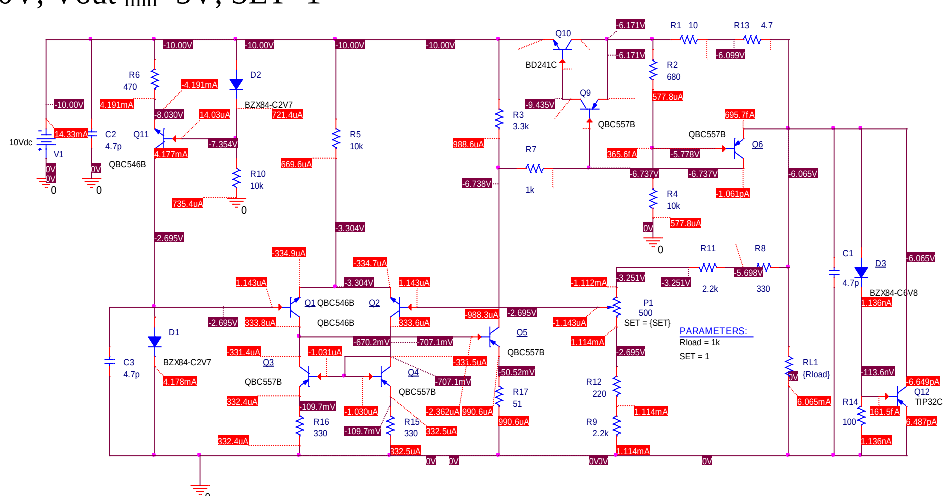


Fig. 3.6.2.

Vin $_{max}$=13V, Vout $_{min}$=5V, SET=1

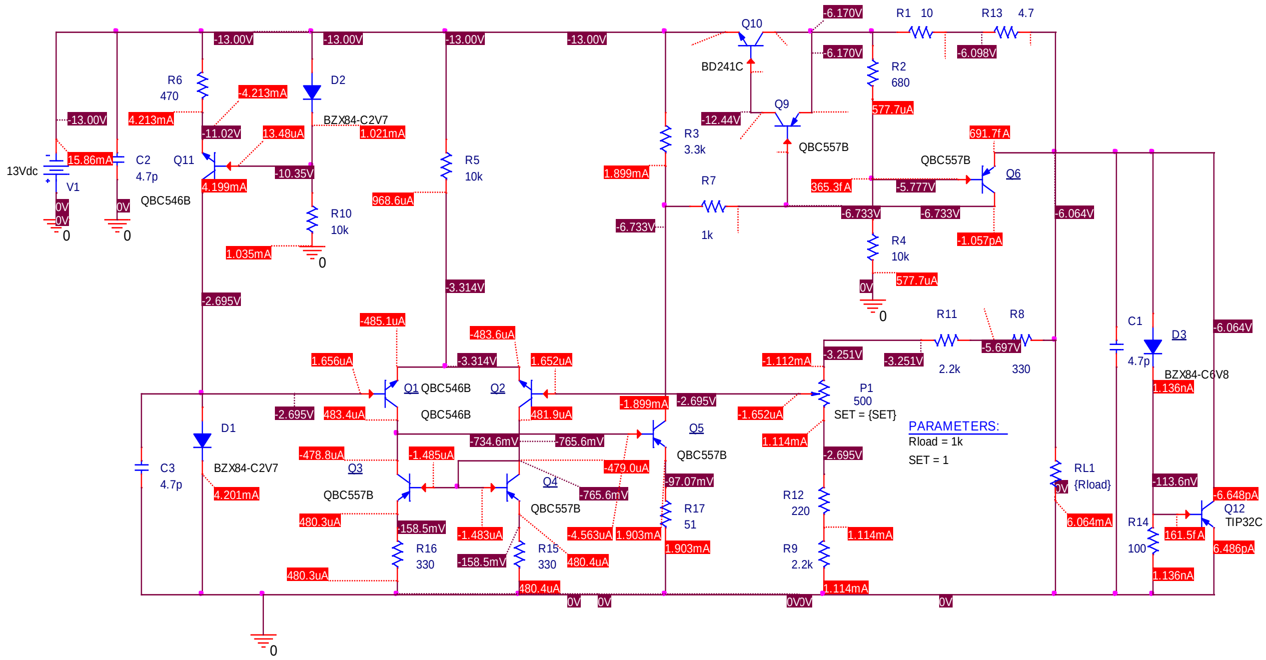


Fig. 3.6.3.

Vin $_{min}$=10V, Vout $_{max}$=6V, SET=0

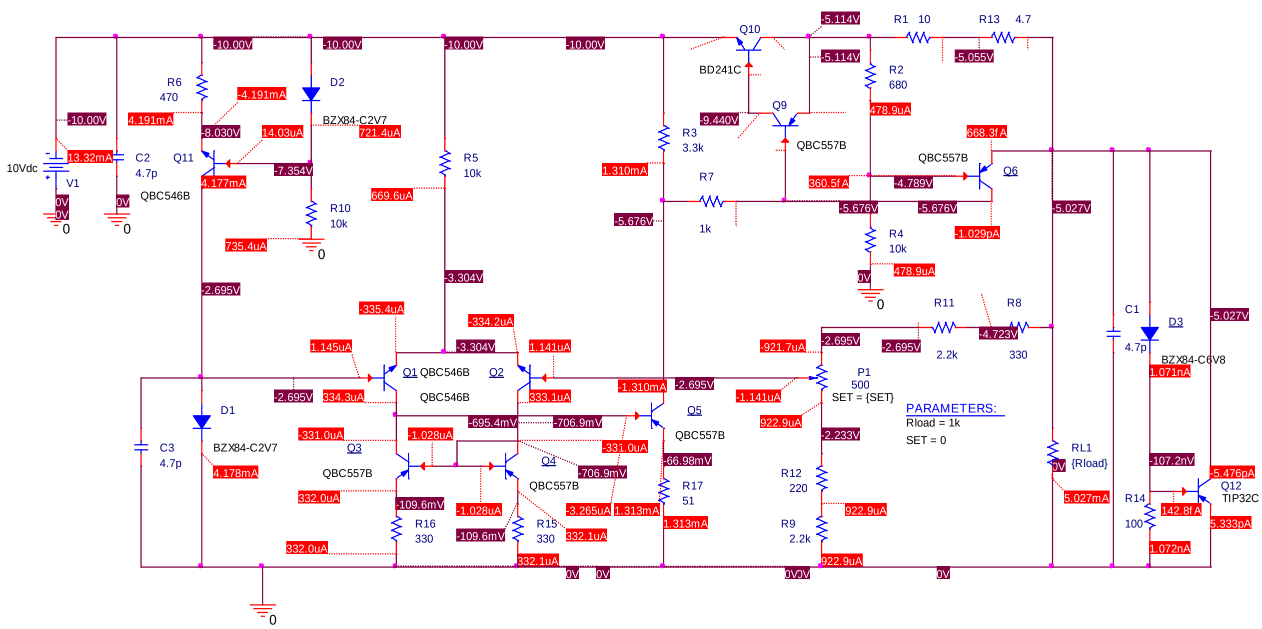


Fig. 3.6.4.

Vin $_{max}$=13V, Vout $_{max}$=6V, SET=0

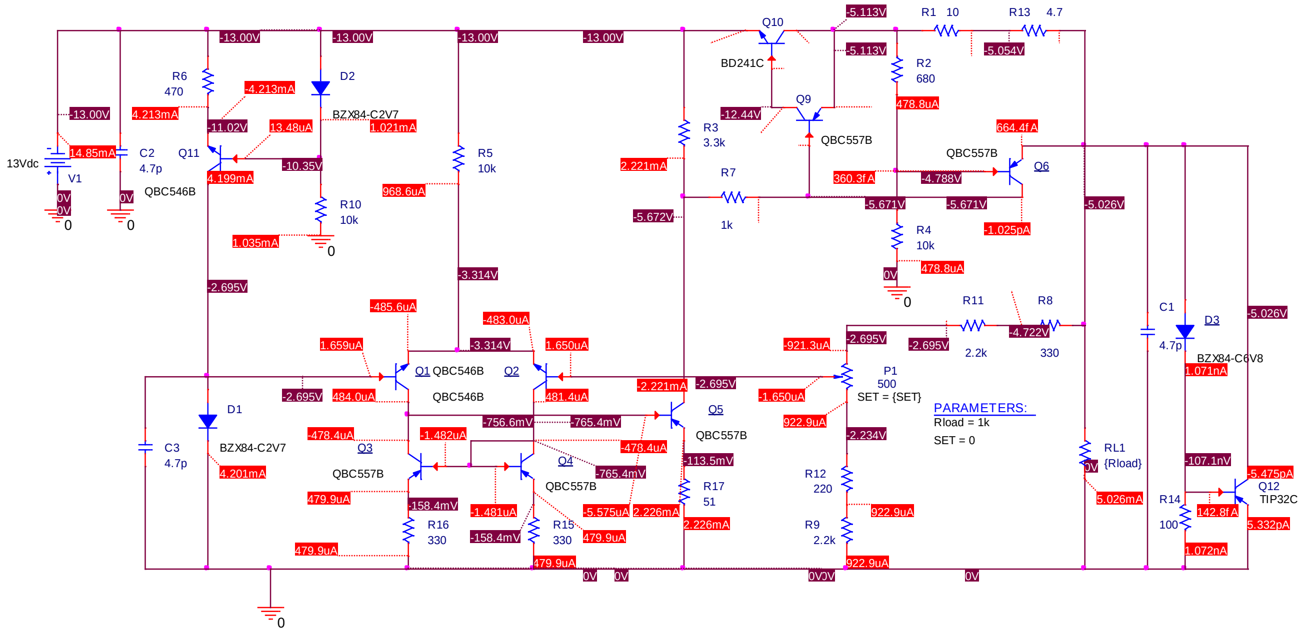


Fig. 3.6.5.

Power dissipation on each component

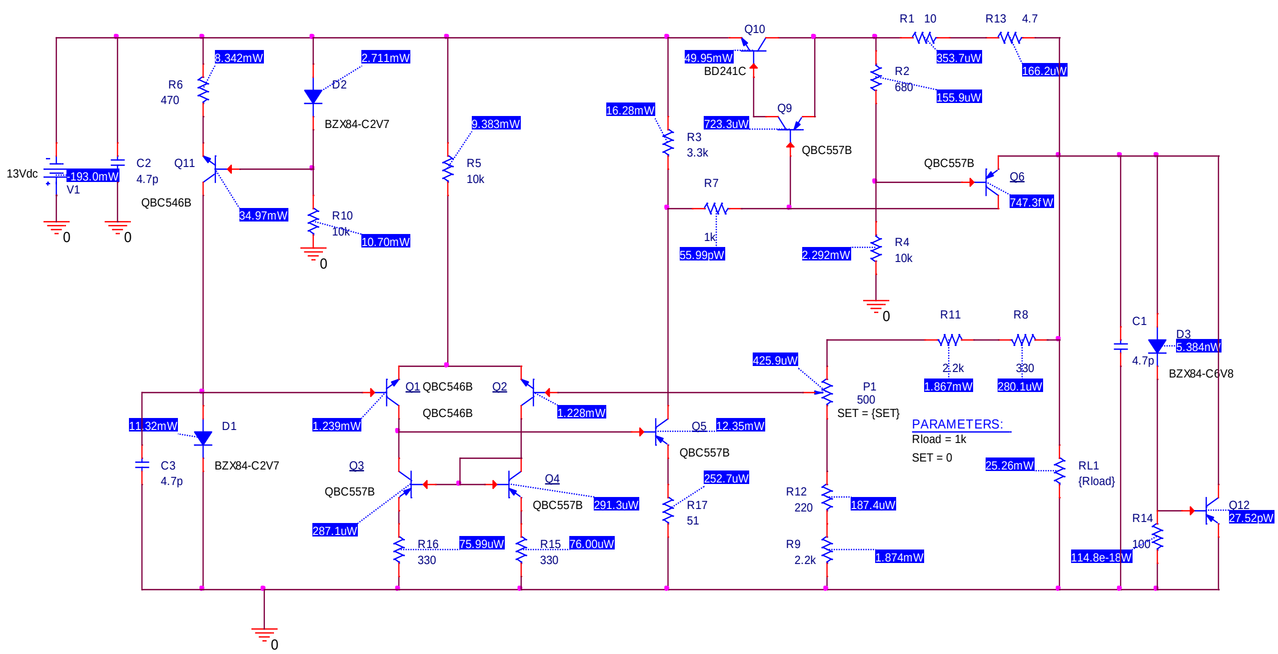
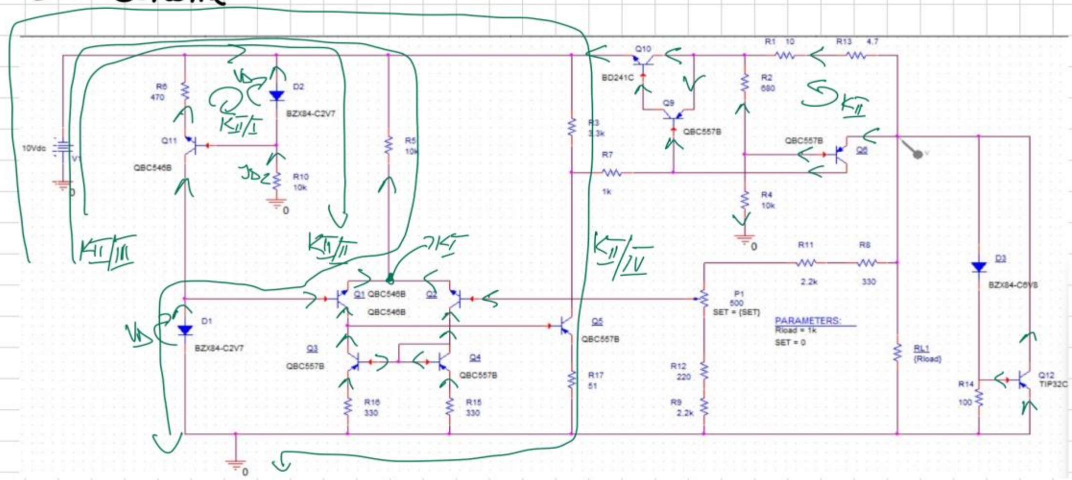


Fig. 3.6.6.

