Technical University of Cluj-Napoca
Faculty of Electronics, Telecommunications, and Information Technology

OrCAD Project

CAD Techniques

Theme: Circuit for controlling soil moisture level for plants

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Requirements

Design an irrigation system that uses resistive moisture sensors to maintain a certain level of relative soil humidity for a plant (moisture level limits are specified in column E). When the soil moisture level has reached the lower limit (from column E), the system will start watering the plant. When the humidity level reaches the upper limit (from column E) the system will give the command to stop watering the plant. From the sensor catalog sheet, it is known that at a variation of the humidity level mentioned in column F, the electrical resistance of the sensor varies linearly in the range specified in column G. The variation of the electrical resistance of the sensor must be converted into a voltage variation in the range [2 ÷ (Vcc-2V)]. Vcc is specified in column H. The irrigation pump is controlled by a hysteresis comparator via a relay which is modeled with a resistor. The state of the pump (on/off) is signaled by an LED of the color specified in column I.

E	**F**	**G**	**H**	**I**
Humidity level to maintain [%]	Maximum humidity range [%]	Sensor resistance[kΩ]	Vcc [V]	LED Color
20 - 40	10 - 90	600 - 100	15	Red

Table 1. Project Requirements

Following the proposed, theoretical, project requirements, a hardware solution will be presented in the next pages. The project respectively the circuit that will perform the action of automatically water a plant is going to be composed of only analog devices, including no microcontrollers or other data aquation systems. This hardware solution can be incorporated into bigger irrigation systems by making slight changes to the logic of the circuit or by including voltage reading devices that will be able to convert the analog values into digital ones, then interpret them with a computer.

Theoretical aspects of the circuit

The role of the circuit

In today's world more and more of the agricultural field gets automatized, with the reason of making the overall agricultural processes more efficient and faster. One way to improve the work done in the field is to automate the most vital part of the job, and that is the watering of the plant part. To make any type of plant grow healthy the amount of water and the frequency of the watering sessions is crucial. The circuit requirements of a circuit that will automate the process must consider the length of the watering sessions and the amount of water. It must notify the user when it starts the process and when it finishes it. It must follow as many safety standards as possible, to ensure low to zero accidents for the users but also for the surroundings of the circuit.

Initial circuits proposed for implementation

To match the specified requirements the irrigation system will be composed of many subcircuits that will work concomitantly to ensure the best performance.

The circuit that reads the humidity of the soil must follow the linear function of the given sensor and not damage the sensor or the surroundings of the sensor. A suitable circuit that will implement the conditions is a **current mirror with a buffer**. The current is fixed by the nature of the circuit and the buffer will provide impedance matching. As seen in the Figure 1. Model of the sensor; it is used a PNP BJT current mirror that will provide the constant current through the resistance of the sensor; the OpAmp is used in the configuration of a Voltage Follower (Buffer), it has a high input impedance and a significant lower output resistance.

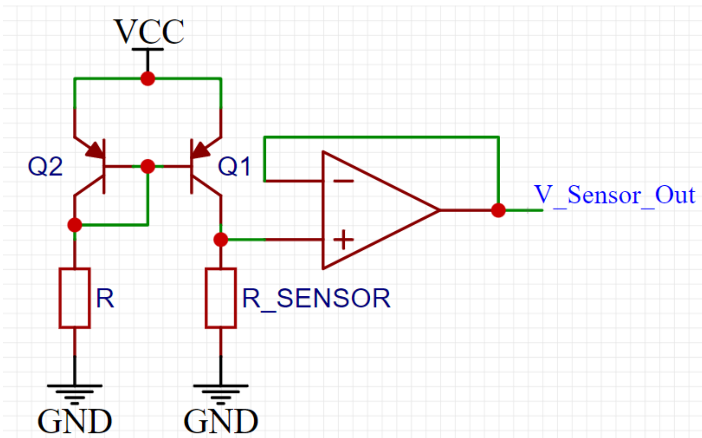


Figure 1. Model of the sensor

For making the changes of the state's automatic the best suited circuit is a **hysteresis comparator**. This circuit will switch the command signal of the water pump based on the specified thresholds that are set by the designer. Proper and stable voltage thresholds are mandatory to water the plant in the desired range; therefore, the circuit must present a notable high stability. As seen in the Figure 2. Non-inverting Hysteresis Comparator; the structure of the circuit is straightforward and robust, that will ensure the stability needed.

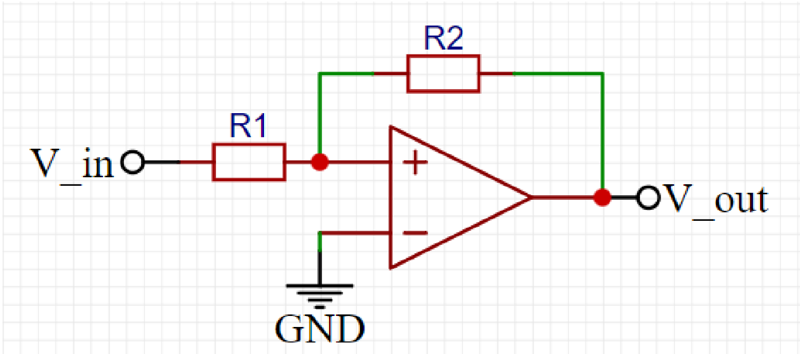


Figure 2. Non-inverting Hysteresis Comparator

For the handling of the high-power water pump a circuit that consists of a **controlled relay** is needed. The device that can handle the still high current consumption of the relay is a power NPN BJT. The circuit must not fail under long usages sessions and must stay reliable regardless of the outside medium. As seen in the Figure 3. Relay Control; a low current command current will control the high current needed for the relay.

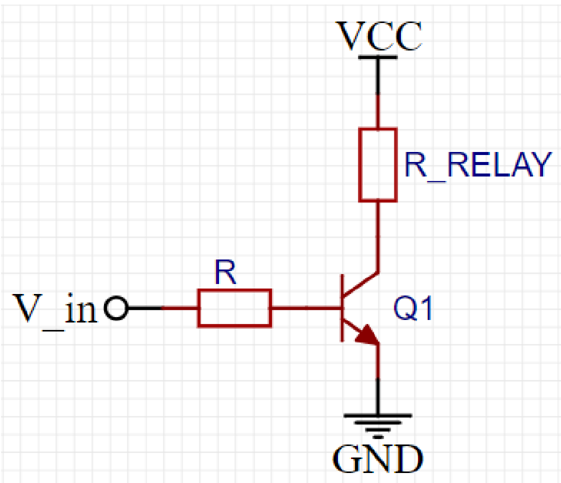


Figure 3. Relay Control

Circuit Implementation - Blocks Analysis

Block Diagram

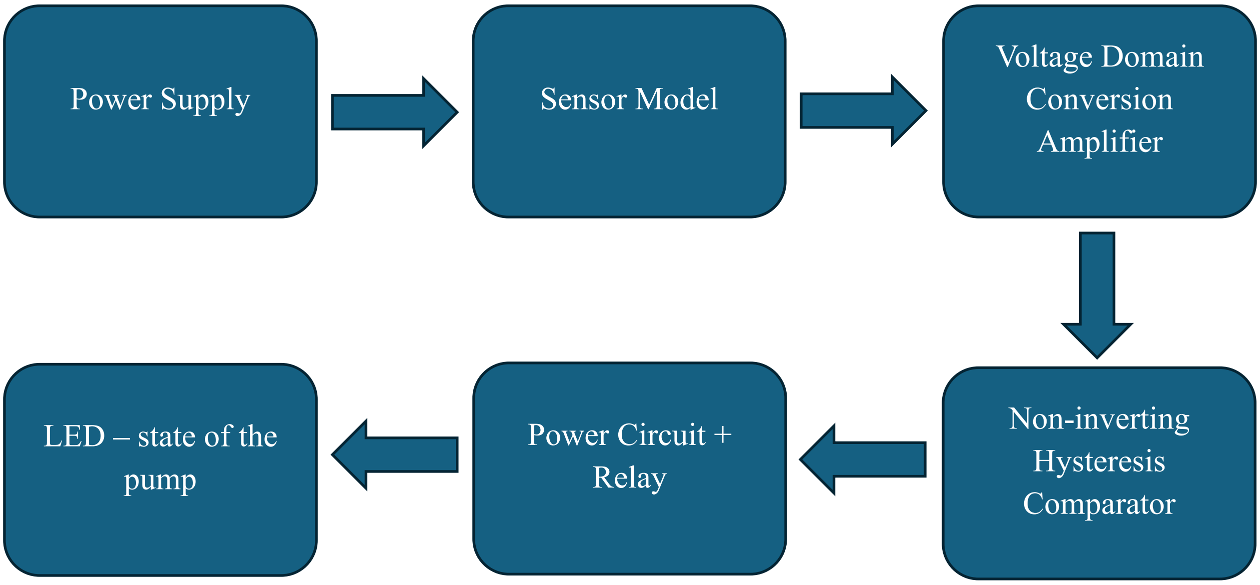


Figure 4: The Block Diagram

As seen in Figure 4: The Block Diagram; the circuit is made from 6 block diagrams, that will perform the necessary signal conversion and interpretation for the whole system. Each of them contains a subcircuit that is the most efficient and safe for its application. Their detailed functionality will be presented later in the document, with all the significant simulations.

Functionality of the circuit

The circuit the proposed VCC = 15V and steps it down to 5V for the sensor, to improve safety around the plant and the soil, for which it must measure the humidity. The lowered voltage is feed in the model of the sensor which will inject a small, microamperes range, current into the ground then measure the resistance of the sensor; that will be converted to volts. The Voltage Domain Conversion Amplifier will make the voltage range of the sensor match the ones from the requirement table. The Non-inverting Hysteresis Comparator will set the threshold voltages that will determine the on / off states of the control signal; this circuit block in addition will command the water pump. The control signal is fed into the input of the power control circuit that will command the relay. The state of the pump is indicated to the user by a red color Led.

Power Supply

Electrical Scheme

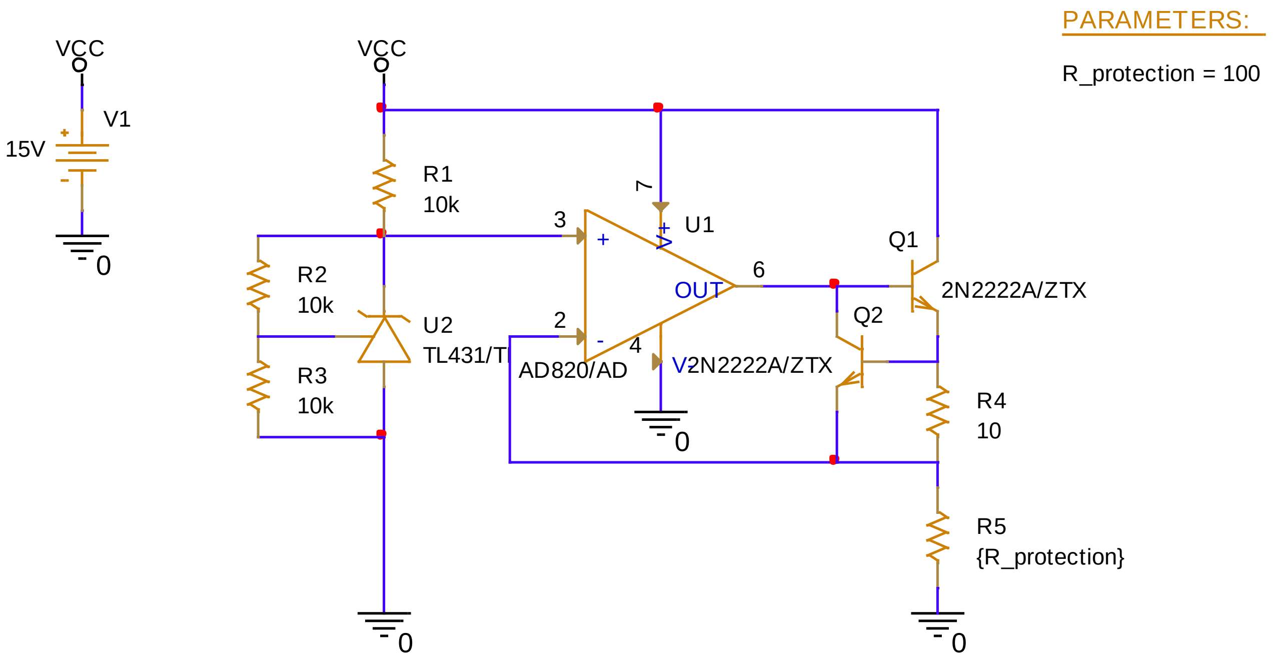


Figure 5. Protected Power Supply

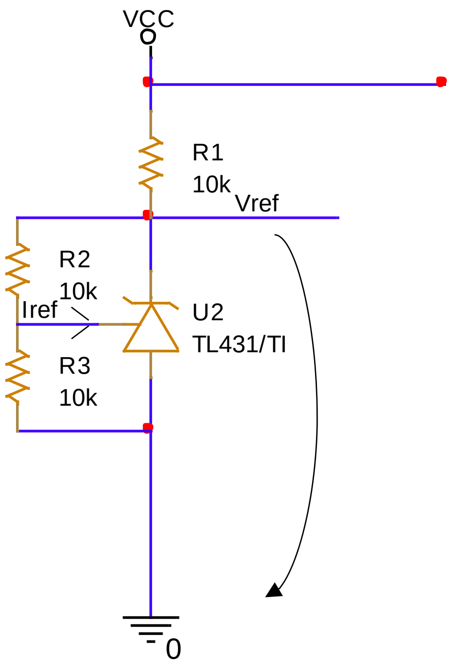
Duty of the circuit

The circuit from the Figure 5. Protected Power Supply; represents a constant voltage regulator that converts the 15V from the main power supply down to 5V. The conversion is done by the usage of an OpAmp and a constant voltage reference; the OpAmp being in a voltage follower configuration, it keeps it differential input voltages up to the same value, therefore the constant 5V reference will be the output voltage of the circuit. The addition of the transistor Q1 is to ensure that the maximum output current is bigger than the OpAmps limited output current. The role of the transistor Q2 and the resistance R4 is to ensure the protection of the circuit, thus the output current won’t exceed the desired maximum current set by the designer.

The reason behind the addition of a lower voltage regulator power supply, with overcurrent and short circuit protection, is the medium and the environment where the circuit will be used. The medium where the sensor will be placed is not ideal with high and abrupt changes in temperature and humidity. To leave a 15V power supply that, potentially does not include any sort of protection to be in contact with such a medium, will certainly lead to faults and hazard to the user and the plants.

Computed values

The voltage computation consists in the properties of the integrated circuit TL431 made by Texas Instruments, which also provided the formula for a desired value of the reference voltage. Wanted V_{ref}=5V:



$$I_{ref} \to 0 \tag{1}$$

$$V_{ref} = V_{ref\_data}\left(1 + \frac{R_2}{R_3}\right) + I_{ref} \cdot R_2 \tag{2}$$

$$V_{ref\_data} = 0.25V \tag{3}$$

$$V_{ref} = 2.5\left(1 + \frac{10k}{10k}\right) + 0 \cdot 10k \tag{4}$$

$$V_{ref} = 0.25 \cdot 2 \tag{5}$$

$$V_{ref} = 5V \tag{6}$$

Figure 6. Voltage reference circuit

As seen in the equation (2), that was provided by the producer of the integrated circuit, the way to set a constant voltage reference higher than the internal one, is to add 2 series resistances of equal values. The computation assumes that the I_{ref} current is so small comparable with the other current that it can be set to 0, as in the (1) reference. The data sheet provides a typical value of V_{ref}=2495mV, not exactly 2.5V, as in the Figure 7. TL431 Internal Voltage Reference.

PARAMETER		TEST CIRCUIT	TEST CONDITIONS	MIN	TYP	MAX	UNIT
V_{ref}	Reference Voltage	See Figure 8-1	$V_{KA} = V_{ref}$, I_{KA} = 10 mA	2470	2495	2520	mV
$V_{I(dev)}$	Deviation of reference input voltage over full temperature range (1)	See Figure 8-1	$V_{KA} = V_{ref}$, I_{KA} = 10 mA		14	34	mV

Figure 7. TL431 Internal Voltage Reference

The maximum output current is the most important aspect of the whole voltage regulator. This was thought to be to a maximum value of 100mA, therefore more sensor modules can be connected and the maximum output current I_{Omax} is limited to a relatively low current. The protection components are the transistor Q2 and the resistance R4. The computed values use the values provided in the datasheets of the components.

Theoretical value of the output current:

$$I_O > I_{Omax} \Longrightarrow V_{Onew} < V_O \quad (7)$$

$$I_{Omax} = \frac{v_{BE}}{R_4} + I_{O,OAmax} - \frac{1}{\beta} \cdot \frac{v_{BE}}{R_4} \quad (8)$$

$$I_{Omax} = \frac{0.7}{10} + 0.025 - \frac{1}{100} \cdot \frac{0.7}{10} \quad (9)$$

$$I_{Omax} = 0.09493A \quad (10)$$

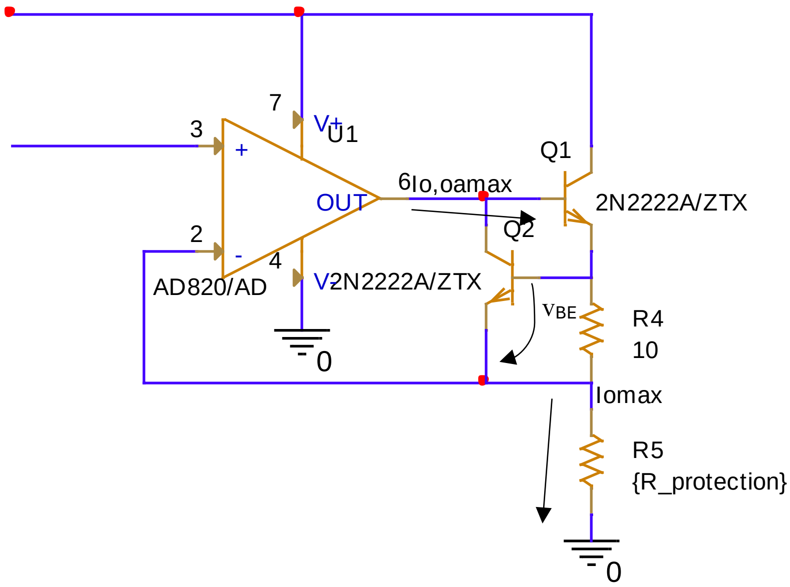


Figure 8. Output current limitation

The minimal output resistance for which the circuit still performs as a voltage regulator.

$$R_{min} = \frac{V_O}{I_{Omax}} \quad (11)$$

$$R_{min} = \frac{5}{0.09493} \quad (12)$$

$$R_{min} = 52.67\Omega \quad (13)$$

The following simulations will demonstrate the functionality of the circuit:

- Simulation profile:

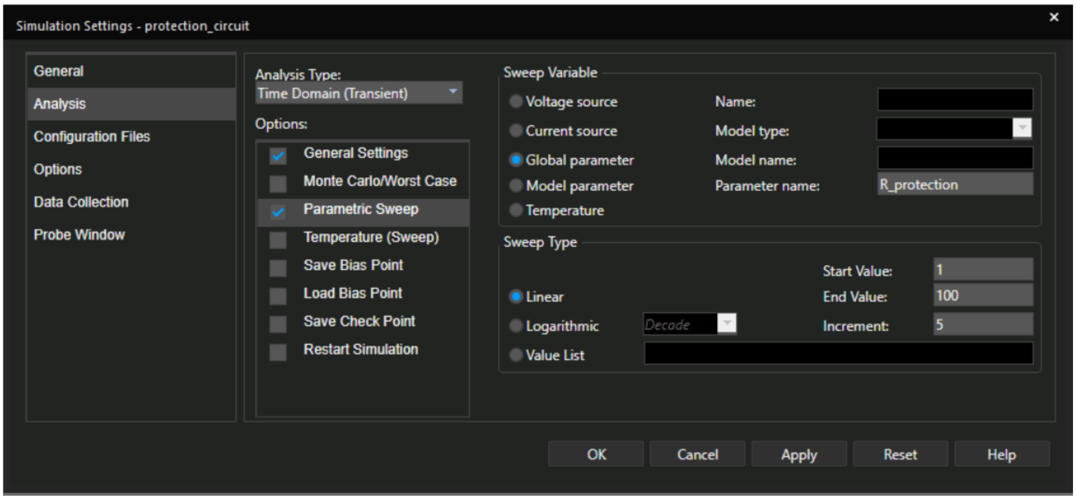


Figure 9. Setting profile for the Protection Circuit

- The change in current with respect to the change of the output resistance:

