Computer Aided Design Project
(Voltage regulators)

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1. Requirements

Vin: 220 V

Vout ∈ [5;15] V

Io_{lim} = 4 A

2. Theoretical support

A voltage regulator is a circuit that creates and maintains a fixed output voltage, regardless of any variations in the input voltage or changes in the impedance of the electronic component that uses it. They are crucial for maintaining a stable power supply for sensitive electronic devices.

Electronic voltage regulators are present in various devices, including computer power supplies, where they ensure that the processor and other components receive stable DC voltages. They also regulate the output of power plants in automobile alternators and central power stations.

In an electric power distribution system, voltage regulators can be installed at a substation or along distribution lines to provide a consistent voltage to all customers, regardless of the amount of power drawn from the line.

2.1. The beginnings of voltage regulators

The earliest solid-state voltage regulators were created in the 1930s and 1940s utilizing germanium and silicon diodes. Although these regulators were more dependable and effective than their electromechanical predecessors, they nevertheless had performance limitations.

The invention of the transistor in the 1950s drastically altered the field of voltage regulation. Transistor-based voltage regulators swiftly replaced earlier designs in power supply construction because they were more compact, effective, and reliable.

Voltage regulator integrated circuits (ICs), which merged the voltage regulation circuitry into a single package, were developed in the 1970s and 1980s because of the development of integrated circuits (ICs). This resulted in the widespread usage of voltage regulators in several electronic applications by making voltage regulation considerably easier and more accessible.

2.2. Types of voltage regulators

There are two main types of voltage regulators: linear and switching. Both types regulate a system's voltage, but linear regulators operate with low efficiency and switching regulators operate with high efficiency. In high efficiency switching regulators, most of the input power is transferred to the output without dissipation.

A linear voltage regulator regulates the output voltage by adjusting the resistance of an active pass device, such as a BJT or MOSFET, using a high-gain operational amplifier.

Linear regulators, such as the MP2018, only require an input and output capacitor to operate.

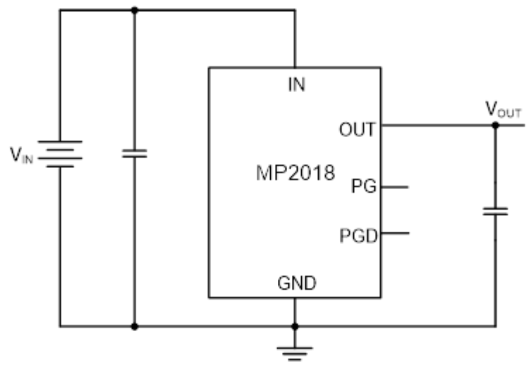


Figure 1 - MP2018 linear regulator.

These regulators are easy to design, reliable, and cost-efficient, with low noise and output voltage ripple. They are step-down converters, meaning the output voltage is always below the input voltage.

Switching regulator circuits are generally more complex to design than linear regulators, requiring external component selection, control loop tuning, and careful layout design. They offer high efficiency, better thermal performance, and support higher current and wider Vin / Vout applications. Switching regulators can achieve greater than 95% efficiency, depending on the requirements of the application.

Unlike linear regulators, they may require additional external components, such as inductors, capacitors, FETs, or feedback resistors.

The HF920 is an example of a highly reliable switching regulator that provides efficient power regulation.

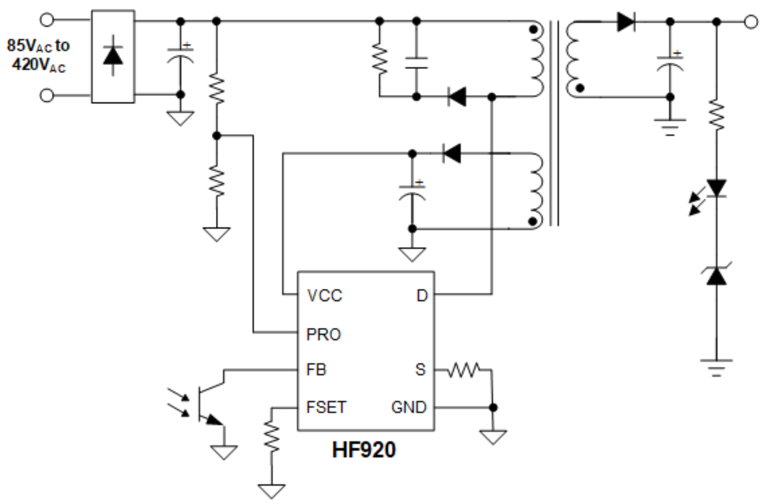


Figure 2 - HF920 switching regulator.

3. Block diagram

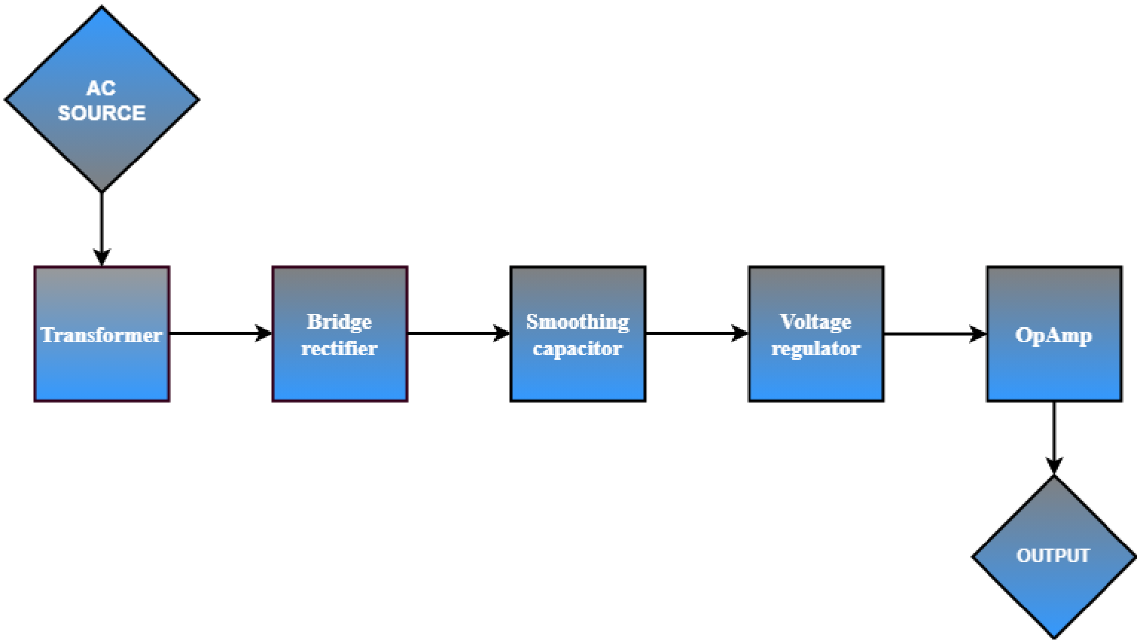


Figure 3. Block diagram

Our input comes from an AC voltage source providing a signal of 310V amp and 50 Hertz frequency.
I used a VSinus source since I can set its amplitude and frequency.

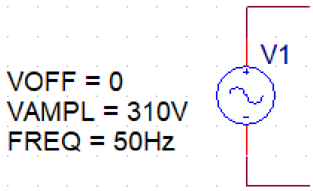


Figure 4. AC Source

Because my project has a higher input voltage, I used a transformer through which I passed the signal in order to get a reasonable voltage for my device.