3.7. Calculus

DC Bias

DC Scheme:



$K_{II}/_{I}$: $V_{BE} + I_{C_{11}} R_6 - V_{Z_2} = 0$

$$V_{BE} - V_{Z_2} = -I_{C_{11}} R_6$$

$$I_{C_{11}} = \frac{V_Z - V_{BE}}{R_6} = \frac{2{,}7 - 6}{470} = 4{,}46\,mA$$

$K_{II}/_{II}$: $V_1 = -V_{Z_2} - I_{D_2} \cdot R_{10}$

$$I_{D_2} = \frac{-V_{Z_2} - V_1}{R_{10}} \Rightarrow \begin{cases} I_{D_2} = \dfrac{-2{,}7+13}{10^4} = 1{,}03\,mA\,(V_{1min}) \\ I_{D_2} = \dfrac{-2{,}7+10}{10 \cdot 10^3} = 0{,}73\,mA\,(V_{1max}) \end{cases}$$

$$I_{Z_1} - I_{C_{11}} = 4{,}46\,mA$$

$$V_{Z_1} = 2{,}7\,V \Rightarrow \begin{cases} V_{Z_1 min} = 2{,}5\,V \\ V_{Z_1 max} = 2{,}9\,V \end{cases}$$

$K_{II}/_{III}$: $V_1 = -I_{R_5} R_5 - V_{Z_1} - V_{BE}$

$$-I_{R_5} = \frac{V_1 + V_{Z_1} + V_{BE}}{R_5} \Rightarrow \begin{cases} I_{R_5} = 0{,}97\,mA\,(V_{1min}) \\ I_{R_5} = 0{,}67\,mA\,(V_{1max}) \end{cases}$$

K_I : $I_{C_1} + I_{C_2} = I_{R5}$, $I_{C_1} = I_{C_2}$ $\Rightarrow I_{C_1} = I_{C_2} = \frac{I_{R5}}{2}$

$$\begin{cases} V_{1min} \Rightarrow I_{C_1} = I_{C_2} = 0{,}485\,mA \\ V_{1max} \Rightarrow I_{C_1} = I_{C_2} = 0{,}3352\,mA \end{cases}$$

$V_{EB3} = V_{EB4}$

$Q_1 ; Q_2 - NPN$

$Q_3 ; Q_4 - PNP$

$\Rightarrow I_{C3} = I_{C4} = \left(-I_{C1,2}\right)$

$$V_{EC3} = V_{EC4} - V_{EB} + I_{C3} R_6 = \begin{cases} -0{,}76\,V & (V_{1\,min}) \\ -0{,}71\,V & (V_{1\,max}) \end{cases}$$

Q_3 & $Q_4 \rightarrow$ normal active regime

Q_6 & $Q_{12} \rightarrow$ blocking state

OCP made with: $R_1, R_{13}, R_2, R_4, Q_6$

OVP made with: D_4, D_5, R_{14}, Q_{12}

$\Rightarrow I_{C12}$ & $I_{C6} \approx 0$

$$\begin{cases} SET = 0 \Rightarrow V_{out\,max} \\ SET = 1 \Rightarrow V_{out\,min} \end{cases}$$

K_{II} (loop $V_{EC5} \rightarrow V_{EB9} \rightarrow V_{out}$):

$V_{EC5} - V_{EB9} = V_{out}$

$V_{EC5} = V_{out} + V_{EB9}$

$$V_{EC5} = \begin{cases} -6 - 0{,}6 = -6{,}6\,V\ (V_{out\,min}) \Rightarrow SET = 1 \\ -5 - 0{,}6 = -5{,}6\,V\ (V_{out\,min}) \Rightarrow SET = 0 \end{cases}$$

$\Rightarrow Q_5 \rightarrow$ normal active regime

$$K_{II}/_{IV}: \quad V_1 = I_{C5}\,(R_3 + R_{17}) + V_{EC5} \Rightarrow I_{C5} = \frac{V_1 - V_{EC5}}{R_3 + R_{17}}$$

$$\begin{cases} I_{C5} = -1{,}9\,mA\ (SET = 1) \\ I_{C5} = -2{,}2\,mA\ (SET = 0) \end{cases} \Bigg| \; V_{1\,min}$$

$$\begin{cases} I_{C5} = -1{,}01\,mA\ (SET = 1) \\ I_{C5} = -1{,}31\,mA\ (SET = 0) \end{cases} \Bigg| \; V_{1\,max}$$

$V_1 = -J_{R_5} R_5 - V_{CE_2} - V_{EC_4} - J_{C_4} R_{15}$

$V_{CE_2} = -V_1 - J_{R_5} R_5 - V_{EC_4} - J_{C_4} R_{15}$

$V_{CE_1} = V_{CE_2} = \begin{cases} 3{,}89\,V & (SET=1) \\ 0{,}89\,V & (SET=0) \end{cases}$

$V_{EC_{12}} = -V_{out} \Rightarrow \begin{cases} V_{EC_{12}} = 6\,V & (SET=1) \\ V_{EC_{12}} = 5\,V & (SET=0) \end{cases} \Rightarrow$ Q_{12} -> normal active regime

$V_{CE_6} \Rightarrow 2V_{BE} - 1{,}2\,V \Rightarrow Q_6 \Rightarrow$ active regime

$V_{out} = V_{CE_{10}} + V_{in}$

$V_{CE_{10}} = V_{out} - V_{in} \Rightarrow \begin{cases} V_{CE_{10}} = 7\,V\,(SET=1) \\ V_{CE_{10}} = 8\,V\,(SET=0) \end{cases} \Big| V_{1\,min} \quad \begin{cases} V_{CE_{10}} = 4\,V\,(SET=1) \\ V_{CE_{10}} = 5\,V\,(SET=0) \end{cases} \Big| V_{1\,max}$

$V_{out} - V_{in} - V_{BE_{10}} = V_{EC_9} \Rightarrow V_{EC_9} = \begin{cases} 6{,}4\,V \\ 7{,}4\,V \end{cases} \Big| V_{1\,min} \quad \begin{cases} 3{,}4\,V \\ 4{,}4\,V \end{cases} \Big| V_{1\,max}$

$V_1 = -V_{CE_{11}} - J_{C_{11}} R_6 - V_{Z_1}$

$V_{CE_{11}} = -V_1 - J_{C_{11}} R_6 - V_{Z_1} = \begin{cases} 10{,}29\,V & (V_{1\,min}) \\ 7{,}29\,V & (V_{1\,max}) \end{cases}$

$\Rightarrow Q_{11}$ - normal active regime

Dissipated Power on each component (Worst case scenarios)

$P_{Q_{11}} = V_{CE_{11}} \cdot J_{C_{11}} = 45{,}89\,mW$

$P_{Q_1} = V_{CE_1} \cdot J_{C_1} = 1{,}88\,mW$

$P_{Q_2} = P_{Q_1} = 1{,}88\,mW$

$P_{Q_3} = V_{CE_3} \cdot J_{C_3} = 0{,}23\,mW$

$P_{Q_3} = P_{Q_4} = 0{,}23\,mW$

$P_{Q_5} = V_{EC5} \cdot I_{C5} = \begin{cases} 7{,}33\ mW & (SET=0) \\ 6{,}66\ mW & (SET=1) \end{cases}$

$P_{Q_6} = V_{CE6} \cdot I_{outmax} = 81{,}6\ mW$

$P_{Q_9} = V_{EC9} \cdot I_{C9} = \begin{cases} 44{,}24\ mW & (SET=1) \\ 50{,}56\ mW & (SET=0) \end{cases}$

$P_{Q_{12}} = V_{EC12} \cdot I_{outmax} = \begin{cases} 0{,}408\ W & (SET=1) \\ 0{,}34\ W & (SET=0) \end{cases}$

$P_{R_1} = R_1 \cdot I_{R_1}^2 = 352{,}83\ \mu W$

$P_{R_2} = R_2 \cdot I_{R_2}^2 = 155{,}36\ \mu W$

$P_{R_3} = R_3 \cdot I_{R_3}^2 = 16{,}11\ mW$

$P_{R_4} = R_4 \cdot I_{R_4}^2 = 2{,}347\ mW$

$P_{R_5} = R_5 \cdot I_{R_5}^2 = 9{,}44\ mW$

$P_{R_6} = R_6 \cdot I_{R_6}^2 = 9{,}34\ mW$

$P_{R_7} = R_7 \cdot I_{R_7}^2 = 55{,}9\ pW$

$P_{R_8} = R_8 \cdot I_{R_8}^2 = 283{,}6\ \mu W$

$P_{R_9} = R_9 \cdot I_{R_9}^2 = 1{,}898\ mW$

$P_{R_{10}} = R_{10} \cdot I_{R_{10}}^2 = 10{,}60\ mW$

$P_{R_{11}} = R_{11} \cdot I_{R_{11}}^2 = 1{,}88\ mW$

$P_{R_{12}} = R_{12} \cdot I_{R_{12}}^2 = 189{,}8\ \mu W$

$P_{R_{13}} = R_{13} \cdot I_{R_{13}}^2 = 165{,}8\ \mu W$

$P_{R_{14}} = R_{14} \cdot I_{R_{14}}^2 = 635 \cdot 10^{-8}\ W$

$P_{R_{15}} = R_{15} \cdot I_{R_{15}}^2 = 77{,}62\ \mu W$

$P_{R_{16}} = R_{16} \cdot I_{R_{16}}^2 = 77{,}62\ \mu W$

$P_{R_{17}} = R_{17} \cdot I_{R_{17}}^2 = 349{,}2\ \mu W$

$P_{D_1} = V_{Z_1} \cdot I_{Z_1} = 12{,}93\ mW$

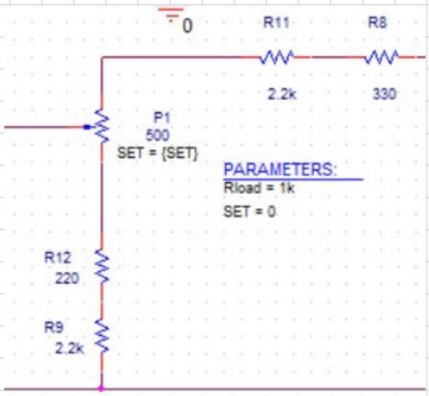
$P_{D2} = V_{D2} \cdot I_{D2} = 2{,}781\ mW$

$P_{D_3} = V_{D_3} \cdot I_{D_3} = 5{,}43\ mW$

Calculus of Load Resistance

$$R_L = \frac{|V_{outmax}|}{I_{outmax}} = \frac{6}{68 \cdot 10^{-3}} \simeq 88{,}5\ \Omega$$

