Controlling the concentration of carbon monoxide

Nisioi Mihai Florin

Technical University of Cluj-Napoca

Faculty of Electronics, Telecommunications, and Information Technology

Second year, group 2022, semigroup 2

Requirements:

Input voltage: 12V DC

Indoor carbon monoxide concentration: 500…14000 ppm

The measurement range of the sensor: 250…15000 ppm

Sensor resistance: 220-22 KΩ

LED colour: purple

Table of contents

1 Schematics 3

1.1 Block diagram 3

1.2 Circuit schematic.. 3

2 Project presentation 4

2.1 Theoretical fundament 4

2.2 Description.. 4

2.2.1 Voltage divider 4

2.2.2 Buffer (voltage follower).. 6

2.2.3 Linear Voltage domain converter 7

2.2.4 Hysteresis Comparator 13

2.2.5 LED & relay.. 15

3 Demo 19

3.1 After standardization electrical scheme 20

3.1.1 Worst-case analysis.. 20

3.1.2 Monte-Carlo analysis 21

3.1.3 Performance analysis.. 22

4 Bill of materials 23

5 Conclusion 24

5.1 References 24

1 Schematics

1.1 Block diagram

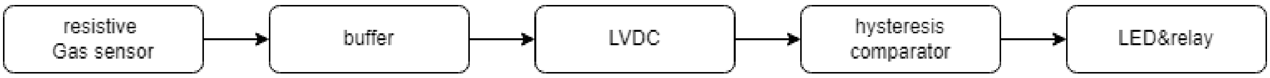


Figure 1-block diagram

1.2 Circuit schematic

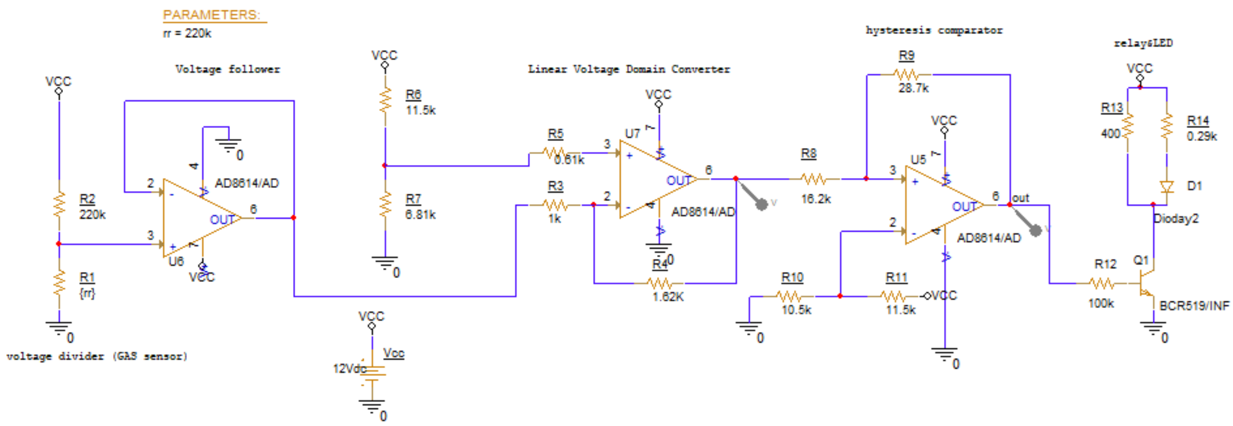


Figure 2-electrical scheme

2 Project presentation

2.1 Theoretical fundament

In Figure 1 it is shown the block diagram of a -electrical scheme which effectively converts the resistance change of a -block diagram into a voltage signal, conditions the signal to the appropriate range, compares it against predefined thresholds with hysteresis, and controls a relay to turn a fan on or off to maintain CO concentration within specified limits. The use of a buffer, linear voltage domain converter, and hysteresis ensures reliable and stable operation. Furthermore, the circuit is implemented with the suitable components in Figure 2.

Important note: The AD8614 rail-to-rail operational amplifier is used due to its compatibility with the supply voltage (5V and 18V) and its ability to provide accurate and stable performance (because of the 7.5V/µs slew rate) in this application.

Single-supply operation: 5 V to 18 V

Figure 3-proof for using AD8614 rail-to-rail OA-datasheet

2.2 Description

2.2.1 Voltage divider

The voltage divider is consisted of 2 resistors, one will be a fixed value and the other one is the resistance of the sensor, and is variable between 22KΩ and 220KΩ.

Converts the variable resistance of the gas sensor, which changes with the concentration of carbon monoxide, into a corresponding voltage. This is achieved using a resistive voltage divider network.

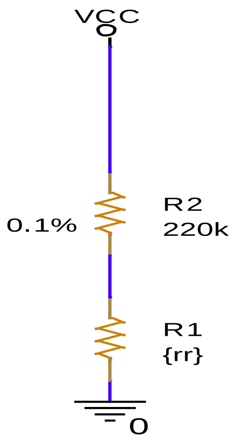


Figure 4-Voltage divider stage

$$V_{cdmin} = \frac{R1}{R1+R2} = \frac{22}{22+220} \times 12 = 1.09V \qquad equation\ 1$$

This is the minimum output voltage of the voltage divider when the sensor resistance is at its maximum (220 KΩ). It corresponds to the lowest CO concentration detectable by the sensor.

$$V_{cdmax} = \frac{R2}{R1+R2} = \frac{220}{22+220} \times 12 = 6V \qquad equation\ 2$$

This is the maximum output voltage of the voltage divider when the sensor resistance is at its minimum (22 KΩ). It corresponds to the highest CO concentration detectable by the sensor.