A transformer is an electrical apparatus designed to convert alternating current from one voltage to another. It can be designed to "step up" or to "step down" the voltage. A transformer has no moving parts and is a completely static solid-state device, which insures, under normal operating conditions, a long and trouble-free life. In our case we want the transformer to step down our voltage to not encounter any danger during the experiment.

This is the scheme from the input till the signal goes into the transformer and gets out stepped down.

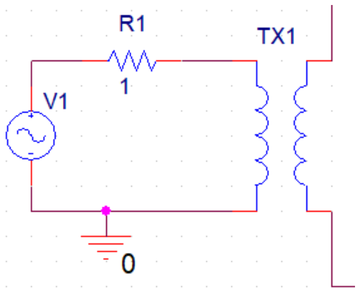


Figure 5. Transformer

I added a small resistance in order for our circuit to have a stable voltage output and to limit the current because according to Ohm’s law the circuit with no resistance would result in an extremely high current.

The AC voltage now lesser in value, goes into a bridge rectifier.

The rectifier is an electrical device used to convert alternating current (AC) into direct current (DC) by allowing a current to flow through the device in one direction only. Diodes work like one-way valves within the rectifier to maintain this flow of current. This process is generally known as “rectification.”

The AC input signal is applied to two diagonally opposite corners of the bridge, while the DC output is taken from the other two corners.
The diodes are arranged such that they conduct current in only one direction, effectively blocking the negative half-cycles of the AC input signal and passing only the positive half-cycles to the output.

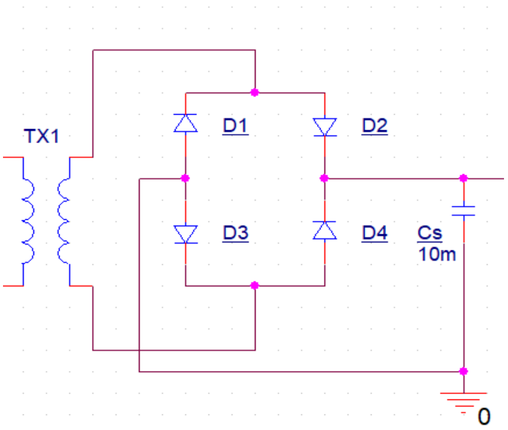


Figure 6. Bridge rectifier

The bridge converts the AC to DC effectively by reversing the polarity of the negative half-cycles and combining them with the positive half-cycles to produce a pulsating DC wave.

Once our lowered signal goes through the process of rectification the signal passes through a capacitor that we call a “smoothing capacitor”. It is called a smoothing capacitor because it acts to smooth or even the fluctuations of the obtained signal.

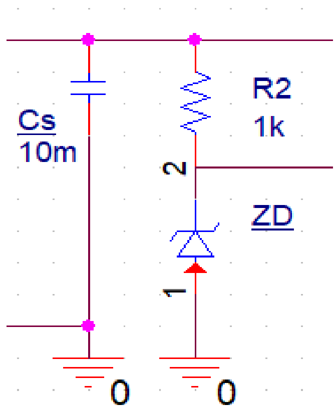


Figure 7. Smoothing capacitor

The voltage regulator part is used to limit the output voltage in our wished interval and then to transmit it next to the circuit needed.
A resistor connected in series with a Zener diode can be used to create a voltage regulator.
The fixed reverse voltage of the Zener diode is used for voltage regulators with a greater output voltage required.

The voltage obtained from the voltage regulator is passed into the potentiometer in series with a resistance connected to the ground.

The resistance is added so that the potentiometer isn't connected to the ground.
We must rotate the potentiometer in order to obtain our desired output voltage.

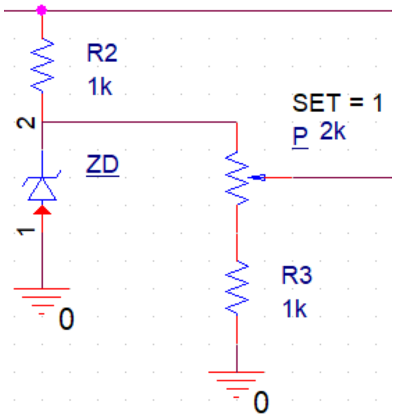


Figure 8. Voltage regulator circuit

The signal is passed into an operational amplifier. In a voltage regulator circuit, an operational amplifier (op amp) typically functions as an error amplifier. Its main property is to amplify the difference between the desired output voltage and the actual output voltage of the regulator.
This amplified error signal is then used to control the regulation process and adjust the output voltage accordingly.

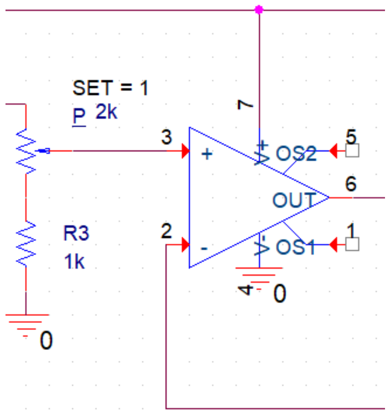


Figure 9. OpAmp

From the output of the OpAmp our signal's only way is through 2 transistors, T1 for amplification of voltage and current and Tp to protect the circuit from short circuit along with resistance Rp.

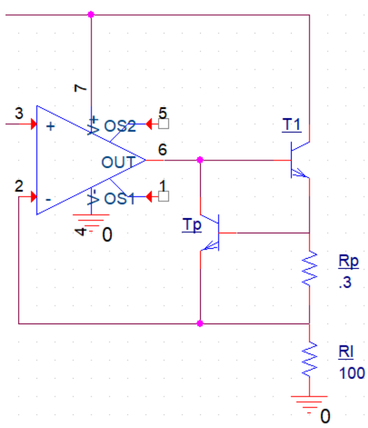


Figure 10. Circuit protection and current amplification

RLoad positioned at the end of the circuit, allows the circuit to respond to load variations, adjust the output voltage, and provide a stable power supply to the connected load. It also helps limit the current flow in case of a short circuit, protecting the circuit components and ensuring safe operation.

4. Calculus

From the input we have a sinusoidal voltage Vin=310V and a frequency f=50Hz.

The input voltage goes through the transformer so that its voltage is stepped down in such a way that it won't affect the functioning of the circuit.

I needed a small resistance so that the current wouldn't break the circuit and to avoid an infinite loop, so I chose a resistance R1=1ohm.

Vp (primary) being the input is: Vin=310v. We must step down the value to a reasonable value. Let's say we take the voltage down to 20V (Vs secondary).
The transformer equation is:

$$\frac{V_p}{V_s} = \frac{N_1}{N_2} = \sqrt{\frac{L1}{L2}} = \frac{310}{20} = 15.5 \qquad (1)$$

We assume L2 is 20mH:

$$15.5^2 = \frac{L1}{L2} => L1 = 240.25 * 20mH = 4.805\ H \qquad (2)$$

The signal is then passed through the bridge rectifier so that the AC signal is converted to a DC one.

Since our voltage is decreasing from the diodes in the bridge rectifier and the smoothing capacitor, I chose to put L1 as 4 H in order to have easier equation calculations with the chosen values.
Smoothing's capacitor equation:

$$C_s = I/(2 * f * V_{pp}) \qquad (3)$$

$$f = 50\ Hz; \quad I = 0.650\ A; \quad V_{pp} = V_H - V_L = 20.503 - 20.029 = 0.474\ V. \qquad (4)$$

$$C_s = 0.650 / (2 * 50 * 0.474) => C_s = 0.01371\ F \qquad (5)$$

Since there is no capacitor of 13.7 mF, I chose to use one of 15mF.