FEEDBACK NETWORK



K_{II}: $V_{T1} = \dfrac{R_{s1}+P_1}{R_{s1}+P_1+R_{s2}} V_{out}$

I choose $P = 500\,\Omega$

$V_{out} \in [-6{,}1; -4{,}9]$ V

2 cases:

$$\begin{cases} V_{T1} = \dfrac{R_{s1}}{R_{s1}+P_1+R_{s2}} V_{out\,max} \\ V_{T2} = \dfrac{R_{s1}+P_1}{R_{s1}+P_1+R_{s2}} V_{out\,min} \end{cases}$$

$$\Rightarrow \begin{cases} 2{,}7 = \dfrac{R_{s1}}{R_{s1}+P_1+R_{s2}} \cdot 6 \\ 2{,}7 = \dfrac{R_{s1}+P_1}{R_{s1}+P_1+R_{s2}} \cdot 5 \end{cases} \Rightarrow \dfrac{R_{s1}}{\cancel{R_{s1}+P_1+R_{s2}}} \cdot 6 = \dfrac{R_{s1}+P_1}{\cancel{R_{s1}+P_1+R_{s2}}} \cdot 5$$

$$\Rightarrow 6R_{s1} - 5R_{s1} - 5P_1 \Rightarrow R_{s1} = 5 \cdot 0{,}5 \cdot 10^3 = 2{,}5\,k\Omega$$

$$2{,}7 = \dfrac{R_{s1}}{R_{s1}+P_1+R_{s2}} \cdot 6 \Rightarrow 2{,}7 = \dfrac{2{,}5k}{2{,}5k+0{,}5k+R_{s2}} \cdot 6$$

$$\Rightarrow 2{,}7 = \dfrac{15k}{3k+R_{s2}} \Rightarrow 2{,}7R_{s2} = 6{,}9k$$

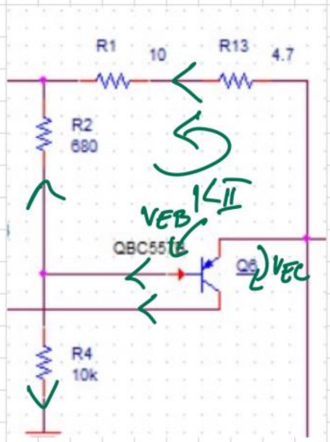
$$R_{s2} = 2{,}55\,k\Omega$$

I adjusted the values, so the circuit works properly:

$$R_{s1} = \begin{cases} R_{12} = 220\,\Omega \rightarrow CF1/4W - 220R \\ R_9 = 2{,}2\,k\Omega \rightarrow CF1/4W - 2K2 \end{cases}$$

$$R_{s2} = \begin{cases} R_{11} = 2{,}2\,k\Omega \rightarrow CF1/4W - 2K2 \\ R_8 = 330\,\Omega \rightarrow CF1/4W - 330R \end{cases}$$

Overcurrent Protection



$V_{R_{SOCP}} - V_{R_1} - V_{EB} = 0$

I assume $V_{R_{SOCP}} = 1\,V$

$I_{Lmax} = (20\% + 1)\, I_{out}$

$I_{out} = 68\,mA$

$I_{Lmax} = \left(\frac{120}{100} \cdot 68\,mA\right) \simeq 82\,mA$

↳ current from which the foldback will start

Fold Back → If the protection detect a very high current, it sends it back at a value much lower than $I_{out\,max}$

$V_{R_{SOCP}} = R_{SOCP} \cdot I_{Lmax} \Rightarrow R_{SOCP} = \frac{V_{R_{SOCP}}}{I_{Lmax}} = \frac{1}{82} \Rightarrow 12{,}19\,\Omega$

For the circuit to work properly, I choose:

$\begin{cases} R_1 = 10\,\Omega \rightarrow CF\,RO\,W\,4J\,01\,00A50 \\ R_{13} = 4{,}7\,\Omega \rightarrow CF1/4W - 4R7 \end{cases}$

$V_{R_2} = V_{R_{SOCP}} - V_{EB}$

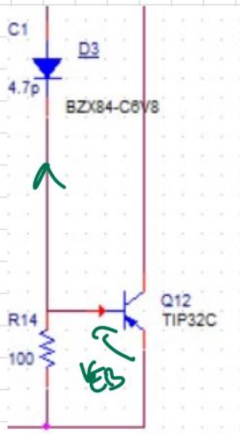
$\frac{R_2}{R_2 + R_4} \cdot 6 = 1 - 0{,}6 \Rightarrow \frac{R_2 + R_4}{R_2} = 15{,}15$

$\Rightarrow 1 + \frac{R_4}{R_1} = 15{,}15 \Rightarrow R_4 = 14{,}15\, R_2$

For the circuit to work properly, I choose:

$\begin{cases} R_2 = 680\,\Omega \rightarrow CF1/4W - 680R \\ R_4 = 10\,k\Omega \rightarrow CF1/4W - 10K \end{cases}$

Overvoltage Protection



$V_{out\,max} = 6V$

We will consider the Diodes working at the min V_O breakdown, $V_{EB} = 0{,}5V$

$V_{O\,break} > V_{O\,max}$

$V_{O\,break} = V_Z + V_{EB}$

For WCS : $V_{O\,break} = V_{Z\,min} + V_{BE\,min}$

$V_{O\,break} = 6{,}8\,V$

$\Rightarrow 6{,}8 = V_{Z\,min} + 0{,}5 \rightarrow V_{Z\,min} = 6{,}3\,V$

From annex I choose $D_3 \rightarrow$ ZPD 6.8 ($V_{Z_3} = 6{,}8V$)

$V_{O\,break\,min} = 6{,}4\,V$

$V_{O\,break} = 6{,}4 + 0{,}5 = 6{,}8\,V$

K_{II} : $V_{EB_{12}} = V_{R_{14}} \rightarrow R_{14} = \dfrac{V_{EB_{12}}}{I_{R_{14}}}$

WCS $\Rightarrow I_{R_{14}} \simeq 5mA \rightarrow$ min working current

$\Rightarrow R_{14} = \dfrac{0{,}5}{5m} = 0{,}1\,k\Omega$

$R_{14} = 100\,\Omega \longrightarrow$ CF1 / 4W - 100R

$V_{O\,break} \rightarrow$ chosen acc. to the annex, since D_3 is the closest a bit greater than $V_{O\,max} = 6\,V$

WCS for Diodes and influence of resistors' tolerance calcul.

SET=0 ; $\epsilon = +5\% \rightarrow$ resistors ; $t = +20\% \rightarrow$ potentiometers

$$V_{Z_1\,min} = 2{,}5 = \frac{R_{12} + R_9}{R_{12} + R_9 + P + R_{11} + R_8} V_{out\,max}$$

$$V_{out\,max} = \frac{2{,}5(220 \cdot 1{,}05 + 2{,}2 \cdot 10^3 \cdot 1{,}05 + 500 \cdot 1{,}2 + 2{,}2 \cdot 10^3 \cdot 1{,}05 + 330 \cdot 1{,}05}{220 \cdot 1{,}05 + 2{,}2 \cdot 10^3 \cdot 1{,}05}$$

$V_{out\,max} \simeq 5{,}70\,V$

$V_{Z_1max} = 2,9\,V = \dfrac{R_{12}+R_9}{R_{12}+R_9+P+R_{11}+R_8} \cdot V_{out\,max} \Rightarrow V_{out\,max} = 6,61V$

SET = 0 ; $t = +5\%$ -> rezistors ; $t = -20\%$ -> potentiometer

$V_{Z_1min} = 2,5V \Rightarrow V_{out\,max} = 5,50V$

$V_{Z_1max} = 2,9V \Rightarrow V_{out\,max} = 6,38V$

SET = 0 ; $t = -5\%$ -> rezistors ; $t = -20\%$ -> potentiometer

$V_{Z_1min} = 2,5V \Rightarrow V_{out\,max} = 5,54\,V$

$V_{Z_1max} = 2,9V \Rightarrow V_{out\,max} = 6,43V$

SET = 0 ; $t = -5\%$ -> rezistors ; $t = +20\%$ -> potentiometer

$V_{Z_1min} = 2,5V \Rightarrow V_{out\,max} = 5,76\,V$

$V_{Z_1max} = 2,9V \Rightarrow V_{out\,max} = 6,68V$

SET = 1 ; $t = +5\%$ -> rezistors ; $t = +20\%$ -> potentiometer

$V_{Z_1min} = \dfrac{R_{12}+R_9+P}{R_{12}+R_9+P+R_{11}+R_8} V_{out\,min} \Rightarrow V_{out\,min} = 4,64V$

$V_{Z_1max} = \dfrac{R_{12}+R_9+P}{R_{12}+R_9+P+R_{11}+R_8} V_{out\,min} \Rightarrow V_{out\,min} = 5,39\,V$

SET = 1 ; $t = +5\%$ -> rezistors ; $t = -20\%$ -> potentiometer

$V_{Z_1min} \Rightarrow V_{out\,min} = 4,78V$

$V_{Z_1max} \Rightarrow V_{out\,min} = 5,55V$

SET = 1 ; $t = -5\%$ -> rezistors ; $t = -20\%$ -> potentiometer

$V_{Z_1min} \Rightarrow V_{out\,min} = 4,72V$

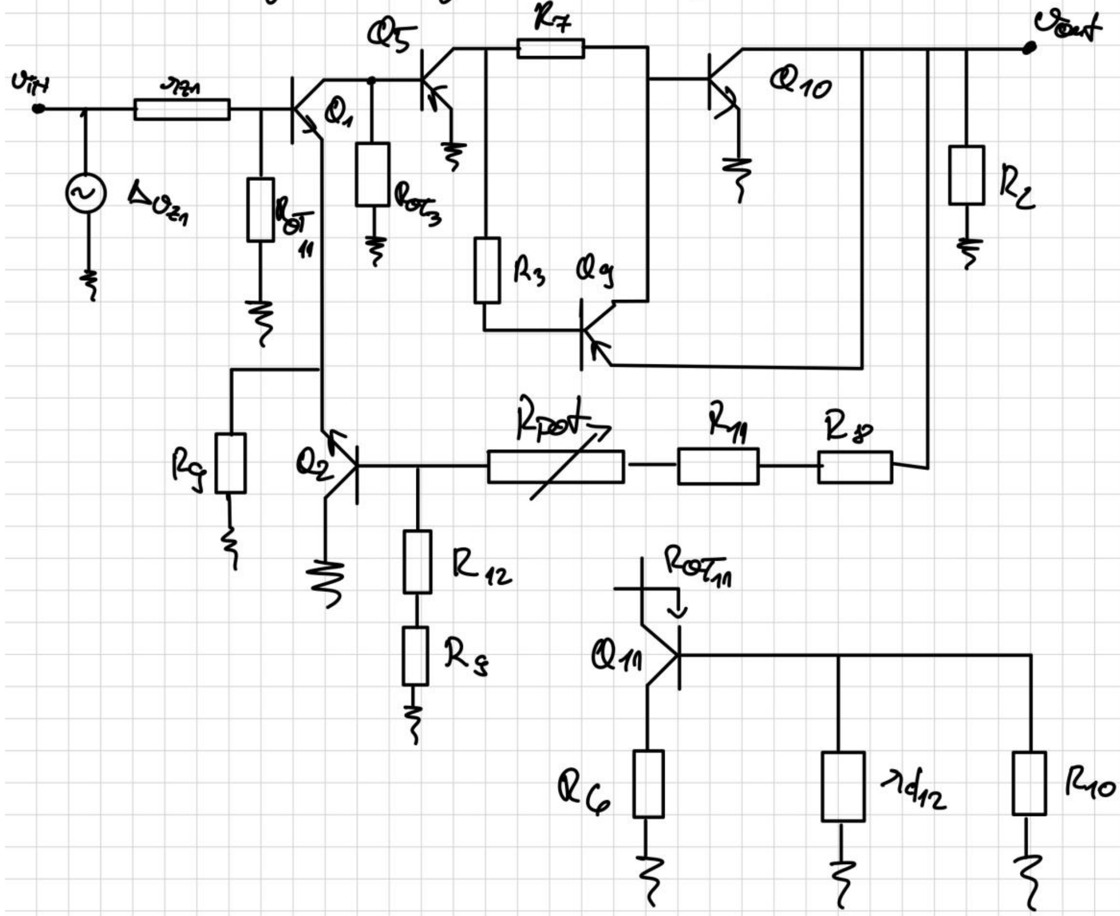
$V_{Z_1max} \Rightarrow V_{out\,min} = 5,48\,V$