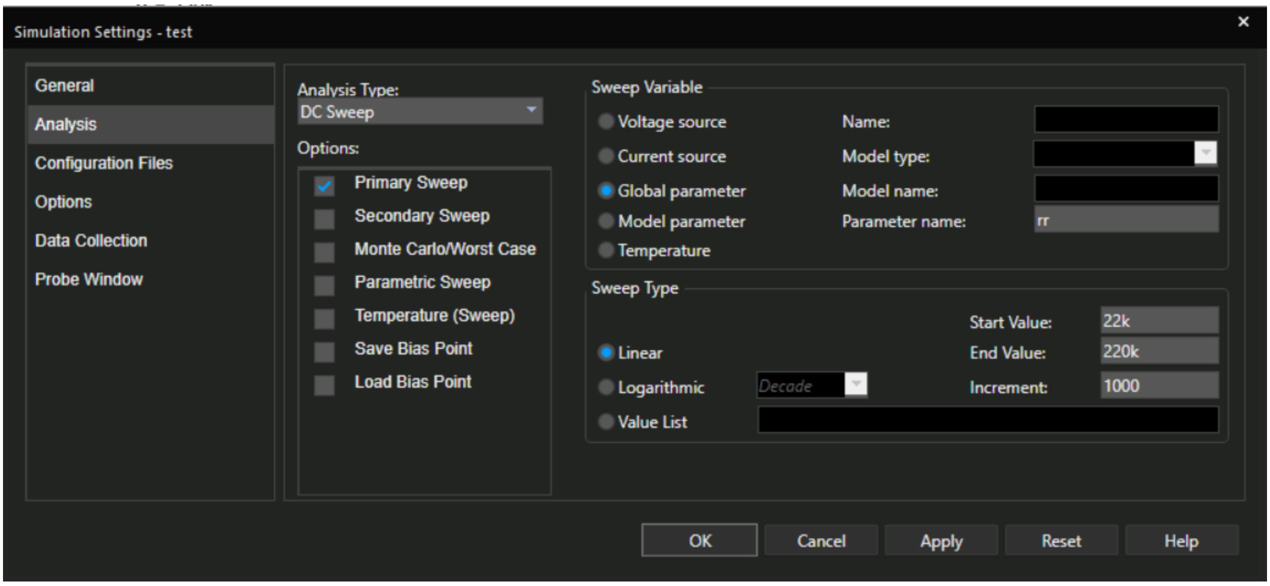


Figure 5-parametric sweep settings profile

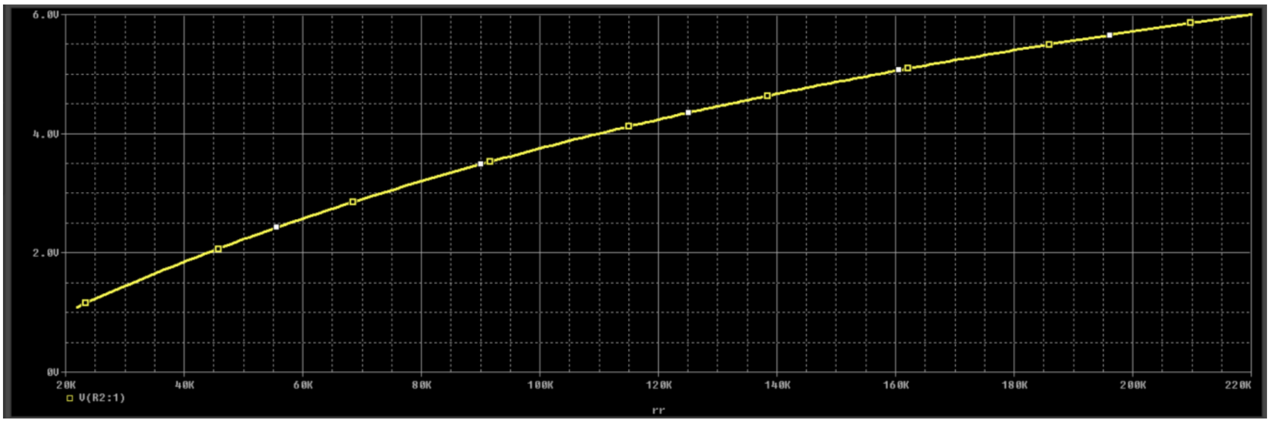


Figure 6-voltage divider result

Trace Name	Y1	Y2
X Values	22.000K	220.000K
V(R2:1)	1.0925	5.9989

Figure 7-output voltage meaurement

Evaluate	Measurement	Value
☑	Min(V(R2:1))	1.09245
☑	Max(V(R2:1))	5.99889

Figure 8-measuring the min/max values of the output voltage

2.2.2 Buffer (voltage follower)

Buffers the voltage from the voltage divider to prevent interfering from other components. The voltage follower has high input impedance and low output impedance, ensuring the signal remains stable for subsequent stages. Due to the fact that the application is done in an enclosure, we must use a buffer to avoid noises in the environment.

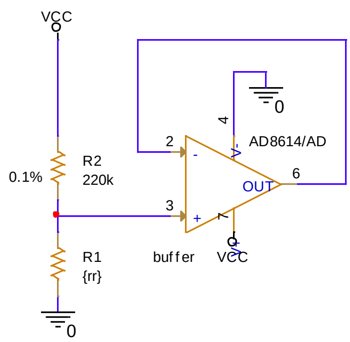


Figure 9-adding the buffer to our circuit

2.2.3 Linear Voltage domain converter

Transforms the buffered voltage signal from the gas sensor into a specific voltage range (2V to 10V) that is suitable for the comparator. This ensures that the voltage variations accurately represent the gas concentration within the desired range.

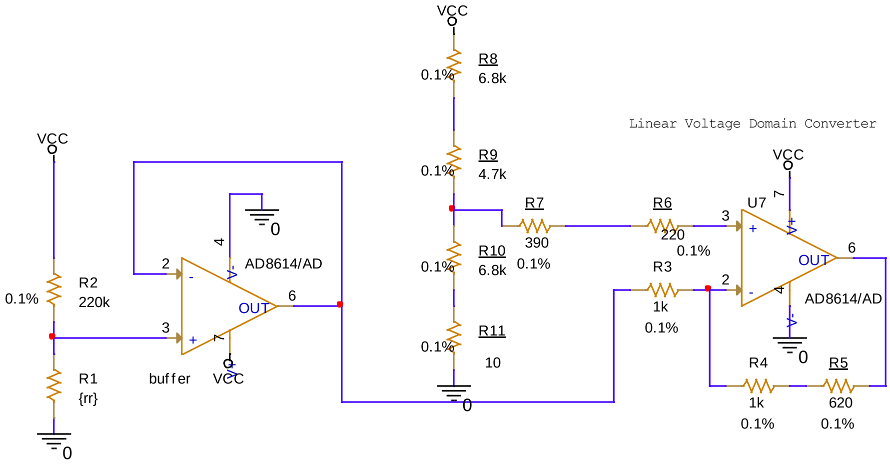


Figure 10-adding Linear Voltage Domain Converter

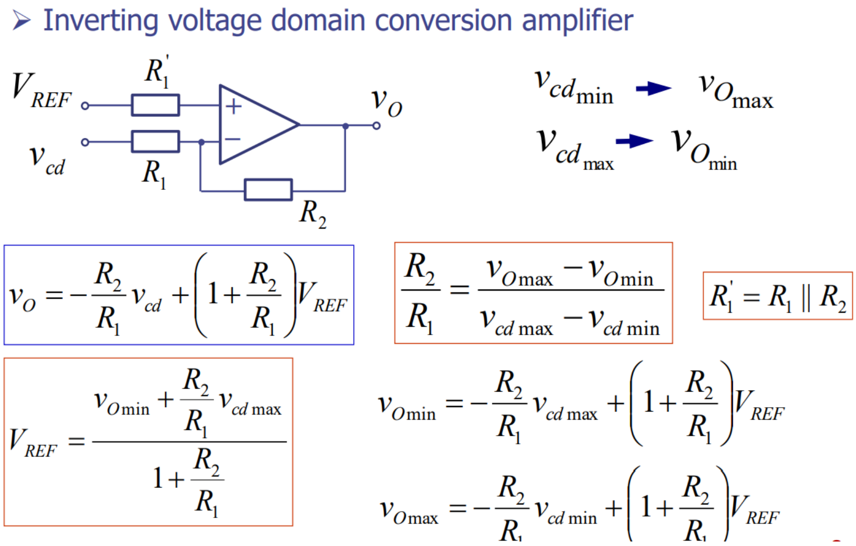


Figure 11-formulas needed for sizing components

$$v_{omin} = 2V$$

$$v_{omax=}V_{cc} - 2V = 10V \qquad equation\ 3$$

$$\frac{R4}{R3} = \frac{vomax - vomin}{vcdmax - vcdmin} = \frac{10 - 2}{6 - 1.09} = 1.62$$

$$R4 = 1.62K, R3 = 1\ K\Omega$$

$$R5 = R3||R4 = 0.61\ K\Omega$$

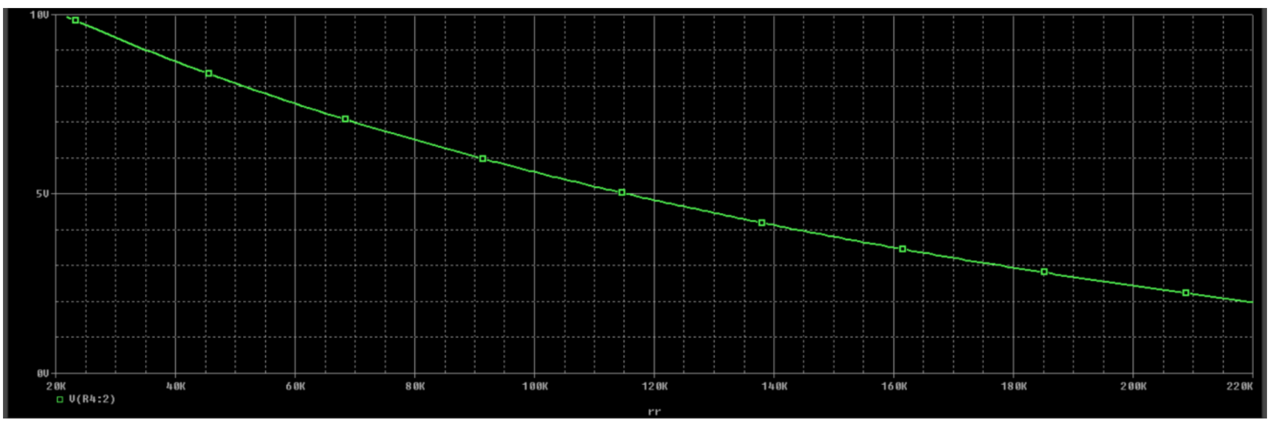


Figure 12-displaying the range of LVDC

$$Vref = \frac{vomin + \frac{R4}{R3} \times vcdmax}{1 + \frac{R4}{R3}} = \frac{2 + 1.62 \times 6}{1 + 1.62} = 4.47V \qquad equation\ 4$$