R2 and ZD are used to maintain a constant voltage and the voltage goes through the potentiometer and then in the opAmp and from there to the output.

My Zener diode is a standardized component which has Vz =15V and it has perfect voltage for our circuit.

A voltage divider is needed to regulate in the right interval, so we have R3, so the potentiometer isn't connected directly to the ground. If we modify potentiometer's value by rotating, we shall obtain 5-15[V].

The circuit has negative feedback:

$$V+ = V- \;;\; V- = Vo \tag{6}$$

$$V+ = Vo \tag{7}$$

$$k = 1 \Rightarrow V^{+} = \frac{kP+R}{P+R} * V_z \text{, the output must be 15V} \tag{8}$$

$$k = 0 \Rightarrow V^{+} = \frac{R}{P+R} * V_z \text{, the output must be 5V} \tag{9}$$

To get 5V the ratio must be 1/3 * 15 so we deduce that P is 2 times bigger than R.
I chose some standardized values:

$$P = 2k\Omega \;; \quad R = 1k\Omega \,. \tag{10}$$

After going through the OpAmp the current and voltage is amplified by transistor T1, Tp serves as anti-short-circuit protection along with Rp.
Since I studied the data sheet of transistor T1, the Voltage Base-Emitter is 0.6 V for our transistor to work.
Protection resistance equation:

$$R_p = \frac{VR_p}{I_{olim}} \tag{11}$$

$$VR_p = V_{BE,on} = 0.6\, V \tag{12}$$

$$R_p = \frac{0.6}{4} = 0.15\, \Omega \tag{13}$$

The circuit ends with Rload, it is not different from a normal resistor as it is used as a load to the output of the circuit, that is why it is called Load resistor.

To have a clean voltage regulation device our Rp must .15Ω and Rl 100 Ω.
But due to unexpected losses of current in real life or different components specification in order for our current to be limited at 4A Rp must be .14Ω and I found a real resistor with that value.

When the load resistor is at the smallest value that's when we get out maximum current.

When Rp is lower than that value the circuit is no longer limited to 4 A.

5. Standardization

Table 1. Standardization of components

Component	Value	Tolerance	Manufacturer Name
R1	1 Ω	± 5%	CFR0S2J010JA10
L1	4 H	---	159S HAMMOND
L2	20 mH	---	SSHB21HS-08200
D1,D2,D3,D4	875 mV	---	MUR110
Cs	15 mF	± 5%	SKU-129
R2	1 kΩ	± 5%	MOR01SJ0102A10
ZD	15 V	---	1N4744A
P	2 kΩ	---	B00YSMMBPI
R3	1 kΩ	± 5%	MOR01SJ0102A10
OpAmp	---	---	UA741CP
T1, Tp	---	---	Q2N3716
Rp	.14 Ω	± 1%	CSN05FTEVR140
Rl	100 Ω	± 5%	CFR0W4J0101A50
Rl2	1 Ω	± 5%	CFR0S2J010JA10

6. Final Scheme and Simulation Results

6.1. Electrical scheme

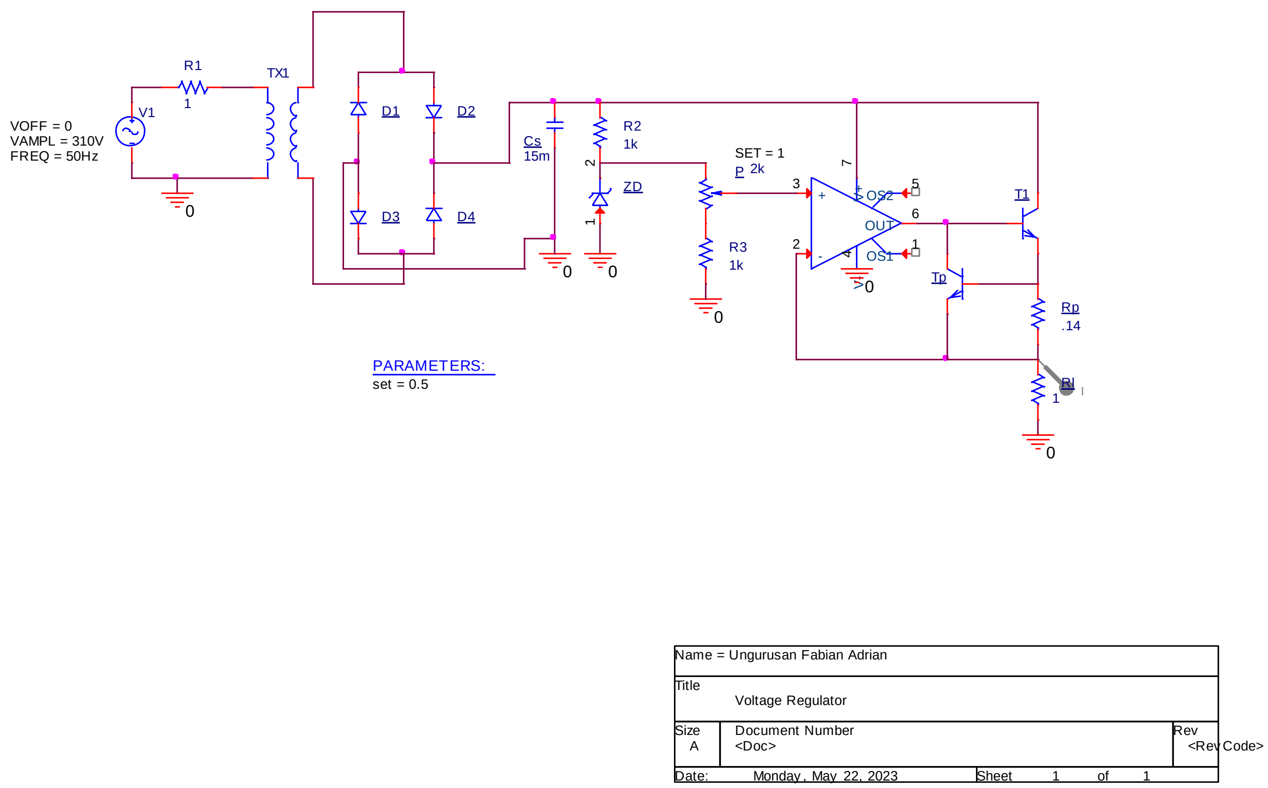


Figure 11. Voltage regulator electrical scheme

6.2. Analyses

6.2.1. Parametric sweep and performance analysis

Firstly, I want to show the transient analysis that I set for all the simulations. The 'Run to time' is given by calculating the period. We know that frequency is 50Hz and the inverse of it is our period, if we want to show 5 periods we will have:

$$T = \frac{1}{f} = \frac{1}{50} = 20ms \;\; => \;\; 5T = 100ms \quad (14)$$

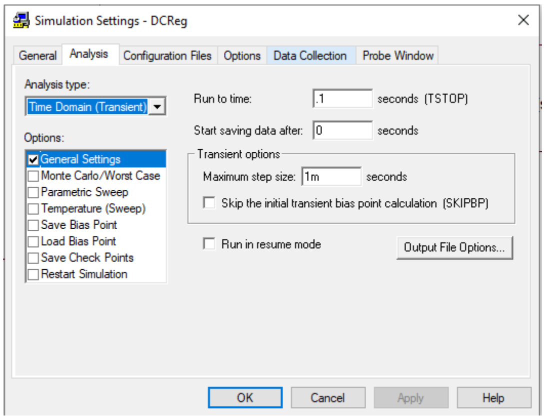


Figure 12. Transient analysis simulation profile

By sweeping the value of the global parameter {set} assigned to our potentiometer we can see how the voltage changes between the voltage levels we want to see [5; 15] V.