SET = 1 ; $t = -5\%$ -> rezistors ; $t = +20\%$ -> potentiometer

$V_{Z_1min} \Rightarrow V_{out\,min} = 4,57\,V$

$V_{Z_1max} \Rightarrow V_{out\,min} = 5,30V$

Small signal analysis AC computations



$$r_{d_1} = \frac{n \cdot V_T}{J}$$

$$R_{OT_{12}} = r_o = \frac{V_A}{J_{C_{11}}} \rightarrow \text{Early Voltage}$$

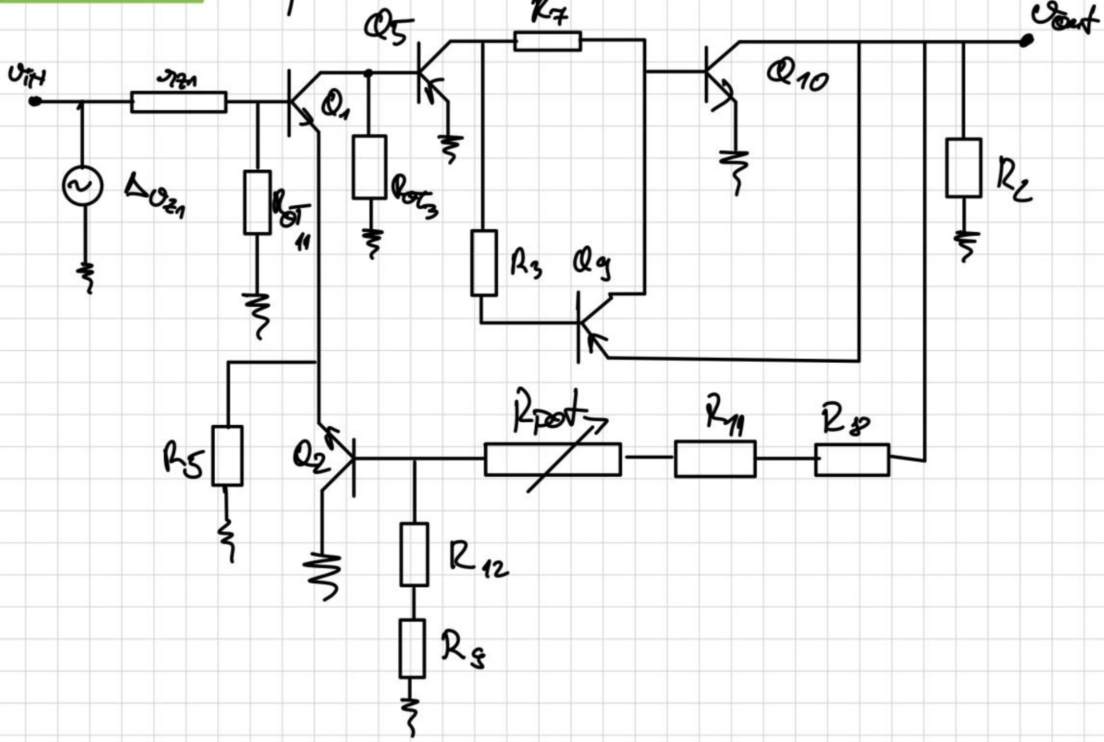
$$r_{z_1} = 75\ \Omega$$

$$r_{ce_1} = \frac{V_A}{J_{C_1}};\quad r_{ce_2} = \frac{V_A}{J_{C_2}};\quad r_{ce_5} = \frac{V_A}{J_{C_5}};\quad r_{ce_9} = \frac{V_A}{J_{C_9}};\quad r_{ce_{10}} = \frac{V_A}{J_{C_{10}}}$$

$$\begin{cases} g_{m_1} = 40 J_{C_1} \\ r_{be_1} = \frac{\beta_{F_1}}{g_{m_1}} \end{cases} \begin{cases} g_{m_2} = 40 J_{C_2} \\ r_{be_2} = \frac{\beta_{F_2}}{g_{m_2}} \end{cases} \begin{cases} g_{m_5} = 40 J_{C_5} \\ r_{be_5} = \frac{\beta_{F_5}}{g_{m_5}} \end{cases} \begin{cases} g_{m_9} = 40 J_{C_9} \\ r_{be_9} = \frac{\beta_{F_9}}{g_{m_9}} \end{cases} \begin{cases} g_{m_{10}} = 40 J_{C_{10}} \\ r_{be_{10}} = \frac{\beta_{F_{10}}}{g_{m_{10}}} \end{cases}$$

$$\beta_{F_1} = \beta_{F_2} = \beta_{F_5} = \beta_{F_9} = \beta_{F_{10}} = 200$$

$$\boxed{SET = 0} \Rightarrow \begin{cases} V_{out\,max} \\ V_{in\,min} \end{cases}$$



$r_{ce1} = r_{ce2} = \frac{100}{1,6} = 62,5\,k\Omega$ $\begin{cases} g_{m1} = 64\,mA/V \\ r_{be1} = 3,125\,k\Omega \end{cases}$

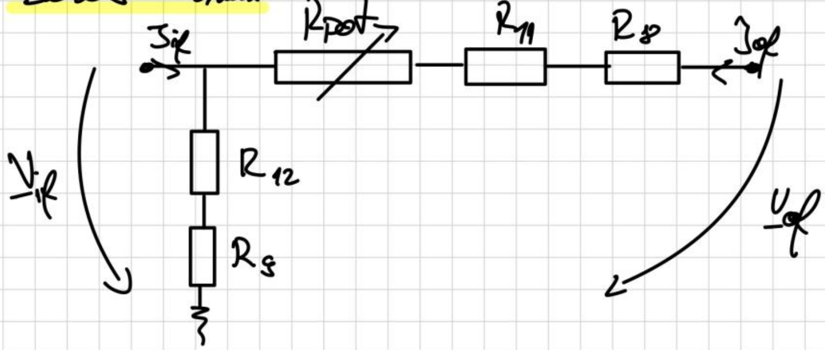
$r_{ce5} = 41,75\,k\Omega$

$r_{ce10} = 34,79\,k\Omega$ $\begin{cases} g_{m2} = 64\,mA/V \\ r_{be2} = 3,125\,k\Omega \end{cases}$ $\begin{cases} g_{m5} = 96\,mA/V \\ r_{be5} = 2,08\,k\Omega \end{cases}$

$\begin{cases} g_{m10} = 122,4\,mA/V \\ r_{be10} = 1,63\,k\Omega \end{cases}$

$$\boxed{R_{OT3} = \frac{V_A}{I_{C3}} = \frac{65}{1,6} = 40,62\,k\Omega}$$

Series - shunt

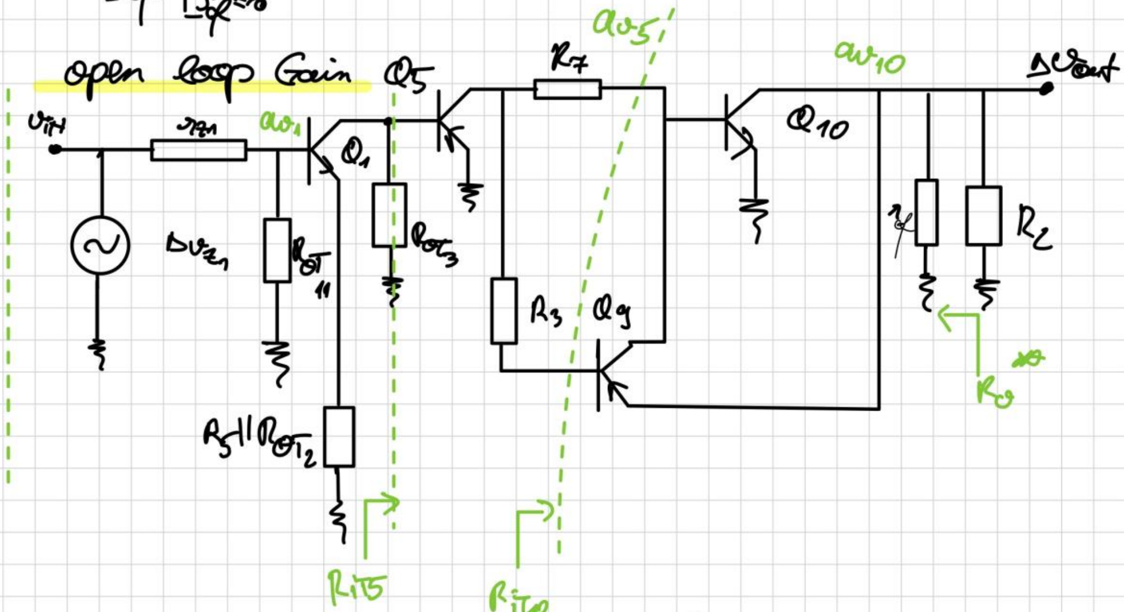


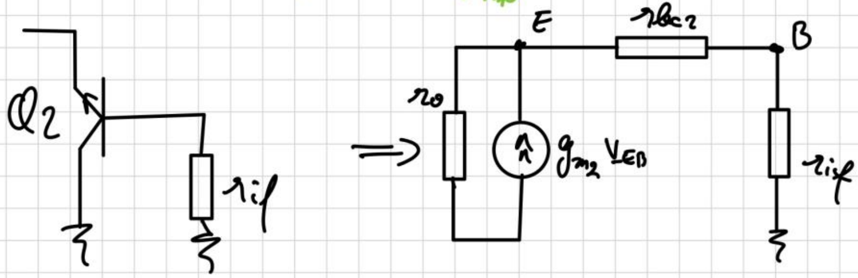
$$f_v = \frac{R_{12}+R_9}{R_{12}+R_9+R_{pot}+R_{11}+R_8} = \frac{2420}{5450} = 0{,}4403$$

$$r_{if} = \left.\frac{V_{if}}{I_{if}}\right|_{V_{of}=0} = (R_{12}+R_9)\,\|\,(R_{pot}+R_{11}+R_8) = 1{,}67\,k\Omega$$

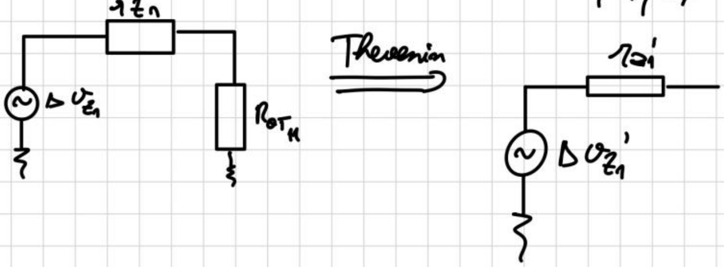
$$r_{of} = \left.\frac{V_{of}}{I_{of}}\right|_{I_{if}=0} = R_{12}+R_9+R_{pot}+R_{11}+R_8 = 5{,}45\,k\Omega$$

open loop Gain Q5





Common collector $\Rightarrow R_{OT_2} = \frac{r_{bb2}+r_{if}}{1+\beta_F} \,\|\, r_{ce2}$



$$\Delta v_{i1}' = v_{z1} \cdot \frac{R_{OT11}}{R_{OT11} + r_{z1}} \quad ; \quad r_{z1}' = r_{z1} \| R_{OT11}$$

$$a_v = \frac{\Delta v_o'}{\Delta v_{z1}'} = a_{v1} \cdot a_{v5} \cdot a_{v10}$$

$$a_{v1} = \frac{-\beta_F (R_{iT5} \| R_{OT3})}{r_{be1} + (1+\beta_F)(R_9 \| R_{OT2})} \Rightarrow R_{iT5} = r_{ce5} \quad \text{(common emitter stage)}$$

$$a_{v5} = -g_{m5} \left(R_3 \| (R_7 + R_{iT10}) \| r_{ce5} \right)$$

$$R_{iT10} = r_{be10} + (1+\beta_F)(r_{of} \| R_L \| r_{ce10})$$

$$a_{v10} = \frac{(1+\beta_F)(r_{of} \| R_L \| r_{ce10})}{r_{be10} + (1+\beta_F)(r_{of} \| R_L \| r_{ce10})} \Rightarrow \boxed{a_v = 20{,}03}$$