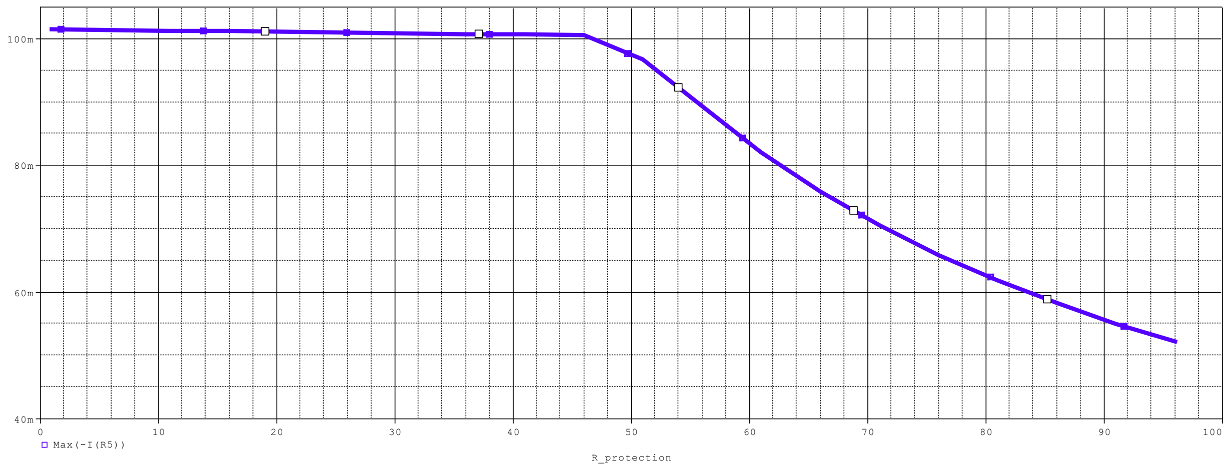


Figure 10. Maximum output current

- The change in voltage with respect to the change of the output resistance:

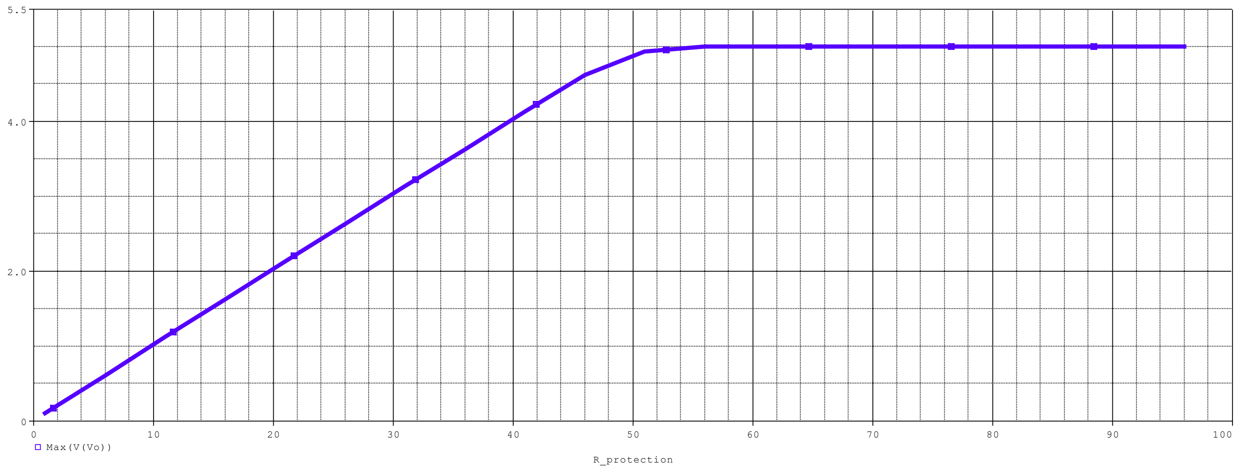


Figure 11. Minimum output voltage

From the simulations: Figure 10. Maximum output current; Figure 11. Minimum output voltage; is clear that the output current won't exceed the proposed value of I_{Omax}=0.1A and the minimum load resistance is around R_{min}=50Ω. The values of the passive components exist on the market, so standardization isn't necessary.

Component description

1. **TL431 Precision Programmable Reference**: it is a three-terminal adjustable shunt regulator, with specified thermal stability over a broth temperature range. The output voltage can be set to any value between Vref (approximately 2.5 V) and 36 V, with two external resistors. These devices have a typical output impedance of 0.2 Ω. Active output circuitry provides a very sharp turn-on characteristic, making these devices excellent replacements for Zener diodes.

2. **AD820 Operational Amplifier**: it is an OpAmp with single-supply operation from 5 V to 30 V. The output swing is rail-to-rail. Minimum output current has the value of 15 mA. I short circuit has the value of 25mA.

3. **2N222A General Purpose NPN Bipolar Transistor**: it is the perfect electronic device for performing tasks that require low to medium current handling. It is a rather common transistor that can be easily found, with a current gain β = 100 for Ic around 100mA. And an absolute maximum collector current Ic=600mA.

Sensor Model

Sensor

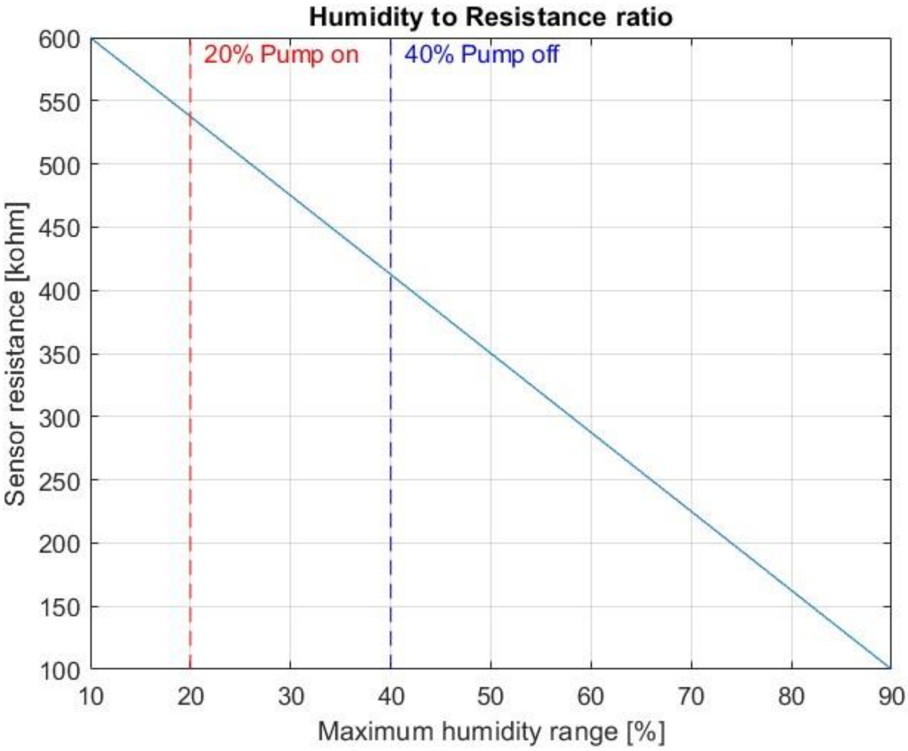


Figure 12. Sensor Resistance over Soil Percentage Humidity

As seen in the Figure 12. Sensor Resistance over Soil Percentage Humidity; the resistance of the resistive soil moisture changes linearly with respect to the humidity of the soil. The graph was derived from the data sheet of the presented sensor. The critical states of the circuit functionality lie on the 20% and 40%, where the circuit will start to water the plant or stop doing it; therefore, precision is highly necessary at these points.

To convert the percentages of soil humidity into actual resistance values, to be processed furthermore the following computations were needed. The equation being linear is going to follow the general linear equation of a function.

$$y = m \cdot x + b \qquad (14)$$

- y – is the humidity percentage (H) [%]
- m - is the slope of the line
- x - is the sensor resistance (R) [kΩ]
- b – is the humidity at zero resistance

$$H = m \cdot R + b \tag{15}$$

From the formula (14) and the meaning of each parameter form the general form the more accurate for the presented context formula was derived, seen in the formula (15).

$$\begin{cases} 10 = m \cdot 600 + b \\ 90 = m \cdot 100 + b \mid (-1) \end{cases} \tag{16}$$

$$\begin{cases} 10 = m \cdot 600 + b \\ -90 = -m \cdot 100 - b \end{cases} + \tag{17}$$

$$-80 = m \cdot 500 \tag{18}$$

$$-\frac{80}{500} = m \tag{19}$$

$$-0.16 = m \tag{20}$$

$$10 = -0.16 \cdot 600 + b \tag{21}$$

$$106 = b \tag{22}$$

From the formulas starting with (16) and up to the (21) the necessary coefficients were computes, therefore the needed values of m=-0.16 (20) and for b=106 (22) were obtained.

$$R = \frac{H-b}{m} \tag{23}$$

- The resistance of the sensor for the humidity level of 20%:

$$R = \frac{20-106}{-0.16} \quad (24)$$

$$R = 537.5[k\Omega] \quad (25)$$

- The resistance of the sensor for the humidity level of 40%:

$$R = \frac{40-106}{-0.16} \quad (26)$$

$$R = 412.5[k\Omega] \quad (27)$$

As presented in the equations (25) and (27) the values of the resistances for the required percentages are computed.

Electrical Scheme

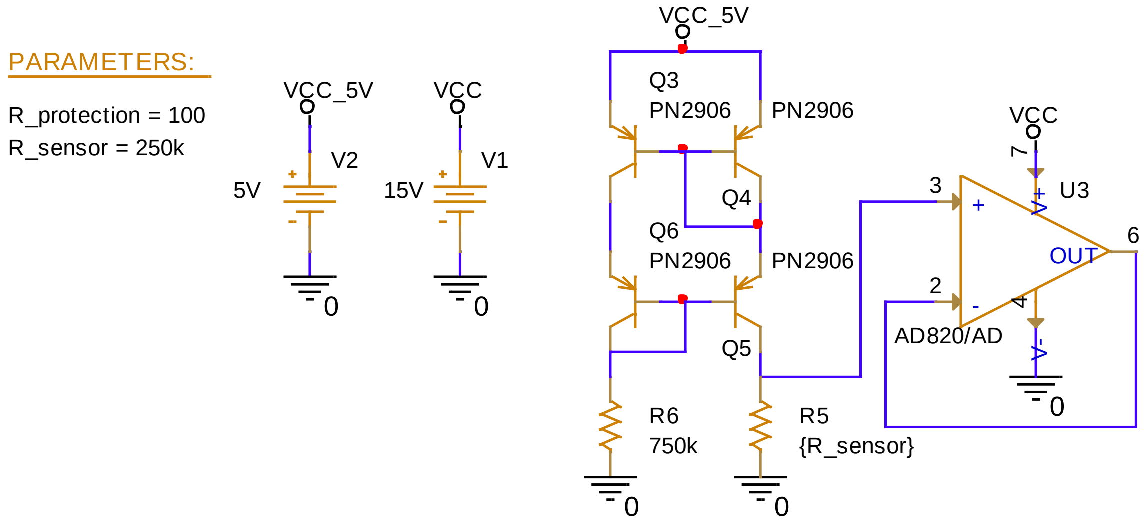


Figure 13. Wilson Current Mirror with OpAmp Buffer

Duty of the circuit

The circuit from Figure 13. Wilson Current Mirror with OpAmp Buffer; represent the circuit that will read the resistance of the sensor, while also protecting it by providing a small current at the output. The OpAmp buffer has the duty of creating impedance matching between the high impedance at the input and the low output impedance needed at the output.

The method of converting the resistance of the sensor into a voltage is by injecting a constant current into it then measuring the voltage across it, therefore the usage of the PNP version of the current mirror. This method is preferable in this situation since that current will go through the environment where the plant sits, the value of it vital. By sending a crucial low current through the sensor, the problem of burning the plant by overcurrent or the problem of intoxicating the plant by electrolysis are reduced to a minimum.

Computed values

The **Balanced Wilson current mirror** is superior in terms of performance over the simple proposed current mirror. This circuit uses 4 PNP BJTs that source current for the output load. The configuration provides a more stable current distribution over the whole circuit as it can be seen in the next diagram; Figure 14. Balanced Wilson Current Mirror. The current from the “right side” of the circuit are balanced with the ones from the “left side”; this produces a significantly smaller output current variation for the variation of the load resistance.

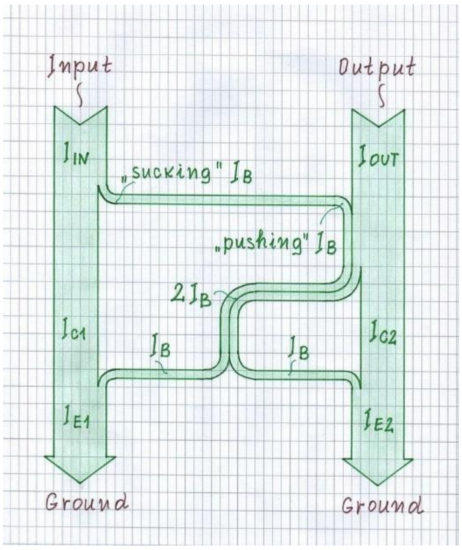


Figure 14. Balanced Wilson Current Mirror

For the circuit from the Figure 13. Wilson Current Mirror with OpAmp Buffer; the output current variation stands in the interval from (28):

$$\Delta I = 5.09849uA - 5.09469uA \qquad (28)$$

$$\Delta I = 0.0038uA \implies \Delta I = 3.8nA \qquad (29)$$

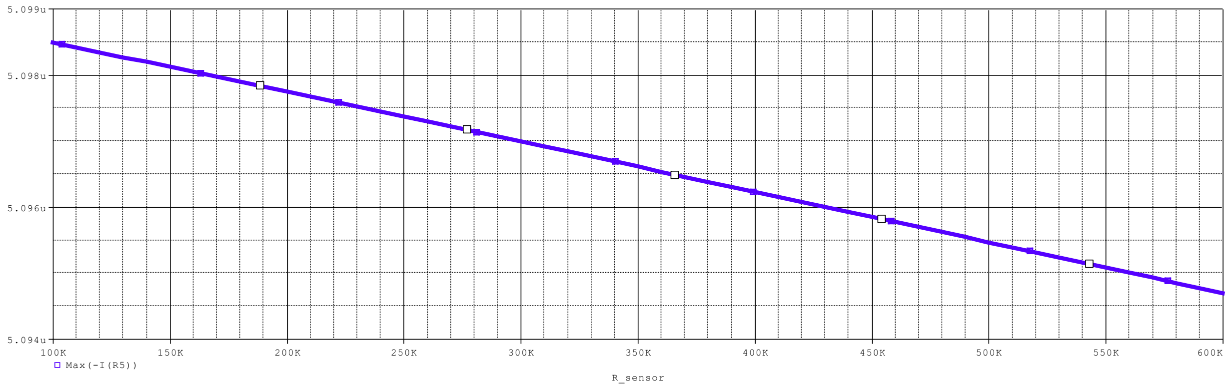


Figure 15. Output Current Variation

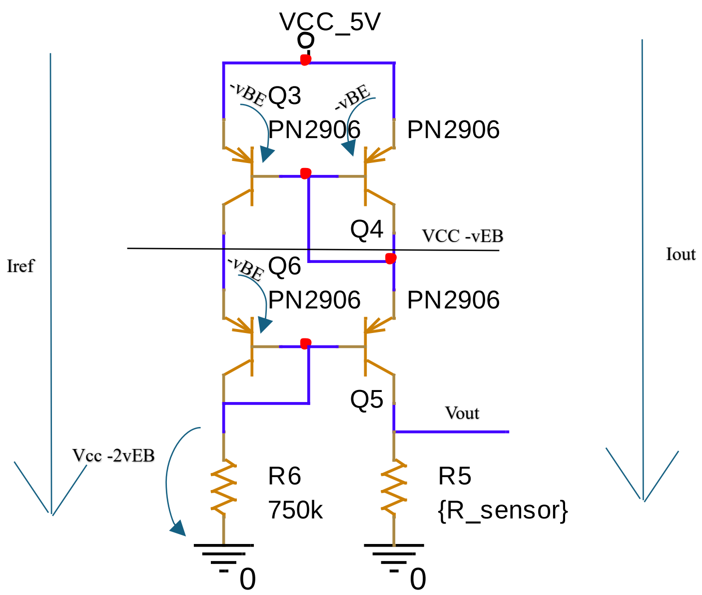


Figure 16. Resistance to Voltage Configuration

The value of I_{out}=5uA is small enough to not cause any harm or damage and is high enough to create a significant voltage drop across the resistance. Thus, the reference current will be I_{ref}=5uA.

$$I_{ref} = \frac{VCC\_5V-(v_{BE\_Q3}+v_{BE\_Q6})}{R_6} \tag{30}$$

$$R_6 = \frac{VCC\_5V-(v_{BE\_Q3}+v_{BE\_Q6})}{I_{ref}} \tag{31}$$

$$R_6 = \frac{5-(0.6+0.6)}{5u} \tag{32}$$

$$R_6 = 760[k\Omega] \tag{33}$$

I_{ref} ; I_{out}	Value [uA]	R_6 $[k\Omega]$
Max(-I(R5))	5.03230	760

Table 2. Reference current with Computed Resistance

The value of the resistor R_6 = 760 [kΩ] does not fit any industry standard, therefore the closest value found is R_6 = 750 [kΩ].

$$I_{ref} = \frac{5-(0.6+0.6)}{750 \cdot 10^3} \tag{34}$$

$$I_{ref} = 5.066uA \tag{35}$$

I_{ref} ; I_{out}	Value [uA]	R_6 $[k\Omega]$
Max(-I(R5))	5.09849	750

Table 3. Reference current with Standardized Resistance

$$V_{out} = I_{out} \cdot R_{sensor} \qquad (36)$$

- The maximum output voltage, for $R_{sensor} = 600[k\Omega]$

$$V_{outMax} = 5u \cdot 600k \qquad (37)$$

$$V_{outMax} = 3V \qquad (38)$$

- The minimum output voltage, for $R_{sensor} = 100[k\Omega]$

$$V_{outMin} = 5u \cdot 100k \qquad (39)$$

$$V_{outMin} = 0.5V \qquad (40)$$

The OpAmp AD820, is connected in a voltage follower configuration to provide impedance matching, therefore, to not influence in any way the resistance of the sensor. The input impedance is in the range of hundreds of Giga-ohms, thus the parallel connection with the sensor resistance which is in the range of hundreds of Kilo-ohms, won't be noticeable; as seen in the Figure 17. AD820 Input Impedance.