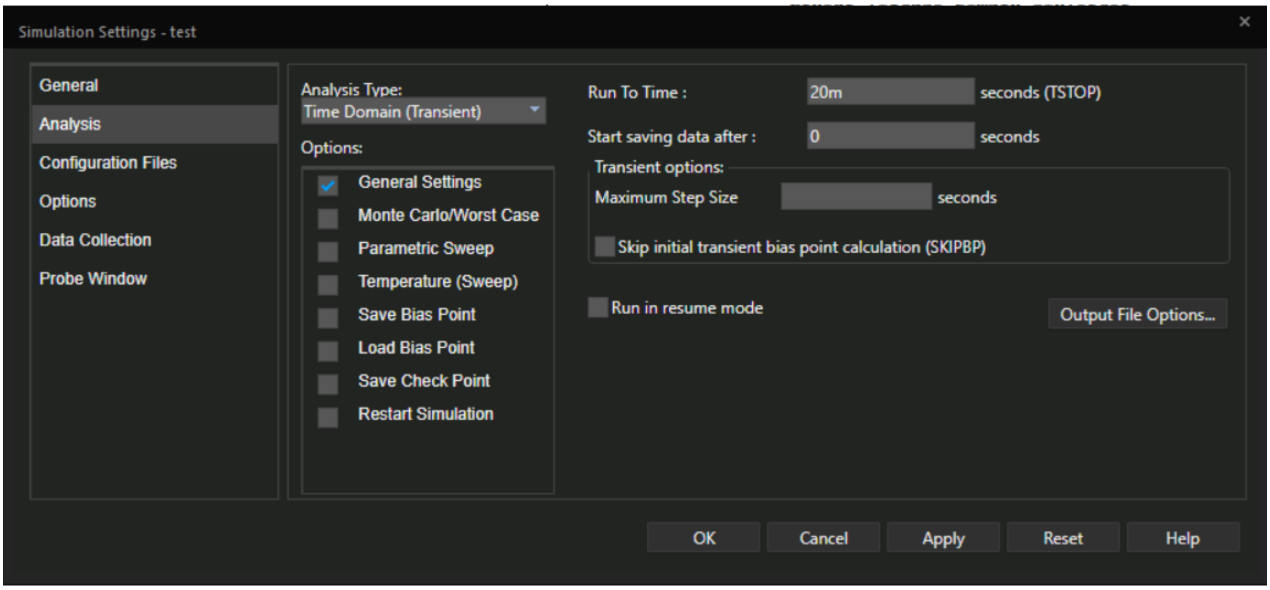


Figure 13-time domain analysis settings profile

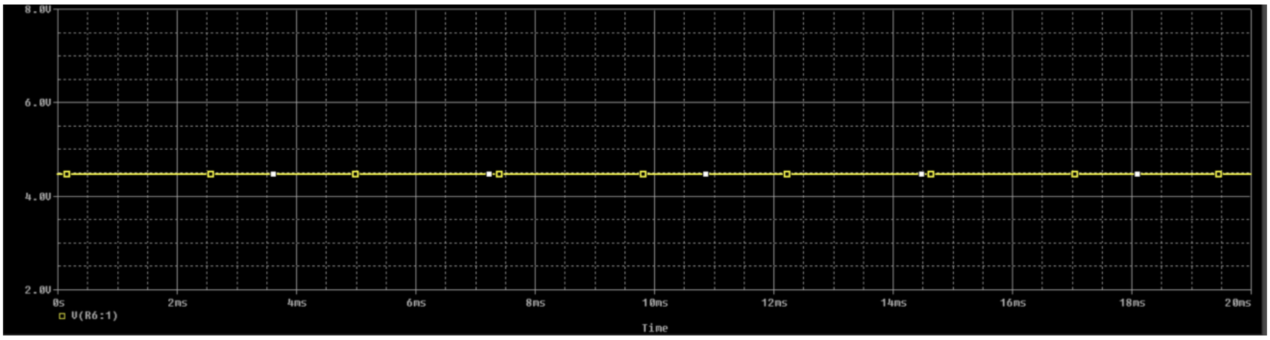


Figure 14-checking if Vref is suitable

Evaluate	Measurement	Value
☑	Max(V(R6:1))	4.46321

Figure 15-proof that Vref is suitable

Using this tool, we find the suitable resistances:

$$R6 = 11.5K, \qquad R7 = 6.81K$$

We need further the resistive thresholds such that we can use them next, in hysteresis.

Use first grade equation:

Compute the slope:

Lets say we define 2 points: $A(250; 220)$ and B(15000; 22)

$$m = \frac{y_B - y_A}{x_B - x_A} = \frac{22 - 220}{15000 - 250} = -\frac{198}{14750} \qquad equation\ 5$$

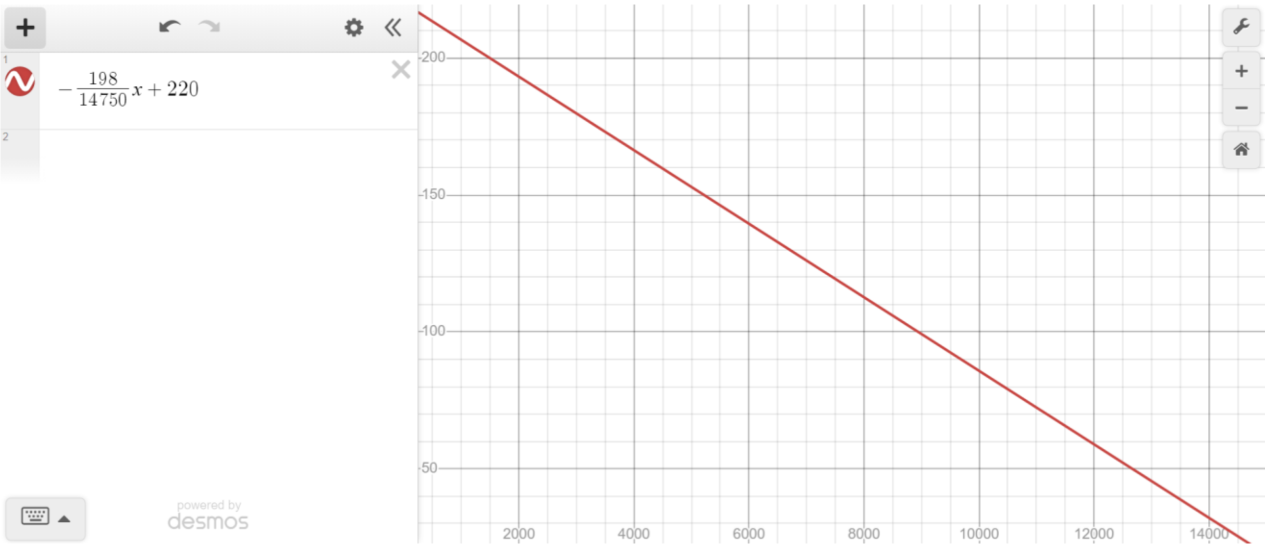
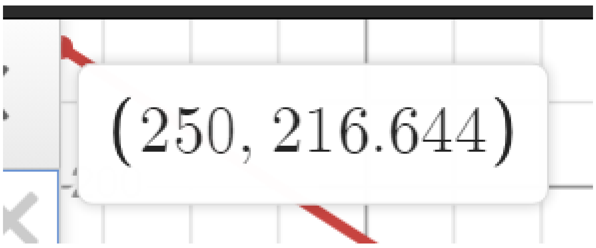
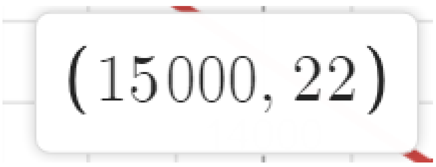


Figure 16-representation of the gas concentration in terms of sensor resistance



If we look at the extremities, we can see that we need shift right by 250 to get the desired values.

After shifting:



The points are corresponding.