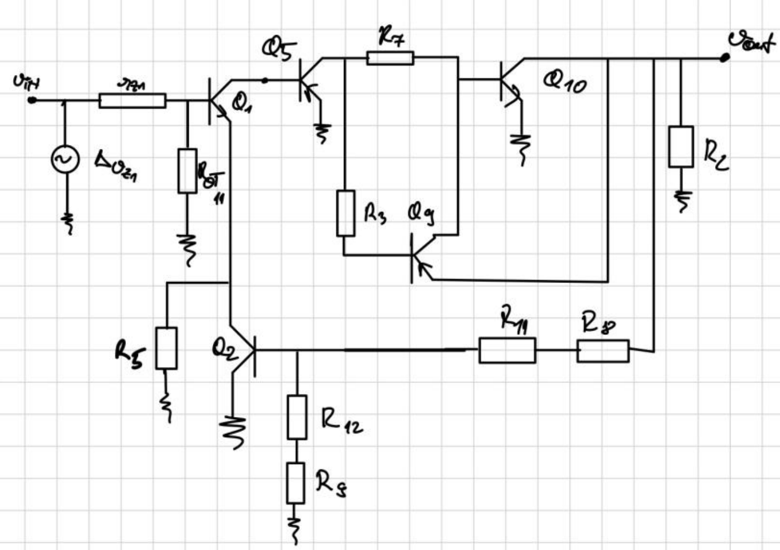
$$R_o^{*} = r_{of} \| R_{OT10} \| R_L = 2\ \Omega$$

$$R_{OT10} = \frac{r_{be10} + R_{OT5}}{1+\beta_F} \| r_{ce10} \Rightarrow R_{OT5} = R_7 \| R_3$$

$$T = f_o \cdot a_v = 8{,}90$$

$$\frac{1}{R_o} = \frac{1+T}{R_o^{*}} - \frac{1}{R_L} = 1{,}6\ \Omega < 2\ \Omega$$

$\boxed{\text{SET} = 1}$ $\left\{ \begin{array}{l} V_{out\,min} \\ V_{in\,amp} \end{array} \right.$



$$r_{ce_1} = r_{ce_2} = \frac{100}{2{,}4} = 41{,}6\ k\Omega$$

$$r_{ce_5} = 14{,}95\ k\Omega$$

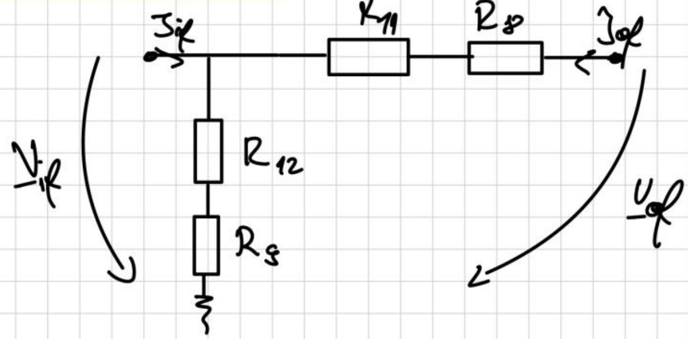
$$r_{ce_{10}} = 48{,}87\ k\Omega$$

$$\begin{cases} g_{m_1} = 96\ mA/V \\ r_{be_1} = 2{,}08\ k\Omega \end{cases}$$

$$\begin{cases} g_{m_2} = 96\ mA/V \\ r_{be_2} = 2{,}08\ k\Omega \end{cases} \qquad \begin{cases} g_{m_5} = 296\ mA/V \\ r_{be_5} = 0{,}675\ k\Omega \end{cases}$$

$$\begin{cases} g_{m_{10}} = 86\ mA/V \\ r_{be_{10}} = 2{,}32\ k\Omega \end{cases}$$

Series - shunt

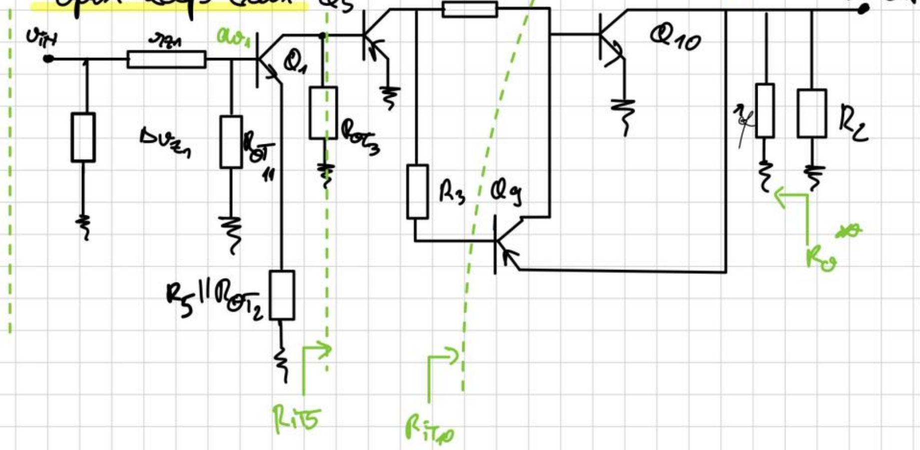


$$f_v = \frac{R_{12} + R_9}{R_{12} + R_9 + R_{11} + R_8} = \frac{2420}{4950} = 0{,}48$$

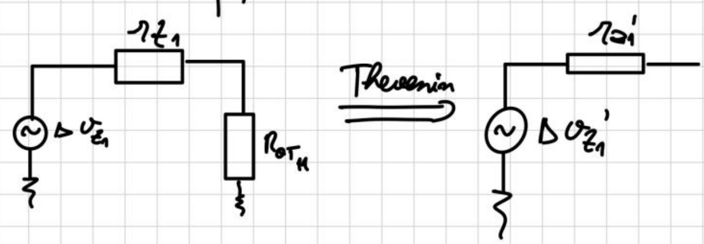
$$r_{if} = \frac{V_{if}}{I_{if}}\bigg|_{V_{of}=0} = (R_{12} + R_9) \,||\, (R_{11} + R_8) = 1{,}23\ k\Omega$$

$$r_{of} = \frac{V_{of}}{I_{of}}\bigg|_{I_{if}=0} = R_{12} + R_9 + \cancel{R_{est}} + R_{11} + R_8 = 4{,}95\ k\Omega$$

open loop Gain Q5



$$R_{OT_2} = \frac{r_{be2} + r_{if}}{1+\beta_F} \parallel r_{ce2}$$



$$\Delta v_{z_1}' = \Delta v_{z_1} \cdot \frac{R_{OT_{11}}}{R_{OT_{11}} + r_{z_1}} \quad ; \quad r_{z_1}' = r_{z_1} \parallel R_{OT_{11}}$$

$$a_v = \frac{\Delta v_o'}{\Delta v_{z_1}'} = a_{v_1} \cdot a_{v_5} \cdot a_{v_{10}}$$

$$a_{v_1} = \frac{-\beta_F \; R_{iT5}}{r_{be_1} + (1+\beta_F)(R_g \parallel R_{OT_2})} \Rightarrow R_{iT_5} = r_{ce5} \quad \text{(common emitter stage)}$$

$$a_{v_5} = -g_{m_5}\left(R_3 \parallel (R_7 + R_{iT_{10}}) \parallel r_{ce5}\right)$$

$$R_{iT_{10}} = r_{be10} + (1+\beta_F)(r_{of} \parallel R_L \parallel r_{ce10})$$

$$a_{v_{10}} = \frac{(1+\beta_F)(r_{of} \parallel R_L \parallel r_{ce10})}{r_{be10} + (1+\beta_F)(r_{of} \parallel R_L \parallel r_{ce10})} \Rightarrow \boxed{a_v = 14{,}12}$$

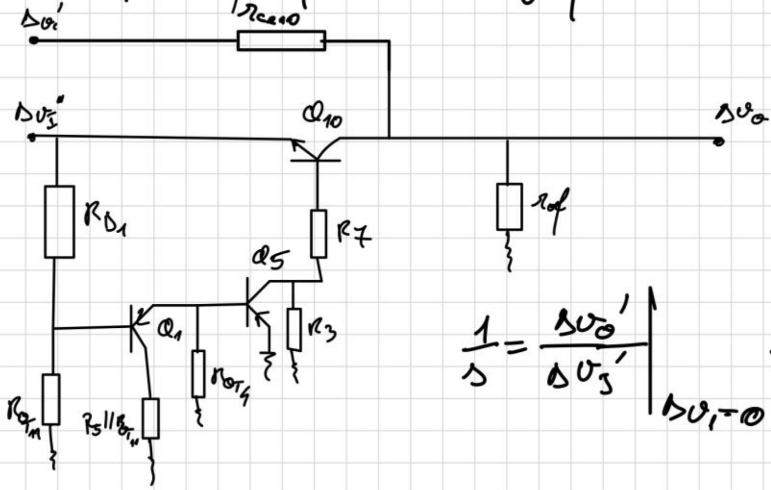
$$R_o^{*} = r_{of} \parallel R_{OT10} \parallel R_L = 2{,}2\ \Omega$$

$$R_{OT_{10}} = \frac{r_{be10} + R_{OT5}}{1+\beta_F} \parallel r_{ce10} \Rightarrow R_{OT_5} = R_7 \parallel R_3$$

$$T = f_v \cdot a_v = 6{,}77$$

$$\frac{1}{R_o} = \frac{1+T}{R_o^{*}} - \frac{1}{R_L} = 1{,}2\ \Omega < 2\ \Omega$$

Computations for stability factors s and S ($R_L=\infty$)



$$\frac{1}{s}=\left.\frac{\Delta v_o'}{\Delta v_J'}\right|_{\Delta v_1=0}+\left.\frac{\Delta v_o''}{\Delta v_J''}\right|_{\Delta v_J=0}$$

$$\text{I}: \left.\frac{\Delta v_o'}{\Delta v_J'}\right|_{\Delta v_J''=0}=\frac{r_{of}\,\|\,R_{OT10}}{r_{ce10}+r_{of}\,\|\,R_{OT10}}\quad \begin{cases} SET=0 \Rightarrow R_{OT10}=r_{ce10}\\ SET=1 \Rightarrow R_{OT10}=r_{ce10}\end{cases}$$

$$\text{II} \left.\frac{\Delta v_o''}{\Delta v_J''}\right|_{\Delta v_J'=0}=\frac{(r_{be10}+R_7+R_3)\,\|\,(\beta_F+1)\,r_{of}}{(r_{ce10}+(r_{be10}+R_7+R_3)(1+\beta_F))\,r_{of}}$$

$$SET=0 \Rightarrow \frac{1}{s}=0{,}0041$$

$$\frac{1}{S}=\frac{\frac{1}{s}}{1+T}=0{,}00052$$

$$\Rightarrow S=1923{,}07>79$$

$$SET=1 \Rightarrow \frac{1}{s}=0{,}005 \Rightarrow \frac{1}{S}=0{,}0043 \Rightarrow$$

$$\Rightarrow S=2325{,}81>79$$

4. Simulations

To analyse the circuit I did the following simulations:

4.1. DC SWEEP

To see how the output voltage varies with respect to the input voltage and the potentiometer's position, I used a variable DC source. The examples show that when the potentiometer is set to 0 or 1, the output voltage stays constant at the lowest and maximum values listed in the requirements.

Vin $_{min}$=10V, Vout $_{min}$=5V, SET=1

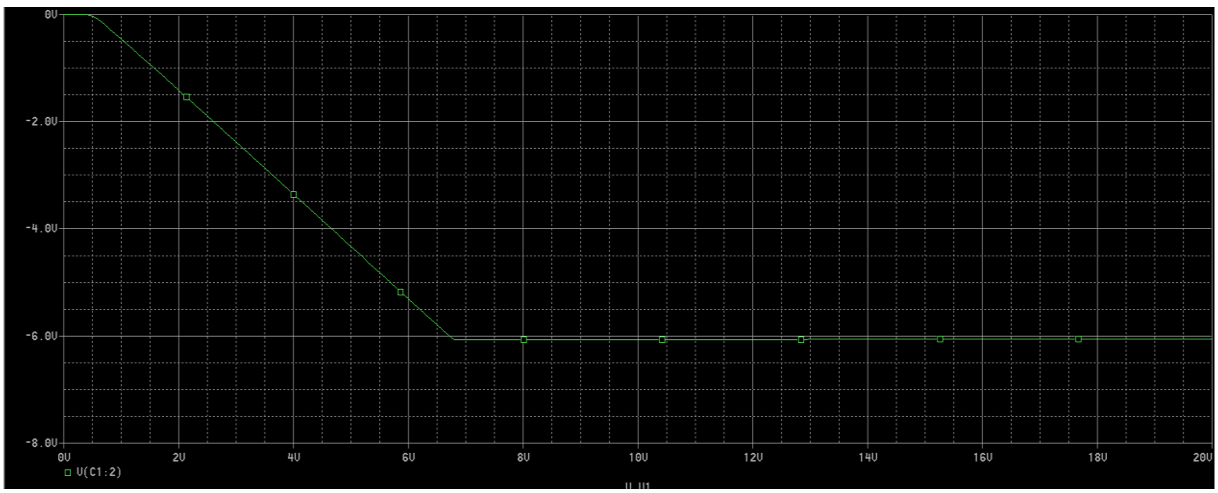


Fig. 4.1.1.

