**University POLITEHNICA of Bucharest**
Faculty of Electronics, Telecommunications and Information Technology

# Project 1
# Voltage Regulator

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Group: 431F

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Dr. Ing. Mihaela Pantazica

Year: 3

# Project Requirements

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

**N= 1**

- **Negative supply voltage between - 6 ÷ - 11 [V];**
- **Negative programmable output voltage between - 1 ÷ - 4[V];**
- **The output current through the load between (0) ÷ (20) [mA];**
- **Short circuit protection of the output terminals with constant current limiting circuit**

# Introduction

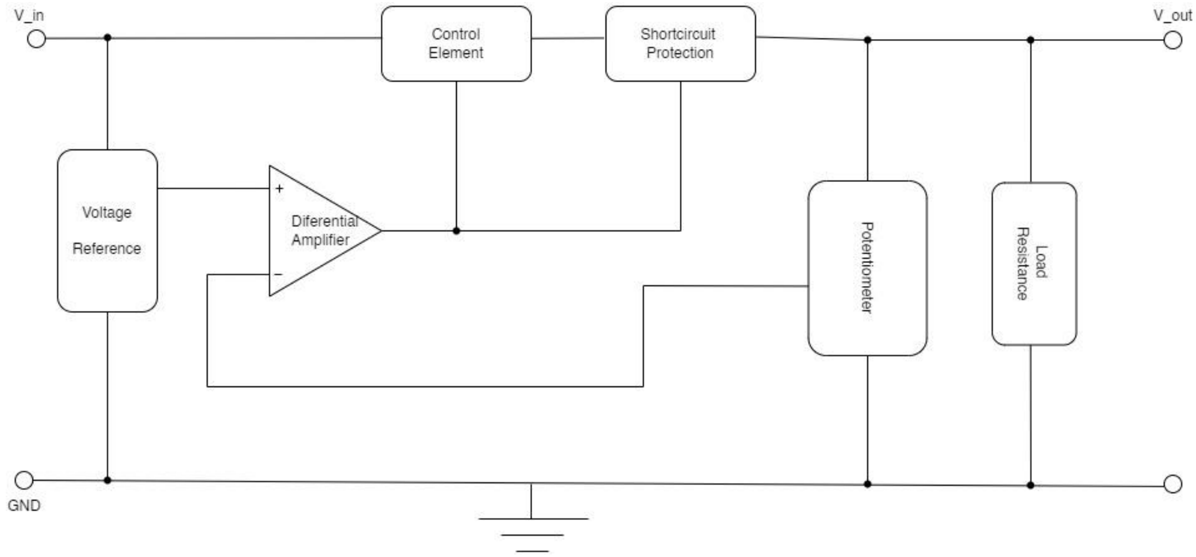
In our day to day lives, we use electronic devices for most of our tasks. Whether it's our phones, laptops, televisions or home devices, electricity plays a big role in our modern lives and in the modern era most humans would not be able to get by without them. However, this lifestyle comes with a very big drawback and that is the fact that we constantly need electrical sources in order to keep our devices working. Since most buildings have been connected to a power grid, we might say that our inconveniences stop here, but in fact we are faced with another problem: most outlets give a power supply voltage of 220V or 230V, depending on the region where we live, which is way too big for most of the devices we use. Not to mention that in some cases, this voltage might fluctuate. This is where a voltage regulator comes into picture.

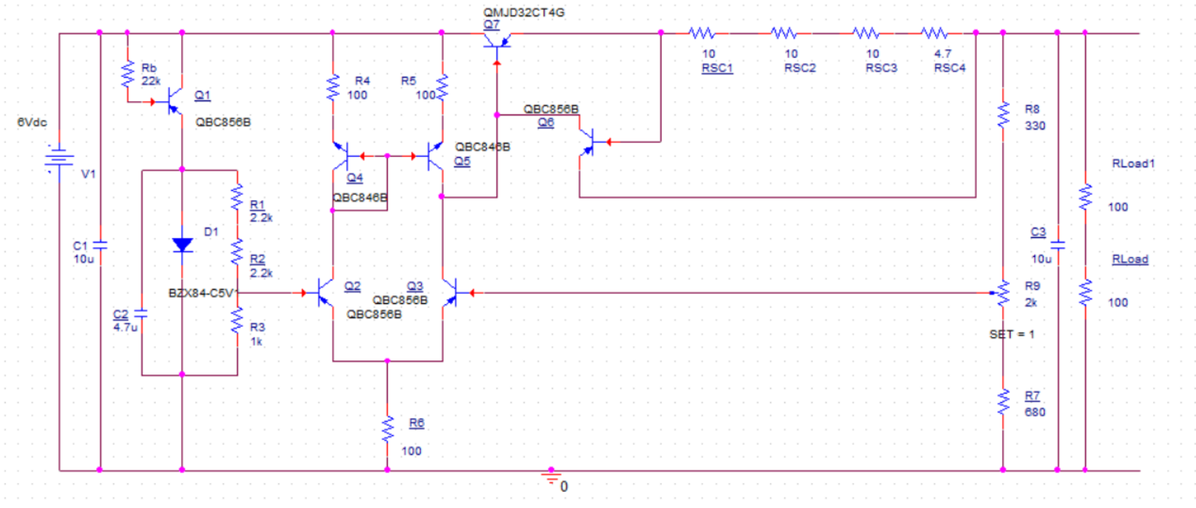
A linear voltage regulator is a three-terminal electrical device that helps keeping the output voltage at a chosen constant value. It usually contains a transistor controlled by a negative feedback circuit that has the purpose of producing a specified output voltage that remains stable despite variations in load current and/or input voltage.

The regulating device (which acts like a variable resistor) may be placed in parallel with the load (shunt regulator - our case for this project) or between the source and the regulated load (series regulator). We can make use of Zenner diodes and series resistors (for the simple case) alongside with Amplifiers (error or differential), power pass elements and so on (for the more complex applications). This is why, linear voltage regulators are actually non-linear circuits (since they contain non-linear components and because it has a constant output voltage that doesn't depend on the input voltage).

Although linear voltage regulators have many advantages (they are cheap, simple and have a quick response to changes in the circuit) they have a big disadvantage and that is the fact that they are very inefficient due to the voltage drop across the pass element which can cause the regulator to heat up.

# Block diagram



# Summary of the blocks

**Voltage Reference:**

The voltage reference is built with a Zener diode that receives constant current through R1. Since the diodes provided in the annex have a higher voltage than the lowest output voltage needed, I implemented a voltage divider in order to lower the voltage through the base of the transistor Q2. I also added a resistor in the base of transistor Q1 (Rb) of very high value in order to limit the current that was passing through the diode to around 10mA.

**Differential Amplifier:**

It amplifies the difference between two input voltages and it copies the current flowing through one device (in our case, the voltage reference block) to another device (the potentiometer block) through a current mirror, keeping the output constant no matter the load value.

**Control Element:**

The series control element is represented by a single high power MJD transistor. This gives the best amplification factor.

**Shortcircuit Protection:**

The shortcircuit protection is an element that is meant to limit the base current of the control element transistor when voltage increases. The four resistances and transistor make sure to attenuate the current that passes through the load, even when we have a spike of energy in our circuit.

