Project Manual: Pollution Sensor and Re-Director

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Description:

The operational goal of the circuit is to be able to determine which of two roads are the safest to travel on. We attempt to tackle the real world issue of CO and CH4 poisoning for people living in Urban areas; those that choose to bike or walk more often than not. Studies have shown that bikers and pedestrians in cities such as NYC are at real risk of adverse health effects due to air pollution [1].

In these urban areas, the largest source of air pollution is caused by vehicles traveling through those areas. Of the exhaust gas concentration, the largest component is typically Carbon Monoxide (CO) and another substantial component is Methane (CH4). Our circuit is designed to work within these conditions. Our circuit will measure the CH4 and CO levels in the air on a fork in a road and determine which of our “roads” is the safest to traverse on from an air pollution standpoint by lighting an LED to signify the road with the lower level of pollution.

<u>Block Diagram:</u>

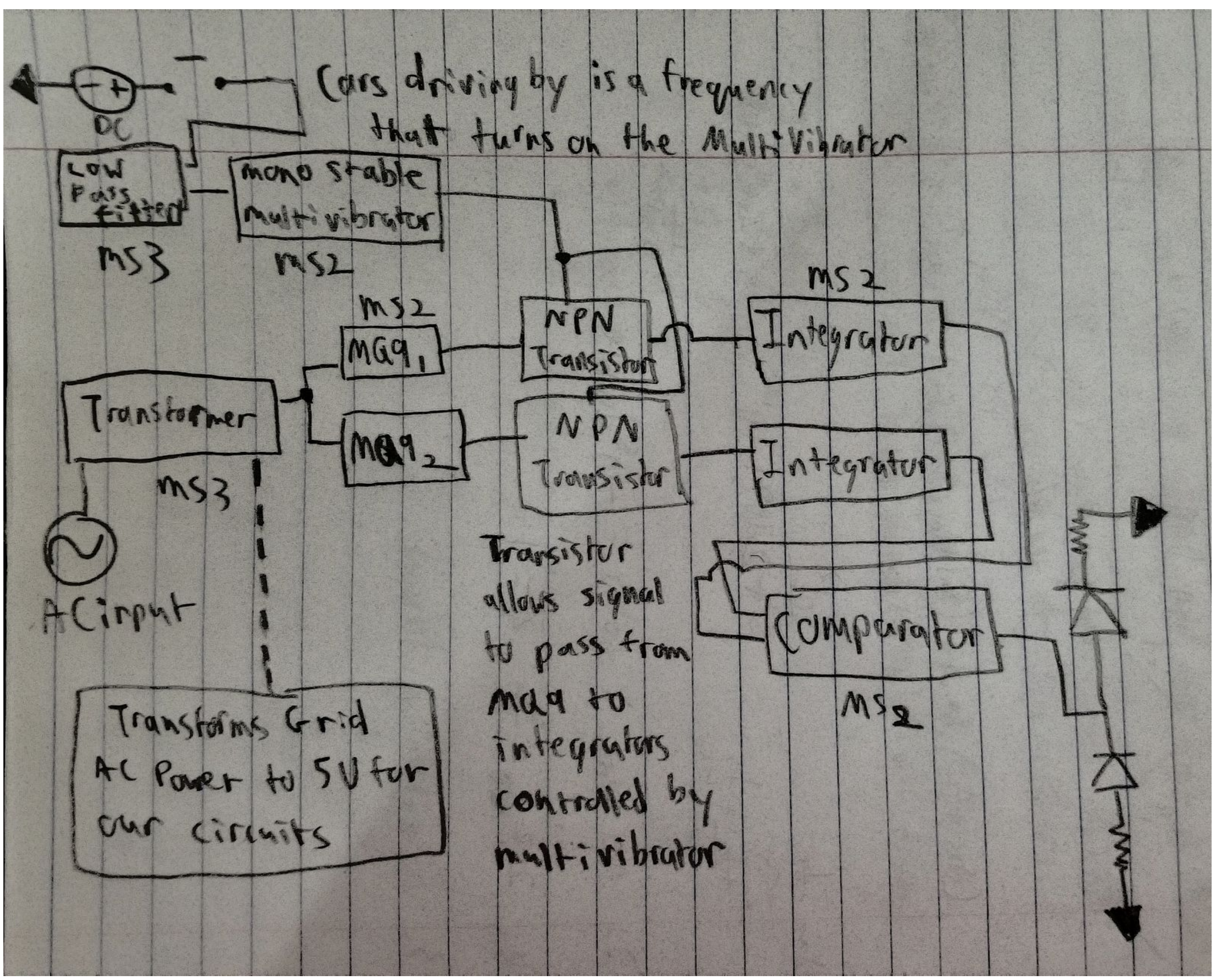


Figure 1: Block Diagram Overview

<u>Complete schematic:</u>

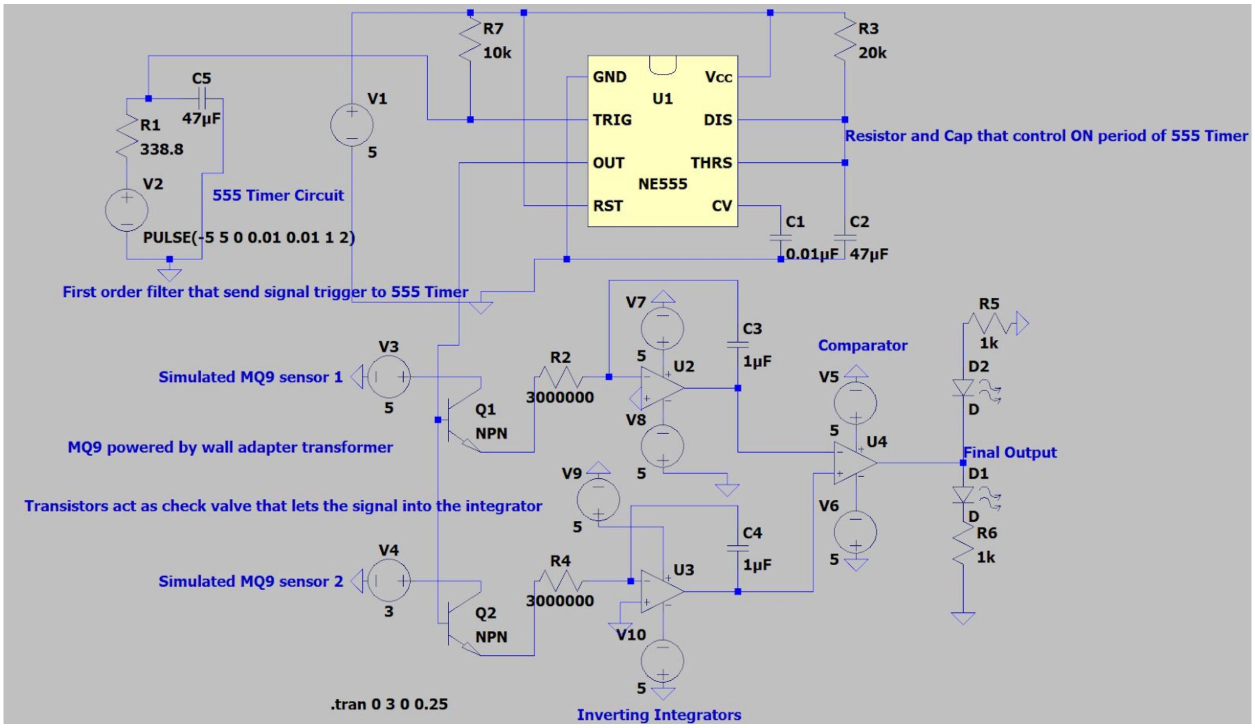


Figure 2: The Main Schematic

The circuit operation is as follows. The Resistor R3 and the Capacitor C2 control the period of integration. When cars drive past our "pressure plate" we send that signal to our Low Pass Filter. If the frequency is within our desired range then the signal triggers our 555 timer. The 555 timer acts as a monostable multivibrator that allows the signal from the MQ9 sensors to pass through to our integrators. Our integrators integrate the signal for the ON time of the 555 timer.

<u>Frequency effect:</u>

The table below shows some frequency ranges and how they affect our circuit. The percentage represents how often our circuit operates as expected in that range.

Frequency Range	Circuit Performance
0 - 10Hz	100%