Vin $_{min}$=10V, Vout $_{max}$=6V, SET=0

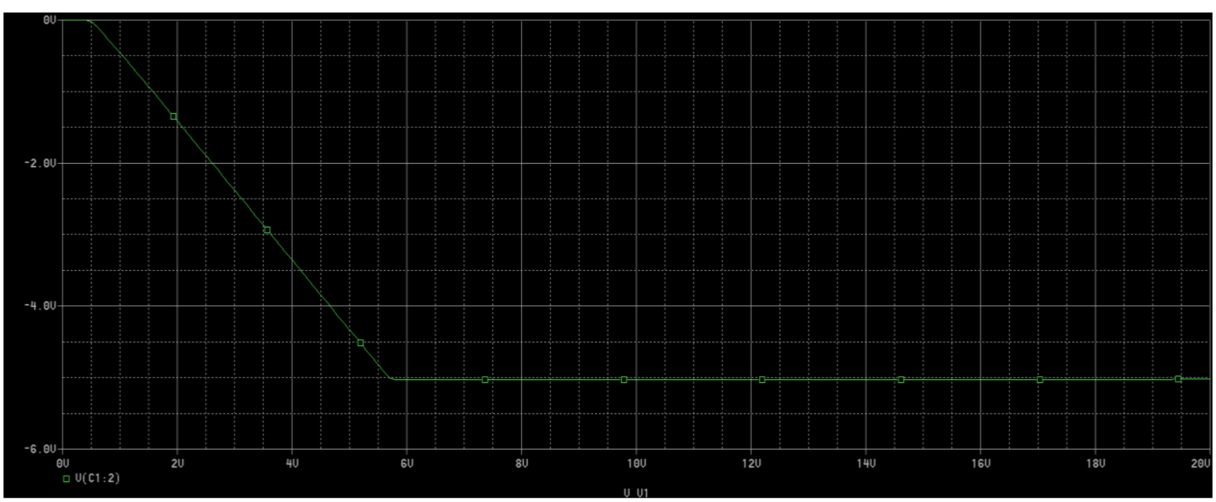


Fig. 4.1.2.

Vin $_{max}$=13V, Vout $_{min}$=5V, SET=1

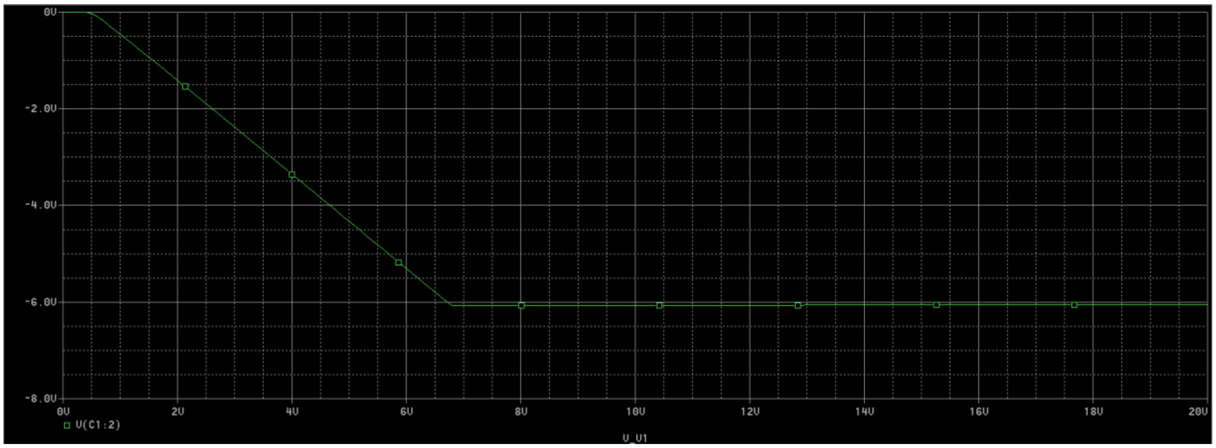


Fig. 4.1.3.

Vin $_{max}$=13V, Vout $_{max}$=6V, SET=0

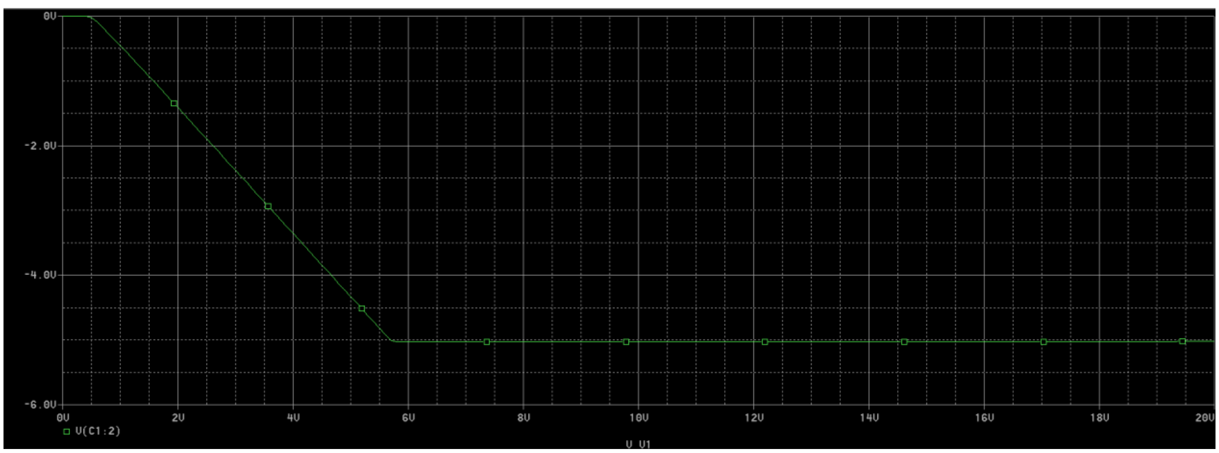


Fig. 4.1.4.

4.2. Output Voltage Level with the Potentiometer at 50%

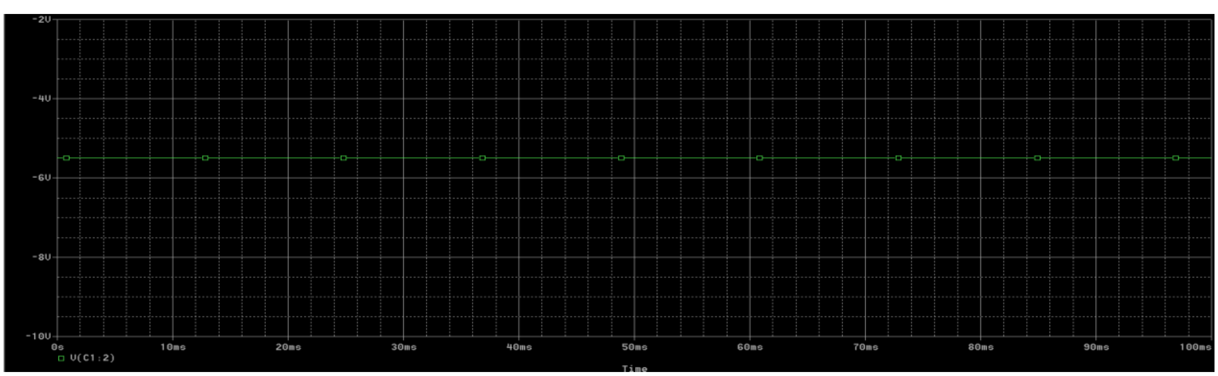


Fig. 4.2.

4.3. Simulation of Overcurrent Protection

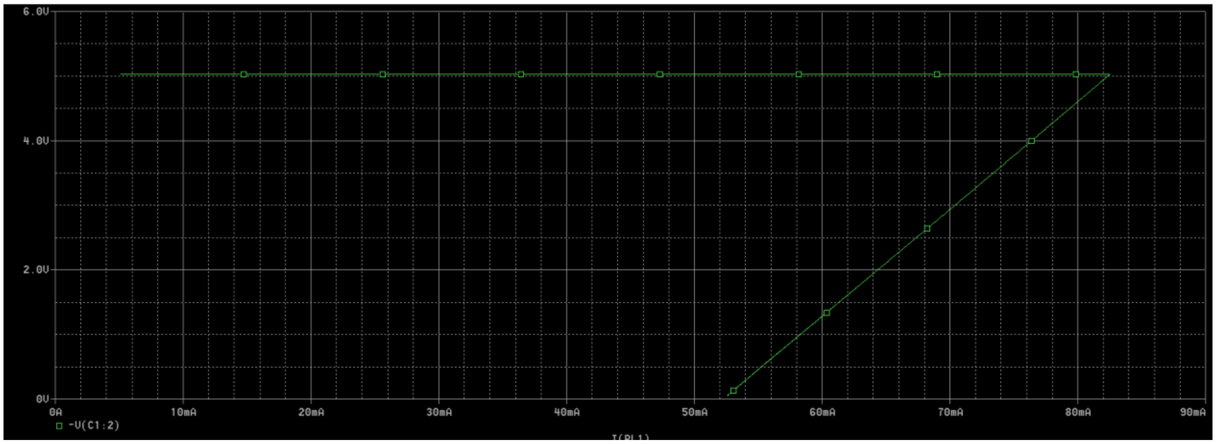


Fig. 4.3.

I_{short}=52.959mA
I_{knee}=82.347mA

4.4. Simulation of Overvoltage Protection

The circuit must be independently examined in order to model the overvoltage protection. I connected a resistance and a Variable DC source in series. According to the simulation results, the voltage stabilizes around the diodes' threshold voltage.

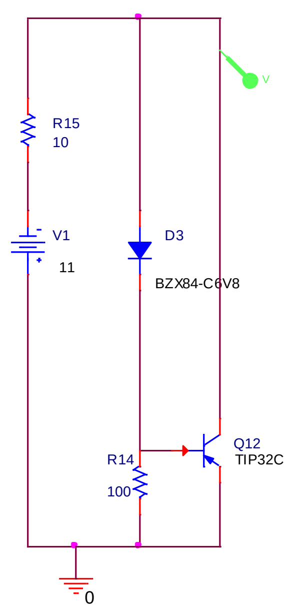


Fig. 4.4.1.

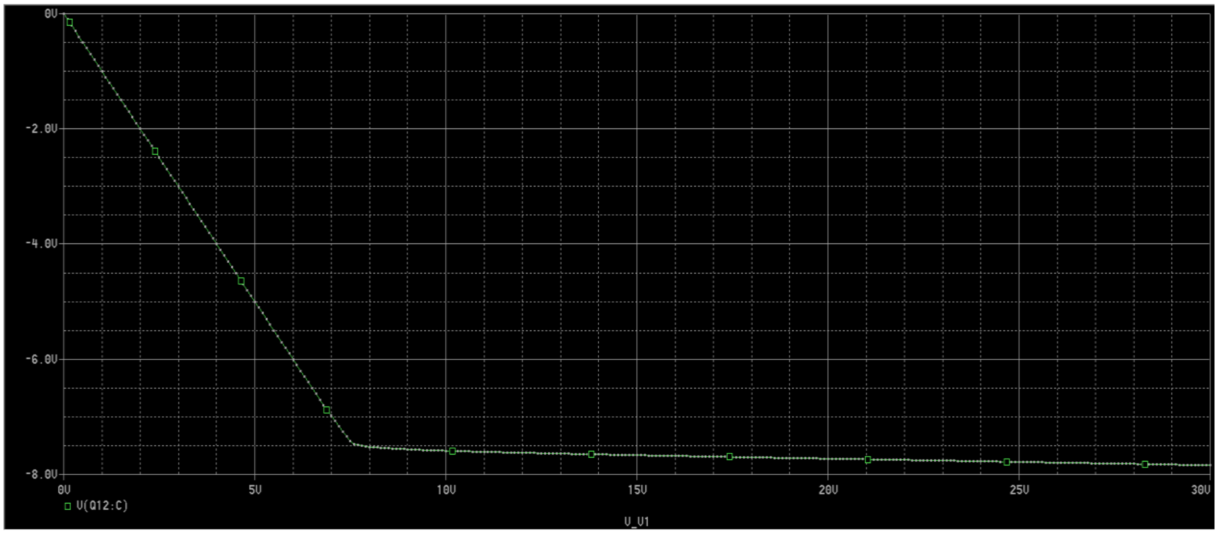


Fig. 4.4.2.