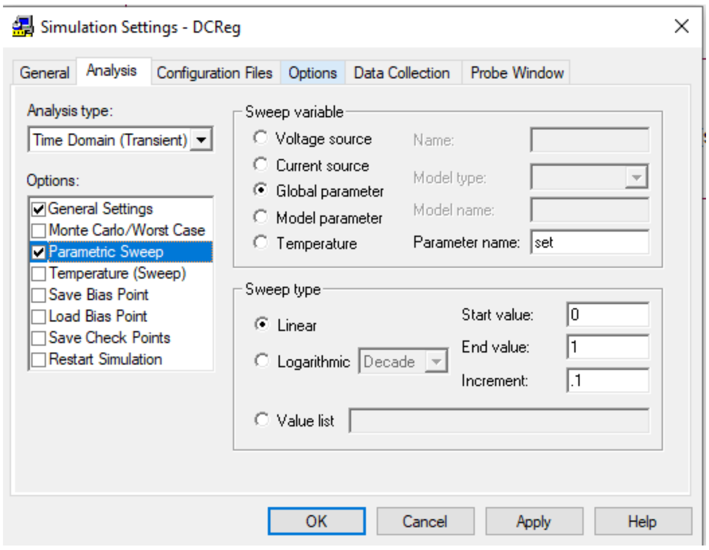


Figure 13. Parametric sweep simulation profile for voltage regulation

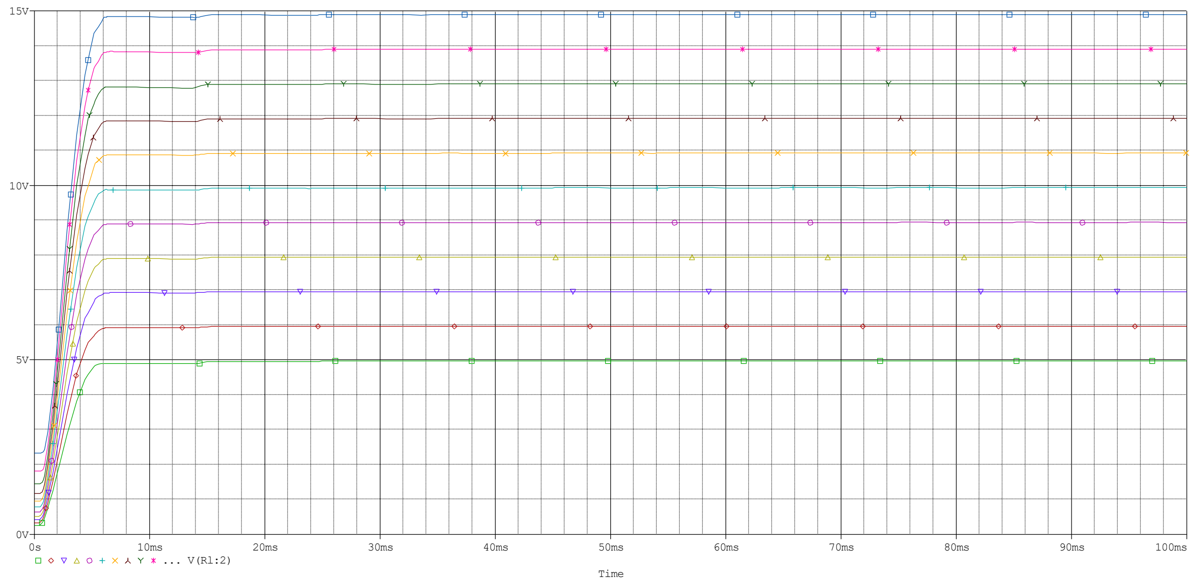


Figure 14. Parametric analysis

Table 2. Range of values

Trace Color	Trace Name	Y1
	X Values	26.222m
CURSOR 1,2	V(Rl:2)	4.9633
	V(Rl:2)	5.9557
	V(Rl:2)	6.9484
	V(Rl:2)	7.9406
	V(Rl:2)	8.9330
	V(Rl:2)	9.925
	V(Rl:2)	10.918
	V(Rl:2)	11.909
	V(Rl:2)	12.902
	V(Rl:2)	13.894
	V(Rl:2)	14.887

After the parametric analysis we must do a performance analysis to see if our circuit does what it is intended to do.

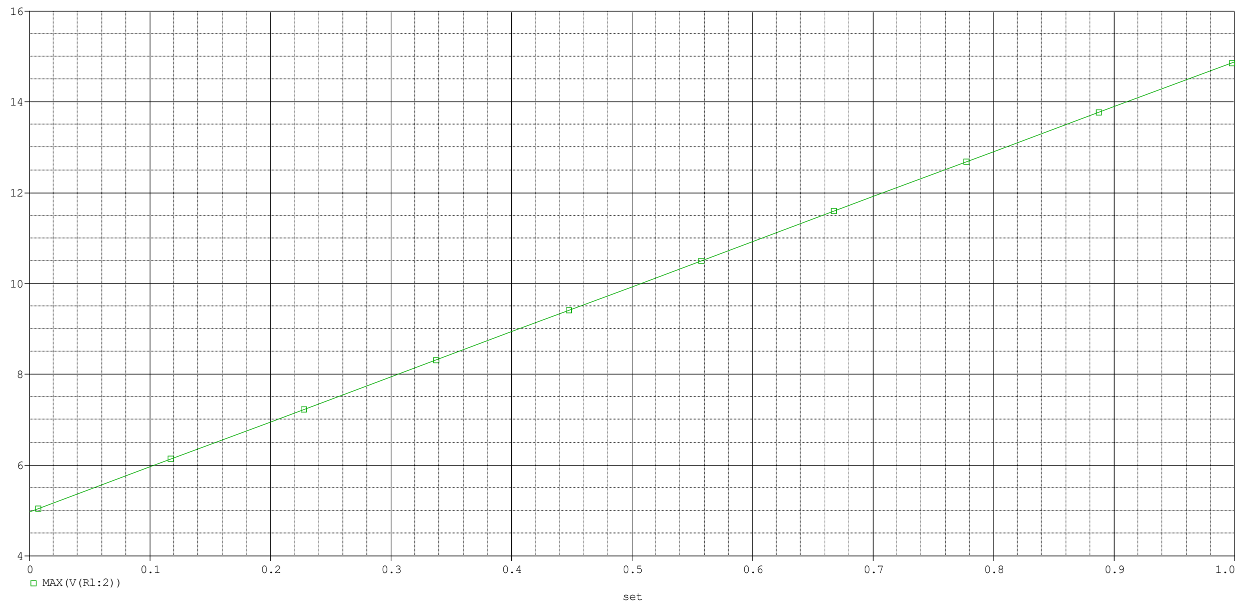


Figure 15. Performance analysis

Maximum current achievable when giving Rl the lowest value(.1Ω).