10 - 25Hz	50%
>25Hz	0%

<u>Other Designs</u>:

Our research shows very few examples that perform our circuit operation. Some examples that are simple are normal CO detectors. Our circuit is different from that operation because it doesn’t check an immediate concentration, it checks over a larger period of time and outputs based on a comparison.

Furthermore the circuit we are designing is not to be used in normal homes like most CO/CH4 detectors or comparison circuits. It’s specifically designed to tackle a problem present in Urban Cities with high vehicle traffic.

Operation and Design

Monostable mutivibrator

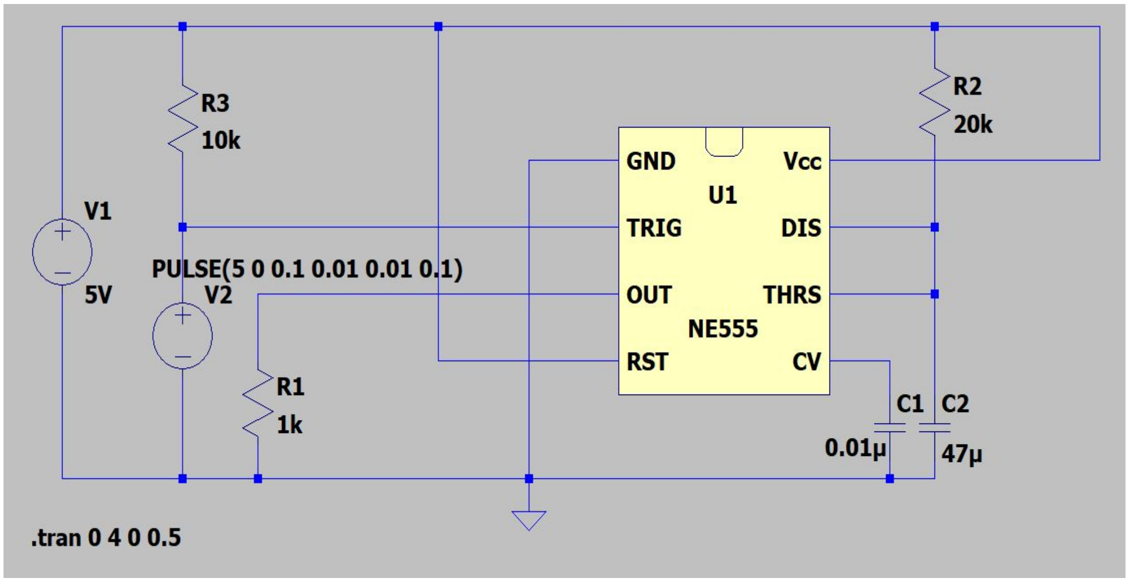


Figure 3: Monostable mutivibrator implemented with a 555 timer

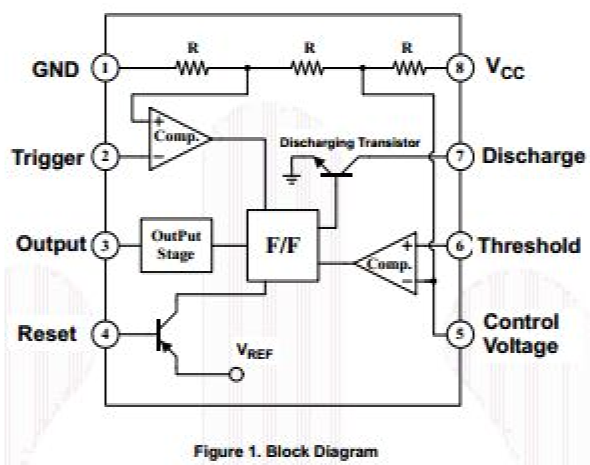


Figure 4: Internals of the NE555

The input to the monostable mutivibrator is a single square pulse that represents an external trigger, for its ease of implementation and testing, that goes from 5V to 0V and serves as the "negative edge" for the timer since the 555 TRIG pin is negative trigger edge (another alternative is to have a DC 5V connect to a switch that connect to the TRIG pin). When the pulse source does its job, it becomes disconnected from the circuit and that will put the source V1 in series with R2 and C2. The 555 timer circuit then becomes a RC circuit. The OUT pin will remain high as long as C2 is below $\frac{2}{3}$ of the source voltage. Thus to find the time for the monostable mutivibrator to remain high, it boils down to solve the differential equation for the voltage of the capacitor C2 and set that equal to 3.33 V. The values for the source voltage, R2 and C2 can be changed to prolong or decrease the time the 555 timer remains high.

$$\frac{dV_{c2}}{dt} + \frac{1}{R_3 C_2} V_{c2} = \frac{V_{source}}{R_3 C_2} \quad \text{(equation 1)}$$

The output of the monostable mutivibrator is a single square pulse with an amplitude of 5V with a variable pulse width determined by equation 1.