**Potentiometer:**

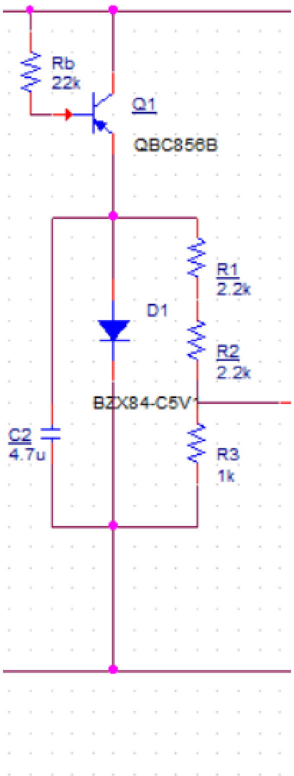
The potentiometer block also contains the negative feedback part of the circuit. R9 is a potentiometer (of value 2k Ohms) that can be set between 0 (for the output voltage -4V) and 1 (for the output voltage -1V). In order to choose the other resistances we had to compare the output voltage with the reference voltage through the Zener diode. After making the necessary computations, I chose the resistances from the Annex with the closest values to the ones that I have computed in order to obtain a satisfactory result at the output.

**Load:**

The block is formed by a load resistance. I chose the value for this resistance in order to have a good value (in the ranges specified by the requirements) for both the output voltage and the output current.

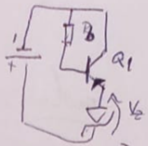
# Detailed explanations

### Voltage Reference




Chosen components:
Rb = 3.9 ohms
Q1 = BC856B low power transistor
D1 = 5.1V Zener Diode

Voltage reference




$V_Z = 5{,}1\,V$
$I_Z = 5\,mA$
$\Rightarrow V_{in} = (R_b \cdot I_b + V_Z)$ , $V_{in} = [-6 ; -11]$

$\downarrow$ we choose this

$\Rightarrow 6 = R_b \cdot I_B + V_Z$

$I_b = \frac{I_C}{\beta} = \frac{7}{310} \Rightarrow R_b = \frac{6 - V_Z}{I_b} = \frac{6 - 5{,}1}{7} \cdot 310 = 39{,}85\,k\Omega$

$\Rightarrow R_b = 22\,k\Omega$

$V_{out} < V_Z \rightarrow$ Reference $= -0{,}9$

$\rightarrow V_{out} = \frac{V_Z \cdot R_3}{R_1 + R_3} \Rightarrow 0{,}9 = \frac{5{,}1 R_3}{R_1 + R_3}$

$R_3 = 1k \Rightarrow 0{,}9 = \frac{5{,}1}{R_1 + 1} \Rightarrow R_1 \cdot 0{,}9 = 5{,}1 - 0{,}9 \Rightarrow R_1 = \frac{5{,}1 - 0{,}9}{0{,}9}$

$= 4{,}66\,k\Omega$

$\Rightarrow$ I took two resistances of $2.2\,k\Omega$

## Control element and shortcircuit protection

Short circuit

Max current for load -> $I_{Load} = \frac{|V_{out\_max}|}{R_L} = \frac{4}{200} = 20mA$

• 20% error for short circuit

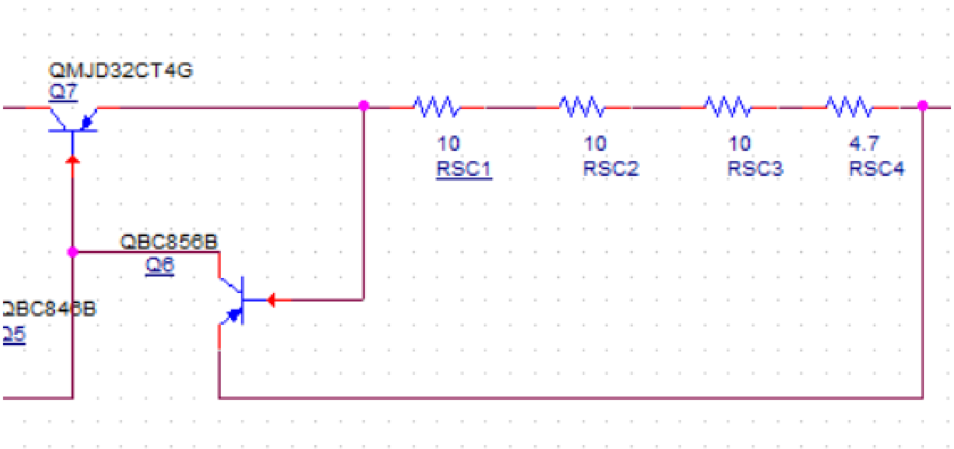
$I_{sc} = I_{Load} + 0,2\,I_{Load} = 20 + 4 = 24mA$

Find $R_{sc}$ : $R_{sc} = \frac{V_{BE}}{I_{sc}} = \frac{0,6}{20 \cdot 10^{-3}} = 30\Omega$