Input Impedance				
Differential		$10^{13}\|\|0.5$	$10^{13}\|\|0.5$	Ω||pF
Common Mode		$10^{13}\|\|2.8$	$10^{13}\|\|2.8$	Ω||pF

Figure 17. AD820 Input Impedance

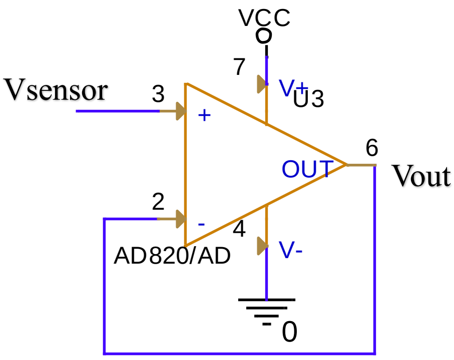


Figure 18. OpAmp Voltage Follower

$$\exists NF \Longrightarrow v^- = v^+ \tag{41}$$

$$\begin{cases} v^- = V_{out} \\ v^+ = V_{sensor} \end{cases} \tag{42}$$

$$V_{out} = V_{sensor} \tag{43}$$

- Simulation profile:

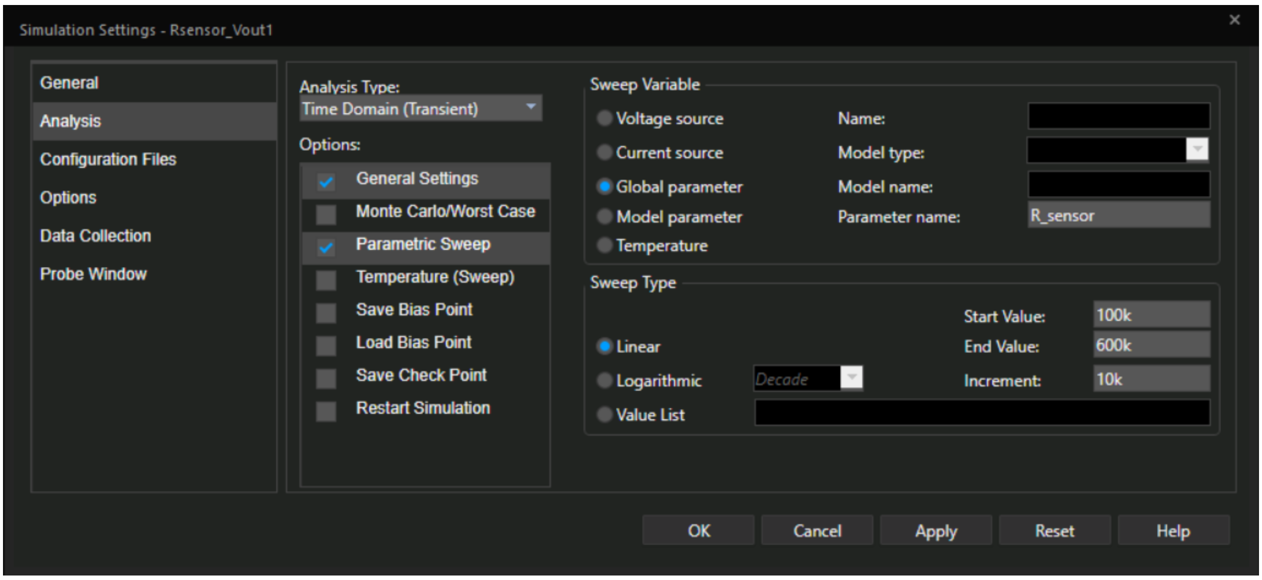


Figure 19. Simulation profile for Sensor testing

- Output Voltage variation of the Second Block Diagram based on the resistance of the humidity sensor:

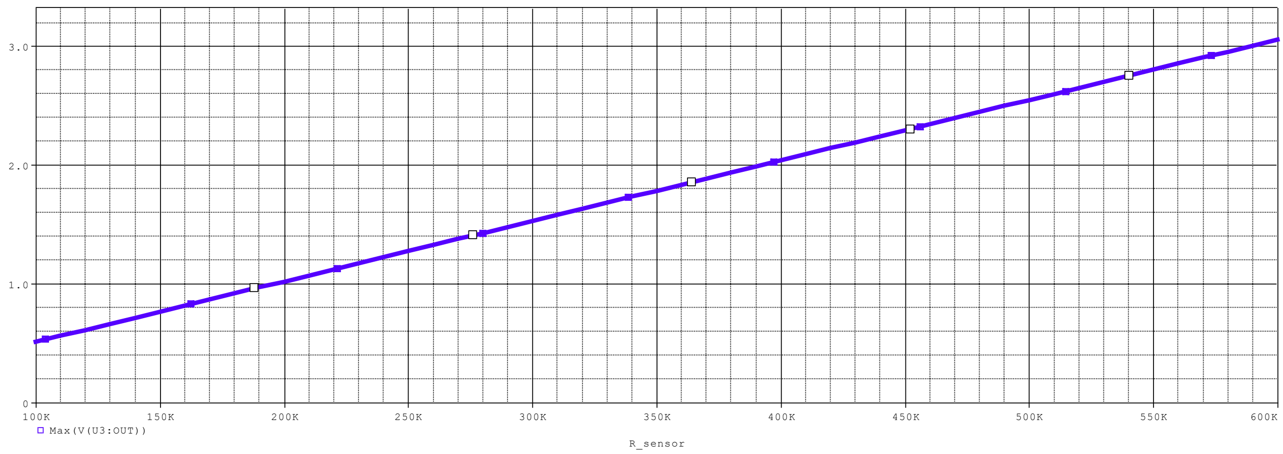


Figure 20. Sensor voltage with respect of its resistance

	Simulated values:
V_{outMin} [V]	509.31128m
V_{outMax} [V]	3.05653

Table 4. Simulated Values of the Voltage across the Sensor

Component description

1. **PN2906 PNP BJT –** is the proper choice of transistor for this application, due to the low currents that it must handle and the precision of its operation.

Voltage Domain Conversion Amplifier

Electrical Scheme

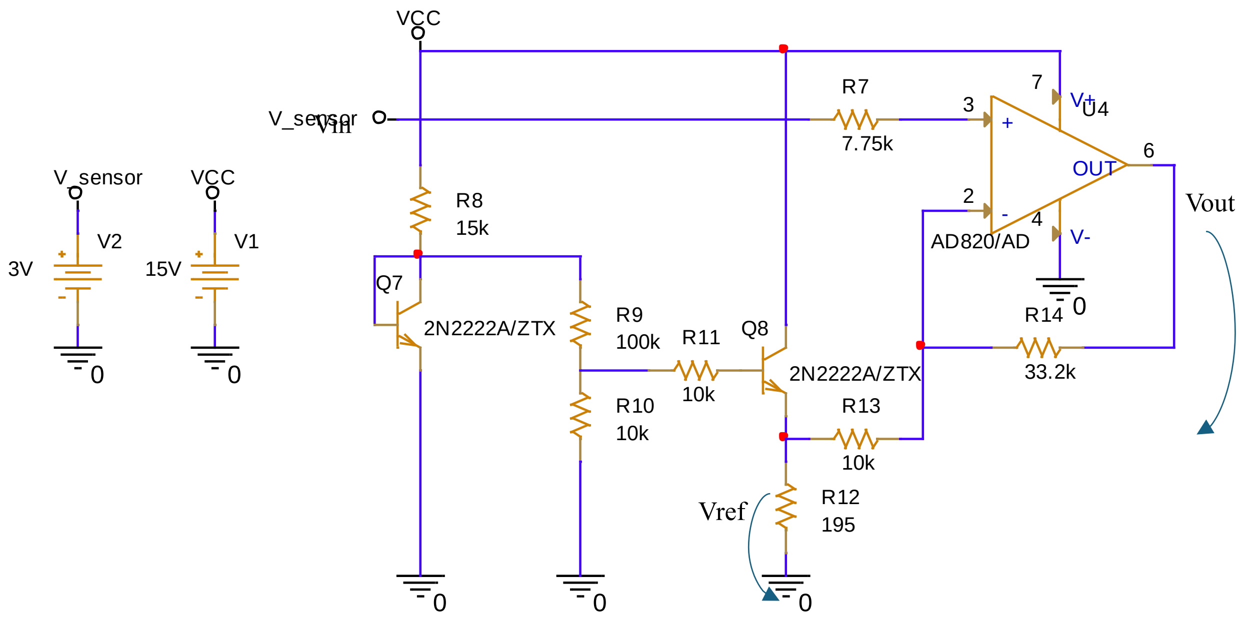


Figure 21. Voltage Domain Conversion Amplifier

Duty of the circuit

The above circuit from the Figure 21. Voltage Domain Conversion Amplifier; has the role of converting the voltage across the resistive humidity sensor to the values from the requirements table. The circuit needs a small voltage reference that will be provided with the NPN BJT that is connected into a Transistor Diode configuration, to step down the power supply voltage. The next functional block from the scheme is another BJT amplifier in Emitter Follower configuration, that will act like a buffer between the reference and the actual circuit. From the nature of the configuration the OpAmp circuit will reliably convert the linear domain of the input voltage to another linear domain with different interval limits.

Computed values

Voltage Domain Conversion Amplifier computations:

Range of the input voltage (sensor voltage):

$$Vin \in [0.5V; 3V]$$

Range of the output voltage needed [2 ÷ (Vcc-2V)]:

$$Vout \in [2V; 13V]$$

$$\exists NF \Rightarrow v^- = v^+ \tag{44}$$

$$\begin{cases} v^- = \frac{R_{14}}{R_{13}+R_{14}} \cdot V_{ref} + \frac{R_{13}}{R_{13}+R_{14}} \cdot V_{out} \\ v^+ = V_{in} \end{cases} \tag{45}$$

$$V_{in} = \frac{R_{14}}{R_{13}+R_{14}} \cdot V_{ref} + \frac{R_{13}}{R_{13}+R_{14}} \cdot V_{out} \tag{46}$$

$$V_{out} = \left(\frac{R_{14}}{R_{13}} + 1\right) V_{in} - \frac{R_{14}}{R_{13}} \cdot V_{ref} \tag{47}$$

Gain of the Amplifier computation:

$$a = \frac{R_{14}}{R_{13}} + 1 \Rightarrow a = \frac{V_{out\_max} - V_{out\_min}}{V_{in\_max} - V_{in\_min}} \tag{48}$$

$$\frac{R_{14}}{R_{13}} + 1 = \frac{13-2}{3-0.5} \Rightarrow \frac{R_{14}}{R_{13}} = 3.4 \tag{49}$$

If the resistance ratio is met and the values are in range of Kilo-ohms any values can be chosen. I choose for R_{13}=10 [kΩ], therefore: R_{14}=34 [kΩ]. At the inputs of an OpAmp, impedance matching is mandatory for proper functionality, thus the resistance R_7 is the parallel combination of R_{13} and R_{14} and has the value of 7.72 [kΩ].

Resistor	Value [kΩ]
R_7	7.72
R_{13}	10
R_{14}	34

Table 5. Voltage Domain Converted - Computed Resistances

Voltage reference computation:

$$V_{ref} = \frac{\left(\frac{R_{14}}{R_{13}}+1\right)V_{in}-V_{out}}{\frac{R_{14}}{R_{13}}}\Big|_{max\ or\ min} \quad (50)$$

$$V_{ref} = \frac{\left(\frac{34}{10}+1\right)3-13}{\frac{34}{10}} \quad (51)$$

$$V_{ref} = 0.058823[V] \quad (52)$$

- Simulation profile:

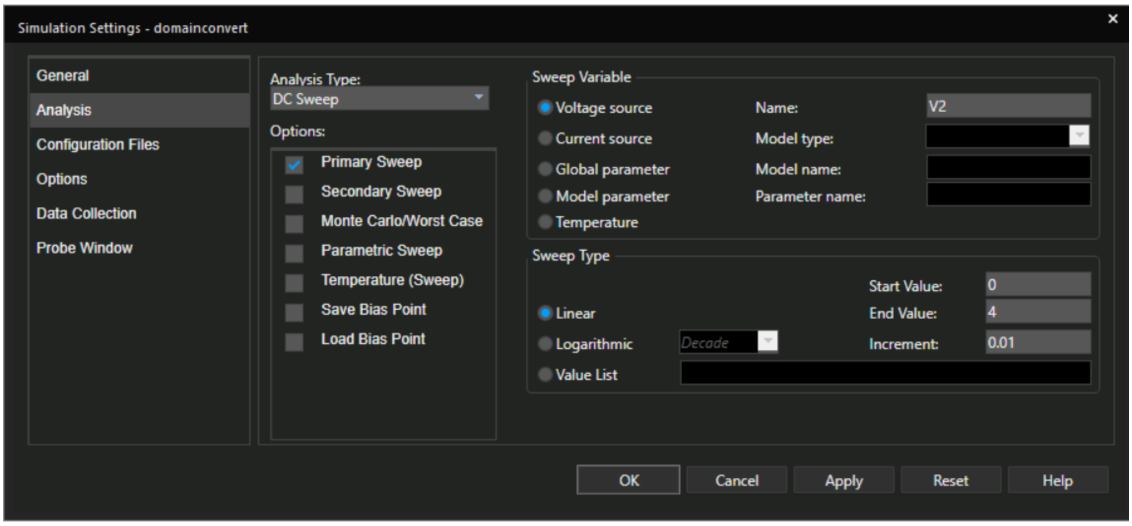


Figure 22. Simulation profile for Voltage Domain Convert Test

- Simulated values and graphs:

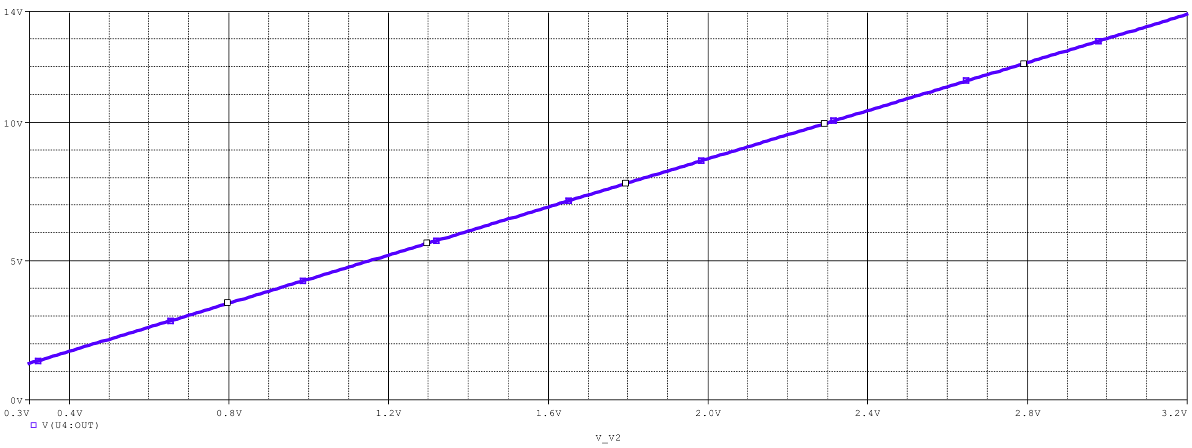


Figure 23. Voltage Range - Computed Values

Trace Color	Trace Name	Y1
	X Values	500.706m
CURSOR 1,2	V(U4:OUT)	2.1651

Trace Color	Trace Name	Y1
	X Values	3.0000
CURSOR 1,2	V(U4:OUT)	13.004

Figure 24. Min and Max values from both Domains - Computed Values

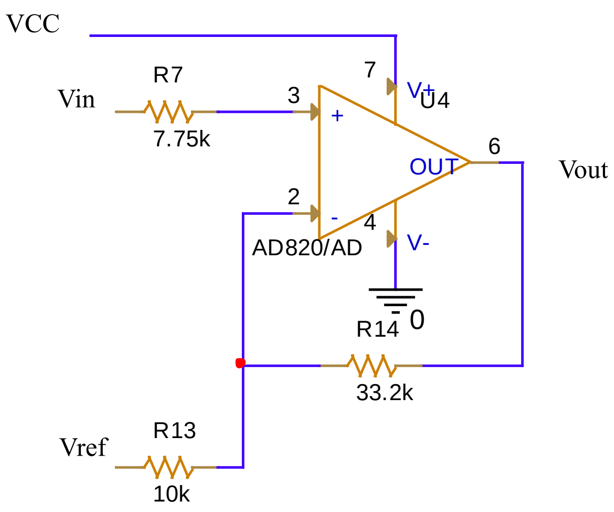


Figure 25. Voltage Domain Converter Amplifier – Standardized values

Values of resistances after standardization:

Resistor	Value [kΩ]
R_7	7.75
R_{13}	10
R_{14}	33.5

Table 6. Voltage Domain Converted - Standardized Resistances

- Simulations after standardization:

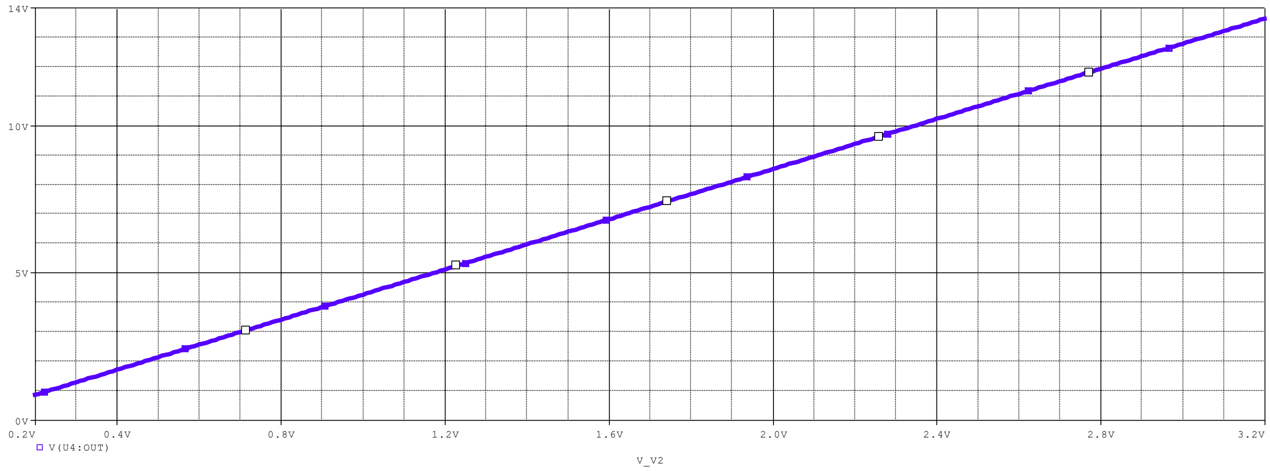


Figure 26. Voltage Range - Standardized Values

Trace Color	Trace Name	Y1
	X Values	500.848m
CURSOR 1,2	V(U4:OUT)	2.1259

Trace Color	Trace Name	Y1
	X Values	3.0030
CURSOR 1,2	V(U4:OUT)	12.781

Figure 27. Min and Max values from both Domains - Standardized Values

As seen in the Figure 24. Min and Max values from both Domains - Computed Values; and in Figure 27. Min and Max values from both Domains - Standardized Values; the upper limit of the interval decreased a significant 0.2V. Furthermore, in the project this variation won't make a difference because the sensor and the other involved component are not perfect and their voltages and current will compensate for the voltage loss. The negative feedback from all the subsystems that form the schematic will regulate the output signal to the desired values.

The voltage reference being of such small value will be taken from a transistor in Diode configuration, and the 0.6V voltage across it will be further divided into the desired 0.058V needed. It is used as a NPN Transistor instead of a regular diode because the diode needs more current than the transistor to give a stable reference voltage.

$$\frac{VCC - v_{BE}}{Ic} = R_8 \qquad (53)$$

$$\frac{15 - 0.6}{1m} = R_8 \qquad (54)$$

$$14.4[k\Omega] = R_8 \qquad (55)$$

From the obtained v_{BE} the voltage division can be made more efficient.

$$V_{ref} = \frac{R_9}{R_{10}+R_9} \cdot v_{BE} \tag{56}$$

$$\frac{V_{ref}}{v_{BE}} = \frac{R_9}{R_{10}+R_9} \Longrightarrow \frac{0.0588}{0.6} = \frac{R_9}{R_{10}+R_9} \tag{57}$$

If the resistances respect the ratio and are in Kilo-ohm range, any value can be chosen. I choose R_9=10 [kΩ], therefore: R_{10}=92.04 [kΩ].

Resistor	Value [kΩ]
R_8	14.4
R_9	92.04
R_{10}	10

Table 7. Transistor diode - Voltage Reference - Computed values

Standardization of the resistances, in the process were chosen the resistances with the closest values or the ones that do not influence the overall circuit in a negative way.