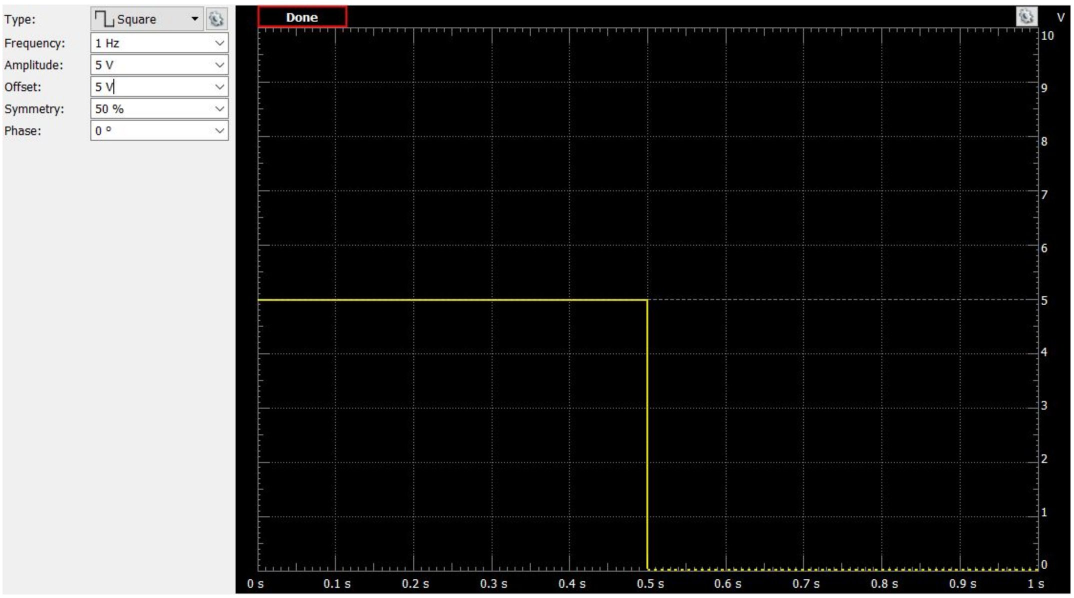


Figure 5: Pulse input to TRIG pin, manual trigger, non repeating square wave (5V to 0V)

Figure 6: YELLOW is the output of the 555 time. It has a pulse width of 1 second and amplitude of around 4.6V when the TRIG pin (BLUE) becomes low.

MQ9 sensor [2]

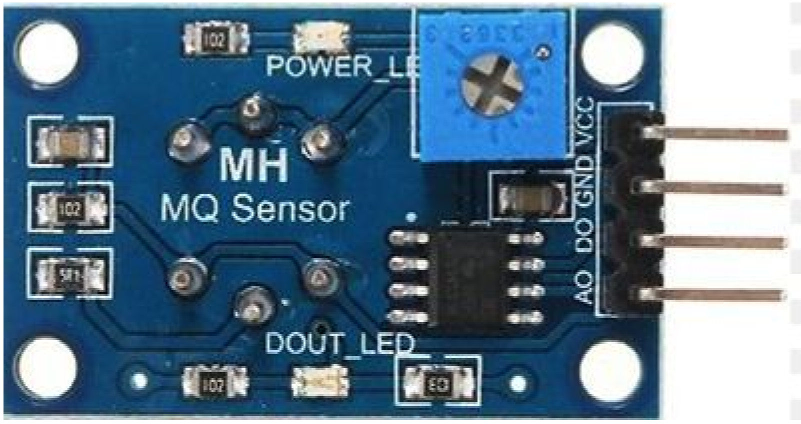


Figure 7: MQ9 sensor

MQ9 sensors are gas detecting equipment that are sensitive to carbon monoxide and methane. The sensor has 4 pins: power, ground, AC reading, and DC reading. The power pin requires 5V±0.1 and the AC and DC output ranges from 1.4V±0.1 to 5V±0.1. The sensor is affected by temperature and humidity where increasing temperature will lead to its internal resistance to decrease. The sensor can operate between -20℃ to 50℃ and should be operated with relative humidity of Less than 95%. For sensors to work properly, the sensors need to be preheated for 48 hours and can detect 20ppm-2000ppm carbon monoxide, 500ppm-10000ppm methane, and 500ppm-10000ppm liquefied petroleum gas. The input to the MQ9 is the output from the 555 timer which should be 5V.

Figure 8: YELLOW is the output of the 555 time/input to MQ9 and supplies ~4.6V to MQ9 power pin

The output of the MQ9 is higher in settings where more carbon monoxide , methane, and liquefied petroleum gas are detected. Figure 9, clean air has lower AC reading than other environments, so when an MQ9 has a higher reading, we are able to tell that that particular MQ9 is relatively more polluted than the other MQ9 sensor. Using the AC pin for reading is suggested since it is more accurate since it's an instantaneous reading, but in theory both the AC or DC pins can be used.