↳ I choose it slightly bigger to fit better in the intervals

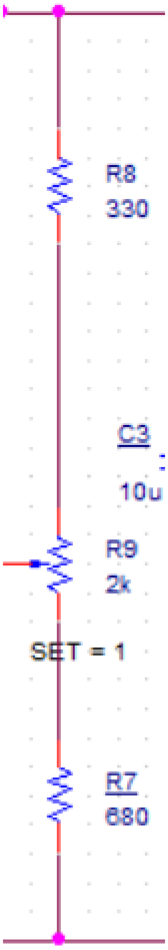
=> 3 res. of $10\Omega$

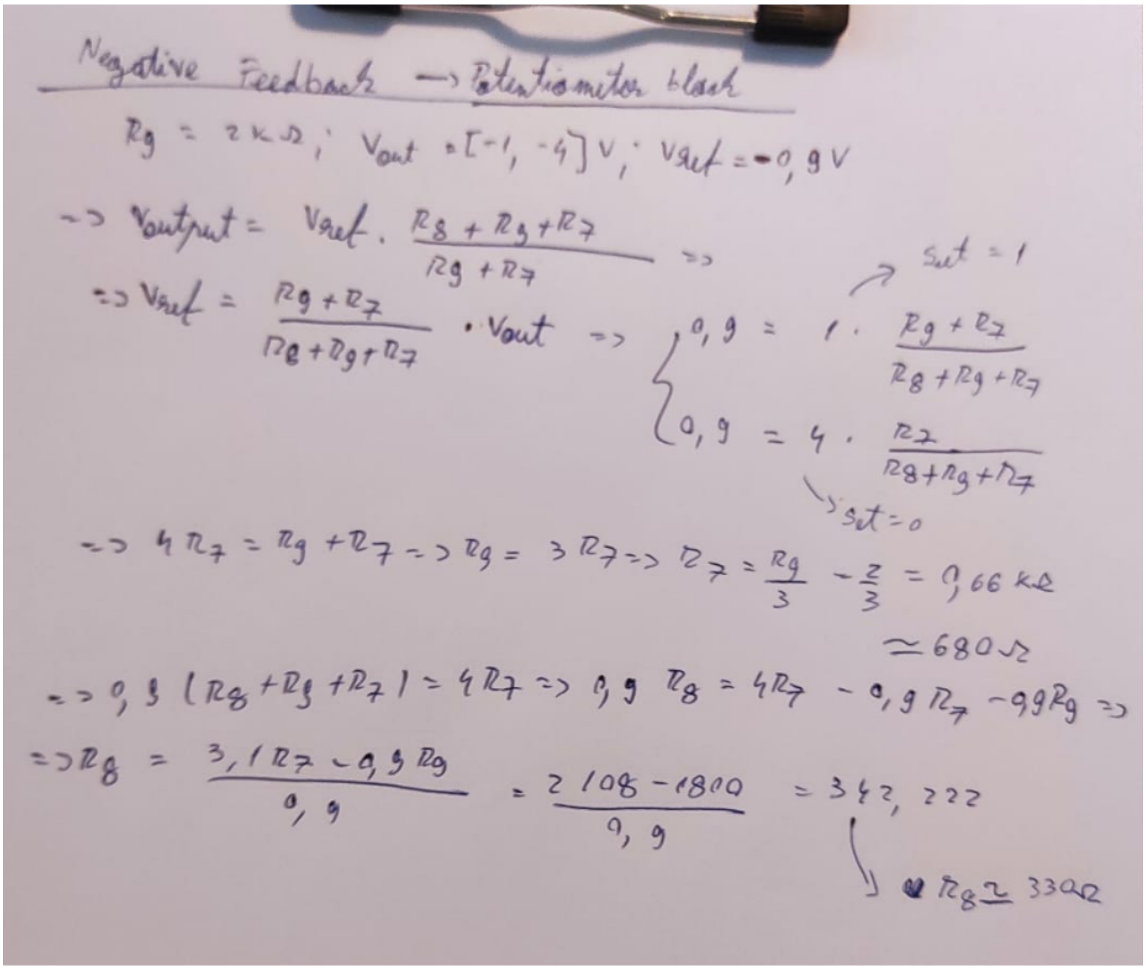
1 res. of $4,7\Omega$




Chosen components:
3 Rsc= 10 Ohms, 1 Rsc = 4.7 Ohms
Q6 = BC856B low power transistor
Q7 = MJD32CT4G high-power transistor (

# Potentiometer



Negative Feedback → Potentiometer block

$R_9 = 2k\Omega$; $V_{out} \in [-1, -4]\,V$; $V_{ref} = -0{,}9\,V$

$$\Rightarrow V_{output} = V_{ref} \cdot \frac{R_8 + R_9 + R_7}{R_9 + R_7} \Rightarrow$$

$$\Rightarrow V_{ref} = \frac{R_9 + R_7}{R_8 + R_9 + R_7} \cdot V_{out} \Rightarrow \begin{cases} 0{,}9 = 1 \cdot \dfrac{R_9 + R_7}{R_8 + R_9 + R_7} & \text{set} = 1 \\ 0{,}9 = 4 \cdot \dfrac{R_7}{R_8 + R_9 + R_7} & \text{set} = 0 \end{cases}$$

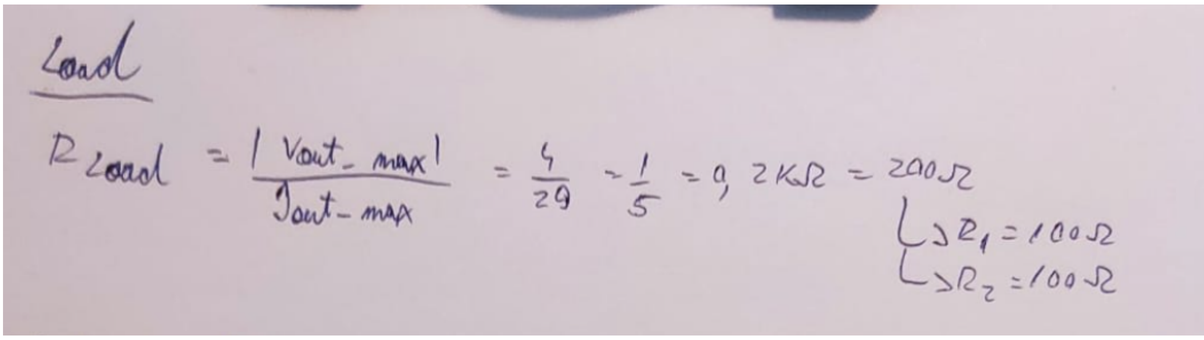
$$\Rightarrow 4R_7 = R_9 + R_7 \Rightarrow R_9 = 3R_7 \Rightarrow R_7 = \frac{R_9}{3} = \frac{2}{3} = 0{,}66\,k\Omega \simeq 680\,\Omega$$

$$\Rightarrow 0{,}9\,(R_8 + R_9 + R_7) = 4R_7 \Rightarrow 0{,}9\,R_8 = 4R_7 - 0{,}9\,R_7 - 0{,}9\,R_9 \Rightarrow$$

$$\Rightarrow R_8 = \frac{3{,}1\,R_7 - 0{,}9\,R_9}{0{,}9} = \frac{2108 - 1800}{0{,}9} = 342{,}222 \rightarrow R_8 \simeq 330\,\Omega$$

Chosen components:
R8 = 330 Ohms
R8 = 680 Ohms
R8 = 2kOhms  potentiometer

## Load

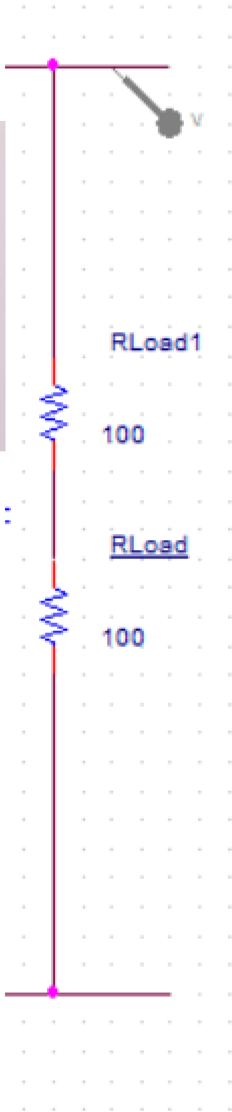


Load

$$R_{Load} = \frac{|V_{out\_max}|}{I_{out\_max}} = \frac{4}{29} \sim \frac{1}{5} = 0{,}2\,k\Omega = 200\,\Omega$$