Now the final formula for computing the resistive thresholds will look like this:

$$-\frac{198}{14750} \times (x - 250) + 220 \qquad equation\ 6$$

Where first coefficient is the slope and the second coefficient is the greatest value of the resistor. Replacing with our values (500 and 14000), we obtain resistive thresholds for our application:

$$-\frac{198}{14750} \times (14000 - 250) + 220 = 35.42\ K\Omega \qquad equation\ 7$$

$$-\frac{198}{14750} \times (500 - 250) + 220 = 216.64\ K\Omega \qquad equation\ 8$$

So, $R_{th} \in [35.42;\ 216.64]$

Now find Vth values based on Rth values.

$$V_{refb1} = \frac{216.42}{216.42 + 220} \times 12 = 5.88V \qquad equation\ 9$$

$$V_{ThL} = -\frac{R4}{R3} \times V_{refb1} + \left(1 + \frac{R4}{R3}\right) \times V_{ref} = -1.62 \times 5.88 + 2.62 \times 4.47 = 2.19V$$

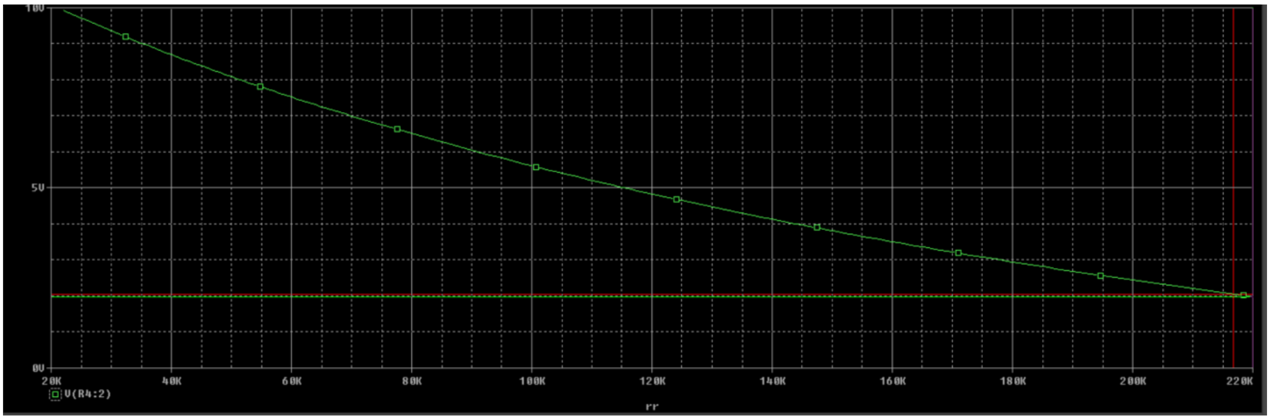


Figure 17-output voltage of VthL

Trace Color	Trace Name	Y1	Y2	Y1 - Y2
	X Values	216.761K	220.000K	-3.2394K
CURSOR 1,2	V(R4:2)	2.0484	1.9765	71.949m

Figure 18-voltage measurement

Close to 2.19V calculated previously.

$$V_{refb2} = \frac{35.42}{35.42 + 220} \times 12 = 1.66V \qquad equation\ 10$$

$$V_{ThH} = -\frac{R4}{R3} \times Vrefb2 + \left(1 + \frac{R4}{R3}\right) \times Vref = -1.62 \times 1.66 + 2.62 \times 4.47 = 9.04\text{V}$$

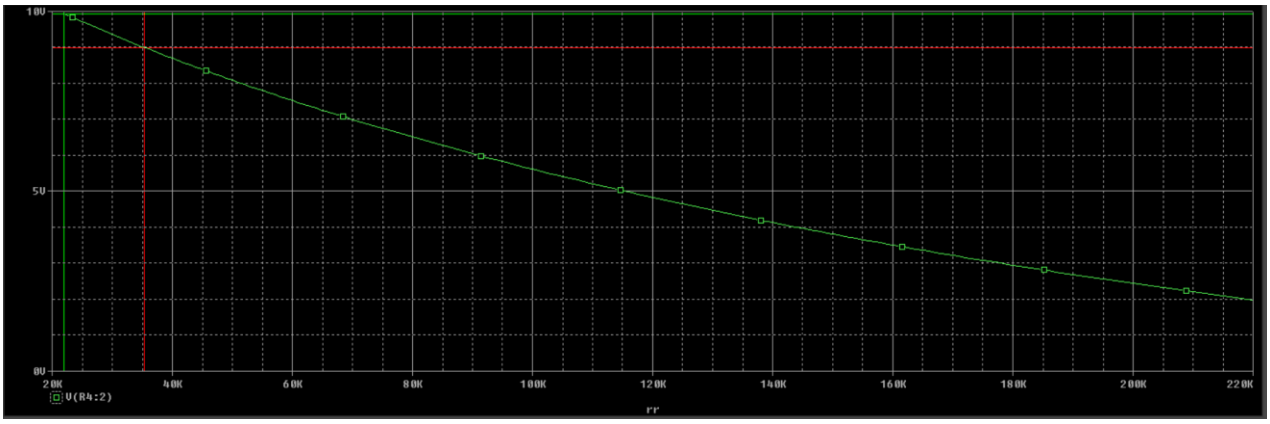


Figure 19-output voltage of VthH

Trace Color	Trace Name	Y1	Y2	Y1 - Y2
	X Values	35.352K	22.000K	13.352K
CURSOR 1,2	V(R4:2)	8.9999	9.925	-924.824m

Figure 20-VthH measurement

Close to 9.04V calculated previously.

2.2.4 Hysteresis Comparator

In this gas detection application, a hysteresis comparator is used to provide stable switching behavior and prevent rapid oscillations of the output signal when the gas concentration is near the threshold level. By incorporating hysteresis, the comparator creates two distinct voltage thresholds: one for turning on the LED and another for turning it off. This ensures that minor fluctuations in gas concentration do not cause the LED to flicker, thereby enhancing the reliability and stability of the detection system.

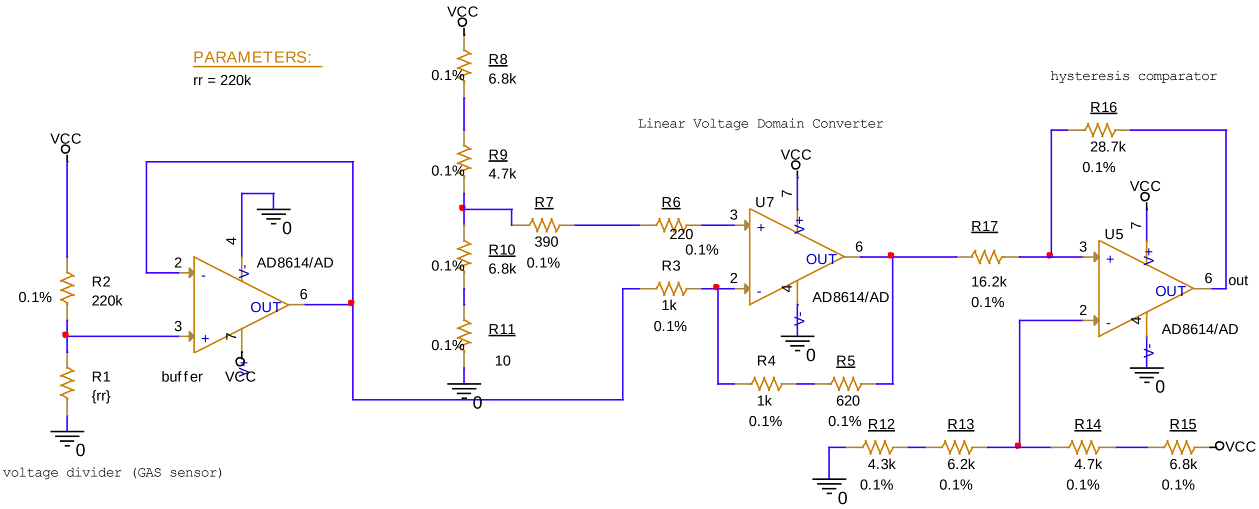


Figure 21-adding Hysteresis Comparator to our circuit

Sizing the Hysteresis Comparator resistors:

$$\begin{cases} V_{ThL} = -\dfrac{R_9}{R_8} \times V_{OH} + \left(1 + \dfrac{R_9}{R_8}\right) \times V_{REF} \\ V_{ThH} = -\dfrac{R_9}{R_8} \times V_{OL} + \left(1 + \dfrac{R_9}{R_8}\right) \times V_{REF} \end{cases}$$

I. Utilization as **comparator**, in switching mode

$$v_O \in \{V_{OL}\,;\,V_{OH}\}$$

$v_D > 0$, $v_O \to +\infty$, v_O limited by the positive supply $v_O = V_{OH} \approx +V_{PS}$

$v_D < 0$, $v_O \to -\infty$, v_O limited by the negative supply $v_O = V_{OL} \approx -V_{PS}$

Figure 22-theoretical support regarding the supply of Hysteresis comparator

Considering this, V_{OH}=12V; V_{OL}=0V, V_{thH}, V_{thL} calculated previously and solving the system above, we get the ratio: $\frac{R_8}{R_9} = 0.57$. Find 2 resistors that match this:

Resistor Ratio

Find the best combination of resistors to satisfy the given ratio, using values from the series selected above.