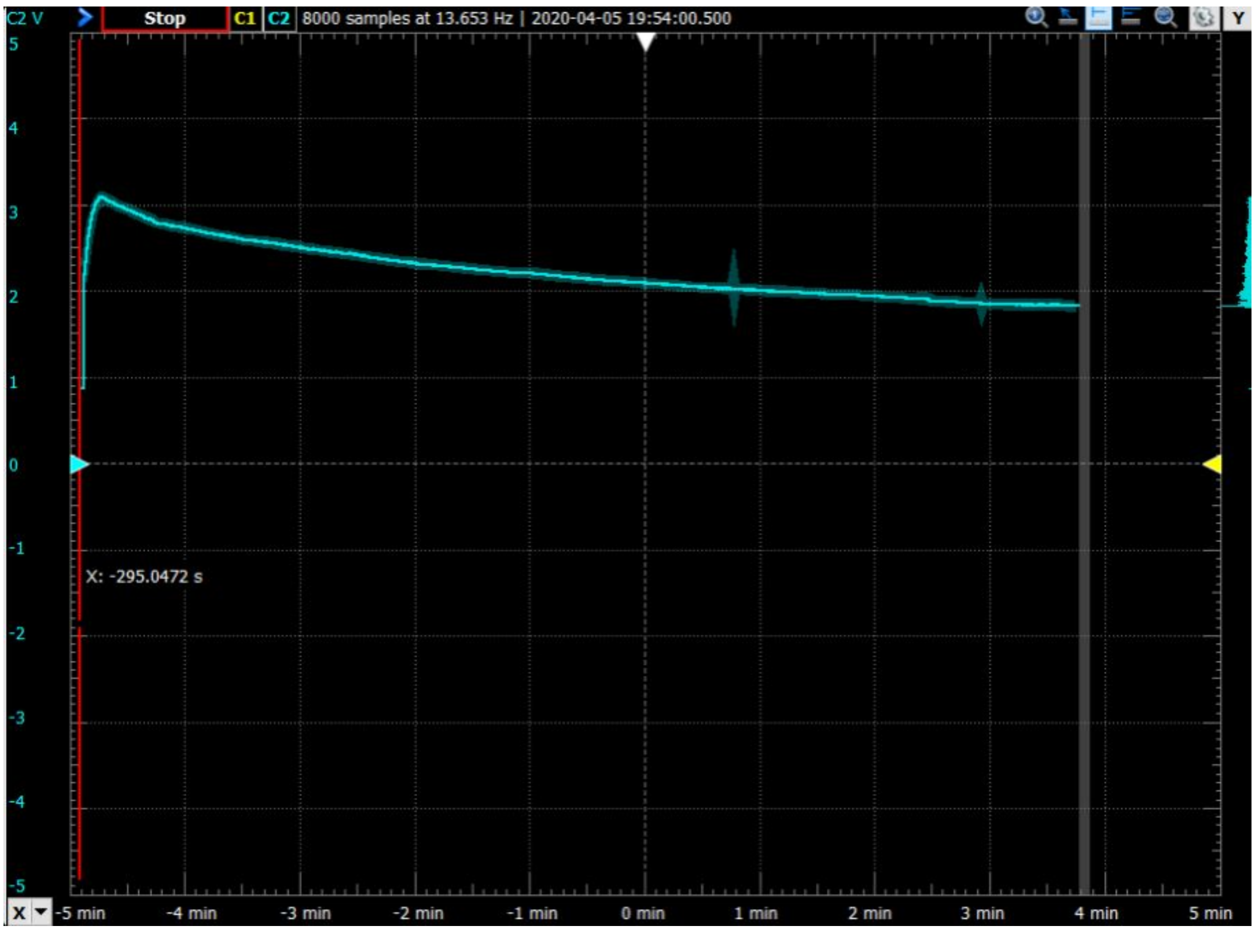


Figure 9: output of the MQ9's AC pin in my room (clean air).

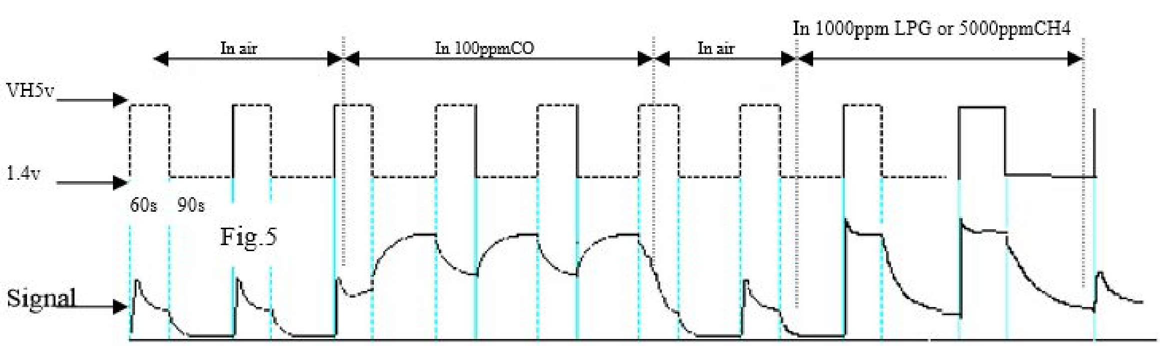


Figure 10: MQ9's signal output for various settings

Inverting Integrators

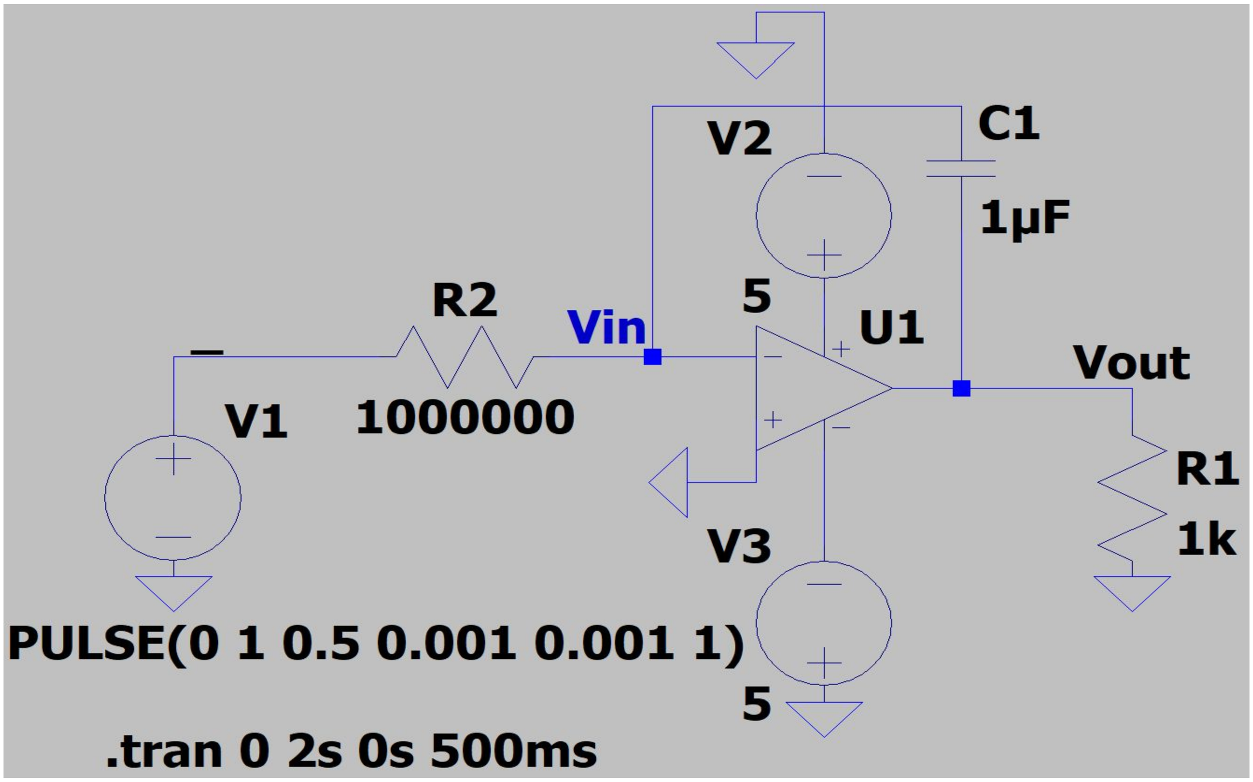


Figure 11: Inverting Integrator with a amplification of 0.33 of V1 and saturation of 5V