Resistor	Value [kΩ]
R_8	15
R_9	100
R_{10}	10

Table 8. Transistor diode -Voltage Reference - Standardized values

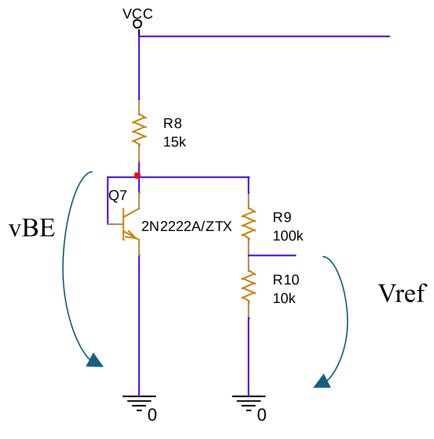


Figure 28. Transistor Voltage Reference

At this point if the 2 circuits are connected the output won't be correct and the computed one due to the problem of the impedance matching. The resistances used in the reference circuit are comparable in size to the ones used in the voltage domain converter amplifier, therefore they will interfere with the functionality of the amplifier. To overcome this problem a buffer is needed in between, to act as an impedance matching device. There are many types of buffers, but for the reason of being efficient when it comes to the components use, a simple BJT NPN Emitter Follower will be used.

The external resistances around the buffer can have a rather high tolerance, when it comes to their value, the input resistance comes in series whit the base resistance, thus increasing the overall input resistance. For this purpose, a resistance of R_{11}=10 [kΩ] was chosen. The output resistance cannot be simply chosen because it is placed in the emitter of the transistor, thus it acts with negative feedback on the input of the buffer.

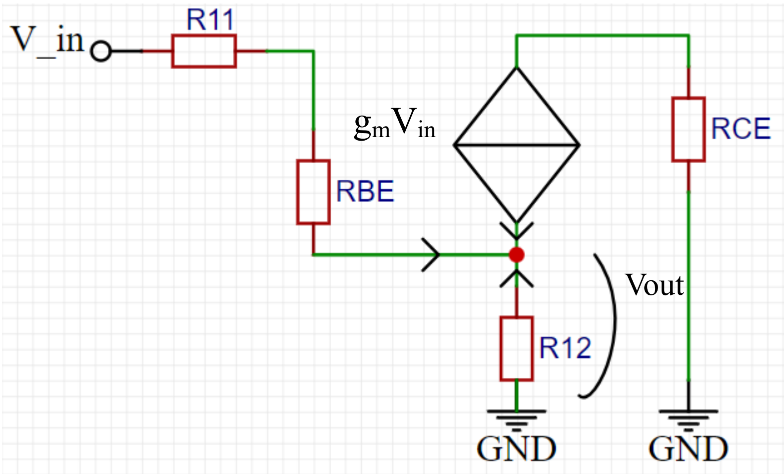


Figure 29. Small signal model of the Emitter Follower Buffer

To compute the needed Emitter resistance, the Small Signal DC Model will be used. From experiments and trials, the best suited collector current has the value of Ic=130uA. The gain, or the ratio $\frac{V_{out}}{V_{in}}$ must be equal to 1 to make a buffer.

$$V_{in} = v_{BE} \tag{58}$$

$$\frac{V_{in}}{R_{11}+r_{BE}} + g_m \cdot v_{BE} + \frac{-V_{out}}{R_{12}} = 0 \tag{59}$$

$$\frac{V_{out}}{V_{in}} = R_{12}\left(\frac{1}{R_{11}+r_{BE}} + g_m\right) \tag{60}$$

$$g_m = 40I_C \Longrightarrow g_m = 0.0052[S] \qquad (61)$$

$$r_{be} = \frac{\beta}{g_m} \Longrightarrow r_{be} = 19.23[k\Omega] \qquad (62)$$

$$R_{12} = \frac{1}{\frac{1}{R_{11}+r_{be}}+g_m} \Longrightarrow R_{12} = \frac{1}{\frac{1}{10\cdot10^3+19.23\cdot10^3}+0.0052} \qquad (63)$$

$$R_{12} = 191.05[\Omega] \qquad (64)$$

The value of $R_{12} = 191.05[\Omega]$ does not meet any resistor standard, thus the value $R_{12} = 195[\Omega]$ is going to be used.

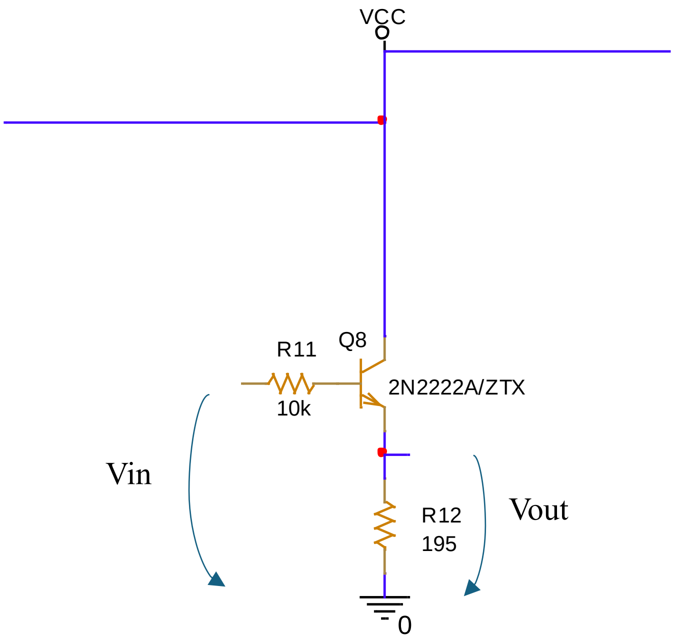


Figure 30. Emitter Follower

Non-inverting Hysteresis Comparator

Electrical Scheme

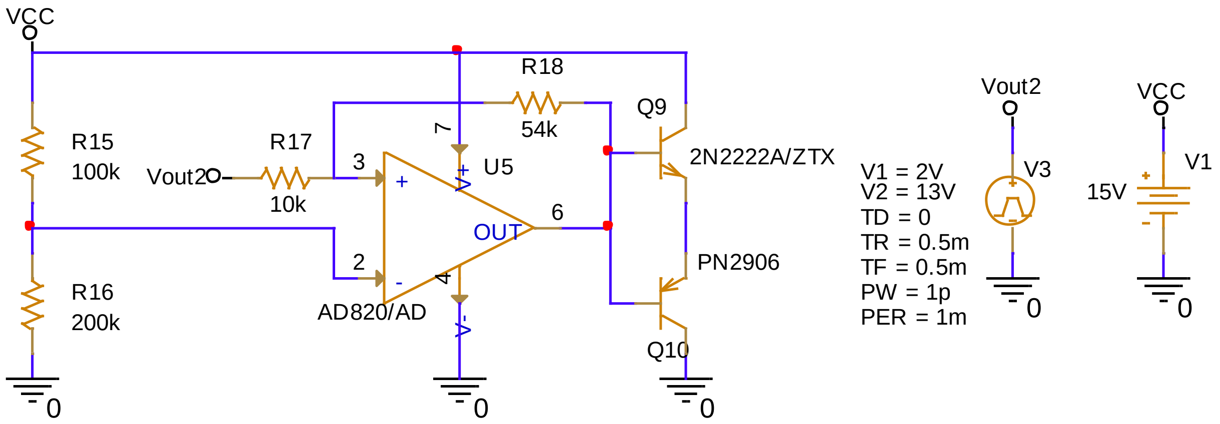


Figure 31. Non-inverting Hysteresis Comparator with reference voltage

Duty of the circuit

The circuit from the Figure 31. Non-inverting Hysteresis Comparator with reference voltage; has the duty to command the relay that will further control the water pump. The voltage references from the circuit V_{ThL} and V_{ThH} are set to be the limits of the state of the pump; therefore, high precision is needed. The Hysteresis comparator is of non-inverting configuration because the direct logic is implemented. The humidity of the soil is inverse proportional to the sensor electrical resistance because the water and the minerals from the soil can conduct the electric current that the sensor circuit can provide. Therefore, as the resistance of the sensor increases to the maximum value $R = 537.5[k\Omega]$ (25), the humidity of the soil decreases, and the water pump must be tuned on; the water pump is kept on until the senor reaches the lowest resistance value of $R = 412.5[k\Omega]$ (27) then the pump is kept off until the resistance of the sensor increases to the previous high value and the cycle repeats itself. The OpAmp AD820 is single rail supplied, thus the need of a voltage reference to shift the Hysteresis VTC upwards to positive values of the input voltage is a must, to provide the true representation of the correct curve.

The main power source is chosen to be only a one rail supply of the specified VCC=15V, and all the OpAmp are single rail supplied; because a dual rail power supply is much harder to maintain and a fist-rate one is high-priced, a client will most probably go for the cheaper single rail model.

Computed values

The threshold values of the hysteresis comparator are determined by the voltages given form the Figure 21. Voltage Domain Conversion Amplifier; that respect the actual resistance of the sensor.

- Resistance to voltage from the Figure 16. Resistance to Voltage Configuration

  - V_{on_sensor} - the voltage for the command "ON" from the Resistance to Voltage circuit:

$$V_{on\_sensor} = R_{ON} \cdot I \quad (65)$$

$$V_{on\_sensor} = 537.5 \cdot 10^3 \cdot 5 \cdot 10^6 \quad (66)$$

$$V_{on\_sensor} = 2.6875[V] \quad (67)$$

  - V_{off_sensor} - the voltage for the command "OFF" from the Resistance to Voltage circuit:

$$V_{off\_sensor} = R_{OFF} \cdot I \quad (68)$$

$$V_{off\_sensor} = 412.5 \cdot 10^3 \cdot 5 \cdot 10^6 \quad (69)$$

$$V_{off\_sensor} = 2.0625[V] \quad (70)$$

- Initial to voltage from the Figure 16. Resistance to Voltage Configuration to Figure 21. Voltage Domain Conversion Amplifier

  - $V_{on\_domain\_converted}$ - the voltage for the command "ON" from the Voltage Domain Converter Amplifier circuit:

$$V_{on\_domain\_converted} = \left(\frac{R_{14}}{R_{13}} + 1\right) V_{on\_sensor} - \frac{R_{14}}{R_{13}} \cdot V_{ref} \quad (71)$$

$$V_{on\_domain\_converted} = \left(\frac{33.5}{10} + 1\right) 2.6875 - \frac{33.5}{10} \cdot 0.058823 \quad (72)$$

$$V_{on\_domain\_converted} = 11.4935[V] \quad (73)$$

- $V_{off\_domain\_converted}$ - the voltage for the command “OFF” from the Voltage Domain Converter Amplifier circuit:

$$V_{off\_domain\_converted} = \left(\frac{R_{14}}{R_{13}} + 1\right) V_{off\_sensor} - \frac{R_{14}}{R_{13}} \cdot V_{ref} \quad (74)$$

$$V_{off\_domain\_converted} = \left(\frac{33.5}{10} + 1\right) 2.0625 - \frac{33.5}{10} \cdot 0.058823 \quad (75)$$

$$V_{off\_domain\_converted} = 8.7748[V] \quad (76)$$

From the previous computation it results that the thresholds for which the OpAmp will perform the correct application are:

$$V_{on\_domain\_converted} = V_{ThH} \Longrightarrow V_{ThH} = 11.4935[V] \quad (77)$$

$$V_{off\_domain\_converted} = V_{ThL} \Longrightarrow V_{ThL} = 8.7748[V] \quad (78)$$

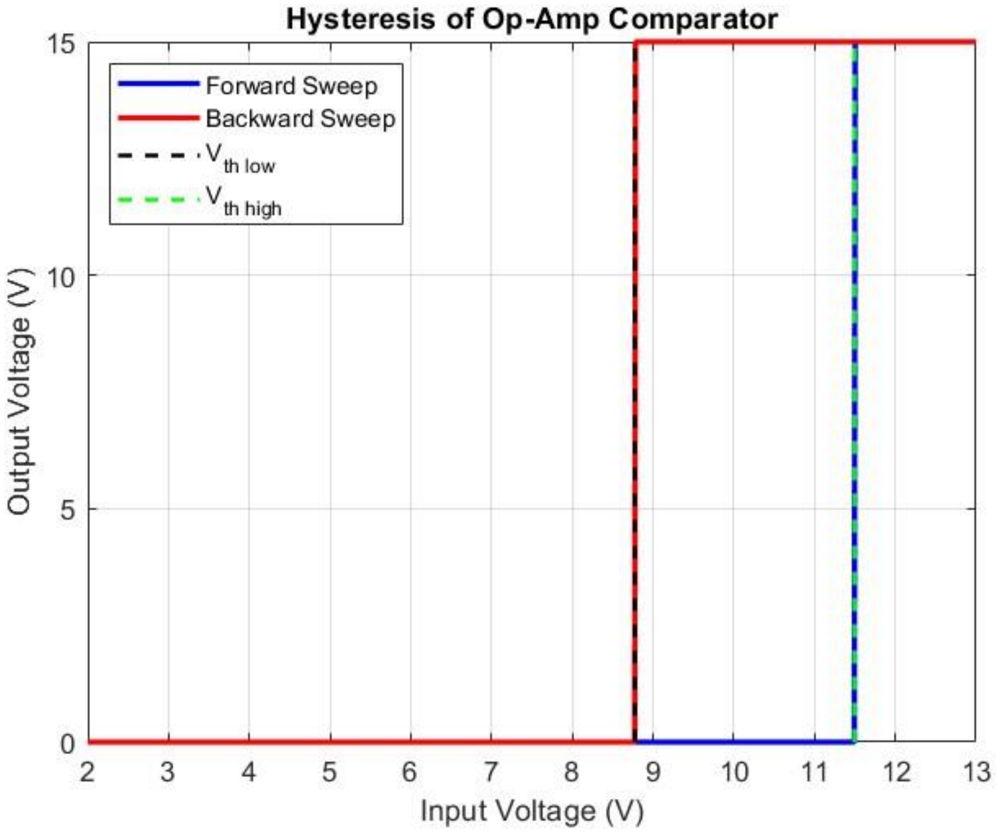


Figure 32. Ideal Hysteresis VTC of the Comparator

The nature of the circuit of only being single rail supplied, it needs a voltage reference to obtain the right values. The resistances R_{17} and R_{18} , after experimental and computational tries, I deliberately chosen to use $R_{17} = 10[k\Omega]$ and R_{18} resistance and the needed voltage reference are the only electrical value that are going to be computed.

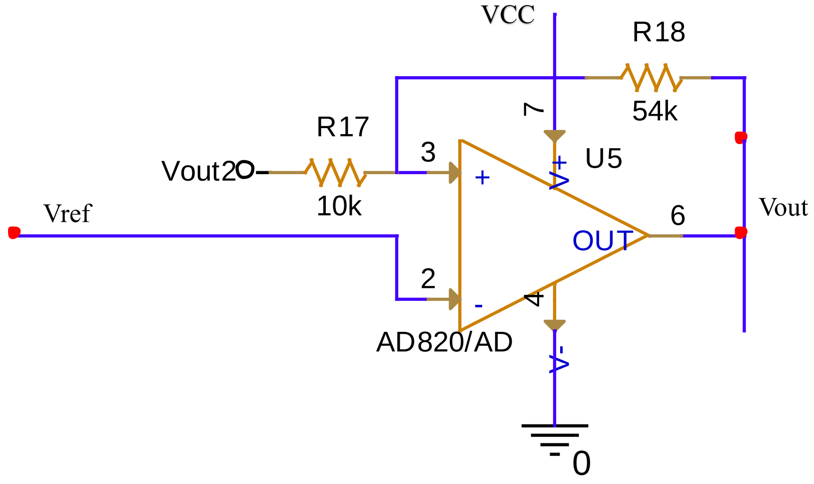


Figure 33. Hysteresis Comparator with Voltage Reference

$$\begin{cases} V_{ThL} = -\frac{R_{17}}{R_{18}} \cdot V_{OH} + \left(1 + \frac{R_{17}}{R_{18}}\right) V_{ref} \\ V_{ThH} = -\frac{R_{17}}{R_{18}} \cdot V_{OL} + \left(1 + \frac{R_{17}}{R_{18}}\right) V_{ref} \end{cases} \quad (79)$$

$$\begin{cases} 8.7748 = -\frac{10}{R_{18}} \cdot 15 + \left(1 + \frac{10}{R_{18}}\right) V_{ref} \\ 11.4935 = -\frac{10}{R_{18}} \cdot 0 + \left(1 + \frac{10}{R_{18}}\right) V_{ref} \end{cases} \quad (80)$$

$$\begin{cases} R_{18} = 55.1734[k\Omega] \\ V_{ref} = 9.7299[V] \end{cases} \quad (81)$$

The value of $R_{18} = 55.1734[k\Omega]$ does not meet any standard thus the value of $R_{18} = 54[k\Omega]$ is going to be used. For the voltage reference, after experimentation the value, of the reference does not need to be very precise, thus it is going to be approximated to $V_{ref} = 10[V]$. A resistive voltage divider is going to be used, the values of the resistances are high enough to not significantly influence the functionality of the circuit and a buffer won't be used in this case; and $R_{15} = 100[k\Omega]$ is used.

$$V_{ref} = \frac{R_{16}}{R_{16}+R_{15}} VCC \Longrightarrow 10 = \frac{R_{16}}{R_{16}+100} 15 \quad (82)$$

$$R_{16} = 200[k\Omega] \quad (83)$$

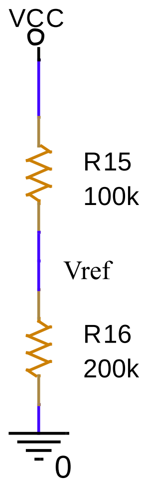


Figure 34. Resistive Voltage Divider

In the circuit that is following this block diagram the output current needed exceeds the maximum rated output current of the AD820 OpAmp, of around $[20 - 30]mA$. To overcome this issue a BJT Puss-Pull configuration is proposed. The advantage is the increased output current capability, and the protection of the OpAmp from overcurrent. The disadvantage is that now, the output voltage swing won't be rail to rail anymore but (VCC-0.6) V and 0.6V. The used transistors are the 2N2222A NPN BTJ and the PN2906 PNP BJT, because of their capability of supporting a high I_c=100mA collector current, that is sufficient for any small load the command circuit will have to drive.