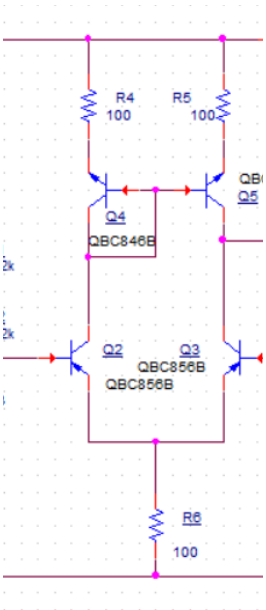
$\hookrightarrow R_1 = 100\,\Omega$

$\hookrightarrow R_2 = 100\,\Omega$



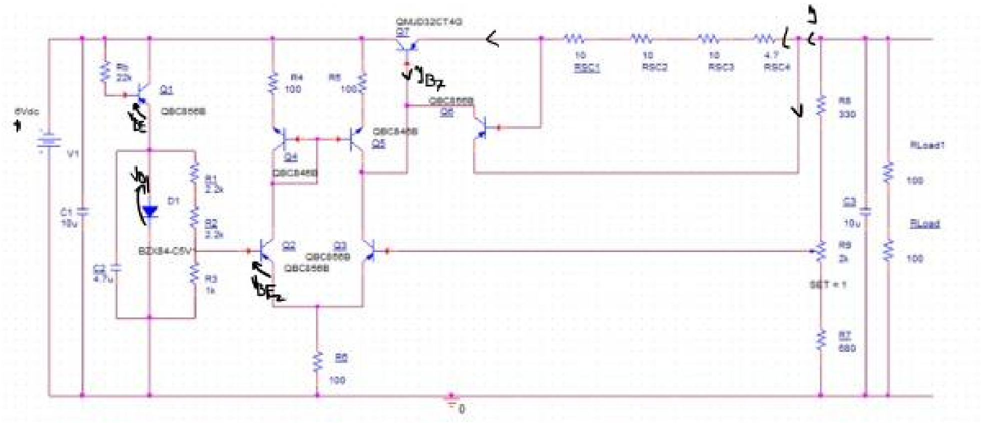

Chosen components:
2 resistors Rload = 100 Ohms

## Differential amplifier




Chosen components:
3 resistors R4, R5 and R6 = 100 Ohms
four BC856B low-power transistors

# Computations




$V_{input} = -R_B I_B + V_{BE1} + V_{D1}$ ; $V_{D1} = 5,1V$

$\Rightarrow V_{in} = -6 \Rightarrow 6 = 22 \cdot I_B + 0,6 + 5,1 \Rightarrow 6 = 22 \cdot \frac{I_{C1}}{\beta_F} + 5,7 \Rightarrow 11,7 = 22 \cdot \frac{I_{C1}}{310} \Rightarrow$

$\Rightarrow I_{C1} = \frac{310 \cdot 11,7}{22} = 164,86 \, mA > I_{Zmin} = 5mA$

Pt $V_{in} = -4 \Rightarrow 11 = 22 \cdot I_B + 5,7 \Rightarrow I_{C1} = \frac{310 \cdot 5,3}{22} = 74,68 \, mA$ } $\Rightarrow$ Diode conducts $\Rightarrow V_{D1} = 5,1V$

$V_{R3} = V_D \cdot \frac{R_3}{R_1+R_2+R_3} = -5,1 \cdot \frac{1}{5,4} = -0,94 \, V \Rightarrow$

$\Rightarrow V_{R3} = V_{BE2} + V_{R6} \Rightarrow V_{R2} = V_{BE} + R_6 I_6 \Rightarrow I_6 = \frac{V_{R2} - V_{BE}}{R_6} = \frac{-0,94+0,6}{0,1} = -3,4 \, mA$

$\Rightarrow I_{E2} = I_{E3} = \frac{I_6}{2} = -1,7 \, mA = I_{C4} = I_{C5}$

$V_{in} = V_{EC1} + V_{D1} \Rightarrow V_{EC1} = V_i - V_{D1} \Rightarrow \begin{cases} -0,9 & (pt \; -6) \\ -5,9 & (pt \; -11) \end{cases} \Rightarrow \begin{matrix} V_{CE1} = 0,9 \, V \\ V_{CE1} = 5,9 \, V \end{matrix}$

$V_{CE5} = 0,6 \, V$ (pt că $V_{E5} - V_{C5} = -0,6$)

$\Rightarrow V_{in} = R_4 I_C + V_{EC2} + R_6 I_6 + V_{CE5} \Rightarrow V_{in} = 0,1 \cdot 1,7 + V_{EC2} + 0,1 \cdot 3,4 + 0,6 \Rightarrow$

$\Rightarrow V_{EC2} = V_i - 0,6 - 0,34 - 0,17 = V_{in} - 1,11 \Rightarrow \begin{cases} V_{EC2} = -7,11 \\ V_{EC2} = -12,11 \end{cases}$

$V_{CE4} = V_{CE5}$ ; $V_{CE3} = V_{CE2}$

Potentiometer in pos 1 $\Rightarrow R_9 = 2K \Rightarrow V_{out} = -1$

$\Rightarrow I_{Load} = \frac{-V_{out}}{R_{Load}} = \frac{1}{0,2} = 5 \, mA = I_{RSC}$

$V_{RSC} = I_{RSC} \cdot R_{SC} = 5 \cdot 0,0347 = 0,1735 \, V < 0,6 \, V \Rightarrow$ blocked transistor

$\Rightarrow I_{C7} = I_{RSC} = 5 \, mA \Rightarrow V_{in} - V_{CE6} - V_{RSC} - V_{out} = 0 \Rightarrow V_{CE6} = V_{in} - V_{RSC} - V_{out} \Rightarrow$

$\Rightarrow V_{CE6} = \begin{cases} 6 - 0,1735 + 1 = 6,8265 \, V \\ 4 - 0,1735 + 1 = 11,8265 \, V \end{cases}$

Potentiometer is 0 => $R_g = 0$ ; $V_{out} = -4V$

=> $I_{Load} = \frac{4}{0,2} = 20\,mA = I_{R5C} + I_{C6}$

$I_{R5C} + I_{B6} = I_{C7}$

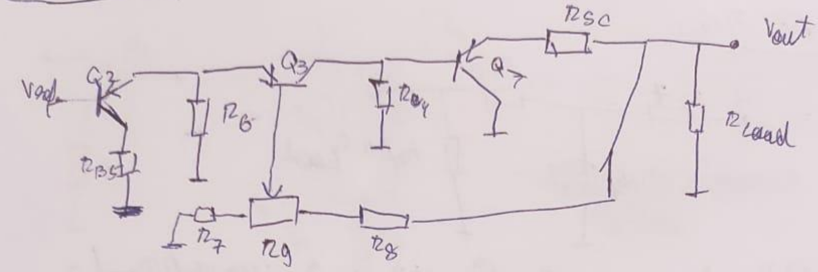
=> $V_{in} = R_5 I_{C4} + V_{CE6} - V_{out}$ =>

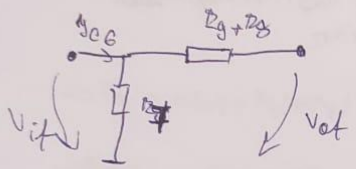
=> $V_{CE6} = V_{in} + V_{out} - R_5 I_{C4} = \begin{cases} 9,83 \to pt\ -6V \\ 14,83 \to pt\ -4V \end{cases}$

$V_{CE7} = V_C + V_{R5C} + V_a = \begin{cases} 10,1735 \to pt\ -6V \\ 15,1735 \to pt\ -1,1V \end{cases}$