The inverting integrator takes a continuous signal and outputs the negative integration of the signal over the period of time the signal is active with an amplification. When the integration yields a result that is over the power supplied to the op amp, the output is simply the power supply voltage. The output will start to decay when the input signal is cut off or 0V. The power to the op amp should be as large as possible so the integration can yield a wide range of possible meaningful results. The equation the determines the output of the inverting integrator is:

$$V_1 = -\frac{1}{R_2 C_1}\int_0^t V_{out}dt \text{ (equation 2)}$$

Where V_1 is the input signal, V_{out} is the output of the inverting integrator, and t is the length of time the V_1 is active. This integrator is chosen instead of a regular non inverting integrator because the non inverting integrators are more difficult to build and require more same value capacitor and this simpler integrator can be built easier and with less components that still satisfy the design requirements. Depending on design needs and power supply voltages, the "amplification" can either be greater than 1 or less than 1. If a design is limited by power supply or if the input wave is large in magnitude, then an amplification of less than 1 should be chosen. Else an amplification of greater than 1 can be considered.

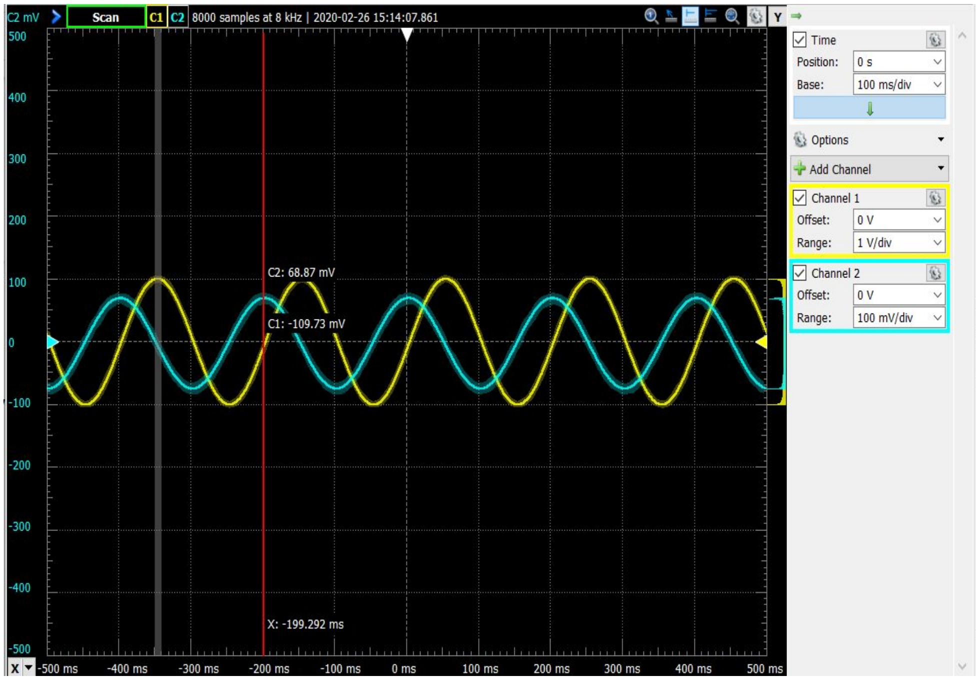


Figure 12: Example of input and output of the inverting integrators. In YELLOW is the cosine wave input and in BLUE is the sine output.

Comparator

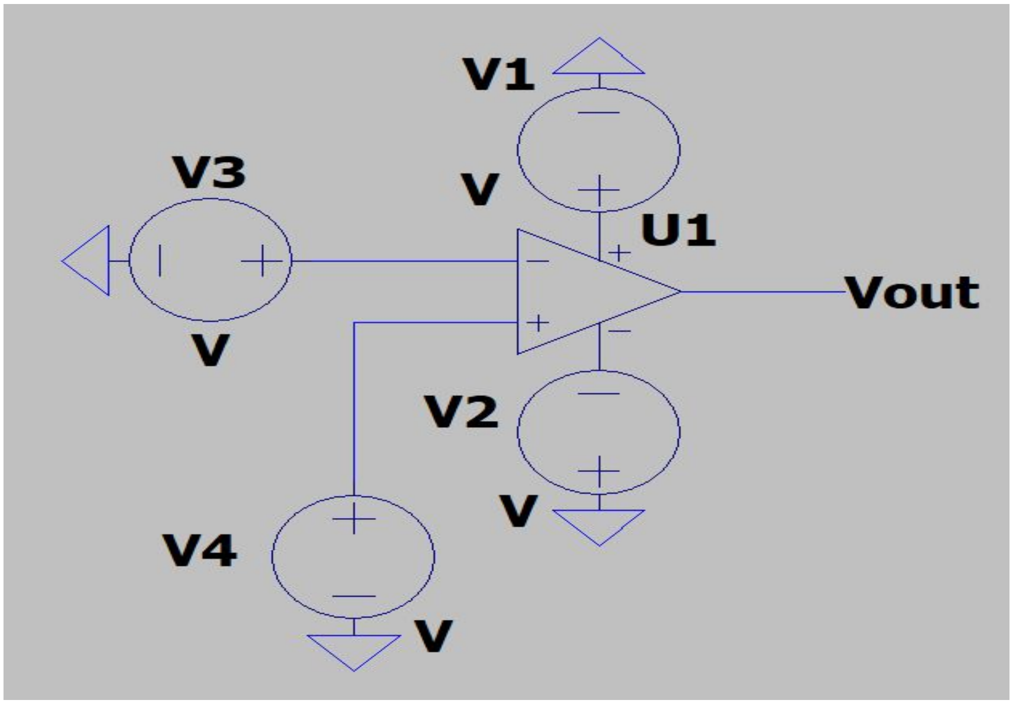


Figure 13: standard comparator, comparing two input signals. Vout can be the positive power supply or the negative power supply

The comparator take in two signals and if the signal on the positive input is largest input then V_{out} is the positive power supply, if the signal to the negative input is the largest then V_{out} is the negative power supply, and if the two signal are equal then V_{out} is 0V.