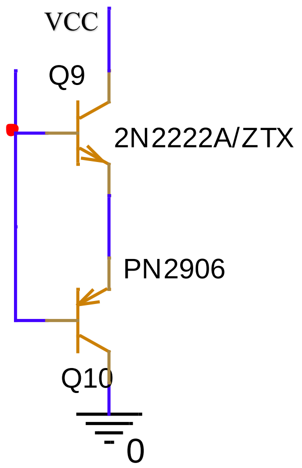


Figure 35. Push Pull BJT Amplifier

- Simulation profile:

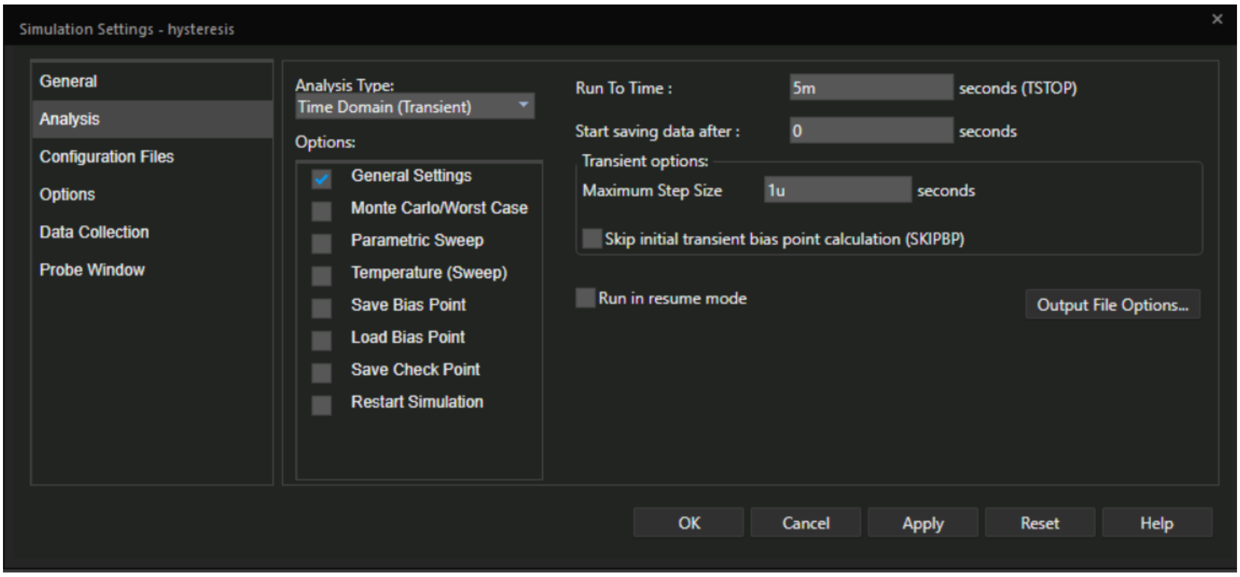


Figure 36. Setting Profile for Hysteresis

- Hysteresis and functionality of the control circuit:

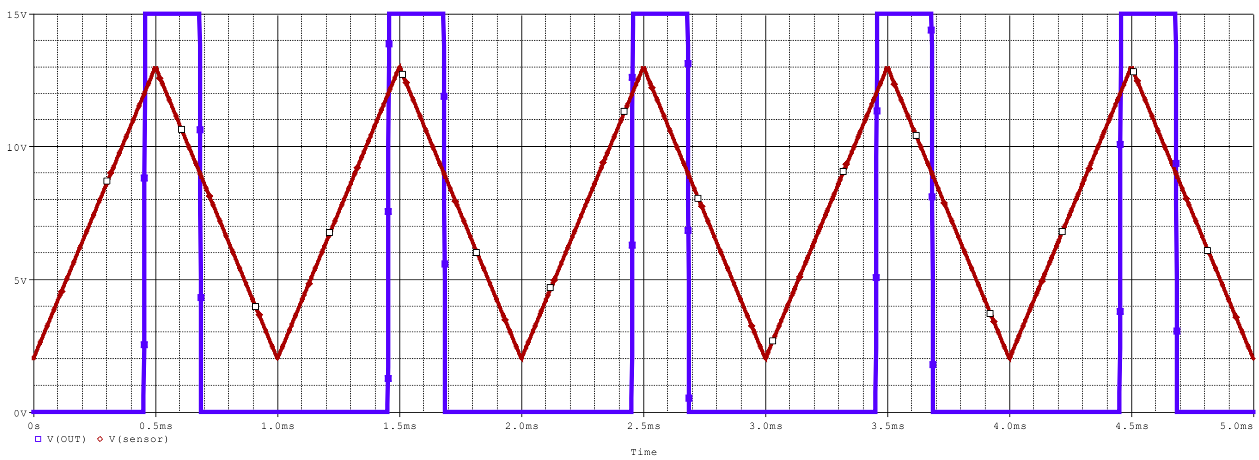


Figure 37. Hysteresis of the Output Command signal with respect to the Sensor Voltage

As seen in the Figure 37. Hysteresis of the Output Command signal with respect to the Sensor Voltage; the Output of the Hysteresis meets the requirements and switches at V_{ThL} and V_{ThH}. A triangular signal was used to simulate the sensor voltage for clean transitions.

Trace Color	Trace Name	Y1
	X Values	457.902u
CURSOR 1,2	V(OUT)	14.988
	V(sensor)	12.069

Trace Color	Trace Name	Y1
	X Values	693.956u
CURSOR 1,2	V(OUT)	7.3749m
	V(sensor)	8.7330

Figure 38. Hysteresis Voltage Thresholds and the Output Voltages

From the Figure 38. Hysteresis Voltage Thresholds and the Output Voltages; the real values at which the switch of the output signals have a slight voltage difference; that does not influence the functionality of the command circuit in such a way that more improvements are necessary. The small improvements for only the V_{ThH} to be the same as the theoretical value, will need the change of components, therefore will increase the cost of it.

Power Circuit + Relay

Electrical Scheme

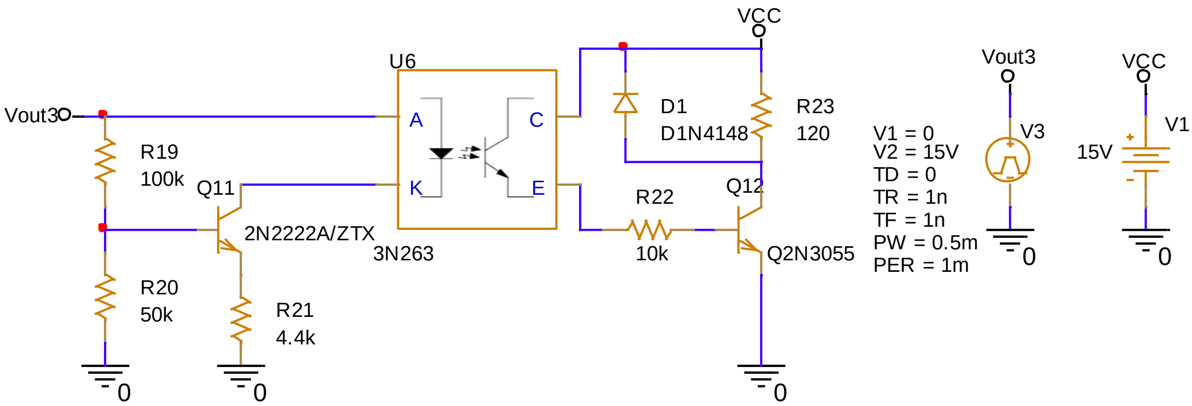


Figure 39. Power circuit of the Relay

Duty of the circuit

The above circuit from the Figure 39. Power circuit of the Relay; has the duty of handling the total power that the relay needs for functioning. The circuit uses an optocoupler electrically isolating the command signal circuit from the power circuit. The control side takes the hysteresis output signal and converts it into the needed current for the optocouplers diode. The power side uses the phototransistor from the optocoupler and switches the power transistor ON or OFF, therefore the coil/ resistance of the relay is energized or not. The D1 diode is used for the protection of the Q12 transistor; in the real world R_{23} is a coil, thus it over voltages when it switches off.

Computed values

At first this circuit is divided into two electrically isolated sections; the connection, or better said, the data transmission is done via an optical medium. Optocouplers are devices widely used to make electrical isolation of the rugged circuits from the more sensible control circuits, that cannot handle a big current value. They can be seen in almost all Relay Driver Modules and Boards, so to respect the practical aspect of the circuit, I have included an Optocoupler to ensure better isolation and to stay in line with the industry standards.

The IR (Infrared) LED is driven by a simple LED one NPN BJT LED driver. It places the LED (load) into the collector of the Q11, transistor and the corresponding series resistance R_{21} into the emitter, the voltage into the base is a division of the signal voltage. The resistance places into the emitter rather than in the collector, in the present configuration of a Common Emitter, acts as Negative Feed-Back system, therefore is improving the stability of the structure. The voltage of the input signal switches between 0V to 15V; to drive the transistor with direct 15V will saturate it quickly thus the power that it would handle is rather big. The solution is to reduce the bias voltage of the Q11 transistor, to a lower value; the value is empirically chosen to be equal with 5V; because is low enough to reduce the power on the transistor.

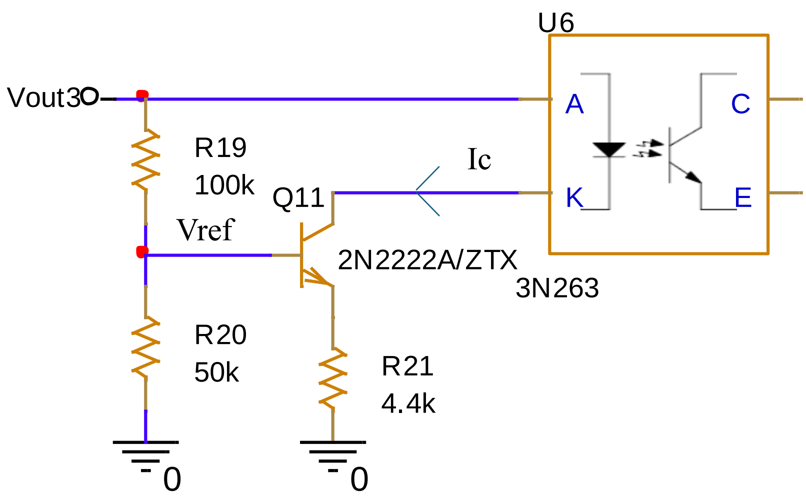


Figure 40. Optocoupler Diode Driver

$$V_{ref} = \frac{R_{20}}{R_{19}+R_{20}} \cdot V_{out3} \tag{84}$$

$$V_{ref} = \frac{50}{100+50} \cdot 15 \tag{85}$$

$$V_{ref} = 5[V] \tag{86}$$

The current through the Optocouplers diode, for proper operation in this application is set to be Ic=1mA.

$$V_{ref} = V_{BE} + I_C \cdot R_{21} \tag{87}$$

$$R_{21} = \frac{V_{ref}-V_{BE}}{I_C} \tag{88}$$

$$R_{21} = \frac{5-0.6}{1 \cdot 10^{-3}} \tag{89}$$

$$R_{21} = 4.4[k\Omega] \tag{90}$$

All the resistances meet the industry standards; therefore, a standardization is not needed. To furthermore demonstrate the value of the current we can look at the DC bias current that flows in the diode. Also, the voltage reference V_{ref} can be checked to ensure the connectivity of the computed values.

Evaluate	Measurement	Value
✓	Max(I(U6:A))	957.73424u

Figure 41. Maximum (steady state) Current Through the Optocouplers Diode

Evaluate	Measurement	Value
✓	Max(V(R19:1))	4.85723

Figure 42. Maximum (steady state) Voltage reference

The second part of the circuit considers the power handling of the entire project; the relays coil being the biggest load that the circuit must supply and command. The Phototransistor of the Optocoupler acts as switch on a direct logic, meaning that, when light hits its base the transistor closes, and in the other case when there is no light the transistor stays open. This switches “on” or “off” the current that flows through the power transistor Q12. The diode D1 has a use only in real life when, instead of the resistance R_{23} is connected the proper relay that has a coil. When the transistor switches off, the energy that the coil stores in its magnetic field, will collapse back into the coil, thus it will create an overvoltage 10 or 100 times bigger that the power supply one; at the pin that is connected to the transistor, that will destroy it in time. To prevent all this, a flyback diode is added, so the current that is generated when the magnetic field collapses flow through the diode and the coil until it fades out.

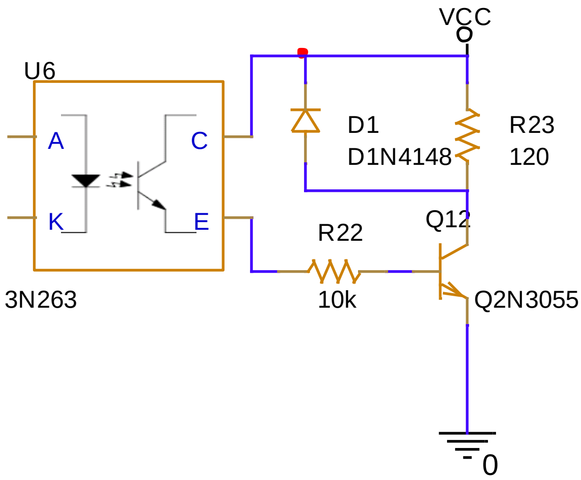


Figure 43. Optocoupler Relay Control

Coil Power	1.2W
Coil Voltage	12V dc
Coil Resistance	120 Ω
Switching Current	10A
Isolation Coil to Contact	1.5kVac
Terminal Type	Through Hole

Table 9. RS PRO, 12V dc Coil Non-Latching Relay DPDT, 10A – Datasheet

From the relays datasheet seen in Table 9; we can compute the voltage across the transistor and the current through the resistance R_{23}. The coil is a 12V one, therefore from the 15V power supply, 3V must drop over the transistor to not destroy the coil with overvoltage. The current of the coil is computed in the relation (91) .

$$I = \frac{V}{R_{23}} \tag{91}$$

$$I = \frac{12}{120} \tag{92}$$

$$I = 0.1[A] \tag{93}$$

Component	Parameter	Value
3N263(TX, TXV) Optocoupler	$V_{CE(SAT)}$ (max) [V]	0.3
2N3055 TOSHIBA Power Transistor	DC Current Gain h_{fe} (max)	70

Table 10. Needed characteristics from the Datasheet of the Power Transistor and the Optocoupler

To size the proper value to the resistance R_{22} the values from the Table 10; are needed.

$$\frac{I_C}{I_B} = \beta \tag{94}$$

$$\frac{I_C}{\beta} = I_B \tag{95}$$

$$\frac{0.1}{70} = I_B \tag{96}$$

$$I_B = 0.0014285[A] \Longrightarrow I_B = 1.4285[mA] \tag{97}$$

$$VCC - V_{CE(SAT)} - V_{BE} - I_B \cdot R_{22} = 0 \tag{98}$$

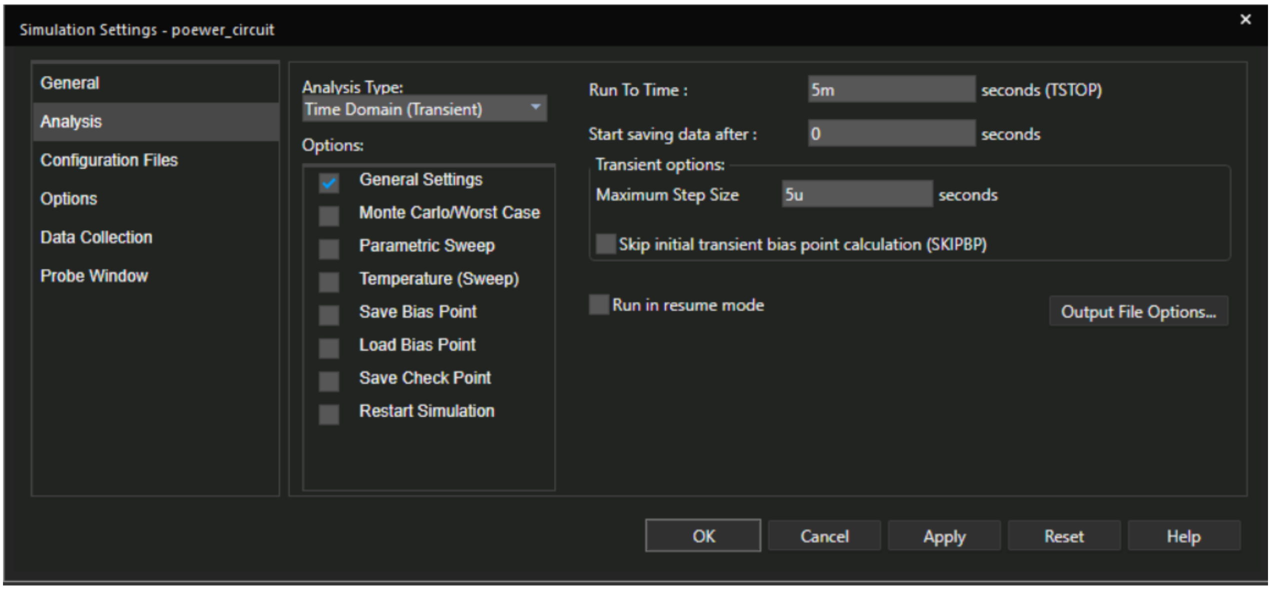
$$\frac{VCC - V_{CE(SAT)} - V_{BE}}{I_B} = R_{22} \tag{99}$$

$$R_{22} = \frac{15 - 0.3 - 0.6}{0.0014285} \tag{100}$$

$$R_{22} = 9.87049[k\Omega] \tag{101}$$

The value of $\mathrm{R}_{22} = 9.87049[\mathrm{k}\Omega]$ (101) is not standardized thus the value of $R_{22} = 10[k\Omega]$ is going to be used.

- Simulation profile:



- Simulation results:

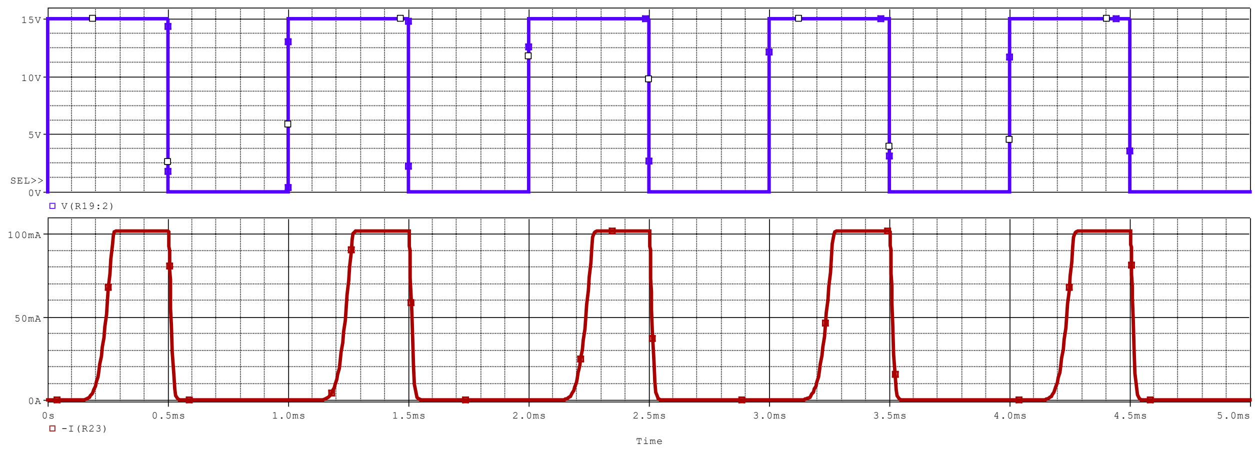


Figure 44. Control Voltage and the Current of the Relay

From the Figure 44. Control Voltage and the Current of the Relay; it can be observed that the 2N3055 transistor has a big input capacitance, therefore the current through the relay does not immediately switch on. This is not a problem because the input test signal is way faster than the nominal operation of the circuit.

- Measurements results

Evaluate	Measurement	Value
☑	Min(V(Q12:C))	2.78915

Figure 45. V_{CE} of the Q12 2N3055 Power Transistor

Evaluate	Measurement	Value
☑	Max(IB(Q12))	1.43024m

Figure 46. I_B of the Q12 2N3055 Power Transistor

Evaluate	Measurement	Value
☑	Max(IC(Q12))	101.75437m

Figure 47. I_C of the Q12 2N3055 Power Transistor

Evaluate	Measurement	Value
☑	Max(W(R23))	1.24254

Figure 48. Maximum Power of the R_{23} resistance of the Relay coil

Component description

1. **3N263 Hi-Reliability Optically Coupled Isolator**; consists of an infrared emitting diode and an NPN silicon phototransistor which are mounted in a hermetically sealed TO-72 package. This optocoupler was chosen because of the low diode current needed for proper functionality and for its high switching speed.

2. **2N3055 TOSHIBA General Purpose Power Transistor**, which is usually used for power regulators, switching and solenoid driver's applications. This transistor was chosen because of its high current capability, and still a relative high gain.

3. **RS PRO, 12V dc Coil Non-Latching Relay DPDT, 10A – Datasheet**; an electrical switching device is one of them to appreciate in applications, regardless of whether it is latching or non-latching Relay. They both represent a different approach to application functionality, bringing the electronics world to life. This relay was chosen because of its high current switching and rather low driving current.