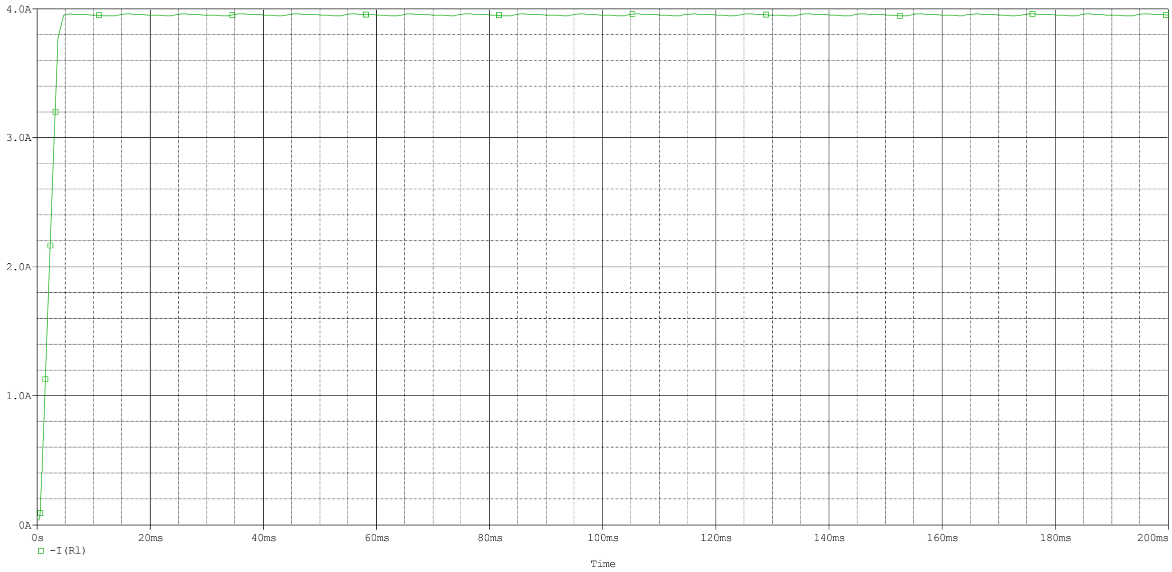


Figure 16. Maximum current in transient analysis

Table 3. Iolim value

Trace Color	Trace Name	Y1
	X Values	21.899m
CURSOR 1,2	-I(Rl)	3.9489

I can do a parametric analysis of the output resistance to see how the current behaves. The simulation profile can be seen below:

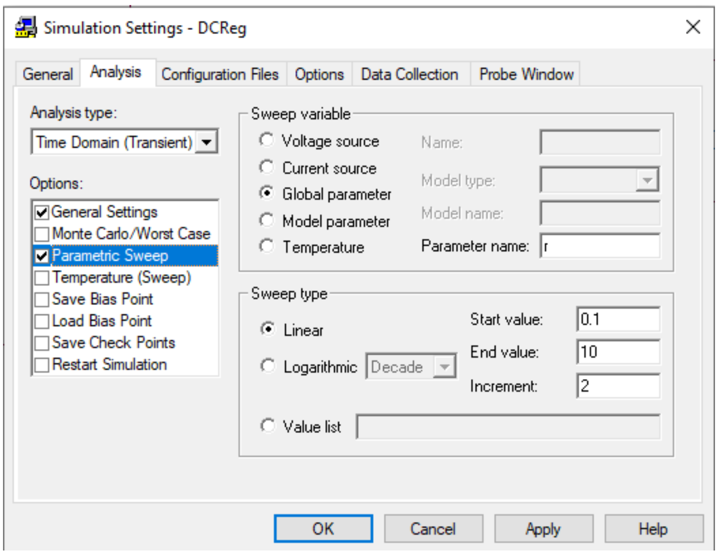


Figure 17. Parametric sweep simulation profile for current

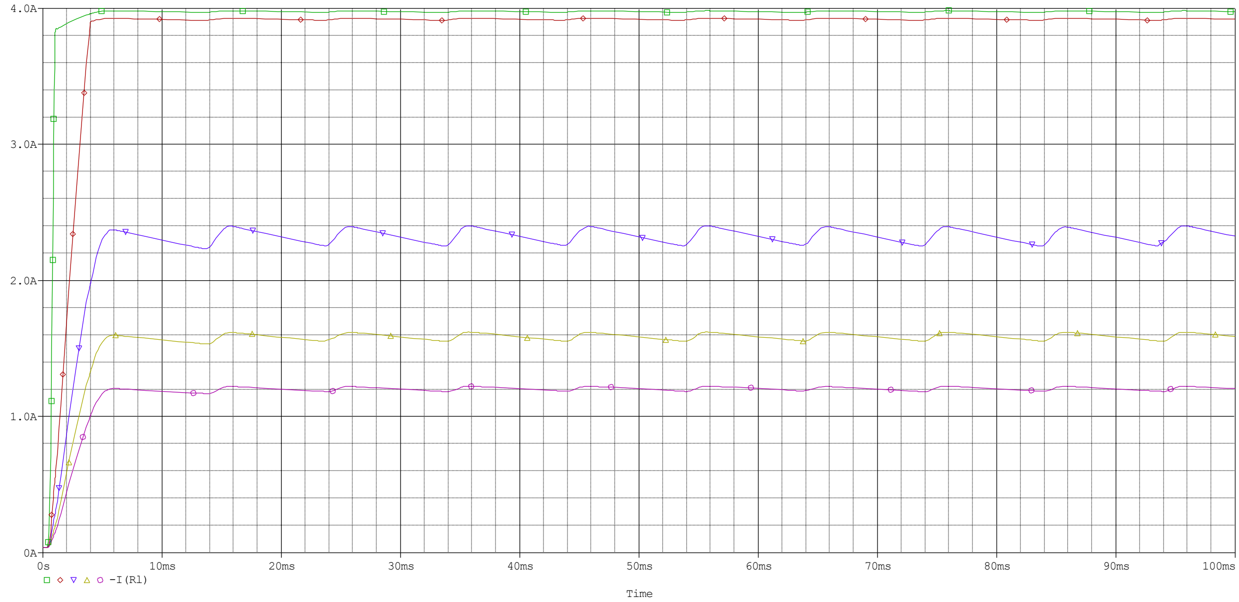


Figure 18. Parametric analysis

And I must do a performance analysis in order to check if our current does what it is expected to do.

From what we see we can understand that the current stays maximum and constant for the values of the resistance varying from 0 to approximately 2, and from 2 it starts decreasing along with the increasing of the resistance and of the voltage.

6.2.2. Monte Carlo analysis

Monte Carlo analysis is essentially a statistical analysis that calculates the response of a circuit when device model parameters are randomly varied between specified tolerance limits according to a specified statistical distribution. The circuit analysis (DC, AC or transient) is repeated several specified times with each Monte Carlo run generating a new set of randomly derived component or model parameter values.

I will do Monte Carlo analysis for the minimum and maximum value of the voltage and for the current.

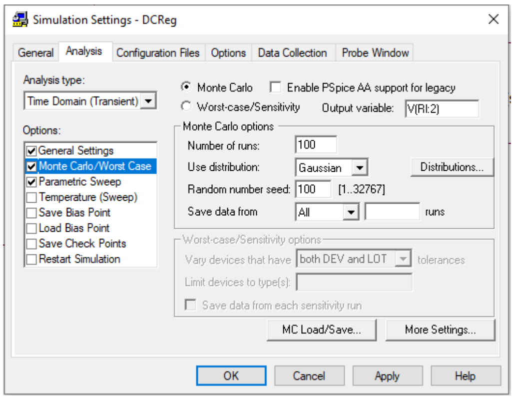


Figure 19. Monte Carlo simulation profile for voltage

The number of runs is better to be as big as possible, for the simulation to catch as many values as possible from the range of values of the components.