4.5. Stabilization Factor (S)

In order to make a simulation for the stabilization factor (S), I connected a sinusoidal source (VSIN) with parameters OFFSET = 0, VAMPL = 0.5, FREQ = 50, AC = 0 in series with the supply. Afterwards, I performed a transient (time-domain) simulation in all possible cases.

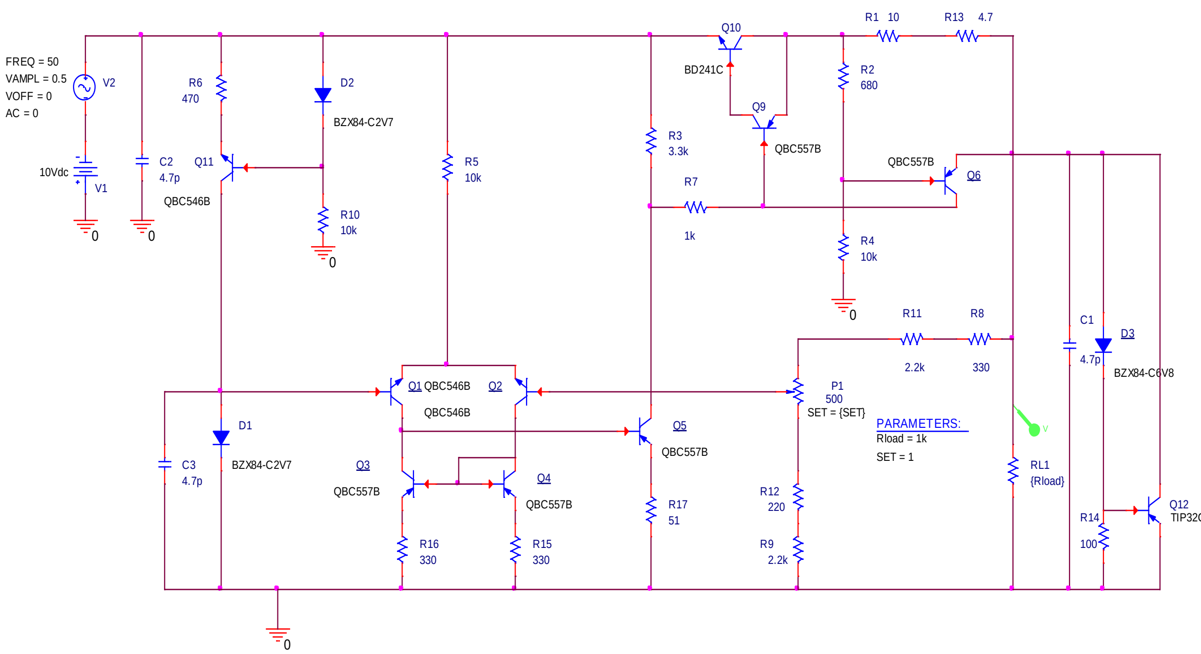


Fig. 4.5.1.

Vin $_{min}$=10V, Vout $_{min}$=5V, SET=1

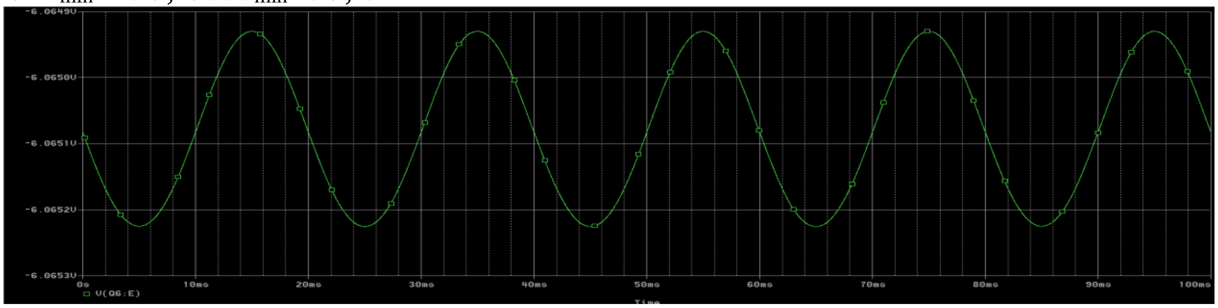


Fig. 4.5.2.

$$S = \frac{1}{-6.0649 + 6.0652} = 3333.33 > 79$$

Vin $_{min}$=10V, Vout $_{max}$=6V, SET=0

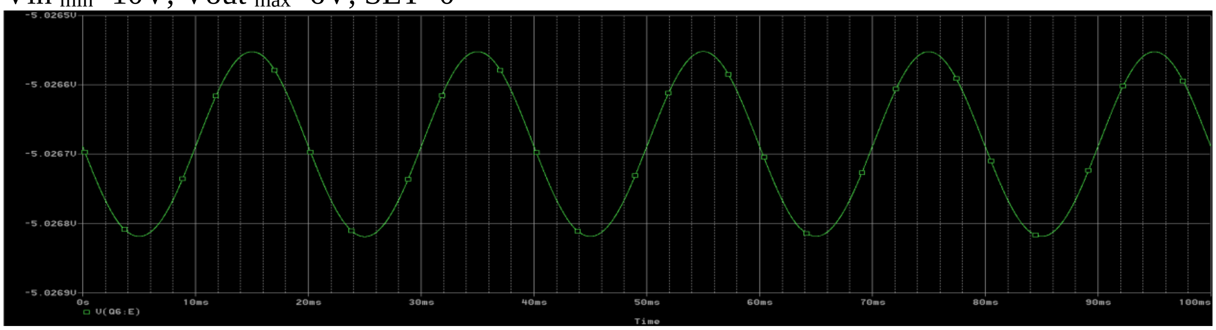


Fig. 4.5.3.

$$S = \frac{1}{-5.0265 + 5.0269} = 2500 > 79$$

Vin $_{max}$=13V, Vout $_{min}$=5V, SET=1

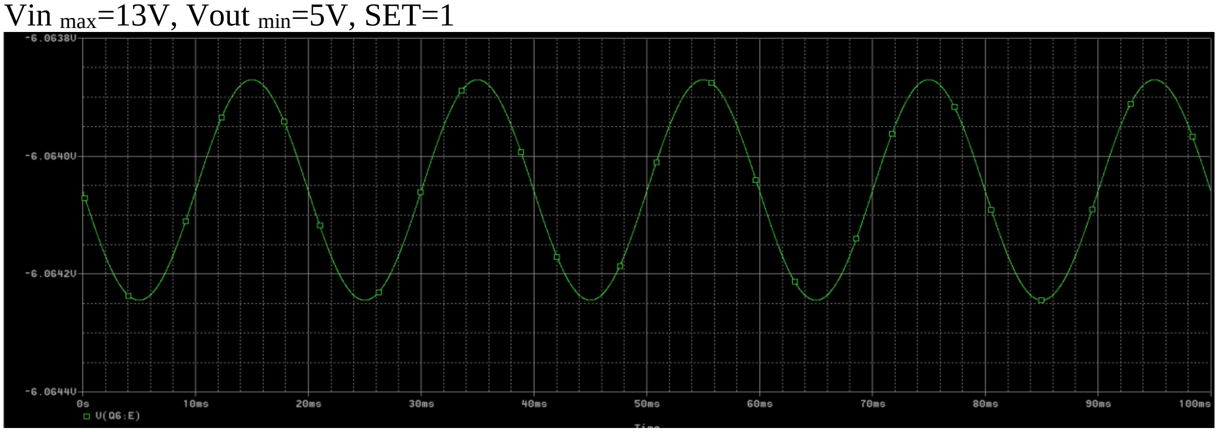


Fig. 4.5.4.

$$S = \frac{1}{-6.0638 + 6.0644} = 1666.66 > 79$$

Vin_{max}=13V, $Vout_{max}$=6V, SET=0

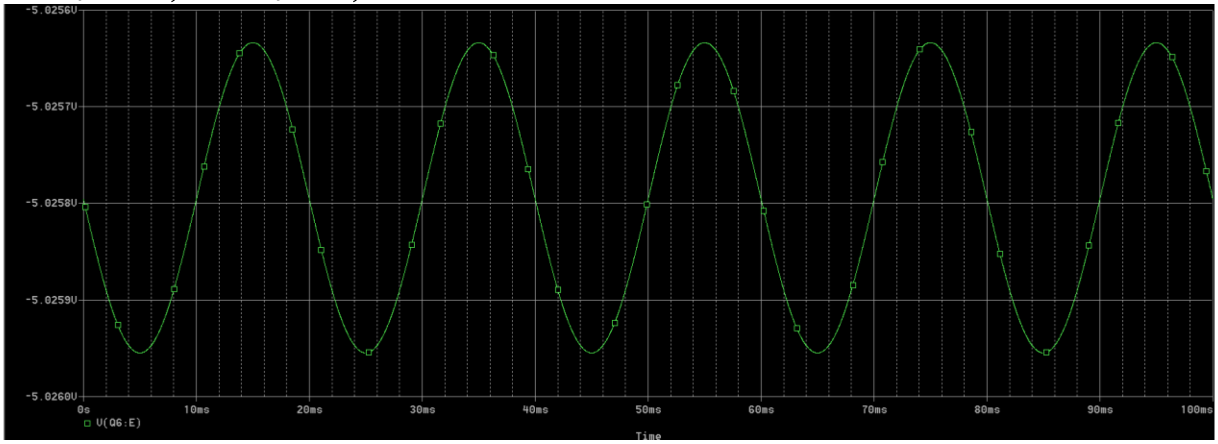


Fig. 4.5.5.

$$S = \frac{1}{-5.0256 + 5.0260} = 2500 > 79$$

4.6. Output Impedance Simulation

In order to run the simulations in all cases for the Output Impedance, I replaced the Load Resistance with a Current Source in AC (IAC), as in the figure below.

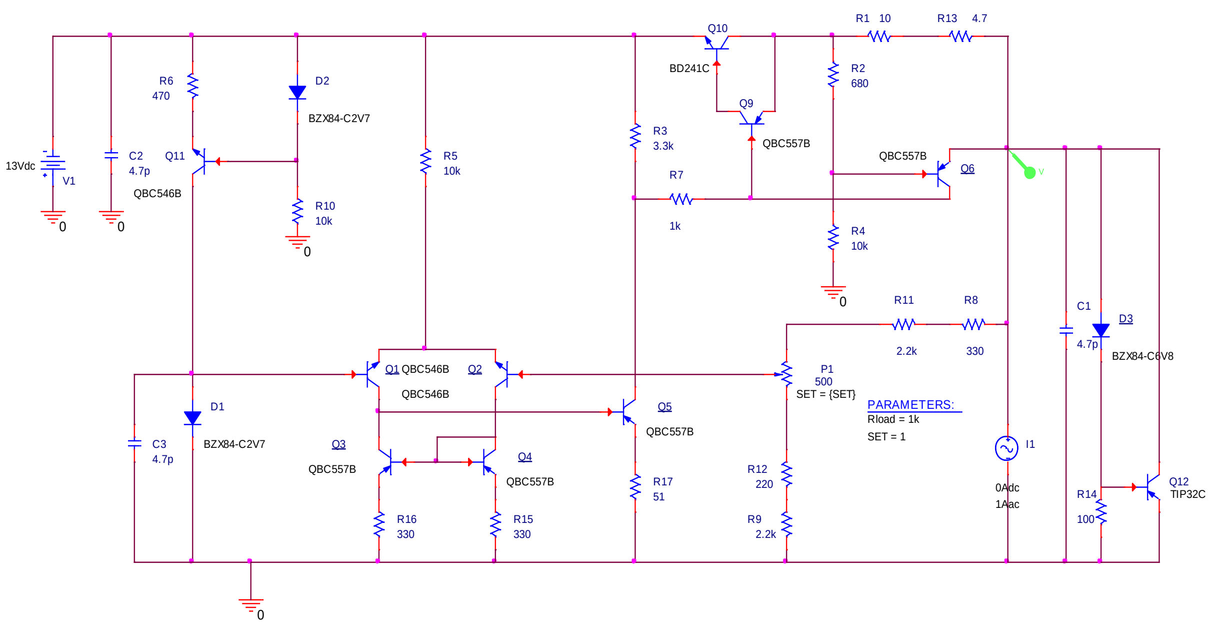


Fig. 4.6.1.