LED – state of the pump

Electrical Scheme

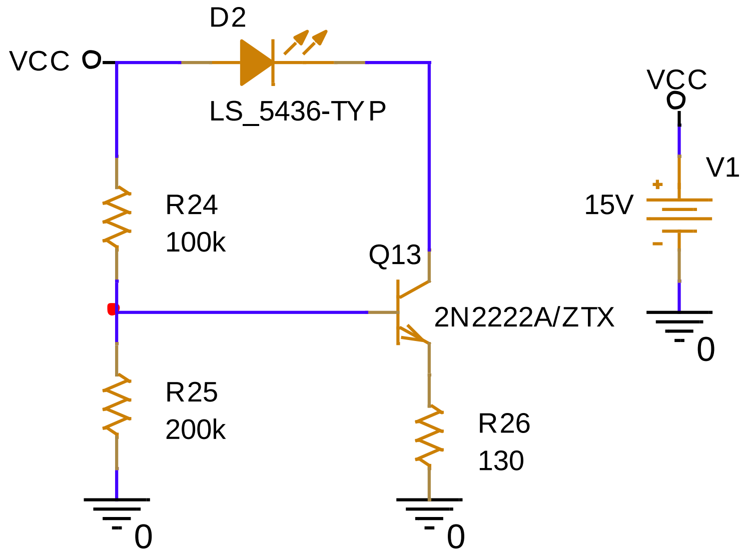


Figure 49. RED LED Driver

Duty of the circuit

The circuit from the Figure 49. RED LED Driver; has the duty of notifying the used about the state of the water pump. The supplied voltage being VCC=15V, using a resistor to step down to the nominal voltage needed for the LED, would be highly inefficient because the resistor will dissipate more power than the LED itself. Another problem is the fact that the current over voltage graph is not linear for LEDs, and a small voltage change would create a much bigger current change; that could cause the destruction of the LED. The solution is by using an LED driver like the one from the photo, that will drive the load with constant current, not constant voltage. Placing the resistor R_{26} into the emitter of the BJT ensures negative feedback, that furthermore improves the stability of the whole system.

Computed values

The datasheet of the Led states a current I_{LED}=20mA and a forward voltage of V_{LED}=2V for Red, or to be more specifical, the color “Super-Red”. This implies that the collector current of the Q13 transistor to be equal with I_C=20mA. For calculation the DC bias of the transistor is not enough to use simplified equations because they assume that almost no current flows into the base are the NPN transistor. To solve this problem, extended calculations are going to be used.

The bias resistances are, and the power supply is going to be transformed into a real voltage source using the Thevenin Theorem.

$$R' = \frac{R_{24} \cdot R_{25}}{R_{24} + R_{25}} \quad (102)$$

$$R' = \frac{100 \cdot 200}{100 + 200} \quad (103)$$

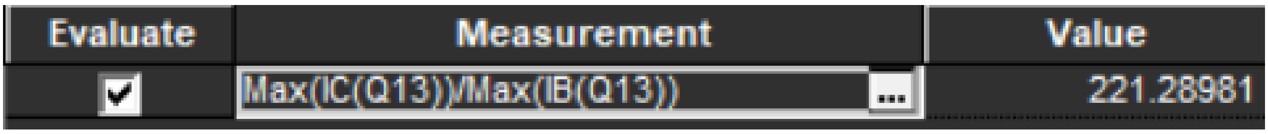
$$R' = 66.6[k\Omega] \quad (104)$$

$$V_{BB} = \frac{R_{25}}{R_{24} + R_{25}} \cdot V_{CC} \quad (105)$$

$$V_{BB} = \frac{200}{100 + 200} \cdot 15 \quad (106)$$

$$V_{BB} = 10[V] \quad (107)$$

The range of the β or h_{fe} from the datasheet does not include the scenario of this application of the 2N2222A BJT NPN, therefore the DC current gain is going to be taken empirically from the simulation. The formula for the gain that is going to be used is the one from (94) therefore:



Evaluate	Measurement	Value
✔	Max(IC(Q13))/Max(IB(Q13))	221.28981

Figure 50. DC current gain β of the 2N222A transistor (Empirically)

To furthermore test the correctness of the value of the current, the emitter current is going to be computed with the given β and the already chosen values of the resistors, on the next page, in the equation (108).

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \frac{R'}{(\beta+1)}} \tag{108}$$

$$I_E = \frac{10-0.6}{130+\frac{66.6 \cdot 10^{-3}}{(221.2898+1)}} \tag{109}$$

$$I_E = 0.02188[A] \Rightarrow I_E = 21.88[mA] \tag{110}$$

- Measurements results:

Evaluate	Measurement	Value
☑	Max(V(VCC))- Max(V(D2:2))	2.01605
☑	Max(I(D2))	21.51085m

Figure 51. Voltage across the LED and Current through the LED

Component description

The Led used is a Hyper 5 mm (T1) LED, Non-Diffused Hyper-Bright LED, of color super-red, produced by Siemens. The super in front of the red significates a higher wavelength of 632nm, that is a more pronounced shade of red. That is also the reason that the LED needs a high voltage of 2V at a current draw of 20mA; high value considering that the usual red LED takes only a around 1.8V to operate.

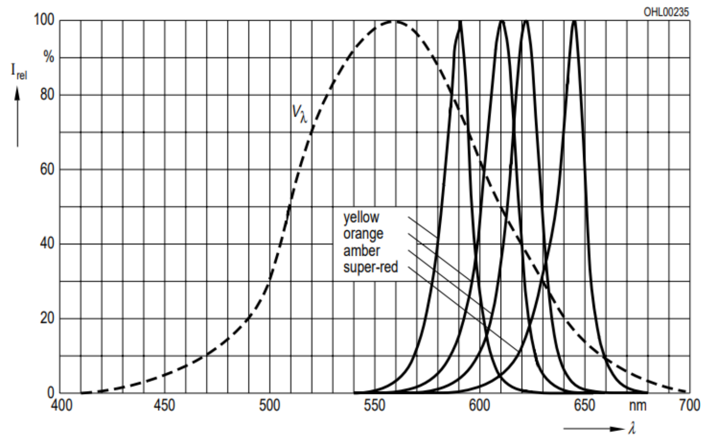


Figure 52. Standard eye response curve - from Siemens Datasheet of the 5436 LED Series

Circuit Implementation - Circuit Analysis

Electrical Scheme – Complete Circuit

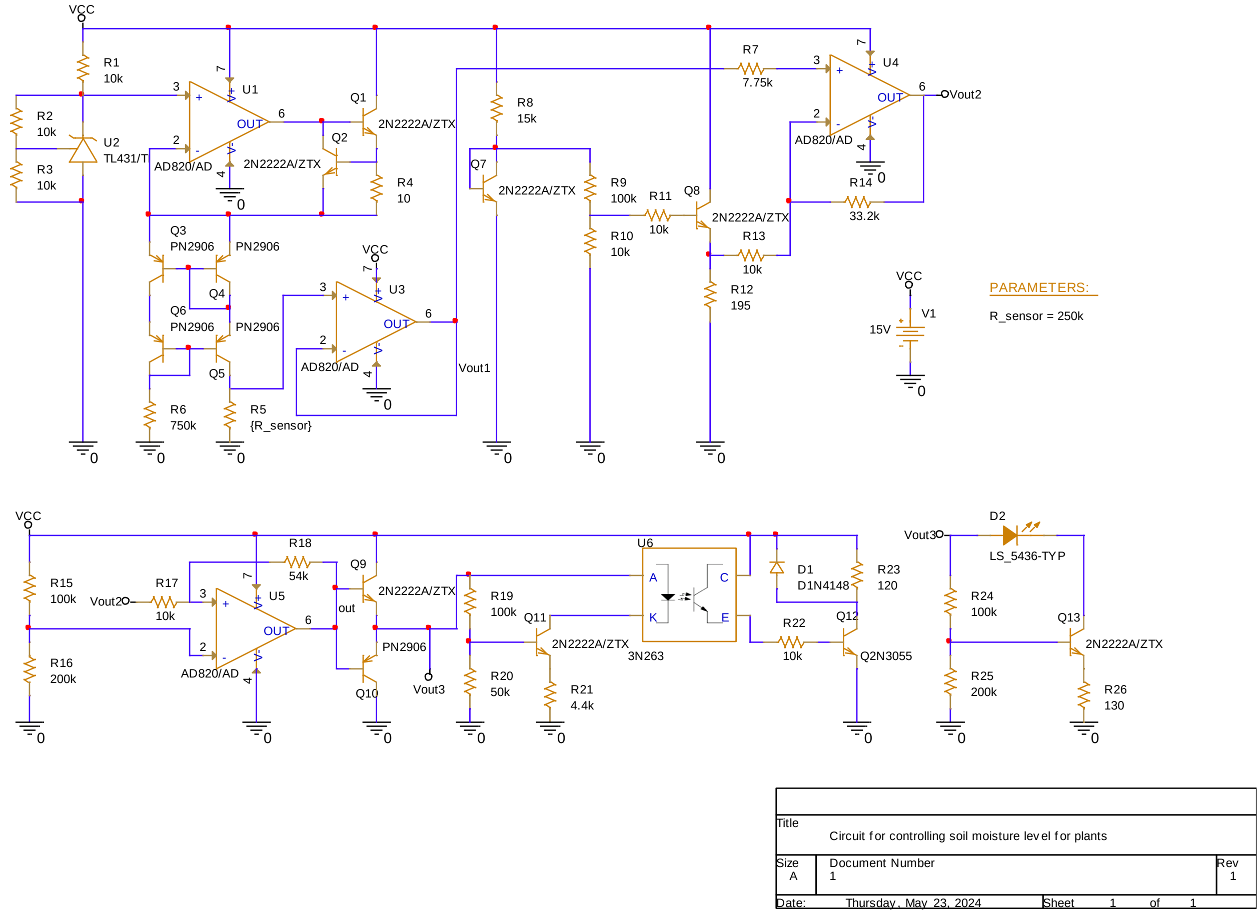


Figure 53. Electrical Scheme - Complete Circuit

In the figure above, is presented the entire circuit, with all the components standardized. Since all the blocks that compose the schematic are already computed and standardized, any furthermore computations won't be made, but instead the focus will be on the overall functionality of it. The expected behavior is as close as the one from each block simulated separately, and with little to no problems regarding the logic or the functionality of the circuit.

Reasons behind the whole project (circuit)

The complexity of the circuit is not strictly related to its performance but to its safety for the user and the environment. The basic function of turning a water pump “on” and “off” can be done with a much simpler circuit, but from a safety point of view maybe not preferable. The focus besides correct functionality is safety. In the wet and humidified environments where the circuit is going to be used, the chances of work hazards increase exponentially. To name a few, it is not specified what kind of voltage source the user is going to use; therefore if the chosen voltage source is some sort of battery, in a hazardous situation a short circuit may occur, and batterie can easily deliver lot of current, and cause a fire of some kind; moreover if the supply is a commercial power supply that steps down mains voltage and rectifies it; introduces not problems of overcurrent but also problems of overvoltage, and deadly electrocution. The solution was to protect the most vulnerable and vital part of the circuit; and that’s the sensor, by reducing the maximum voltage across it to 5V and the current that flows through it to 5uA. Furthermore, in the circuit the use of transistors for voltage references are to substitute diodes that consume more current and would make the circuit less efficient; and for buffers because those are the cheapest types of voltage followers. To jump at the bottom of the circuit the use of the optocoupler might be strange but ensures another layer of protection and it is also used in all the industry rated relay driver boards. The transistor is oversized for the case where the user might connect a water pump directly to the circuit and remove the relay completely. The super-red Led used offers a better and brighter shade of red, that is highly superior to the regular red, that might not be so easily noticed by persons.

Test of the whole circuit

- Simulation profile:

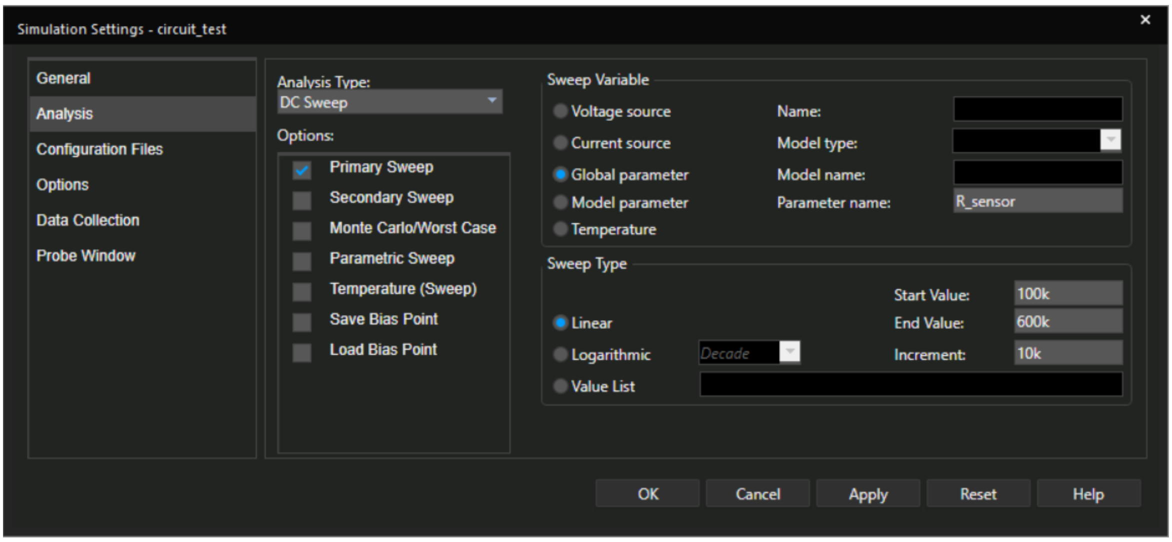


Figure 54. Test Circuit - Simulation profile

Sensor resistance to voltage

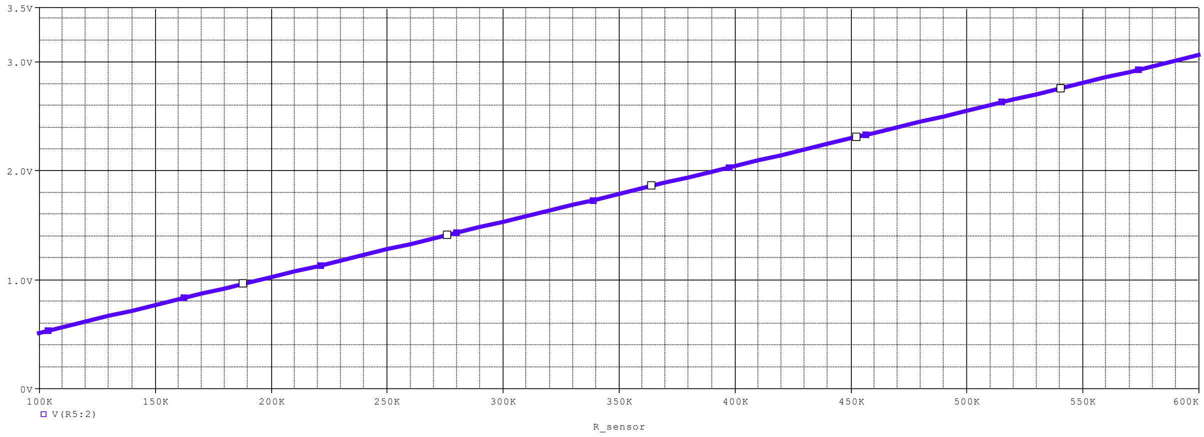


Figure 55. Measured - Sensor resistance to Voltage

Evaluate	Measurement	Value
✔	Max(V(R5:2))	3.05867
✔	Min(V(R5:2))	510.16156m

Figure 56. The Voltages for the Maximum and the Minimum values of R_sensor

In the above figures it can be observed that the real values of the voltage across the resistance of the sensor does match the computed values to some extent, the error being small enough to be accepted. The computed value for the V_{MAX_Sensor}=3[V] and the measured one is $V_{MAX\_Measured\_Sensor}$=3.02867[V], therefore the error is going be as follows in the equation (111):

$$\Delta V_{MAX}[\%] = \frac{|VMAX_{Measured_{Sensor}} - VMAX_{Sensor}|}{VMAX\_Sensor} \cdot 100 \implies \Delta V_{MAX}[\%] = \frac{|3.02867 - 3|}{3} \cdot 100 \quad (111)$$

$$\Delta V_{MAX}[\%] = 0.9556[\%] \quad (112)$$

The same goes for the Minimum value, the computed one being V_{MIN_Sensor}=500[mV] and the measured one being $V_{MIN\_Measured\_Sensor}$=510.16156[mV], equation (113)is used for the error:

$$\Delta V_{MIM}[\%] = \frac{|VMIN_{Measured_{Sensor}} - VMIN_{Sensor}|}{VMIN\_Sensor} \cdot 100 \implies \Delta V_{MIN}[\%] = \frac{|510.16156 - 500|}{500} \cdot 100 \quad (113)$$

$$\Delta V_{MIN}[\%] = 2.032[\%] \quad (114)$$

Sensor resistance to Specified voltage range

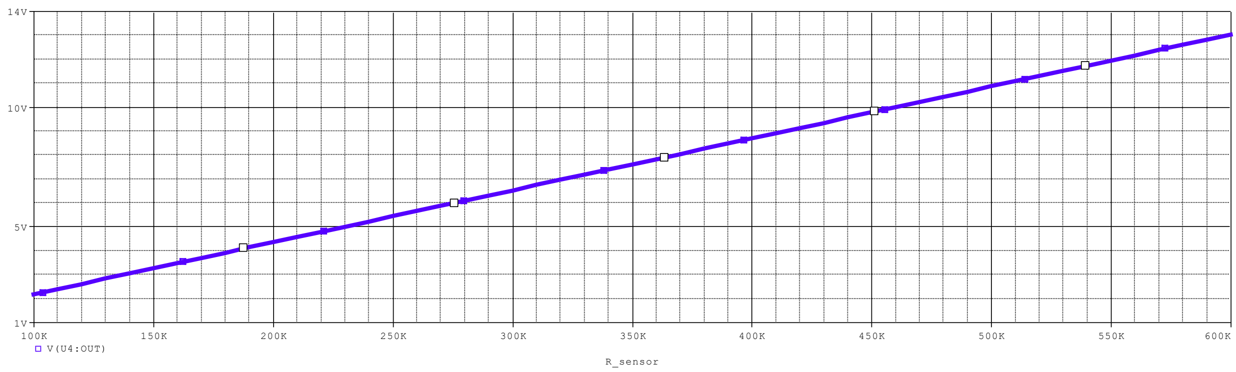


Figure 57. Sensor Resistance to Specified Voltage Range

Evaluate	Measurement	Value
☑	Max(V(U4:OUT))	13.01671
☑	Min(V(U4:OUT))	2.16690

Figure 58. The Maximum and the Minimum Resistances vales for the Voltage Domain Range

The specified voltage range for the maximum swing of the value of the sensor's resistance from the Table 1, is $V_{MAX\_Requirement}$=13[V] and $V_{MIN\_Requirement}$=2[V], from the previous definitely lower values a voltage conversion amplifier was used, to fulfill the required voltage swing. The simulated values of $V_{MAX\_Measured\_Sensor\_Domain}$=13.01671[V] and $V_{MIN\_Measured\_Sensor\_Domain}$=2.16690[V] do not have the exact same values as the required parameters, but the error of the voltage swing is low enough to be acceptable, as computed in the formulas (155) and (117) .

$$\Delta V_{MAX}[\%] = \frac{|VMAX_{Measured_{Sensor_{Domain}}} - VMAX_{Requirement}|}{VMAX_{Requirement}} \cdot 100 \Longrightarrow \Delta V_{MAX}[\%] = \frac{|13.01671 - 13|}{13} \cdot 100 \quad (115)$$

$$\Delta V_{MAX}[\%] = 0.128[\%] \quad (116)$$

$$\Delta V_{MIN}[\%] = \frac{|VMIN_{Measured_{Sensor_{Domain}}} - VMIN_{Requirement}|}{VMIN_{Requirement}} \cdot 100 \Longrightarrow \Delta V_{MIN}[\%] = \frac{|2.16690 - 2|}{2} \cdot 100 \quad (117)$$

$$\Delta V_{MIN}[\%] = 8.345[\%] \quad (118)$$

Voltage Thresholds for Output Signal Switch

- Simulation profile and test conditions:

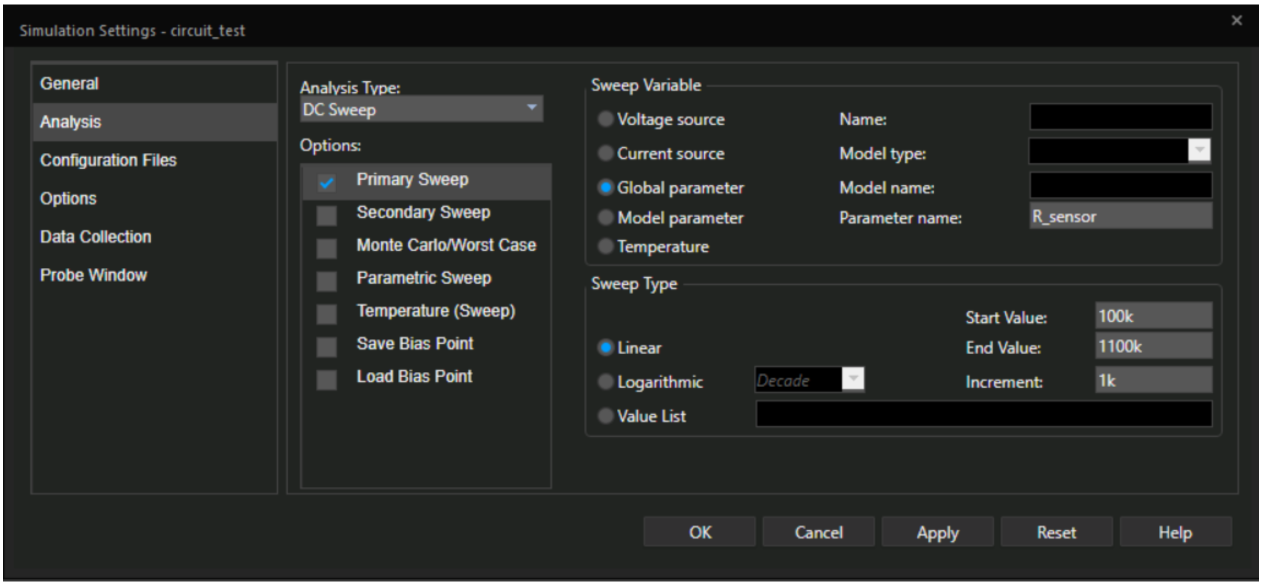


Figure 59. Simulation profile for Hysteresis Comparator testing

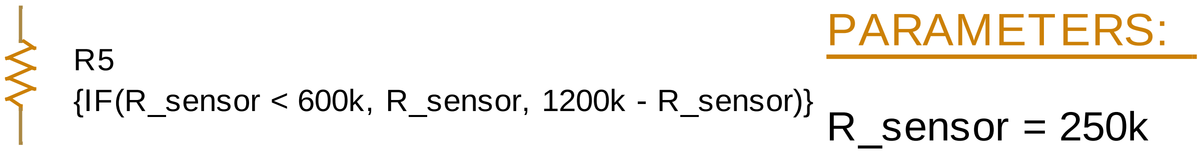


Figure 60. Test conditions

To simulate a more realistic scenario, the resistance should decrease after the water pump is turned on. The signal described above by the simulation profile and the “if” statement from the resistor is a triangular signal that does not perfectly describe the real signal, but it is close enough to verify the functionality of the circuit.