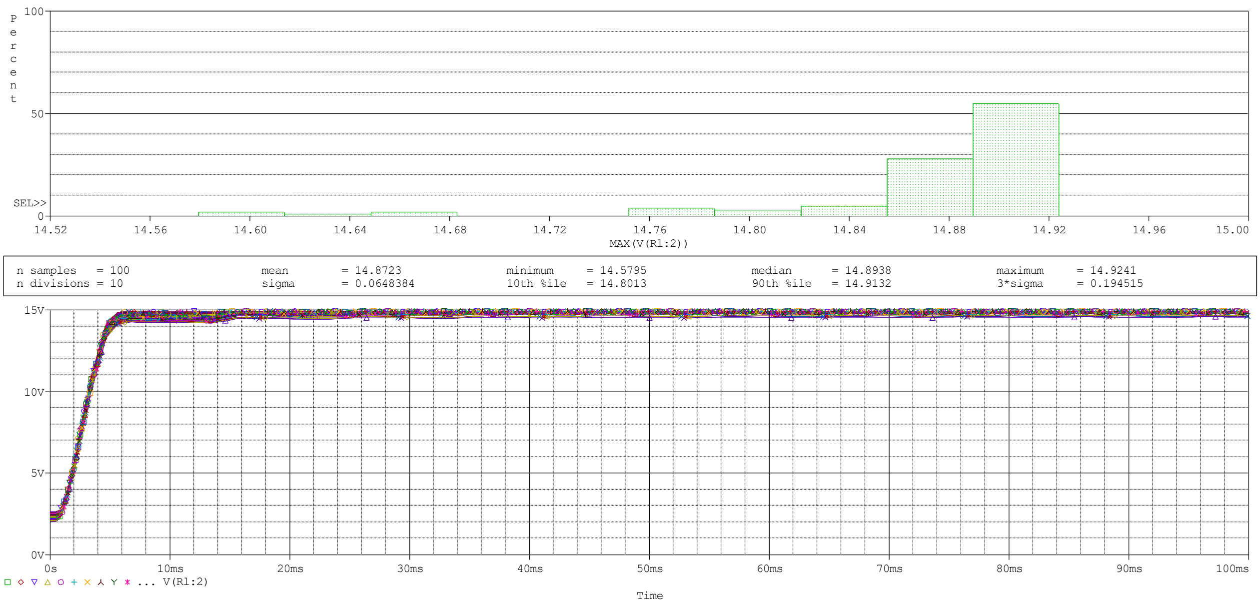


Figure 20. Monte Carlo for maximum voltage

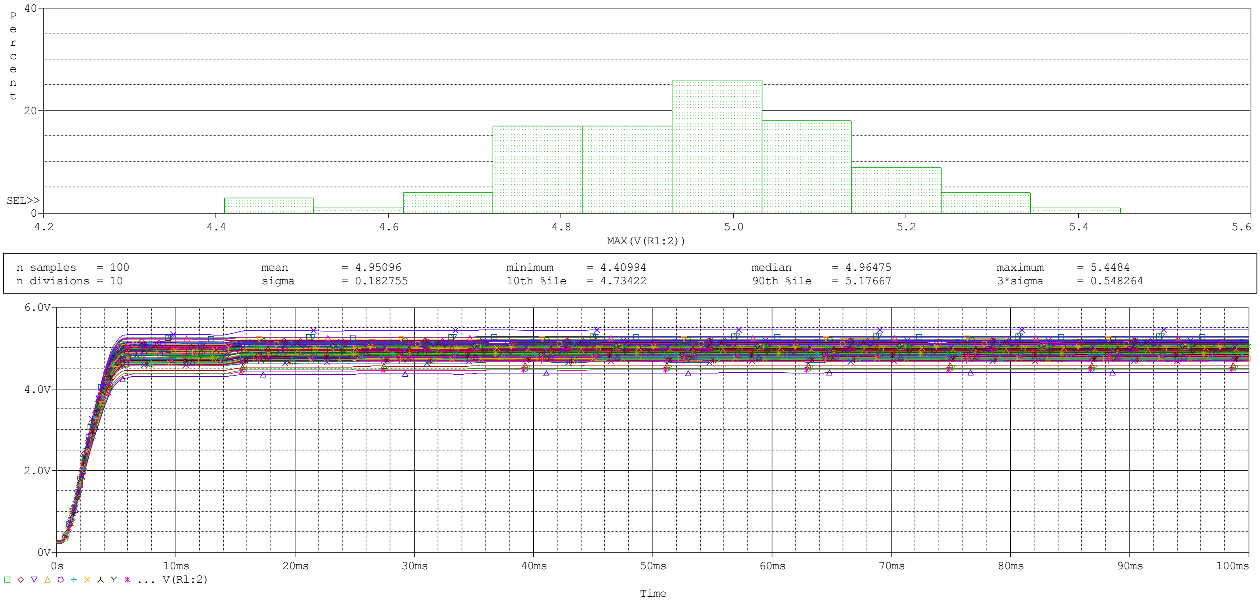


Figure 21. Monte Carlo for minimum voltage

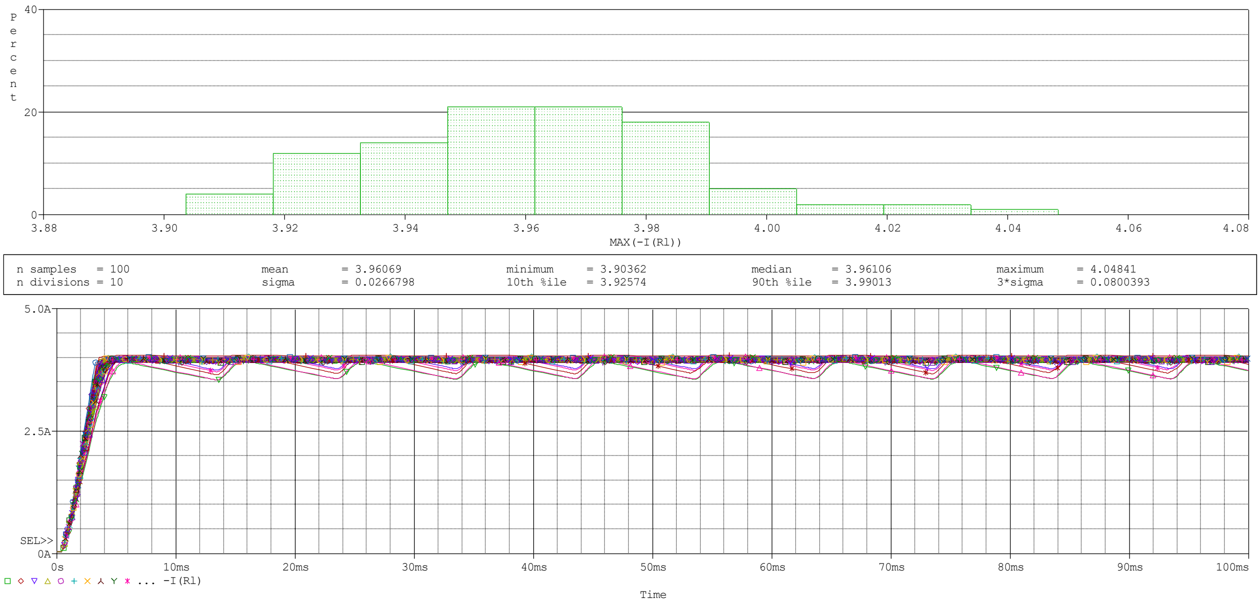


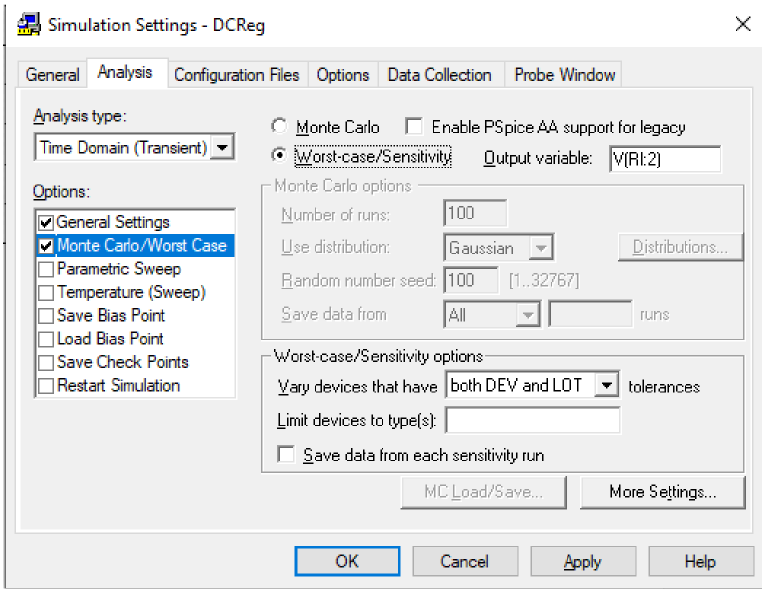
Figure 22. Monte Carlo for current

6.2.3. Worst case/Sensitivity analysis

The process of sensitivity analysis helps identify the essential parameters that significantly impact the operation of the circuit. This analysis evaluates the degree to which each component affects the circuit's operation, both in isolation and when combined with other components. Furthermore, it modifies all values to simulate the worst-case scenario.

Like the Monte-Carlo method, the Worst-Case approach involves multiple iterations of the primary analysis with a single parameter being varied in each run. This enables PSPICE to calculate the sensitivity of the output signal to each parameter. Once the sensitivities are determined, the simulation is rerun, this time varying all parameters to identify the worst-case scenario.

Worst case analysis results can be seen below, but first we have the worst case/sensivity profile simulation settings.



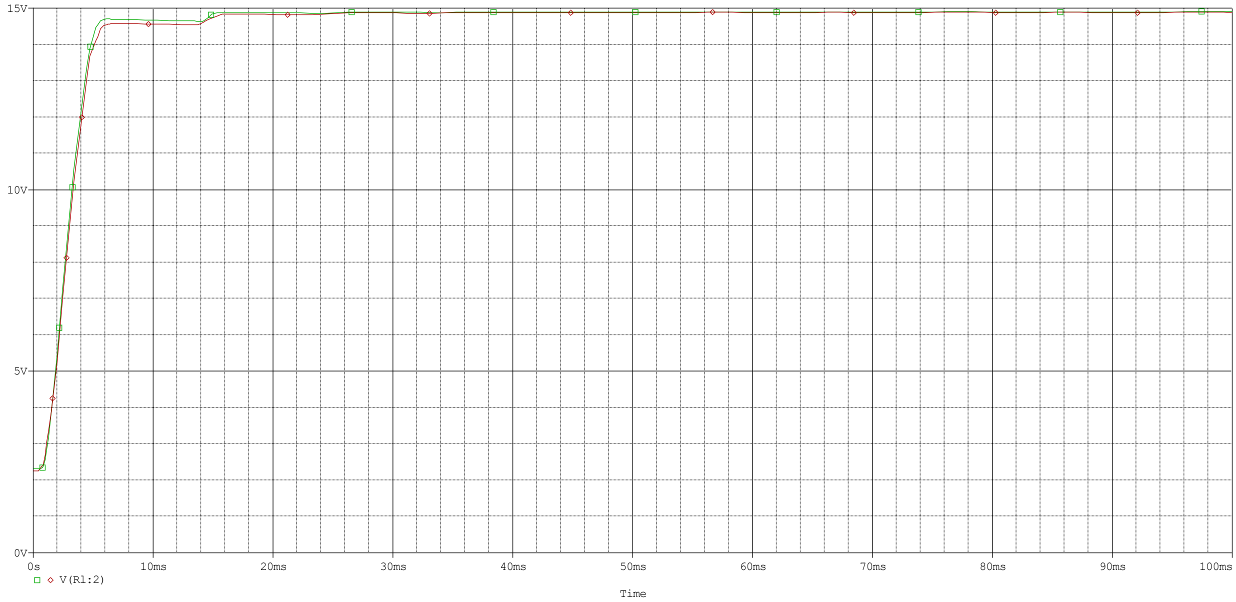


Figure 23. Worst case analysis for maximum voltage

```
                      WORST CASE ALL DEVICES