$I_{C7} = 20,6\,mA$

## DC Bias




Set = 0

$$\Rightarrow \beta_v = \frac{V_{if}}{V_{of}}\Big|_{i_{if}=0} = \frac{R_7}{R_7+R_8} = \frac{0,68}{0,68+0,33} = 0,673$$

$$r_{if} = \frac{V_{if}}{i_{if}}\Big|_{V_{of}=0} = R_7 \parallel R_8 = \frac{R_7 R_8}{R_7+R_8} = \frac{0,2244}{1,01} = 0,222\ k\Omega$$

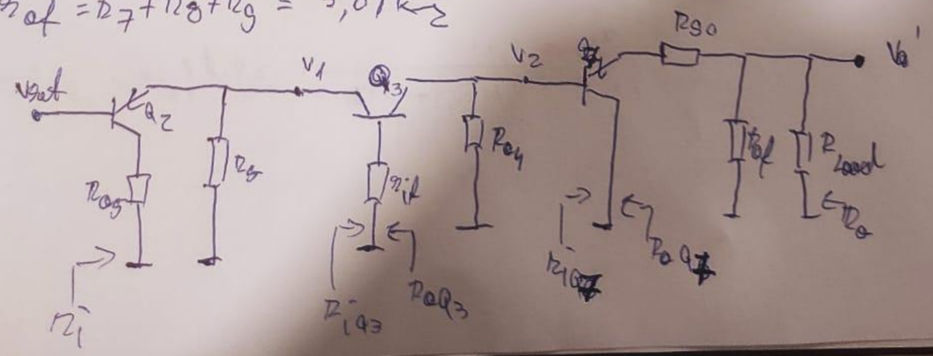
$$r_{of} = \frac{V_{of}}{i_{of}}\Big|_{i_{if}=0} = R_7+R_8 = 1,01\ k\Omega$$

Set = 1

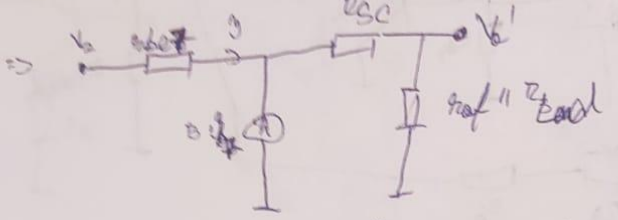
$$\beta_v = \frac{R_7}{R_7+R_8+R_9} = \frac{0,68}{0,68+2+0,33} = 0,673$$

$$r_{if} = R_7 \parallel (R_8+R_9) = \frac{R_7(R_8+R_9)}{R_7+(R_8+R_9)} = \frac{0,68\cdot 2,33}{3,01} = 1,56\ k\Omega$$

$$r_{of} = R_7+R_8+R_9 = 3,01\ k\Omega$$



## AC Bias




$\Rightarrow v_2 = i_b \cdot r_{be7} + R_{SC}\,(i_{b7} + \beta i_{b7}) + i_{b7}(1+\beta)(r_{of} \parallel R_{Load}) =$

$r_{of} \parallel R_{Load} = 0{,}11\,k\Omega$

$= i_{b7}\left[r_{be7} + (1+\beta)\left(R_{SC} + \dfrac{r_{of} \cdot R_{Load}}{r_{of} + R_{Load}}\right)\right]$

$r_{be7} = \dfrac{\beta}{g_{m7}}$

$g_{m7} = \dfrac{21{,}6}{V_{th}} = 0{,}824 \rightarrow \text{set} \rightarrow 0$ ; $g_{m1} = \dfrac{I_{o1}}{V_{th}} = 6{,}39 \rightarrow V_{in} = -6$

$g_{m2} = g_{m3} = \dfrac{I_{C5}}{V_{th}} = 0{,}068$

$g_{m7} = \dfrac{5}{V_{th}} = 0{,}2 \rightarrow \text{set } 1$

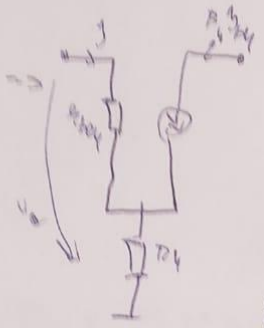
$\rightarrow r_{be7} = \dfrac{20}{0{,}824} = 24{,}27\,k$

$= \dfrac{20}{0{,}2} = 100\,k$

$\Rightarrow v_o' = \dfrac{v_2\,(r_{of} \parallel R_{Load})}{r_{of} \parallel R_{Load} + R_{SC} + r_{be7}}$ ; $a_{v1} = v_1 = \dfrac{v_o'}{v_2} = \dfrac{(r_{of} \parallel R_{Load})}{r_{of} \parallel R_{Load} + R_{SC} + r_{be7}}$

$\Rightarrow a_{v1} = \dfrac{0{,}11}{0{,}11 + 0{,}2 + 24{,}27} \rightarrow \text{Set } 0$

$a_{v1} = \dfrac{0{,}11}{0{,}11 + 0{,}2 + 100\,k} \rightarrow \text{Set } 1$




$$\Rightarrow R_e = \frac{v_e}{i_e} = \frac{r_{be4} i_{b4} + R_4 i_{b4}(1+\beta_4)}{i_{b4}}$$

$$g_{m4} = \frac{I_{c4}}{V_{th}} = 0{,}068$$

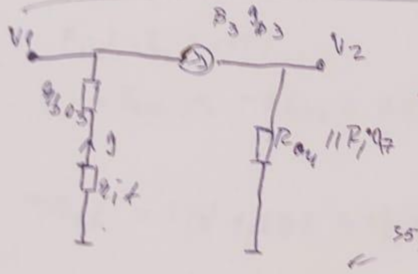
$$r_{be4} = \frac{\beta_4}{g_{m4}} = 32\ k\Omega$$

$$\Rightarrow R_e = r_{be4} + R_4(1+\beta_4) = 32 + 0{,}1 \cdot 221 = 54{,}1\ k\Omega$$

$$R_{e07} = \frac{r_{be7} + R_{e4}}{1+\beta_0} = \frac{24{,}27 + 54{,}1}{23} = 3{,}4 \to \text{set } 0$$

$$R_{iQ7} = r_{be7} + (1+\beta)(R_{80} + r_{of} \parallel R_{Load}) = 100 + 21(0{,}034 + 0{,}11)$$

$$= 103{,}024\ k\Omega\ (\text{set} \to 1)$$




$$\Rightarrow v_2 = -\beta_3 i_{b3}(R_{e4} \parallel R_i Q_7)$$

$$v_1 = -i_{b3}(r_{be3} + r_{it})$$

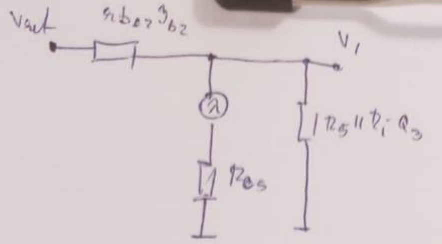
$$r_{be3} = \frac{\beta}{g_{m3}} = \frac{220}{0{,}068} = 3{,}235\ k\Omega$$