- Simulation results and test results:

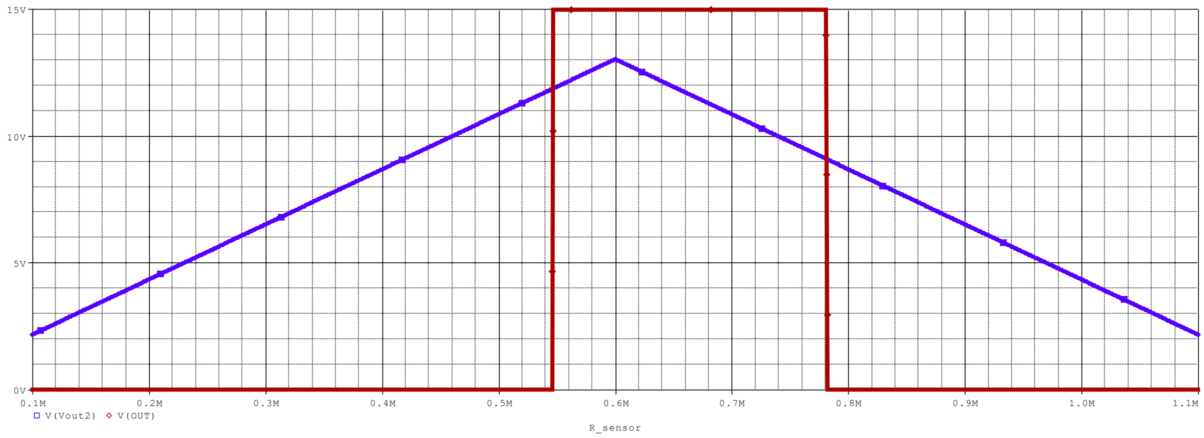


Figure 61. Thresholds for the Hysteresis Comparator - Input Blue - Output Red

Trace Color	Trace Name	Y1
	X Values	547.287K
CURSOR 1,2	V(Vout2)	11.874
	V(OUT)	14.981

Figure 62. V_{ThH} Hysteresis

Trace Color	Trace Name	Y1
	X Values	782.171K
CURSOR 1,2	V(Vout2)	9.0656
	V(OUT)	7.5102m

Figure 63. V_{ThL} Hysteresis

Form the Figure 61; it can be observed that when the input signal, that begin the one from the voltage domain converter amplifier, passes through the Hysteresis voltage thresholds the output signal either switches “on” or “off” depending on the case and state of the circuit. The logic function looks to be right from the graph because, as the humidity gets lower the resistance of the sensor increases, therefore the voltage across it increases and the command signal gets pulled high, thus turning on the water pump. As the water pump is watering the plant the resistance of the sensor gets lower, the voltage across it gets lower; therefore, the signal will pass the lower threshold and the output signal will get pulled to ground turning off the water pump.

In the Figure 62; is presented the measurements result of the high voltage threshold of the comparator. It is worth noting that the switching does not happen to the designed resistance value but one a little bit higher, this implies that the other values are contained in an error margin, and do not exactly match the computed values but are close enough. The error is computed and presented in the next formulas (119) and (121):

$$\Delta R_{MAX}[\%] = \frac{|R_{measured} - R_{computed}|}{R_{computed}} \cdot 100 \Longrightarrow \Delta R_{MAX}[\%] = \frac{|547.287 - 537.5|}{537.5} \cdot 100 \quad (119)$$

$$\Delta R_{MAX}[\%] = 1.820[\%] \quad (120)$$

$$\Delta \mathrm{V_{ThH}}[\%] = \frac{|\mathrm{V_{ThH\_measured}} - V_{ThH\_computed}|}{V_{ThH\_computed}} \cdot 100 \Longrightarrow \Delta \mathrm{V_{ThH}}[\%] = \frac{|11.874 - 11.4935|}{11.4935} \cdot 100 \quad (121)$$

$$\Delta V_{ThH}[\%] = 3.310[\%] \quad (122)$$

The same goes in the V_{ThH} Hysteresis Figure 63. V_{ThL} Hysteresis it is shown the lower threshold value of the Hysteresis comparator, and as expected the values of this measurement do not exactly match the computed values; thus, the same errors will be computed. The difference now is that the resistance for the lower limit must be computed from the measurement, in the equation (123). The following errors are computed in the equation (126) .

$$\mathrm{R_{MIN}} = 1200 - 782.171 \Longrightarrow \mathrm{R_{MIN}} = 417.829[\mathrm{k\Omega}] \quad (123)$$

$$\Delta R_{MIN}[\%] = \frac{|R_{measured} - R_{computed}|}{R_{computed}} \cdot 100 \Longrightarrow \Delta R_{MIN}[\%] = \frac{|417.829 - 412.5|}{412.5} \cdot 100 \quad (124)$$

$$\Delta R_{MIN}[\%] = 1.291[\%] \quad (125)$$

$$\Delta \mathrm{V_{ThL}}[\%] = \frac{|\mathrm{V_{ThL\_measured}} - V_{ThL\_computed}|}{V_{ThL\_computed}} \cdot 100 \Longrightarrow \Delta \mathrm{V_{ThL}}[\%] = \frac{|9.0656 - 8.7748|}{8.7748} \cdot 100 \quad (126)$$

$$\Delta V_{ThL}[\%] = 3.314[\%] \quad (127)$$

In this chapter ware presented the errors that occurred in the realization of the circuit were presented. Those errors might have come from the standardization part of the circuit, or by the non-ideality of the electrical components and devices. The important thing is that the values of the errors are low and very low, only going up to less than 4% relative error.

Current of the relay + LED indicator

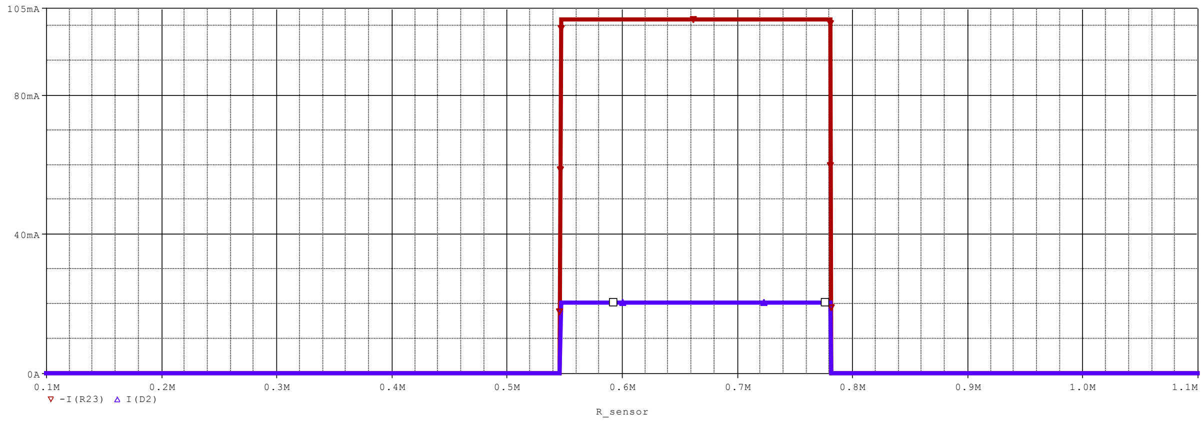


Figure 64. Current through the Relay Resistance - Red; Current through the LED indicator – blue

Evaluate	Measurement	Value
☑	Max(-I(R23))	101.69056m
☑	Max(I(D2))	20.35517m

Figure 65. The value of the Relay current and the value of the RED LED current

As on the previous pages, the measured values are going to be compared to the computed ones and the relative error between them is the indicator of the correctness of the calculations and of the design of the circuit. In the following formulas (128) and (130) the relative error of the current is going to be computed:

$$\Delta \mathrm{I}_{\mathrm{relay}}[\%] = \frac{|\mathrm{I}_{\mathrm{relay\_measured}} - I_{relay\_computed}|}{I_{relay\_computed}} \cdot 100 \Longrightarrow \Delta \mathrm{I}_{\mathrm{relay}}[\%] = \frac{|101.69056 - 100|}{100} \cdot 100 \quad (128)$$

$$\Delta I_{relay}[\%] = 1.690[\%] \quad (129)$$

$$\Delta \mathrm{I}_{\mathrm{LED}}[\%] = \frac{|\mathrm{I}_{\mathrm{LED\_measured}} - I_{LED\_computed}|}{I_{LED\_computed}} \cdot 100 \Longrightarrow \Delta \mathrm{I}_{\mathrm{LED}}[\%] = \frac{|20.35517 - 20|}{20} \cdot 100 \quad (130)$$

$$\Delta I_{LED}[\%] = 1.775[\%] \quad (131)$$

Temperature test of the circuit

The minimum soil temperatures for planting common crops are the following:

1. spring wheat – 3°C;
2. soybeans – 15°C;
3. spring canola and sugar beet – 10°C;
4. sunflower and millet – 16°C;
5. dry beans are the most demanding, requiring 21°C for their successful germination and rooting.

The optimal soil temperature for growing vegetables varies from 18 to 24°C. For example:

1. tomatoes and cucumbers – 16°C;
2. sweet corn – 18°C;
3. watermelons, peppers, and okra are the last ones to sow at 21°C.

Therefore, testing the circuit for extreme temperatures does not make sense, because the plants for which it reads the humidity will die at temperatures above and below the limits specified above. So, the range of -3°C up to 30°C is the proper one because it includes the case when, in spring, the soil might freeze and the case when, in the summer, in the evening on the field is very hot.

- Simulation profile:

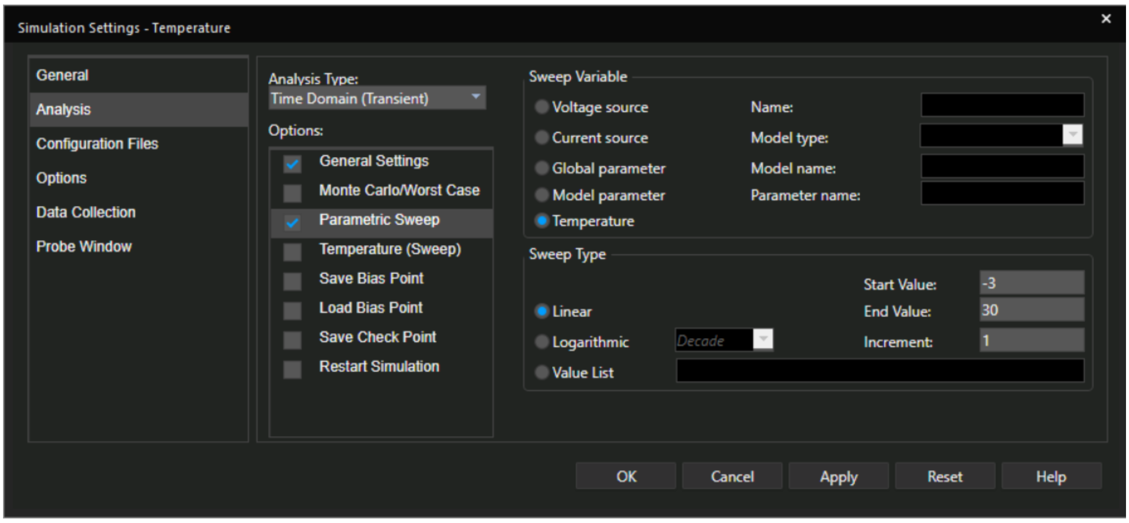


Figure 66. Simulation profile for testing the circuit at different temperatures

- Variation of the High Voltage Threshold of the Hysteresis Comparator with respect to temperature; measured nominal value V_{ThH}=11.874V:

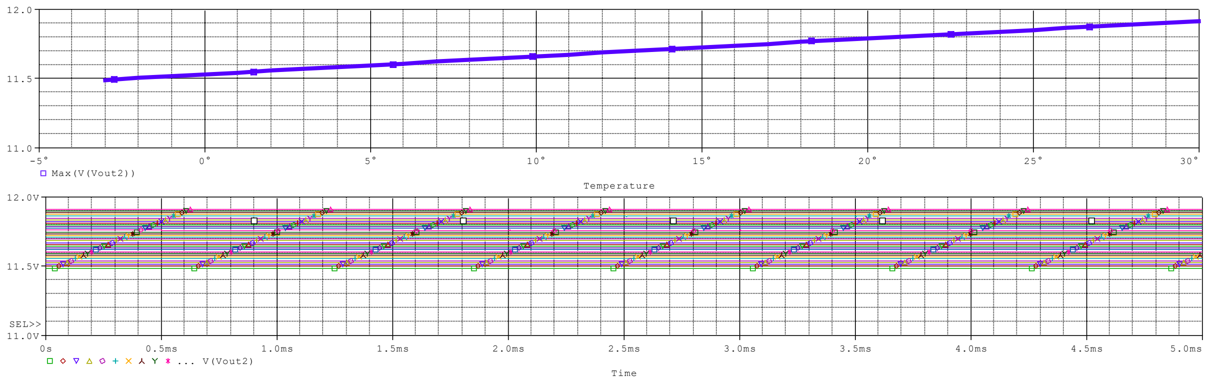


Figure 67. Variation of the High Voltage Threshold with respect to temperature for R_sensor = 547.287kΩ

- Variation of the Low Voltage Threshold of the Hysteresis Comparator with respect to temperature; measured nominal value V_{ThL}=9.0656V:

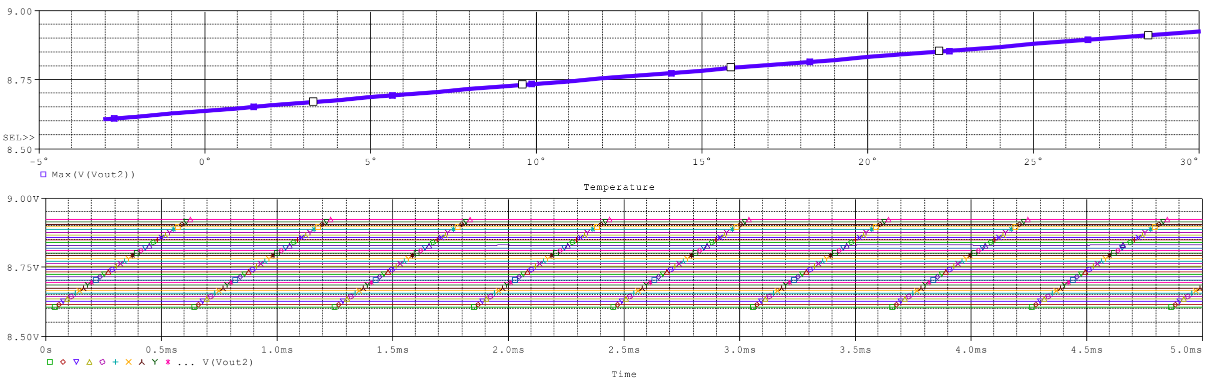


Figure 68. Variation of the High Voltage Threshold with respect to temperature for R_sensor = 410kΩ

For the temperature test was enough to check the variance of the Voltage thresholds because, those are the only limits that decide is the plant gets watered or not. The output voltage is a digital signal, either high or low, so its variance with the temperature does not play a crucial role in the water timing of the plant. From the two graphs it can be observed that both thresholds increase linearly with the temperature, and somewhat proportionally; therefore, the plant is water for the same interval but at a different humidity level.