The equation to determine V_{out} is:

V4>V3→ V_{out} = positive supply Voltage

V3>V4→ V_{out} = negative supply Voltage

V4=V3→ V_{out} = 0V

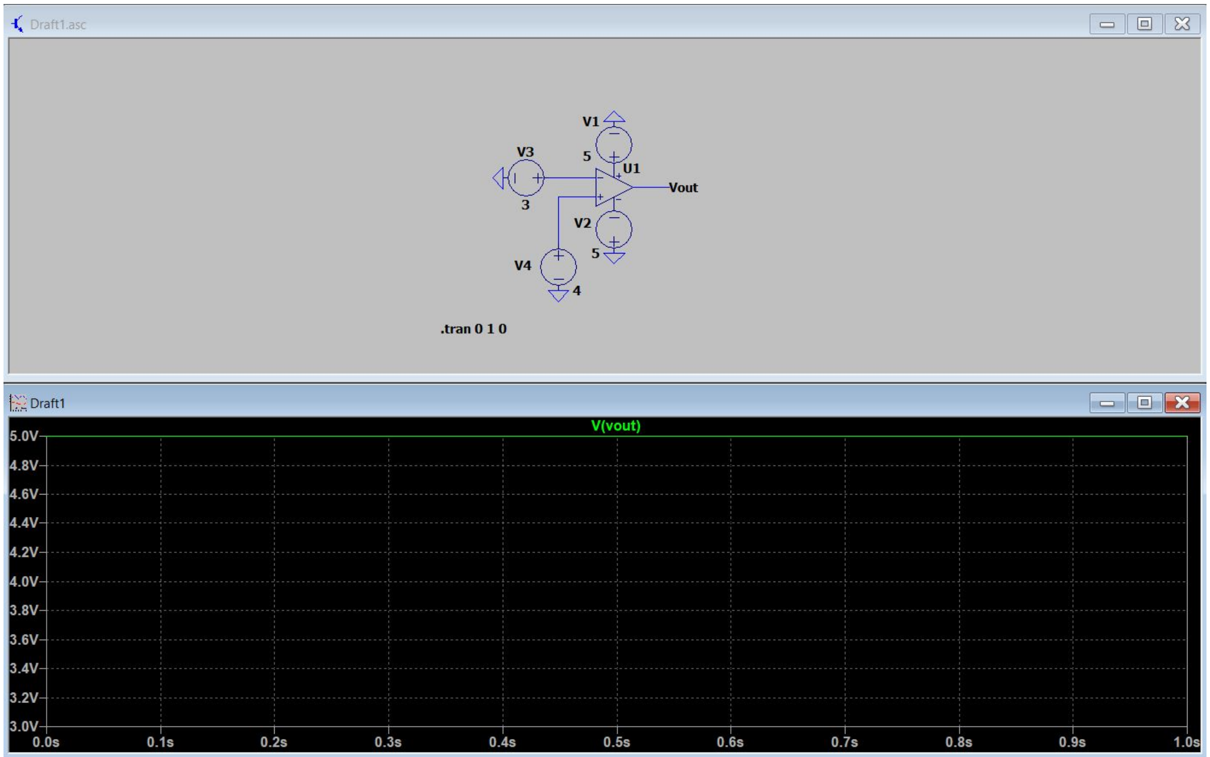


Figure 14: Example of comparator output when positive input is greater than negative input.* V_{out} *, represented by the Green is +5V(+VCC)

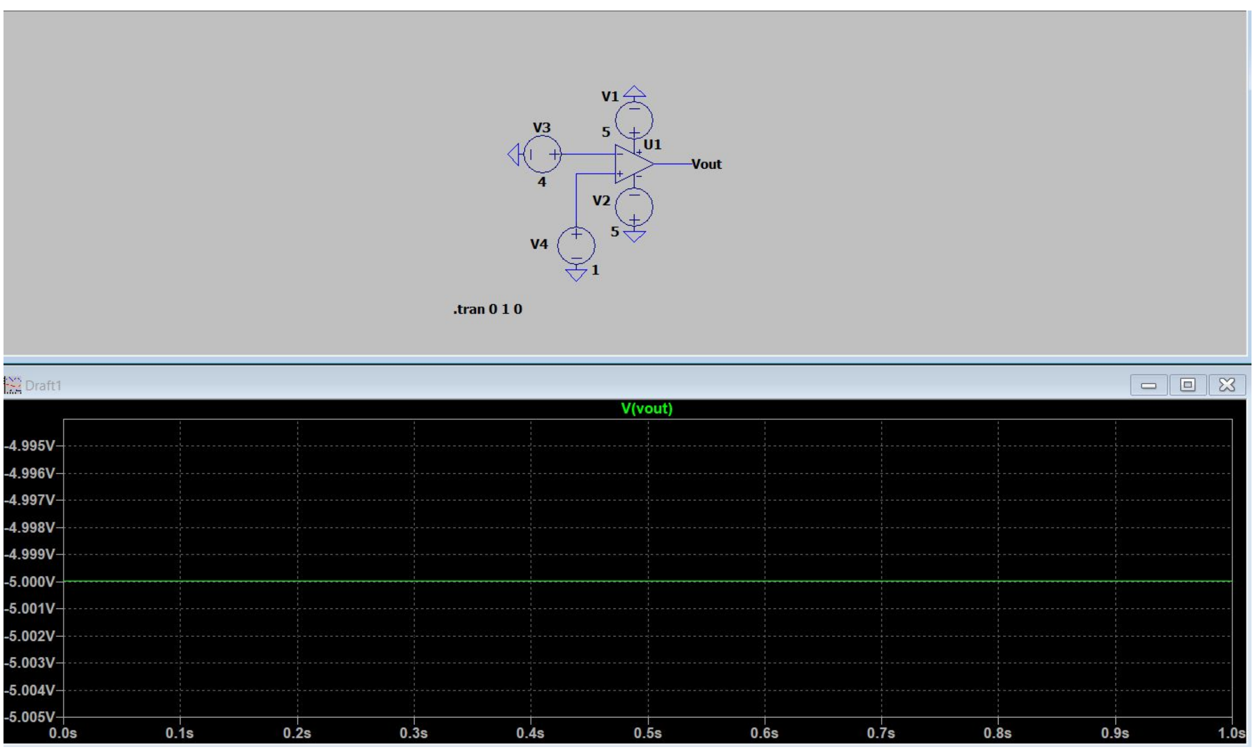


Figure 15: Example of comparator output when negative input is greater than positive input.* V_{out} *, represented by the Green is -5V(-VCC)