Select which type of ratio to solve for:

- (●) Resistor ratio [0.57] R1/R2
- ( ) Voltage divider V_H: [ ] V_L: [ ] $V_H > V_L$

Optional: ☐ Inverse What is this?

Calculate...

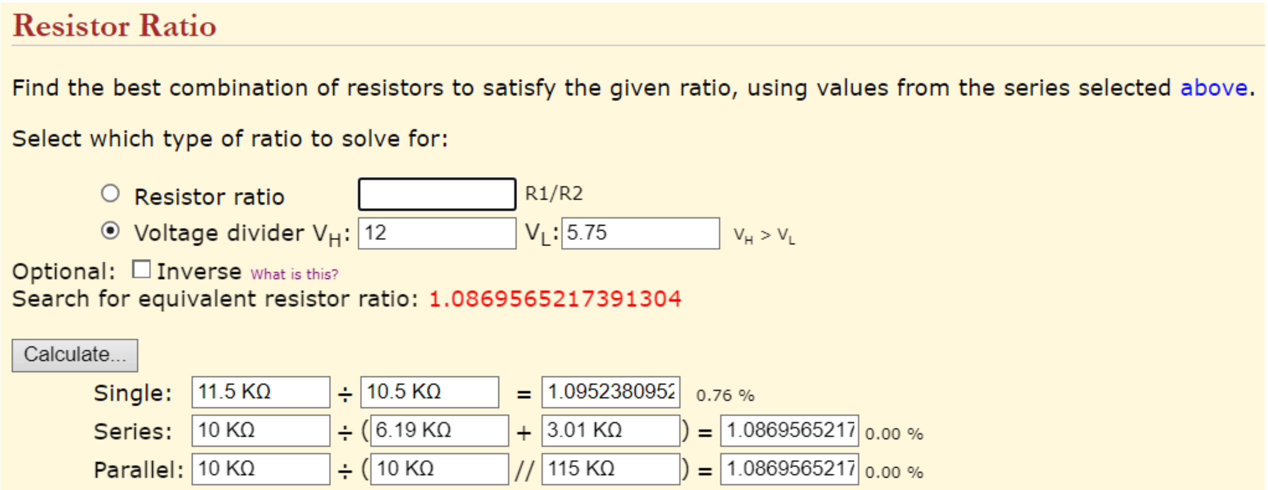
Single:	16.2 KΩ	÷	28.7 KΩ			=	0.5644599303		0.98 %
Series:	27.4 KΩ	÷ (	40.2 KΩ	+	7.87 KΩ	) =	0.5700020802		0.00 %
Parallel:	26.1 KΩ	÷ (	46.4 KΩ	//	3.48 MΩ	) =	0.57		0.00 %

Using Jansson tool, we can find the suitable resistors for this resistance ratio $\frac{R_8}{R_9} = 0.57$:

So, we get $R_8 = 16.2K\Omega$ and $R_9 = 28.7K\Omega$.

Replacing in the second equation, we get Vref=5.75V.

Using Jansson tool, we can find the suitable resistors for our voltage reference value $V_{th} = 5.75V$:



So, we have $R_{10} = 10.5K\Omega$ and $R_{11} = 11.5K\Omega$.

2.2.5 LED & relay

Controls the fan by driving a relay based on the comparator's output. The relay turns the fan on or off to maintain the carbon monoxide concentration within the specified limits. Additionally, an LED indicator shows the fan's operational state, turning on when the fan is activated.

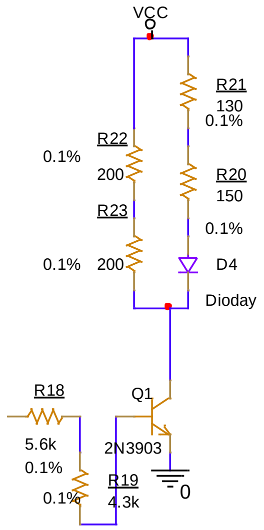


Figure 23-final piece for our circuit-LED & relay stage

Trying different values; applying second theorem of Kirchhoff, we get:

$$KVL: V_{CC} - V_{R14} - V_D - V_{CEsat} = 0 \qquad equation\ 11$$

$$12 - V_{R15} - 3.3V - 0.2V = 0$$

$$V_{R15} = 8.5V$$

$$I_{fwd} = 30mA\ so:$$

$$R_D = \frac{V_{R15}}{I_{fwd}} = \frac{8.5V}{30mA} = 0.28\ K\Omega$$

The resistance of the coil (coil resistance) is 400Ω, seen in the datasheet.

We need to adjust the resistance from the base of the transistor, such that the purple LED will get that 30mA voltage needed, so it will be turned on. Trying different values I just found that, the resistance $R_{12} = 9.9K\Omega$.

When it comes to the purple LED, I was supposed to model it, because it was not found in the PSpice library. So, we use other program called PSpice Model Editor. First, we need a suitable datasheet, from which we extract the forward current VS forward voltage characteristic:

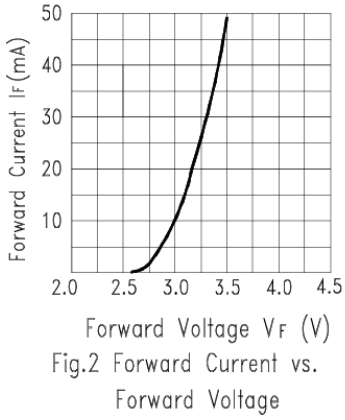


Figure 24-Forward current VS forward voltage characteristic

Having this characteristic, we try to model the purple led as follows:

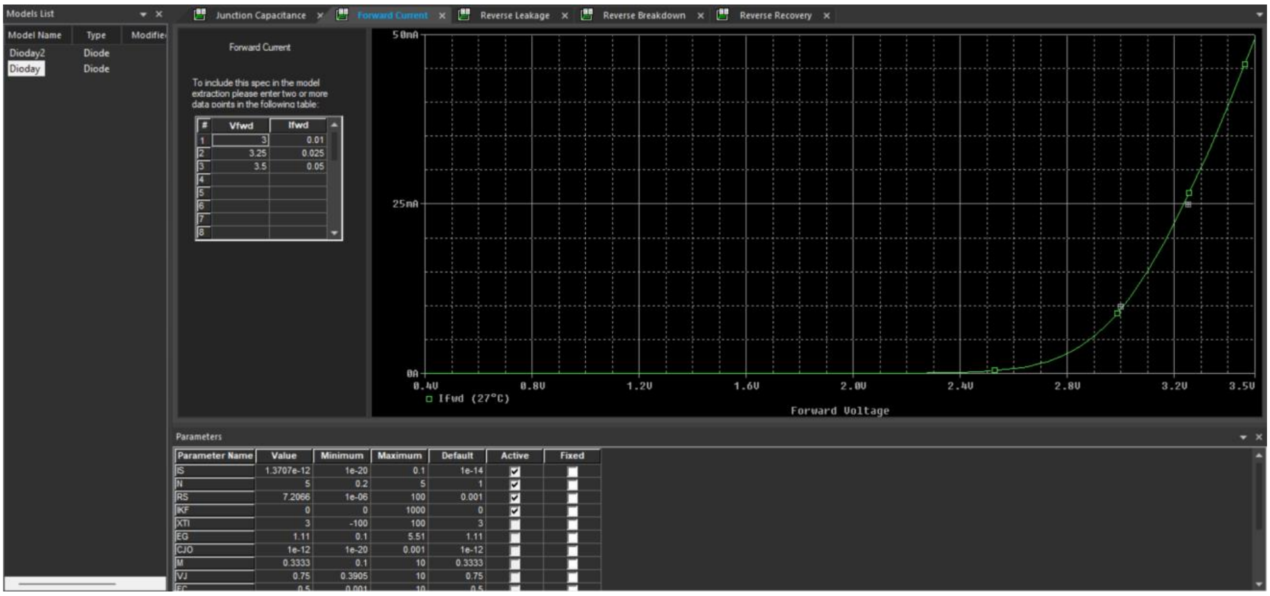


Figure 25-results of modeling purple LED in PSpice Model Editor

Having this result, we can see that it is suitable for our application. I just took three clear points from the characteristic given in the datasheet. So, the purple led will work for forward voltage $V_{FWD} = 3.3V$ and $I_{FWD} = 30mA$, corresponding to the datasheet:

DC Forward Current	I_F	30	mA

Here we have the relay resistance (more exactly the coil resistance parameter) needed for our application:

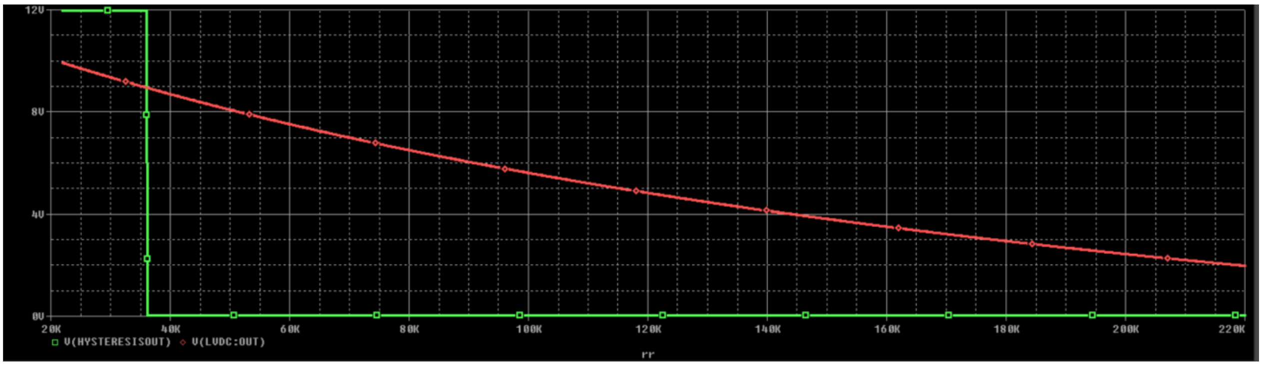
Coil Rating (DC)

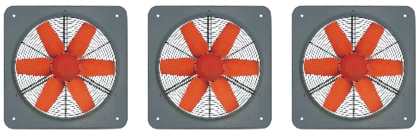
Rated voltage (V)	Rated current ±10 % at 23°C (mA)	Coil resistance ±10 % at 23°C (Ω)
3	120	25
4	91	44
5	72	70
6	60	100
9	40	225
12	30	400
24	15	1600
36	10	3600
48	9.4	5120

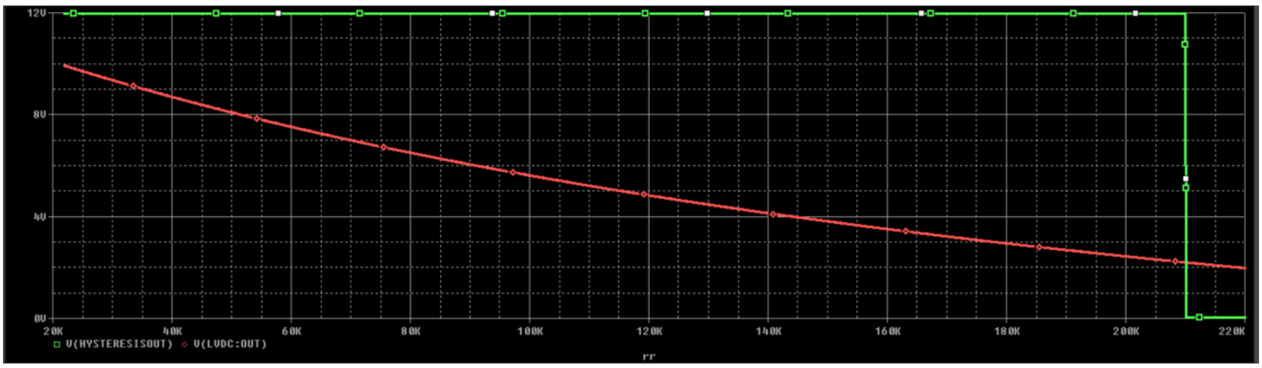
Our case

3 Demo

A short visualization of our gas sensor:

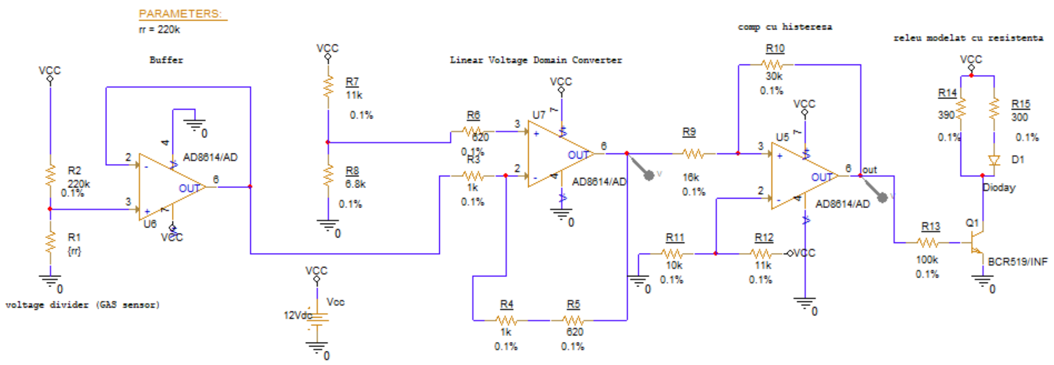






Until now, purely theoretical, but now we use standard components.