Statistical Analysis

Monte-Carlo

- Simulation profile #1:

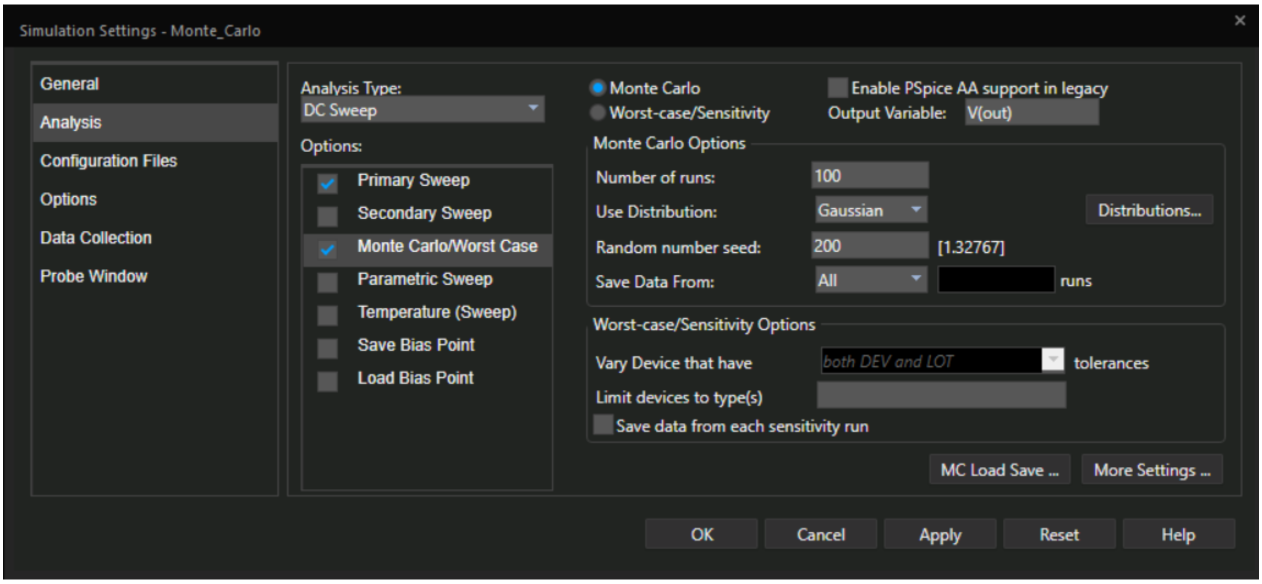


Figure 69. Simulation profile for testing the Voltage interval

- Statistic for the upper limit of the interval; nominal value V_{MAX}=13V:

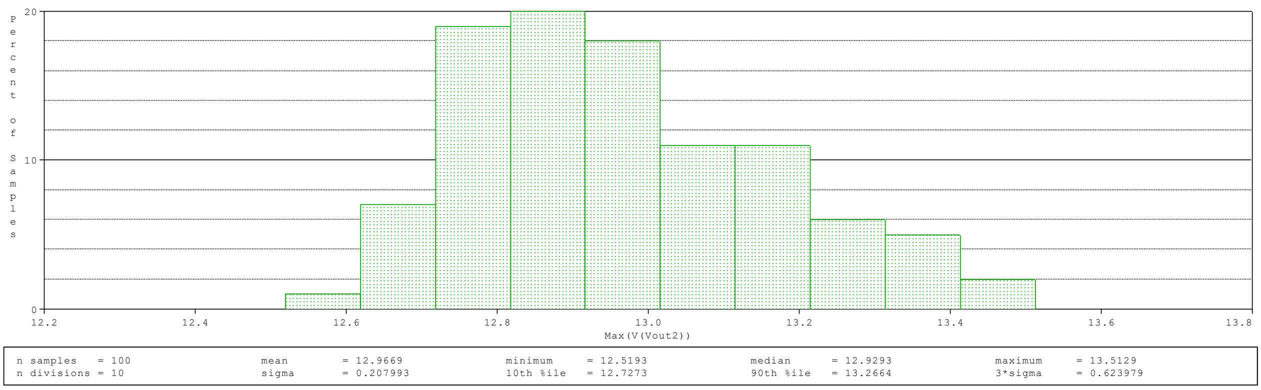


Figure 70. Variation of the Maximum value of the Voltage Interval for R_sensor = 600kΩ

- Statistic for the lower limit of the interval; nominal value V_{MIN}=2V:

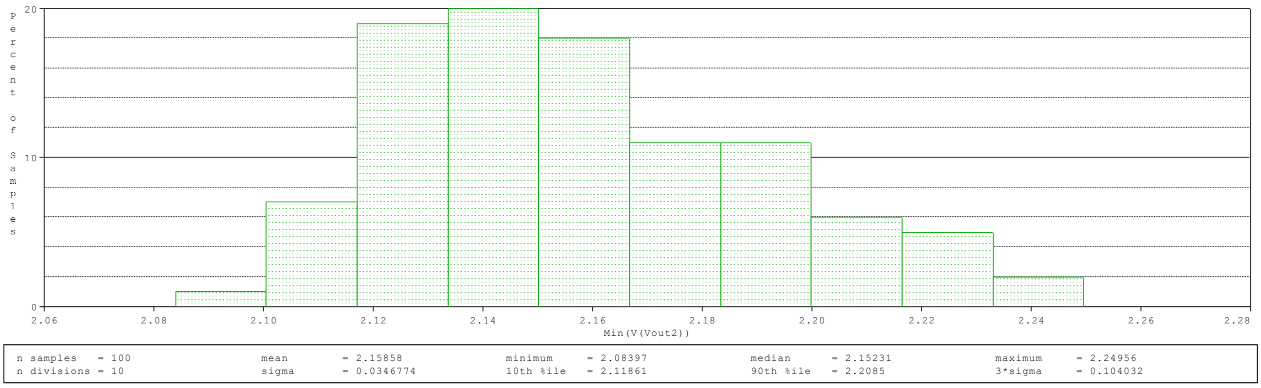


Figure 71. Variation of the Minimum value of the Voltage Interval for R_sensor = 100kΩ

As seen from the Figure 70 and Figure 71 the normal distribution of the samples tends to not settle on the desired value from the requirements table; therefore 1% tolerance resistors are used to keep the probability of the circuit to function as planned high. In the process were used 100 samples to ensure accurate distribution representation at the cost of time of simulation, and storage space.

- Simulation profile #2:

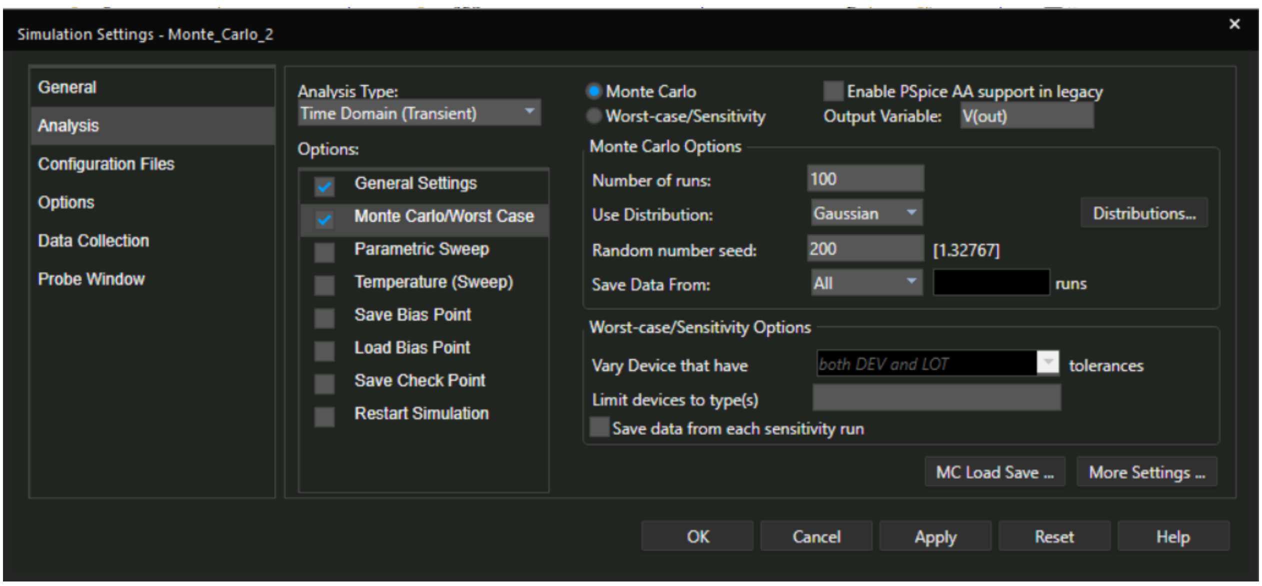


Figure 72. Simulation profile for testing the Voltage Thresholds

- Statistic for the High Voltage Threshold of the Hysteresis Comparator; measured nominal value V_{ThH}=11.874V:

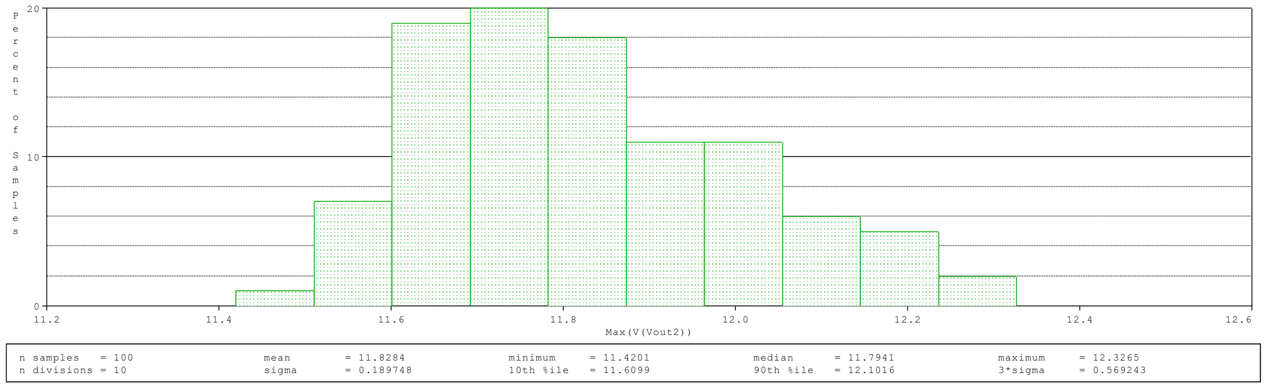


Figure 73. Variation of the High Voltage Threshold for R_sensor = 547.287kΩ

- Statistic for the Low Voltage Threshold of the Hysteresis Comparator; measured nominal value V_{ThL}=9.0656V:

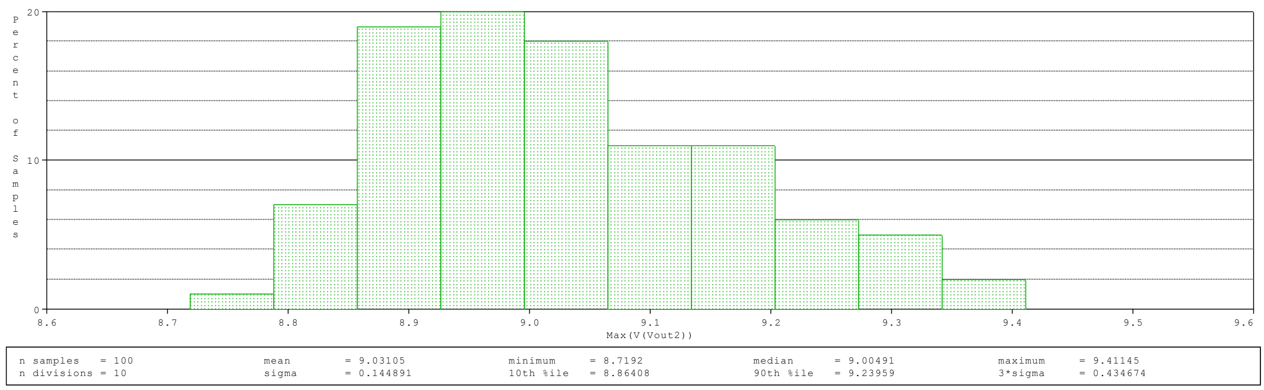


Figure 74. Variation of the Low Voltage Threshold for R_sensor = 417.829 kΩ

The above histograms were computed for the reason of better estimation of the circuits behavior after it is mass produced. This is still an estimation, and nothing can be given with 100% guaranty of ideal functioning, but it is a powerful tool to estimate and approximate the overall way in which the circuit will act. From the histograms presented above, a short conclusion is that the design of the circuit would need to improve and not be influenced so drastically by the rather low tolerances of the resistances.

Worst-Case

- Simulation profile:

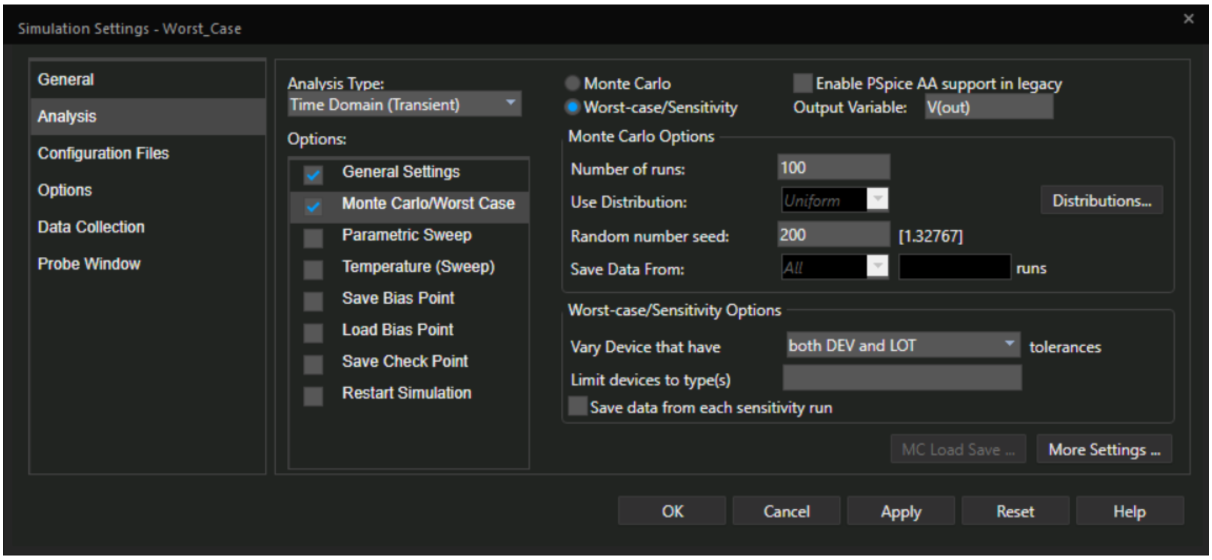


Figure 75. Setting profile for testing the Worst-Case in V_{ThH} and V_{ThL}

- Worst-Case for the High Voltage Threshold of the Hysteresis Comparator; measured nominal value V_{ThH}=11.874V:

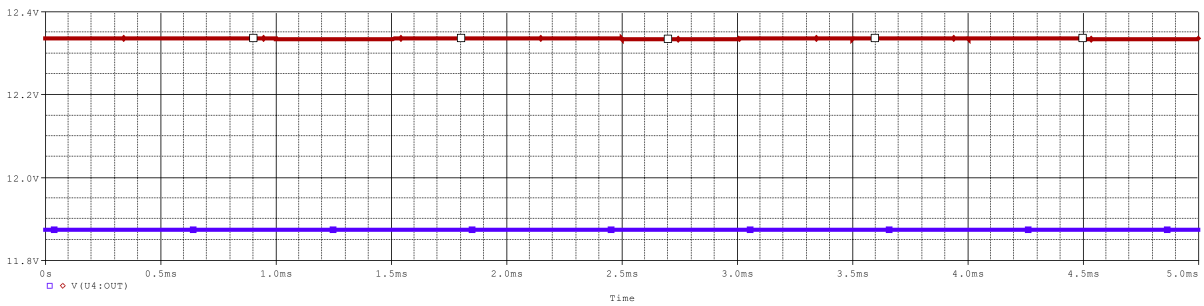


Figure 76. Variation in the Worst-Case of the High Voltage Threshold for R_sensor = 547.287kΩ

Evaluate	Measurement	1	2
✔	Max(V(Vout2))	11.87394	12.33403

Figure 77. Ideal and Worst-Case Voltage Values

- Worst-Case for the Low Voltage Threshold of the Hysteresis Comparator; measured nominal value V_{ThL}=9.0656V:

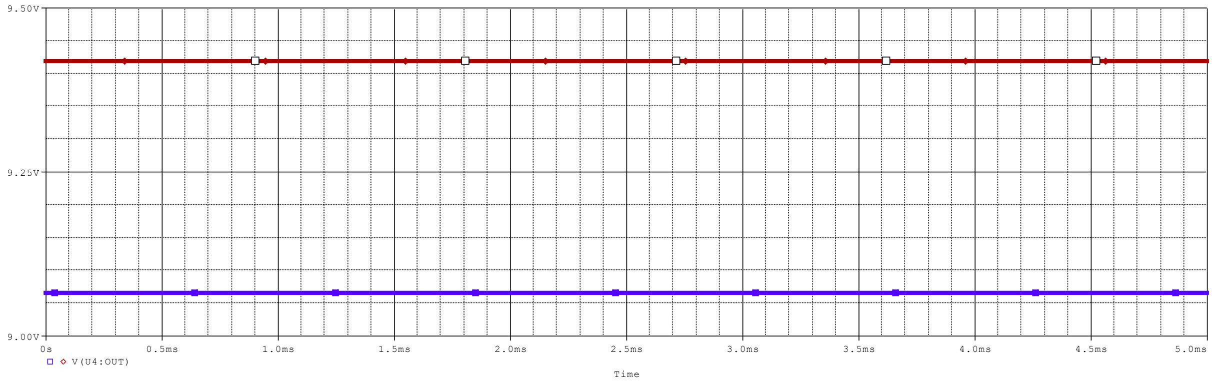


Figure 78. Variation in the Worst-Case of the Low Voltage Threshold for R_sensor = 417.829 kΩ

Evaluate	Measurement	1	2
☑	Max(V(Vout2))	9.06575	9.41855

Figure 79. Ideal and Worst-Case Voltage Values

In the presented graphs and measurements from Figure 76 and Figure 78, in the worst-case with all the tolerances at their highest value, the Voltage Thresholds are changing with a high amount. On the other hand, they both increase and a relative constant rate; thus, the circuit will still switch at the design interval but for different sensor resistance, and soil humidity. There was no need of computing the worst-case for the limit voltages of the sensor's interval because those limits, in a practical case wouldn't be reached anyway with the specifications of this project.

Bill of materials (BOM)

OrCAD Generated BOM with Price Addition

Item	Quantity	Reference	Part	Price (RON)	Buy
1	1	D1	D1N4148	0.54	ardushop.ro_diode
2	1	D2	LS_5436-TYP	0.91	ebay.com_red_led
3	7	Q1, Q2, Q7, Q8, Q9, Q11, Q13	2N2222A/ZTX	0.43	ardushop.ro_2n2222NPN
4	5	Q3, Q4, Q5, Q6, Q10	PN2906	4.59	ebay.com_PN2906
5	1	Q12	Q2N3055	6.9	sigmanortec.roNPN2N3055
6	8	R1, R2, R3, R10, R11, R13, R17, R22	10k	0.15	sigmanortec.ro_10k_rez
7	1	R4	10	2.52	amazon.com_10_rez
8	1	R5 Sensor			
9	1	R6	750k	0.85	eu.mouser.com750k_rez
10	1	R7	7.75k	0.01	digikey.lv_7.75k_rez
11	1	R8	15k	0.002	tme.eu_15k_rez
12	4	R9, R15, R19, R24	100k	0.15	sigmanortec.ro_100k_rez
13	1	R12	195	0.77	digikey.hk_195_rez
14	1	R14	33.2k	0.091	ebay.com_33.2k_rez
15	2	R16, R25	200k	0.36	tme.eu_200k_rez
16	1	R18	54k	0.42	resistor.tedss.com_54k_rez
17	1	R20	50k	0.15	sigmanortec.ro_50k_rez
18	1	R21	4.4k	0.63	digikey.com_4.4k_rez
19	1	R23 Relay	120	52.59	uk.rs-online.com_relays
20	1	R26	130	4.23	eu.mouser.com_130_rez
21	4	U1, U3, U4, U5	AD820/AD	45	ro.mouser.com_AD820A
22	1	U2	TL431/TI	0.248	tme.eu_tl431a
23	1	U6	3N263	1.19	digikey.com_3N263
Total price				280.711 RON	

Table 11. Bill of Materials

To be noted that this total price does not consider the following parameters: the transportation cost, because the part is selected from different distributers; the price of the needed PCB, because at this point there is no PCB design created; additional local or federal taxes considering that the components are from Romanian, American and German online shops; and many technical shops do not let customers buy only one component. This is not the final cost but just a rough estimate. The price of the humidity sensor is not specified either, due to the nature of it, and because is custom made to fit several humidity percentages. A high price is expected here, considering that custom sensors tend to have a higher price.

Conclusions

Improvements

Although the circuit is doing its job reliably and efficiently enough to be placed into production, there is still room for improvement. In the next bullet points are listed the improvements that came out during the building and testing of the circuit:

- Improvement of the stability when it comes to the results from the statistical and worst-case simulations. The results are not bad, but the closer the normal distribution is to the computed value, the better the circuit is going to work, in mass production.

- Improvement of the measured / real values. Although the relative errors between the computed and the measured values are only, at max 3.3%, there is still room for improvement and lower errors.

- Lower the price. The circuit is only in the prototyping phase and is already pricey enough to turn down potential farmers who needed it.

- More protection. The circuit has a couple of protection mechanisms but still lacks protection for reverse protection for the power source, and current limiting protection for the relay, to name a few.

Conclusion

In my opinion, the circuit performs in the desired and required parameters, with a low tolerance and good enough stability. It has a crucial role in today's world, in the field of agriculture, automatic greenhouses and gardening. The process of designing and testing the final circuit implementation, was a long rollercoaster like path; that started with studying a new field of gardening; then I went through many iterations and circuit designs, to improve as much as possible the current consumption respectively the efficiency of the whole circuit. It needs improvement, but at the current state of it, it works well enough to go to the PCB layout design, and then into a real board test scenario. And that's the future for the circuit, physical implementation on a PCB, then tested on a real field.

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