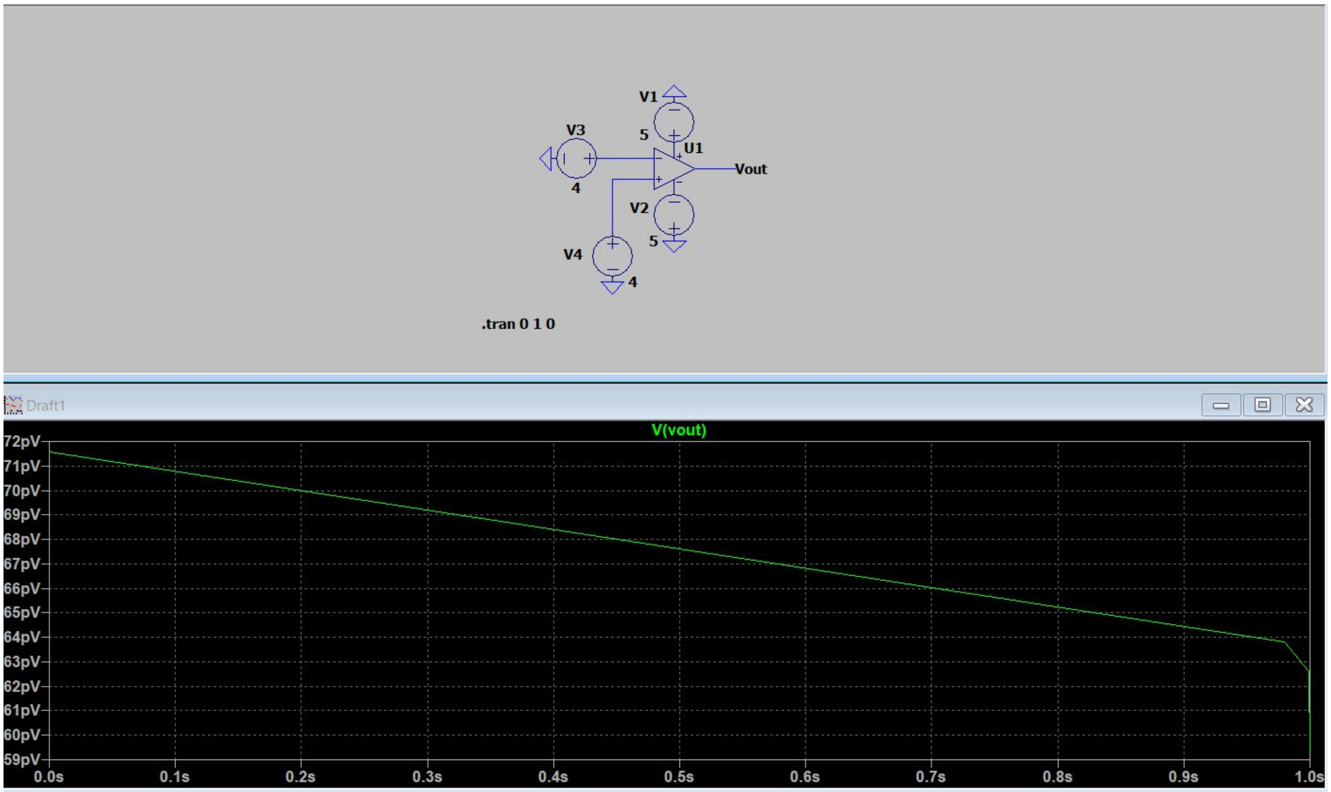


Figure 16: Example of comparator output when negative input is equal to the positive input. V_{out} ***, represented by the Green is 0V***

Transformer

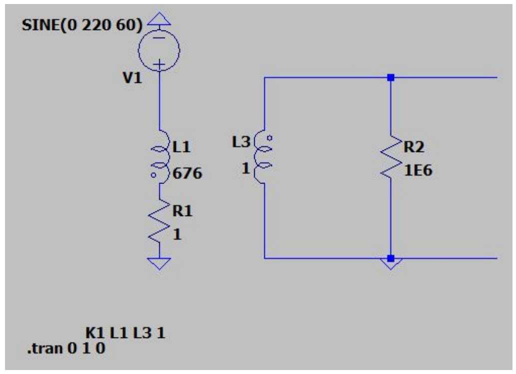


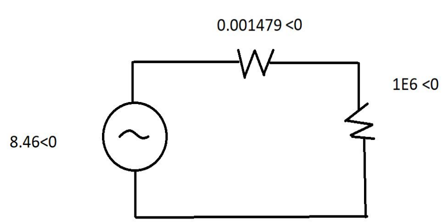
Figure 17: Transformer used in wall adapter powering circuit

In our circuit we are using a switch in wall adapter to power our circuit. This component has a transformer that steps down the wall AC voltage to a level reasonable for our circuit (5V). How it performs this operation is quite simple. First we have a transformer that connects directly to the mains of the outlet and steps it down to desired level. We give an example of the step down function this component can achieve, which is also the scenario used in our built circuit.

We model L1 and L3 as an ideal transformer with a 26:1 ratio. We use the large resistor R2 to simulate the load of the rest of the circuit. Using the referral method, if we referral the primary to the secondary:

The $V_{sp} = \frac{1}{26}(220 < 0)$ = 8.46V<0 on the secondary load (R2)

$Z_{sp} = \frac{1}{26^2}(1) =$ 0.001479 ohms



Using voltage divider to find V_{R2} which is also the voltage to attach load in parallel to R2 in the building block diagram:

$V_{R2} =$ 8.46<0 $\frac{1E6<0}{1000000.00148<0}$

$V_{R2} = 8.46V < 0\ degree$

We want roughly 8.46V on the secondary (R2) because when converting AC to DC with a bridge rectifier we want the peak value to be in between 12V and 5V. We can see this by $8.46V_{AC} = 8.46\ V_{DC}$ assuming no diode drop for the rectifier. This is because our analysis is modeling a 5V wall adapter. This circuit steps down the power line AC voltage to around <12V and feeds that into a 5V regulator that provides a consistent output to the rest of our circuit.

We verify this by showing the simulated voltage across R2 below.