All the simulations are conducted in the AC SWEEP Analysis Type with the following parameters: Start Frequency=1Hz; End Frequency = 10GHz; Points/Decade=1; Logarithmic Type. In all cases it can be observed that $R_O <= 2\Omega$.

Vin $_{min}$=10V, Vout $_{min}$=5V, SET=1

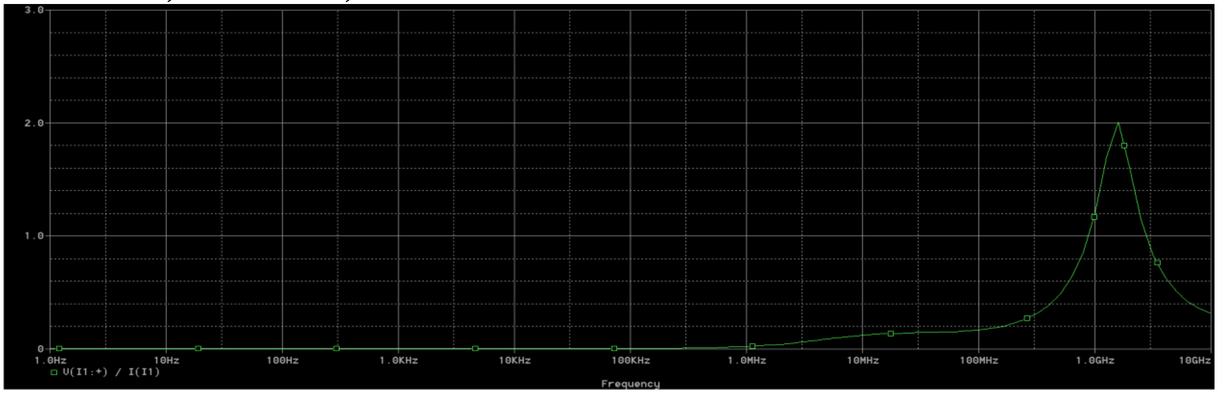


Fig. 4.6.2.

Vin $_{min}$=10V, Vout $_{max}$=6V, SET=0

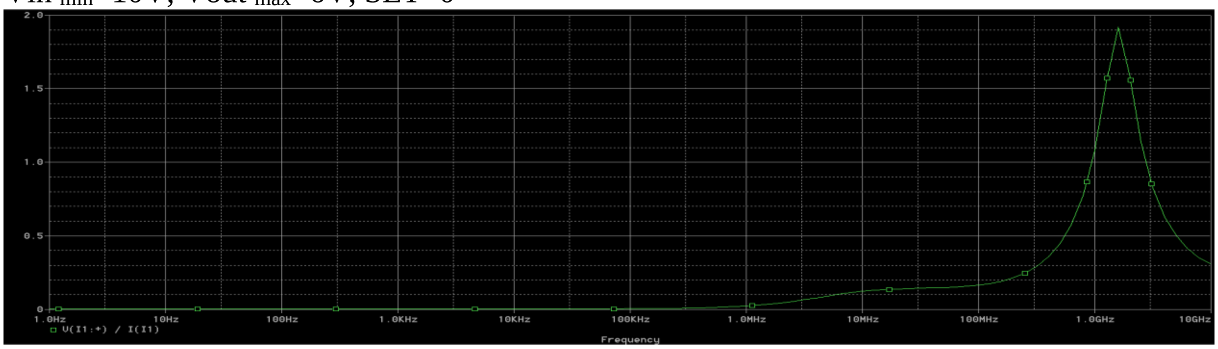


Fig. 4.6.3.

Vin $_{max}$=13V, Vout $_{min}$=5V, SET=1

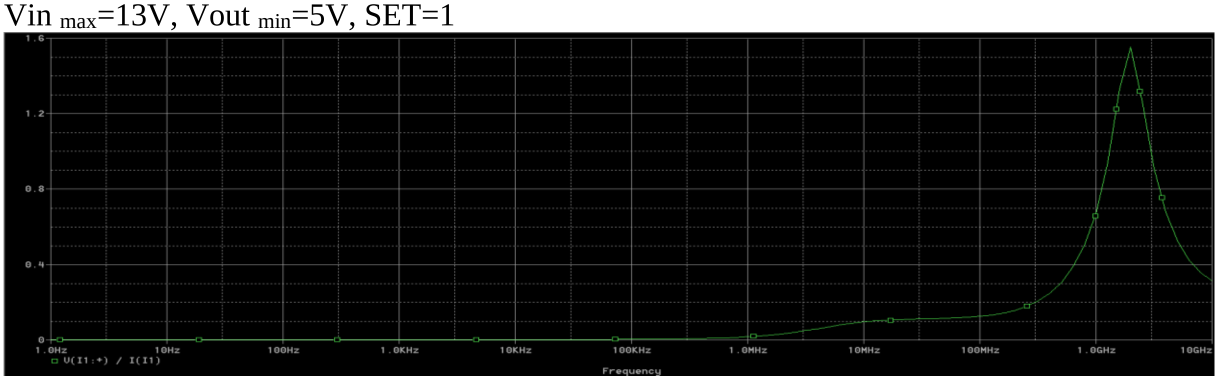


Fig. 4.6.4.

Vin $_{max}$=13V, Vout $_{max}$=6V, SET=0

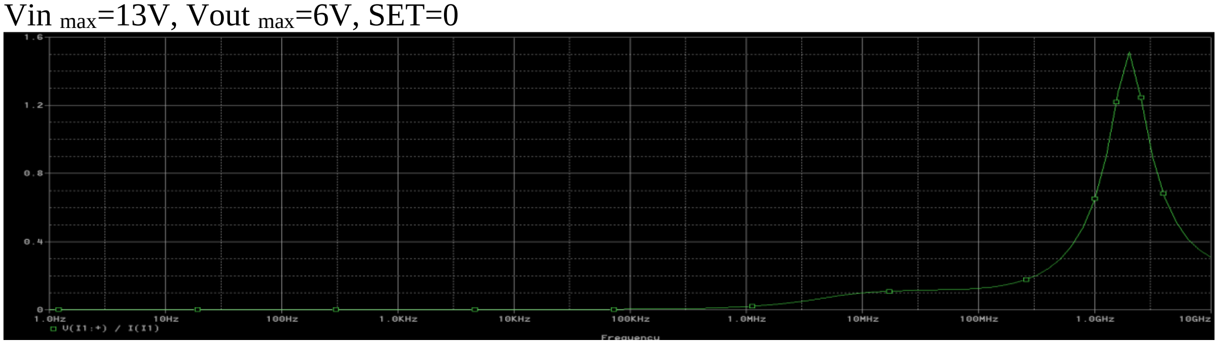


Fig. 4.6.5.

5. Conclusion

To sum up, the voltage regulator project has effectively achieved its goals of creating a circuit that, in spite of changes in input conditions, maintains a steady output voltage within the designated range. Effectively controlling the specified output, the regulator showed strong performance within the required input range. With concerns for efficiency, power dissipation, and practicality, simulations confirmed the design's efficacy.

The research emphasizes how important it is to create voltage regulators that can handle a range of input conditions while maintaining stability and dependability in a variety of situations. Issues that arose during testing were resolved, which helped the project succeed overall.

The results of this study will improve knowledge of voltage regulator design, efficiency factors, and practical applications for applications needing accurate voltage control within specific ranges. The project's potential for additional development and real-world application is increased by suggestions for future improvements and user-friendly features.

6. Mounting Map

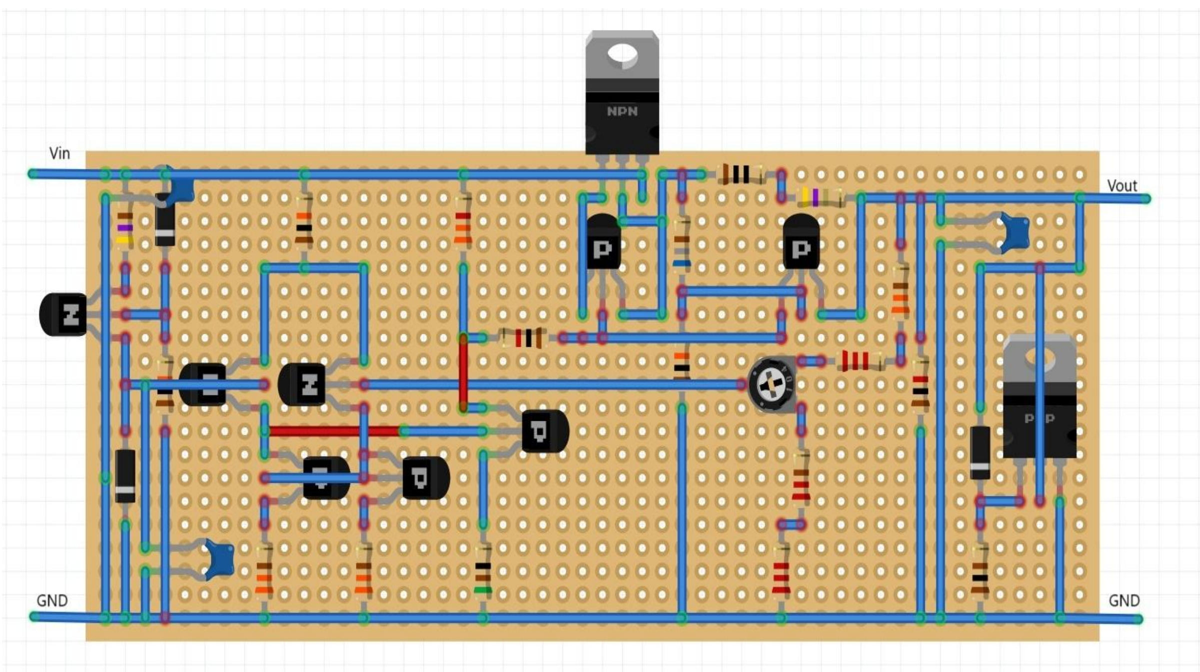


Fig. 6.1.

Bill of Materials [21]

No. Crt.	Component	No. of components	Product name	Manufacturer	Class
1	D1, D2 [1]	2	ZPD2.7-DIO	DIOTEC SEMICON-DUCTOR	Zener Diode
2	D3 [2]	1	ZPD6.8-DIO	DIOTEC SEMICON-DUCTOR	Zener Diode
3	P1 [3]	1	PT15LV02501A2020S	PIHER	Potentiometer
4	Q1, Q2, Q11 [4]	3	BC546BBK	DIOTEC SEMICONDUCTOR	Bipolar Transistor
5	Q3, Q4, Q5, Q6, Q9 [5]	5	BC556BBK	DIOTEC SEMICONDUCTOR	Bipolar Transistor
6	Q10 [6]	1	BD241C	ST MICROELECTRONICS	Bipolar Transistor
7	Q12 [7]	1	TIP32C	ST MICROELECTRONICS	Bipolar Transistor
8	R1 [8]	1	CFR0W4J0100A50	ROYAL OHM	Resistor
9	R2 [9]	1	CF1/4W-680R	SR PASSIVES	Resistor
10	R3 [10]	1	CF1/4W-3K3	SR PASSIVES	Resistor
11	R4, R5, R10 [11]	3	CF1/4W-10K	SR PASSIVES	Resistor
12	R6 [12]	1	CF1/4W-470R	SR PASSIVES	Resistor
13	R7 [13]	1	CF1/4W-1K	SR PASSIVES	Resistor
14	R8, R15, R16 [14]	3	CF1/4W-330R	SR PASSIVES	Resistor
15	R9, R11 [15]	2	CF1/4W-2K2	SR PASSIVES	Resistor
16	R12 [16]	1	CF1/4W-220R	SR PASSIVES	Resistor
17	R13 [17]	1	CF1/4W-4R7	SR PASSIVES	Resistor
18	R14 [18]	1	CF1/4W-100R	SR PASSIVES	Resistor
19	R17 [19]	1	CFRW4J0510A50	ROYAL OHM	Resistor
20	C1, C2, C3 [20]	3	CCK-4P7	SR PASSIVES	Capacitor

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14. R8, R15, R16: https://www.tme.eu/ro/details/cf1_4w-330r/rezistente-tht/sr-passives/
15. R9, R11: https://www.tme.eu/ro/details/cf1_4w-2k2/rezistente-tht/sr-passives/
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