3.1 After standardization electrical scheme



3.1.1 Worst-case analysis

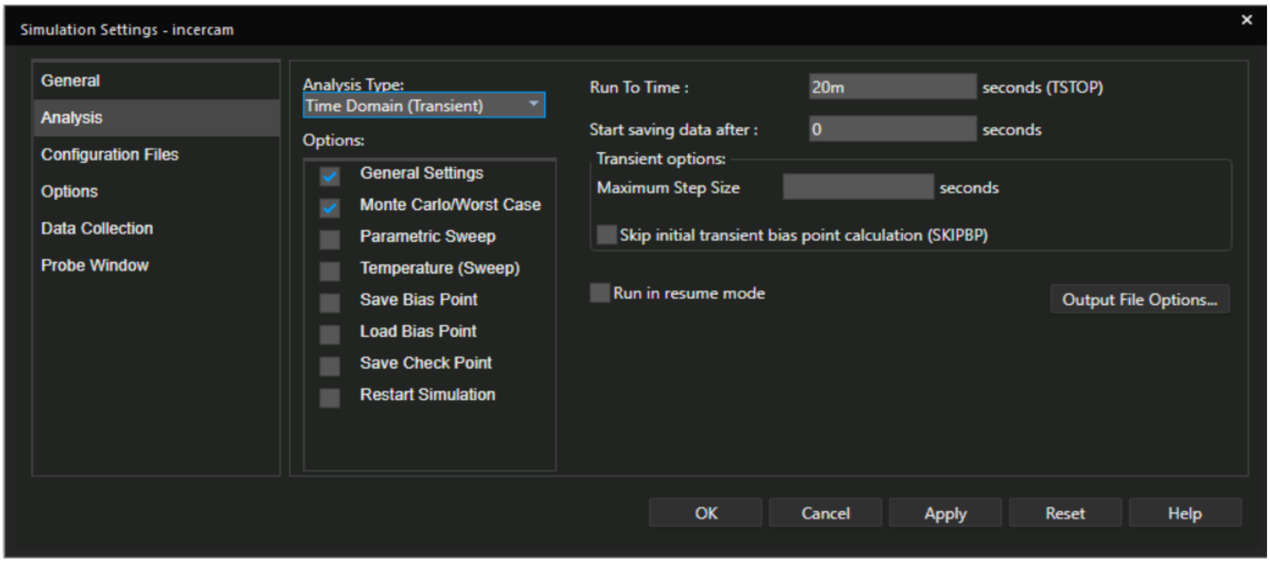


Figure 26 settings profile-primary analysis-time domain

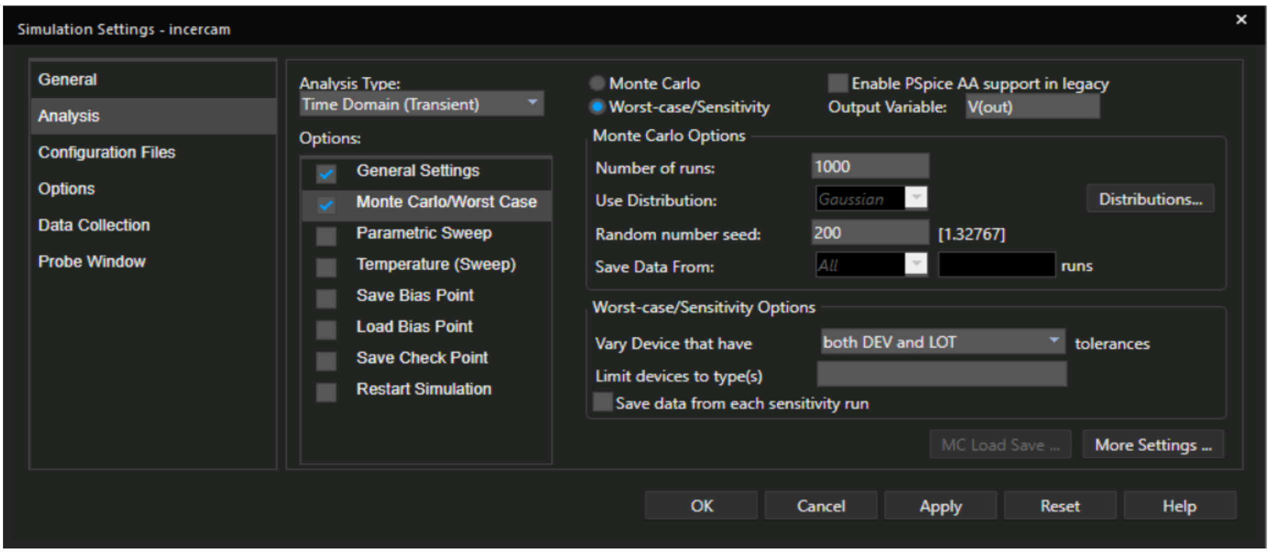


Figure 27-monte-carlo settings profile

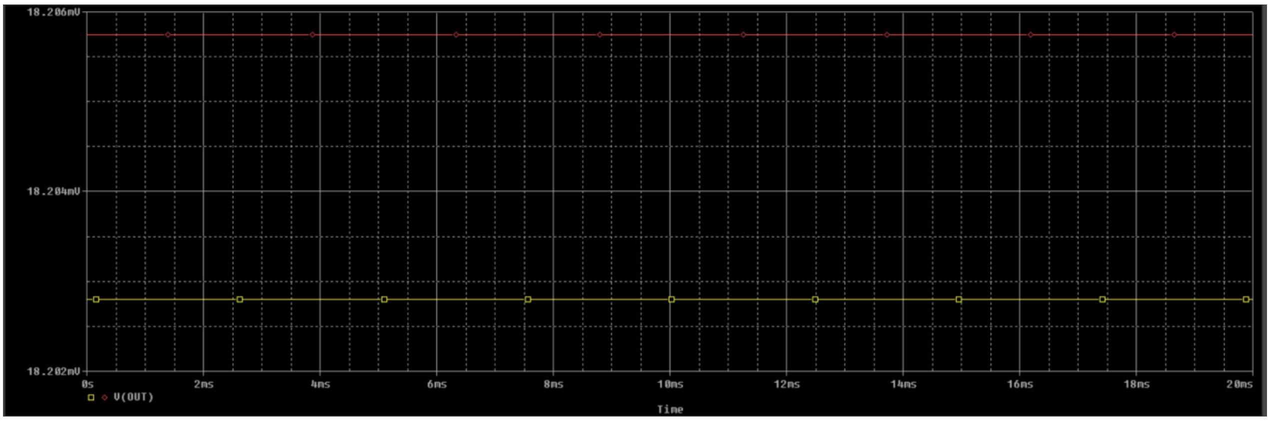


Figure 28 worst-case result

The waveforms labeled with voltages of 18.202 mV, 18.204 mV, and 18.206 mV show stable voltage levels over a period of 20 ms. The flatness of these lines suggests that the voltage domain converter is maintaining a consistent output without significant fluctuations, which is a good sign of stability in this circuit.

3.1.2 Monte-Carlo analysis

In statistical analysis, tolerances may change involuntarily. Monte-Carlo analysis examines the response of a circuit when global parameters vary within tolerance limits according to a statistical distribution. This analysis can be applied to AC, DC, and transient responses. The number of runs represents the values taken within these tolerance limits, which are generated as random values. The distribution of these values can be either Gaussian or uniform.

We keep the same settings for time domain primary analysis, now we set monte-carlo analysis:

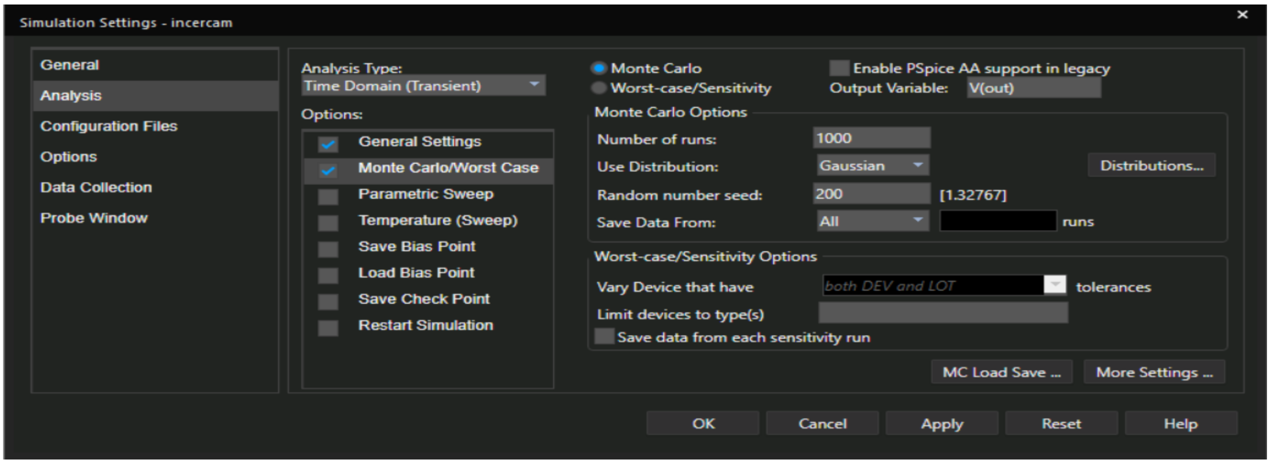


Figure 29 monte-carlo profile settings

We choose to take 1000 runs such that we can clearly see if our output varies or not.

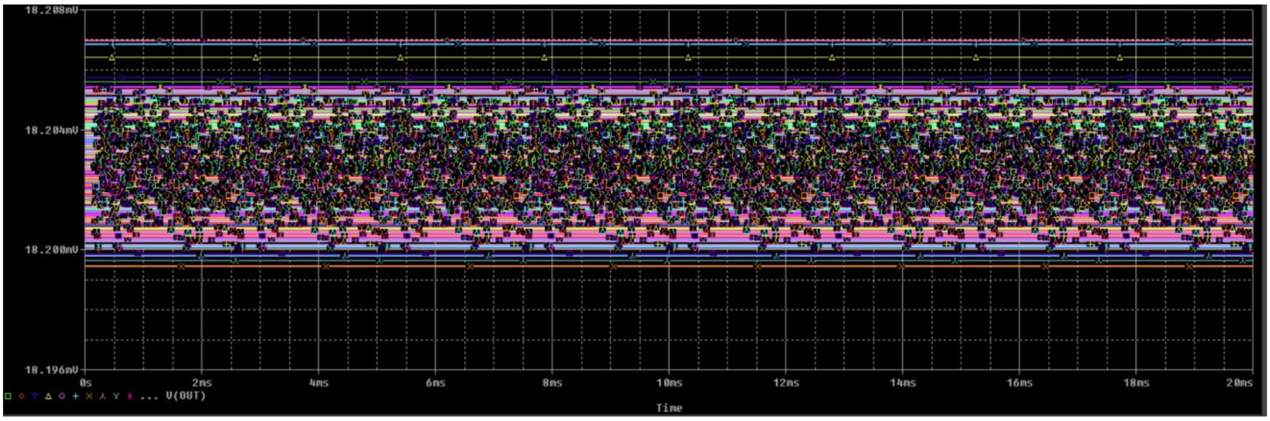


Figure 30 monte-carlo analysis result

As we can see, no variation, so the circuit is stable, meaning that 0.1% tolerance to all components provide us a high level of precision.