35,47

$$a_{v2} = \frac{v_2}{v_1} = \frac{\beta_3(R_{e4} \parallel R_i Q_7)}{r_{be3} + r_{it}} \Rightarrow a_{v2} = \frac{220 \cdot 35{,}47}{32{,}35 + 0{,}222}$$

$$= 239{,}57$$

$$\Rightarrow R_{iQ_3} = r_{be3} + r_{it} = 32{,}35 + 0{,}222 = 32{,}57\ k\Omega$$




$R_{Q5} = R_{Q4} = 54,1\,k\Omega$

$V_{out} = -i_{b2} r_{be2} + R_{Q5} g_{m2} i_{b2}$
$// \; 0,099$

$V_1 = R_5 \| R_i \cdot Q_3 \cdot i_{b2} (\beta_2 + 1)$

$$\Rightarrow a_{V_3} = \frac{R_5 \| R_i \cdot Q_3 (\beta_2 + 1)}{R_{Q5}\beta_2 - r_{be2}}$$

$$r_{be2} = \frac{\beta_2}{g_{m2}} = \frac{220}{9{,}068} = 32{,}35\,k\Omega$$

$$\Rightarrow a_{V_3} = \frac{0{,}099 \cdot 221}{54{,}1 \cdot 221 - 32{,}35} = 0{,}018$$

$$a_V = a_{V_1} \cdot a_{V_2} \cdot a_{V_3} = 0{,}044 \cdot 0{,}018 \cdot 239{,}57 = 1{,}89$$

$$T = a_V \cdot f_V = 0{,}68$$

$$A_V = \frac{a_V}{1+T} = \frac{1{,}89}{1{,}68} = 1{,}125$$

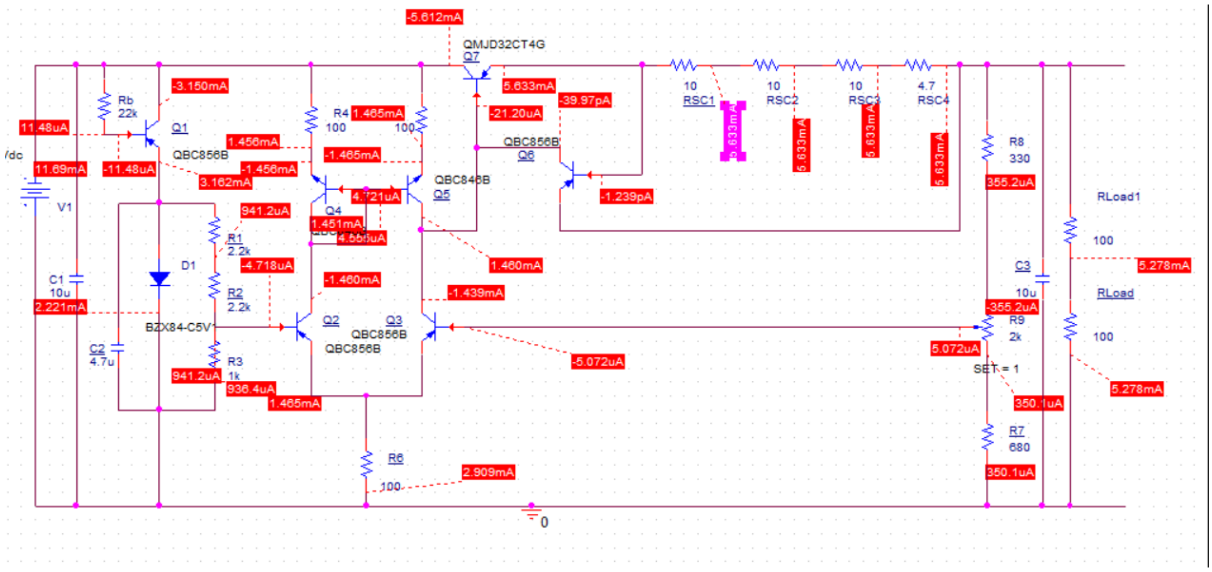
$$R_{if} = R_i (1+T)$$

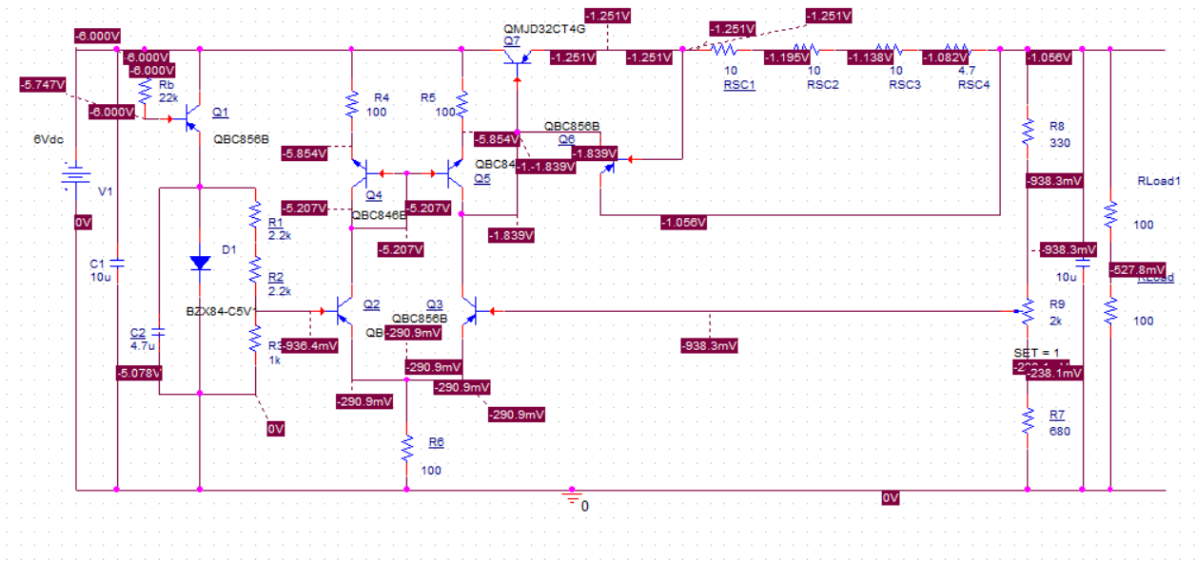
$$R_i = R_{Q5} \cdot \beta_2 - r_{be2} = 54{,}1 \cdot 220 - 32{,}35 = 11\,869{,}65$$
$$= 11{,}8\,M\Omega$$