******************************************************************************


Device        MODEL         PARAMETER    NEW VALUE
C_Cs          C_Cs          C               1.05          (Increased)
R_R1          R_R1          R               1.05          (Increased)
R_R2          R_R2          R               1.05          (Increased)
R_R3          R_R3          R               1.05          (Increased)
R_Rp          R_Rp          R               1.01          (Increased)
R_Rl          R_Rl          R               1.05          (Increased)

**** 05/22/23 00:01:27 ****** PSpice 17.2.0 (March 2016) ****** ID# 0 ********

 ** Profile: "SCHEMATIC1-DCReg"  [ c:\cadence\labhw\projectfinal\voltagereg-pspicefiles\schematic1\dcreg.sim ]

 ****     SORTED DEVIATIONS OF V(N02522)   TEMPERATURE =   27.000 DEG C

                      WORST CASE SUMMARY

******************************************************************************



Mean Deviation =     -.3588
Sigma          =     0

 RUN                    MAX DEVIATION FROM NOMINAL

WORST CASE ALL DEVICES
                         .3588  lower  at T =    4.3621E-03
                        (  96.604% of Nominal)


           JOB CONCLUDED
 AutoConverge Simulator Options
 ITL1 = 150
 ITL2 = 20
 ITL4 = 100
 RELTOL = 0.001
 ABSTOL = 0.001
 VNTOL = 1e-006
 PIVTOL = 1e-013
```