3.1.3 Performance analysis

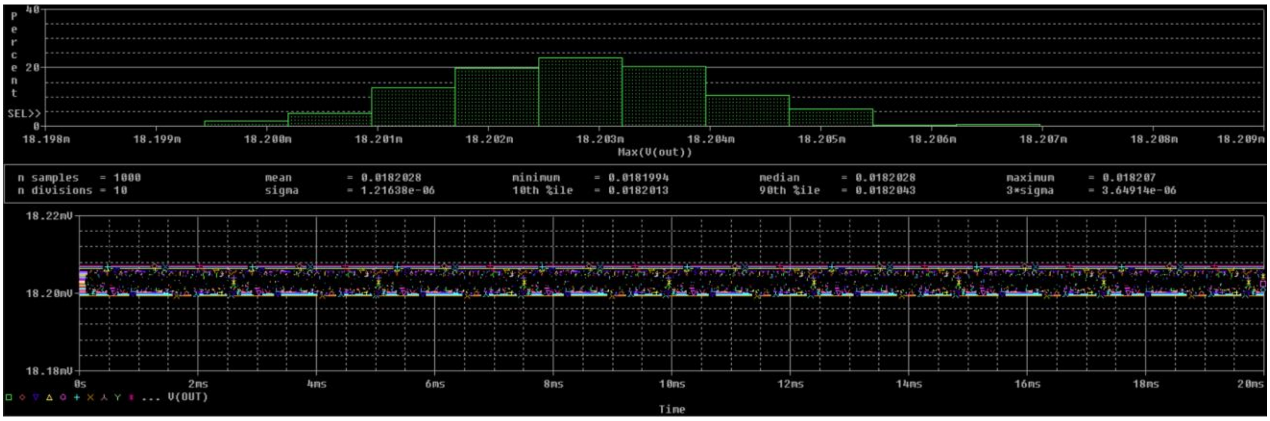


Figure 31 performance analysis result

The results should be fine because of some parameters, which will be explained in what follows:

We can see that our circuit is stable because the histogram bars are tightly clustered around the mean fact that suggests stable performance.

Moreover, we can see that the output voltage has no significant variation within a narrow range (close to the mean).

Low Variability: Smaller sigma and a narrow distribution indicate less variation, which is perfectly fine for our application.

4 Bill of materials

Component	Value	Tolerance	Model	Description	Price/piece (RON)
R2	220 KΩ	0.1%	CPF-A-0603B220KE	Thin Film Resistors - SMD CPF A 0603 25PPM 5K RL	1.52
R3	1 KΩ	0.1%	MCS04020D1001BE000	SMD 1/16W	0.921
R4	1 KΩ	0.1%	MCS04020D1001BE000	SMD 1/16W	0.921
R5	620 Ω	0.1%	CPF0603B620RE1	SMD CPF 0603 620R 25PPM	1.80
R6	220 Ω	0.1%	TNPW0402220RBEED	SMD 1/16W 25ppm	1.75
R7	390 Ω	0.1%	RP0603BRE07390RL	SMD 1/10 Wa 0603 AEC-Q200	0.965
R8	6.8 KΩ	0.1%	ERA-3APB682V	SMD 0603 15ppm AEC-Q200	1.80
R9	4.7 KΩ	0.1%	MCS04020D4701BE000	SMD 1/16W	0.921
R10	6.8 KΩ	0.1%	ERA-3APB682V	SMD 0603 15ppm AEC-Q200	1.80
R11	10 Ω	0.1%	CRT0402-BY-10R0GLF	SMD 1/16watts	1.38
R12	4.3 KΩ	0.1%	TNPW04024K30BEED	SMD 1/16W 25ppm	1.75
R13	6.2 KΩ	0.1%	ERA-2AEB622X	SMD 0402 1/16W	0.782
R14	4.7 KΩ	0.1%	MCS04020D4701BE000	SMD 1/16W	0.921
R15	6.8 KΩ	0.1%	ERA-3APB682V	SMD 0603 15ppm AEC-Q200	1.80
R16	28.7 KΩ	0.1%	ERA-6AEB2872V	SMD 0805 25ppm	0.599
R17	16.2 KΩ	0.1%	ERA-6AEB1622V	SMD 0805 25ppm	0.554
R18	5.6 KΩ	0.1%	ERA-2AEB562X	SMD 0402 1/16W	0.782
R19	4.3 KΩ	0.1%	TNPW04024K30BEED	SMD 1/16W 25ppm	1.75
R20	150 Ω	0.1%	MCS04020D1500BE000	SMD 1/16W	0.921
R21	130 Ω	0.1%	RP73PF1E130RBTD	SMD HP PrecisionResistor 1E 0.1W 130R	1.24
R22	200 Ω	0.1%	ERA-3AEB201V	SMD 0603 1/10W 25ppm	0.599
R23	200 Ω	0.1%	ERA-3AEB201V	SMD 0603 1/10W 25ppm	0.599
Rail-to-rail OA	SR:7.5V/μs	-	AD8614ARTZ-REEL7	Precision Amplifiers SINGLE 18V LCD DRIVER	24.06
Rail-to-rail OA	SR:7.5V/μs	-	AD8614ARTZ-REEL7	Precision Amplifiers SINGLE 18V LCD DRIVER	24.06
Rail-to-rail OA	SR:7.5V/μs	-	AD8614ARTZ-REEL7	Precision Amplifiers SINGLE 18V LCD DRIVER	24.06
LED	30mA, 3.3V	-	-	-	1.07
NPN BJT	-	-	2N3903 TIN/LEAD	BJT NPN 60Vcbo 40Vceo 200mA 625mW	0.45
			FINAL PRICE:		99.78

5 Conclusion

The completion of this project has been both educational and rewarding. The circuit performed as expected, effectively converting the resistance changes from the gas sensor into a voltage signal, conditioning the signal, and controlling the fan to maintain CO concentration within specified limits. Throughout this process, I gained valuable hands-on experience in designing and implementing a functional electronic system.

The cost of the components, all with a 0.1% tolerance, proved to be quite reasonable at approximately 100 RON (99.78). This high precision tolerance contributed to the circuit's overall efficiency and stability, making it a cost-effective solution. The ratio of quality to price was surprisingly good, demonstrating that a well-designed system can be both affordable and highly effective.

Overall, this project has not only met its technical objectives but also highlighted the feasibility of achieving high performance with a modest budget.

5.1 References

- http://193.226.6.189/dce/didactic/ed/C7.%20Hysteresis%20comparators.pdf
- http://193.226.6.189/dce/didactic/ed/C10.%20Applications%20with%20OpAmp..pdf
- http://193.226.6.189/dce/didactic/ed/C8.%20Electronic%20amplifiers.%20Amplifiers%20with%20OpAmp..pdf
- https://biblioteca.utcluj.ro/files/carti-online-cu-coperta/639-5.pdf
- https://www.analog.com/media/en/technical-documentation/data-sheets/AD8614_8644.pdf
- https://cdn.sparkfun.com/datasheets/E-Textiles/Lilypad/Purple%20LEDs%20HT15-2102UPC.pdf
- https://pdf1.alldatasheet.com/datasheet-pdf/download/453220/UTC/2N3906.html
- https://ro.mouser.com/datasheet/2/378/20119191320287145-4912.pdf
- https://jansson.us/resistors.html
- https://www.desmos.com/calculator
- CAD COURSES AND LABORATORIES