$$\Rightarrow R_{if} = 11{,}8 (1{,}68) = 19{,}82\,M\Omega$$

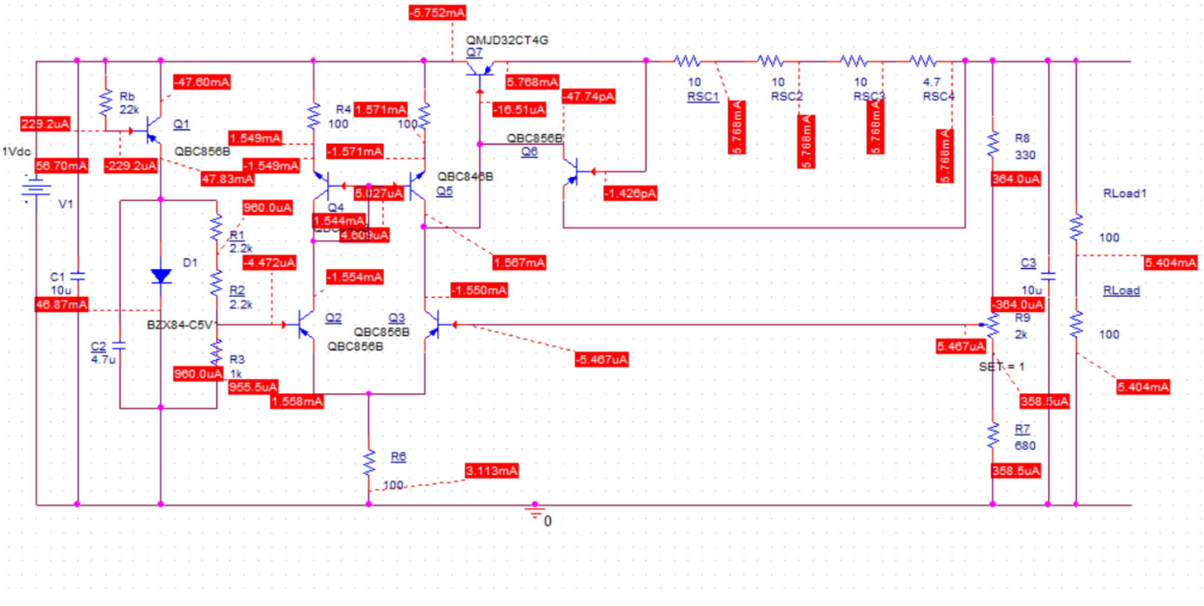
# Simulations

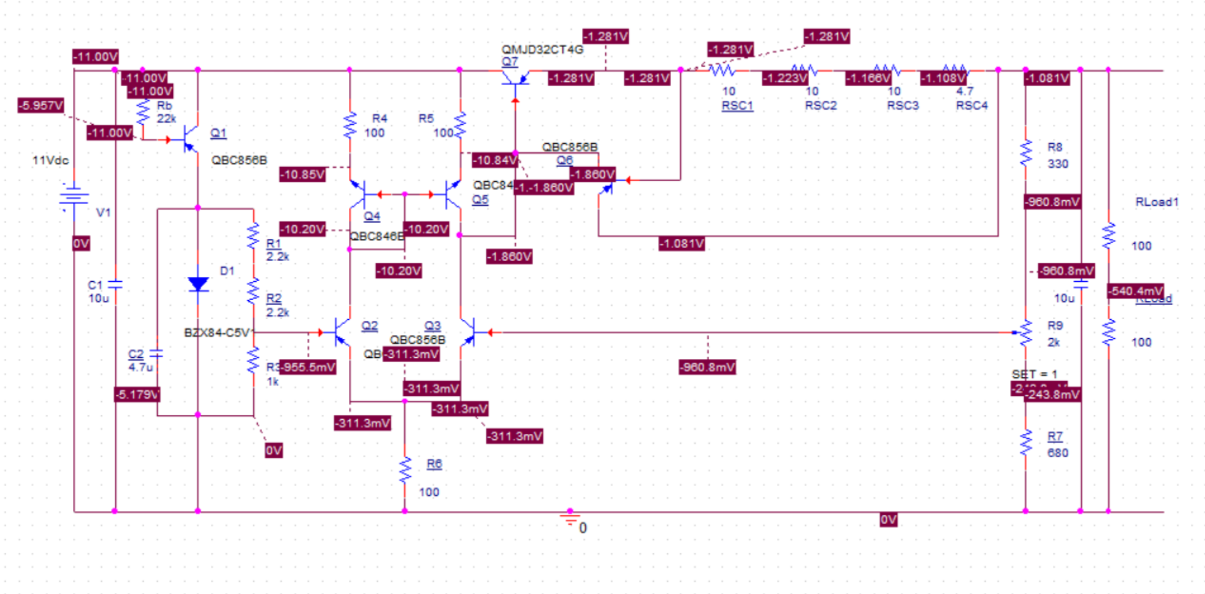
## DC Bias, Vin= -6, Set=1



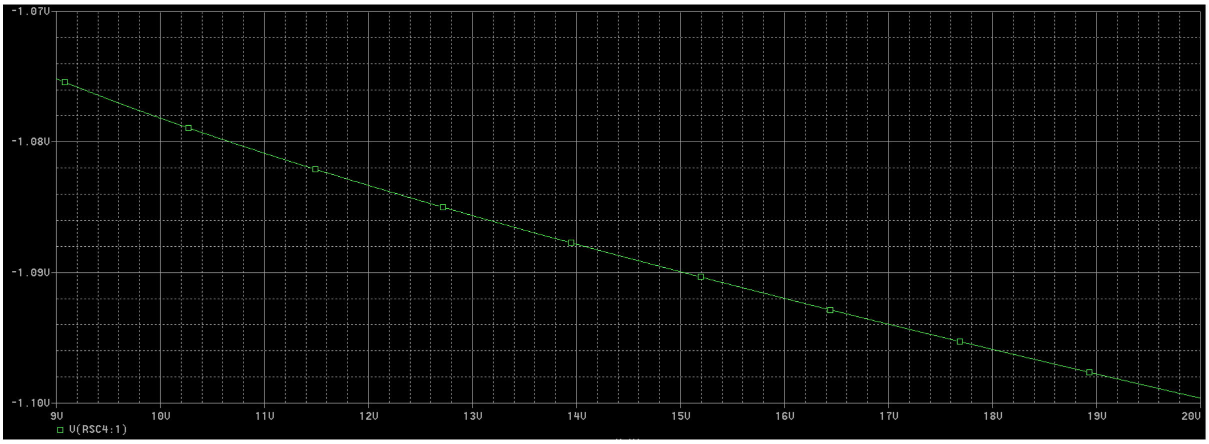



## DC Bias, Vin= -11, Set=1

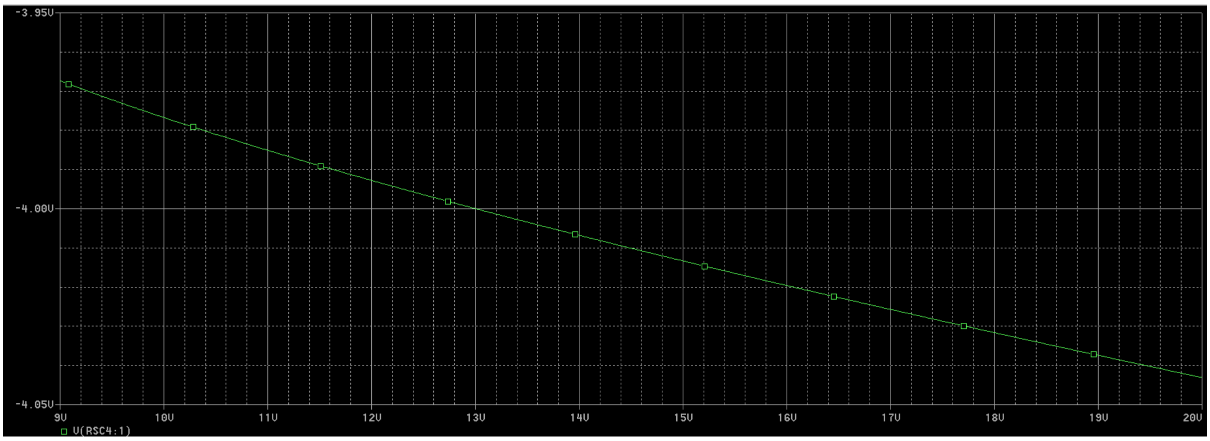


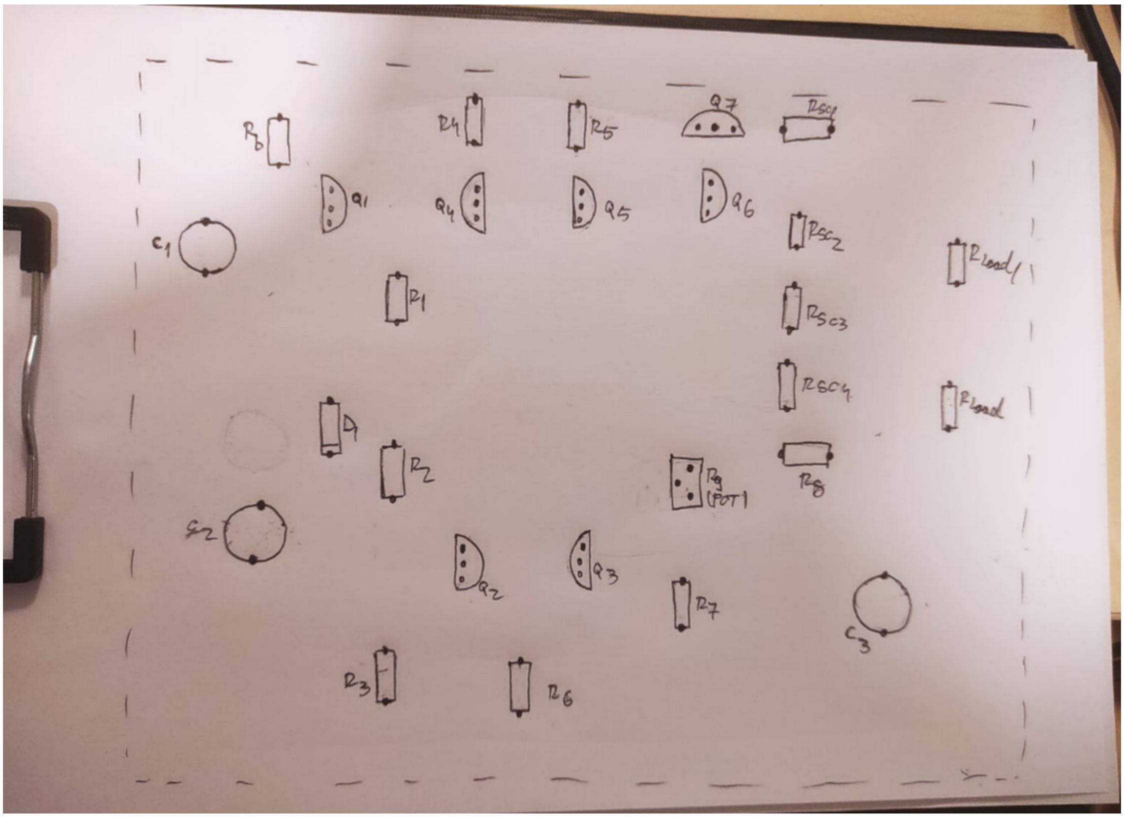
**Set=1, Vout=-1**

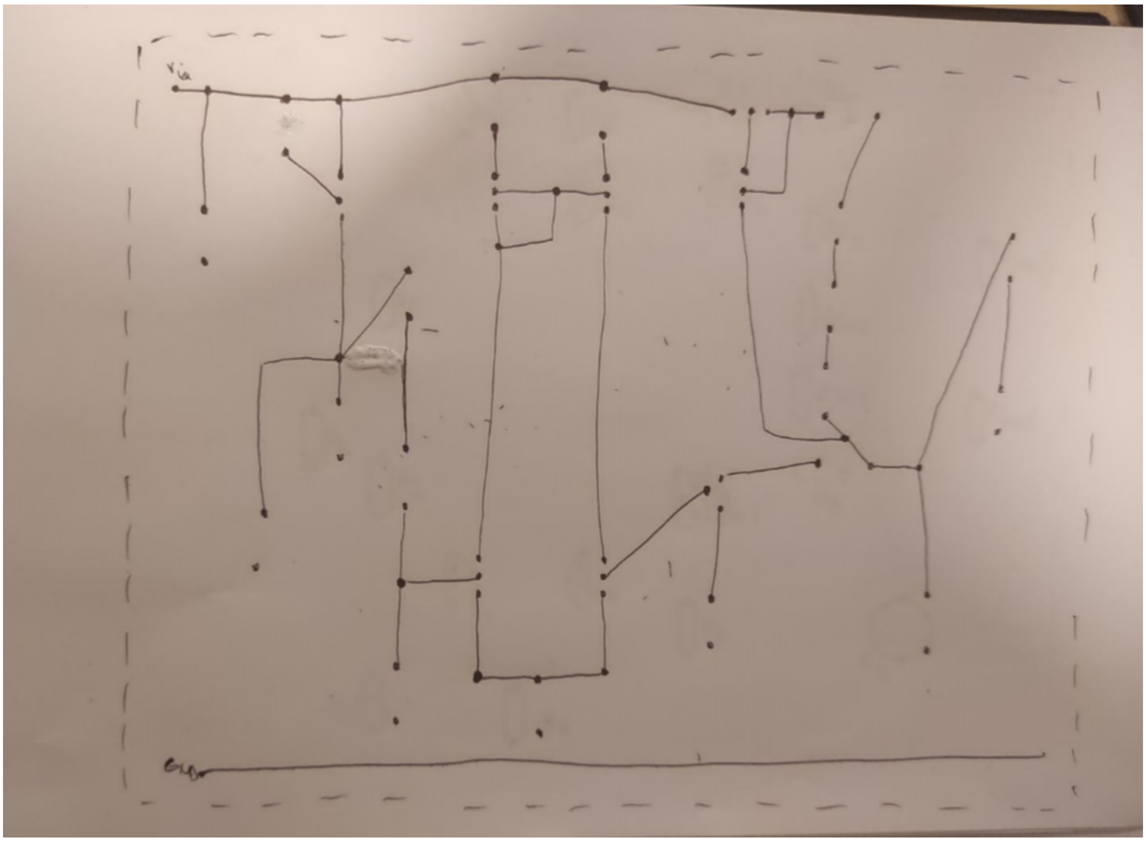



**Set=1, Vout=-4**



# THT Layout



## Conclusions

This project was quite challenging as it was quite hard to find reliable documentation on various parts of this project, so I was faced with beginning the process of trial and error which in turn, turned out to be quite helpful in my process of understanding how this type of circuit works.

Now, I am confident I can take on another project like this and I have found some very interesting resources from which I can borrow some information.

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