Figure 24. Worst case output file for maximum voltage

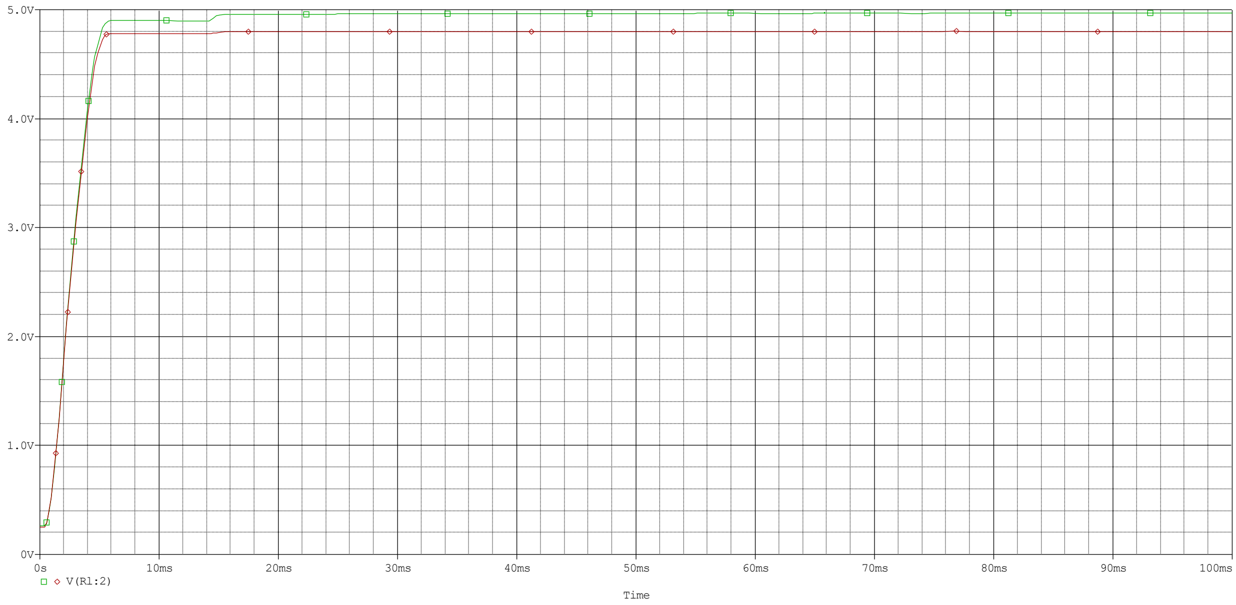


Figure 25. Worst case analysis for minimum voltage

```
                        WORST CASE ALL DEVICES

******************************************************************************


Device        MODEL         PARAMETER     NEW VALUE
C_Cs          C_Cs          C                 .95          (Decreased)
R_R1          R_R1          R                 .95          (Decreased)
R_R2          R_R2          R                 .95          (Decreased)
R_R3          R_R3          R                 .95          (Decreased)
R_Rp          R_Rp          R                 .99          (Decreased)
R_Rl          R_Rl          R                 .95          (Decreased)

**** 05/22/23 00:03:27 ****** PSpice 17.2.0 (March 2016) ****** ID# 0 ********

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 ****     SORTED DEVIATIONS OF V(N02522)   TEMPERATURE =   27.000 DEG C

                        WORST CASE SUMMARY

******************************************************************************



Mean Deviation =     -.1663
Sigma          =     0

 RUN                      MAX DEVIATION FROM NOMINAL

WORST CASE ALL DEVICES
                               .1663  lower  at T =      .0565
                              (  96.651% of Nominal)


          JOB CONCLUDED
 AutoConverge Simulator Options
 ITL1 = 150
 ITL2 = 20
 ITL4 = 10
 RELTOL = 0.001
 ABSTOL = 0.001
 VNTOL = 4.46684e-005
 PIVTOL = 1e-013
```

Figure 26. Worst case output file for minimum voltage

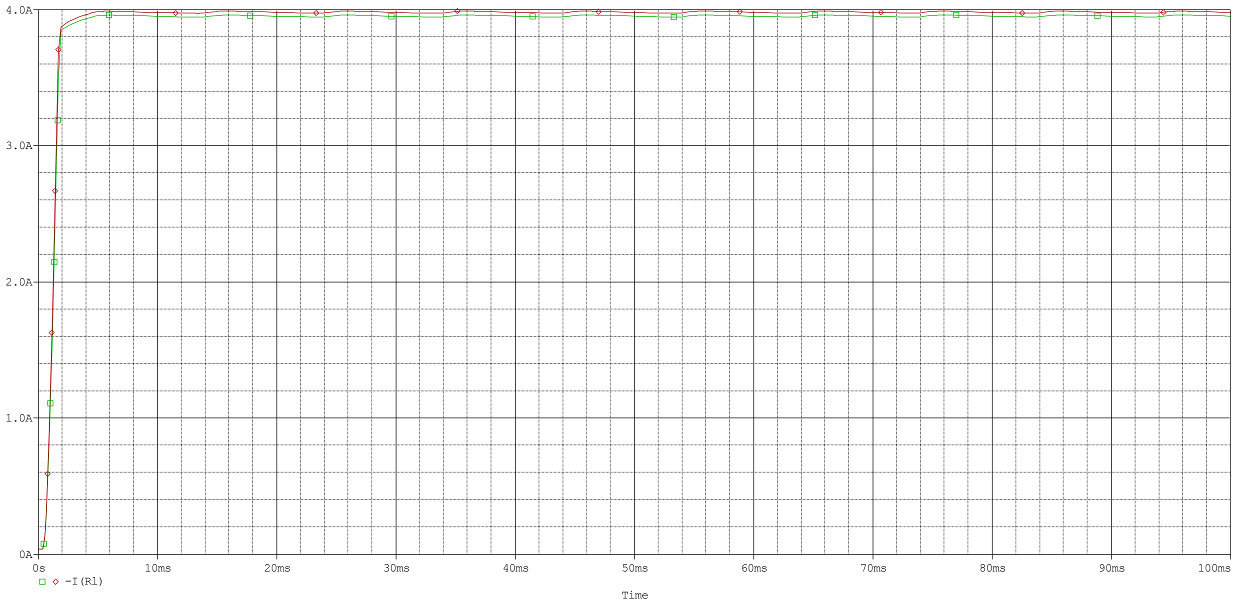

Figure 27. Worst case analysis for current

```
                      WORST CASE ALL DEVICES

******************************************************************************


Device        MODEL         PARAMETER     NEW VALUE
C_Cs          C_Cs          C                 .95          (Decreased)
R_R1          R_R1          R                 .95          (Decreased)
R_R2          R_R2          R                 .95          (Decreased)
R_R3          R_R3          R                 .95          (Decreased)
R_Rp          R_Rp          R                 .99          (Decreased)
R_Rl          R_Rl          R                 .95          (Decreased)

**** 05/22/23 00:07:37 ****** PSpice 17.2.0 (March 2016) ****** ID# 0 ********

 ** Profile:  "SCHEMATIC1-DCReg"  [ c:\cadence\labhw\projectfinal\voltagereg-pspicefiles\schematic1\dcreg.sim ]

 ****     SORTED DEVIATIONS OF V(N02522)   TEMPERATURE =   27.000 DEG C

                      WORST CASE SUMMARY

******************************************************************************



Mean Deviation =     -.1716
Sigma          =     0

 RUN                        MAX DEVIATION FROM NOMINAL

WORST CASE ALL DEVICES
                            .1716  lower  at T =      .0833
                           (  95.653% of Nominal)


          JOB CONCLUDED
```

Figure 28. Worst case output file for current

7. Bill of materials

Table 4. Bill of materials

Reference	Component	Quantity	Price [Ron]
Link	Resistor 1Ω	2	0.48
Link	L1 4H	1	251.02
Link	L2 20mH	1	11.91
Link	Resistor 1kΩ	2	0.53
Link	C 15mF	1	10.60
Link	OpAmp	1	2.89
Link	Zener Diode 15V	1	0.33
Link	Potentiometer 2kΩ	1	40.03
Link	Resistor 100Ω	1	0.025
Link	Transistor	2	54.31
Link	Resistor 140mΩ	1	0.78
Link	Bridge rectifier diodes	4	0.332
			Total: 373.237

8. References

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