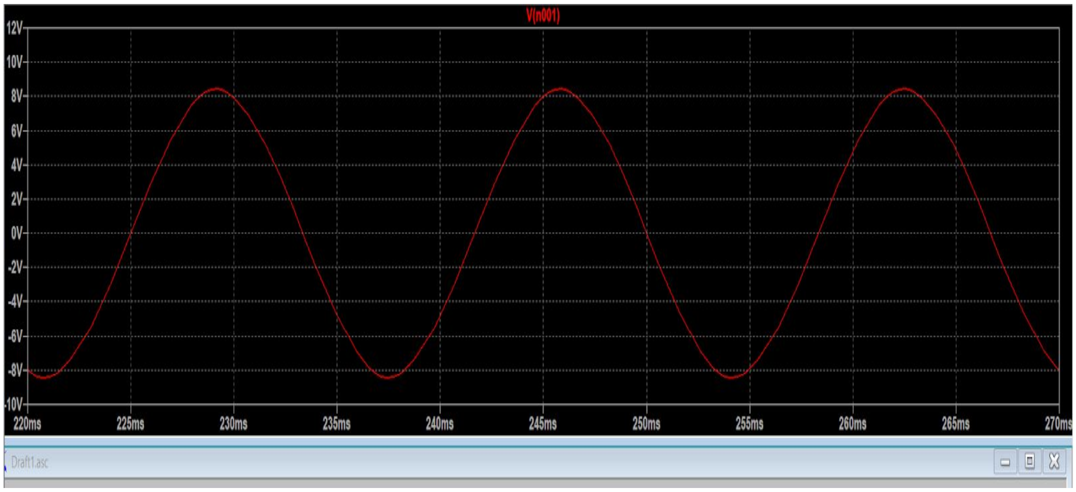


Figure 18: Voltage across R2 (load of our circuit)

We know there is a bridge rectifier and a linear 5V regulator that is at the output of the wall adapter. Therefore we expect a 5V DC at the output of our wall adapter.

Figure 19: Voltage output of wall adapter.

From observing Figure 19 we see that the transformer component is operating as expected.

Low Pass Filter

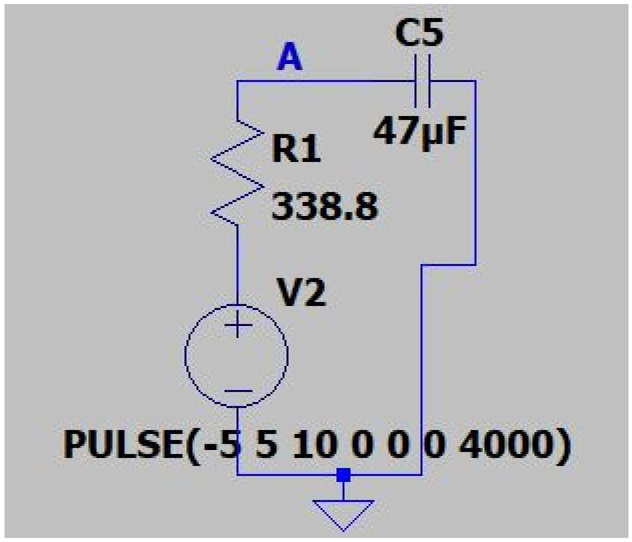


Figure 20: Low Pass Filter Schematic

We have a low pass filter with a resistor value of 338.8 ohms and 47uf capacitor to make the corner frequency 10Hz. The output of the low pass filter at Node A is fed into the trigger pin of the multivibrator to control the output of the sensor to be fed into the inverting integrator. The input of the low pass filter is a square wave.

From filter analysis we get that $H(s)=\frac{62.799}{62.799+S}$. Converting this from radians/sec to frequency we see that our corner frequency is 10Hz. We show the Bode Plot and Phase Plot below.

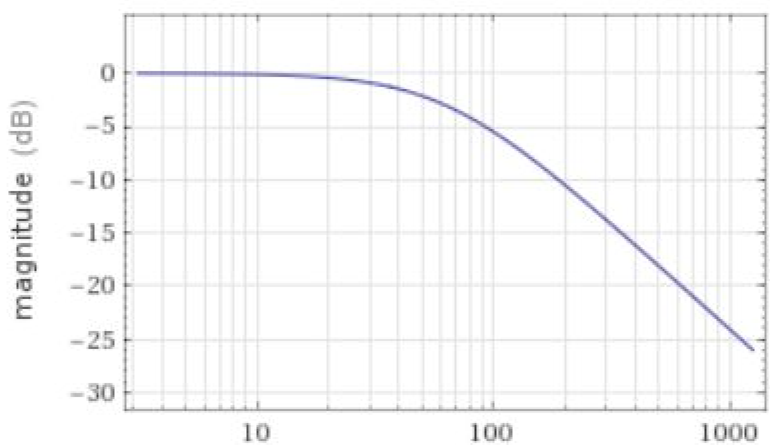


Figure 21: Bode Plot of Low Pass Filter

We can see that on the radians/sec scale (X Axis), we have a drop off starting at 62.799 and afterwards we have -20db/Decade roll off as expected.

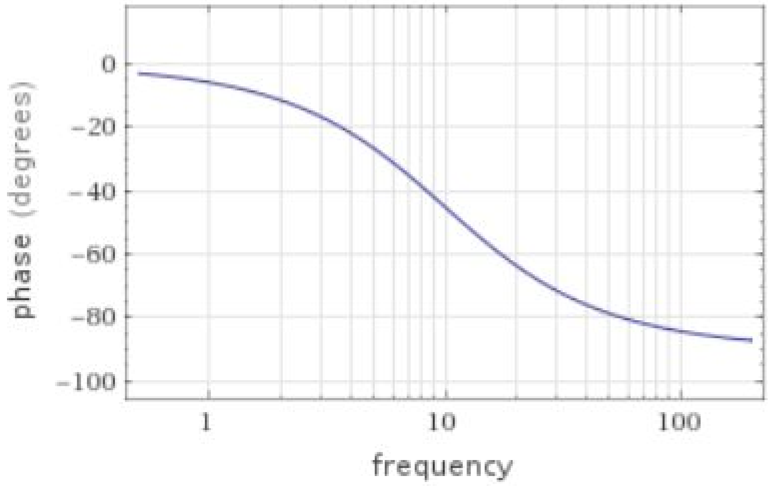


Figure 22: Phase plot of Low Pass Filter

We imagine there is a relay or pressure sensor above a road and when a car passes by, a square wave is generated and sent into the low pass filter. We chose a low pass instead of a high pass because it made the most sense. It is above a certain frequency say 15hz, so 15 cars per second is impossible in cities so it wastes the potential of a high pass filter because those high frequencies cannot be achieved physically. In our design we chose 10 cars to be the cutoff based on a rough estimate of the average number of cars passing a point in a second. If the sensor detects a car, it will allow the square wave into the trigger of the 555 to turn on the sensor. This ensures the sensors will be all conserving the power consumed by the circuit during the quiet period of the day/night.

We show an example of our filters operation below the cut off frequency and after the cutoff frequency.

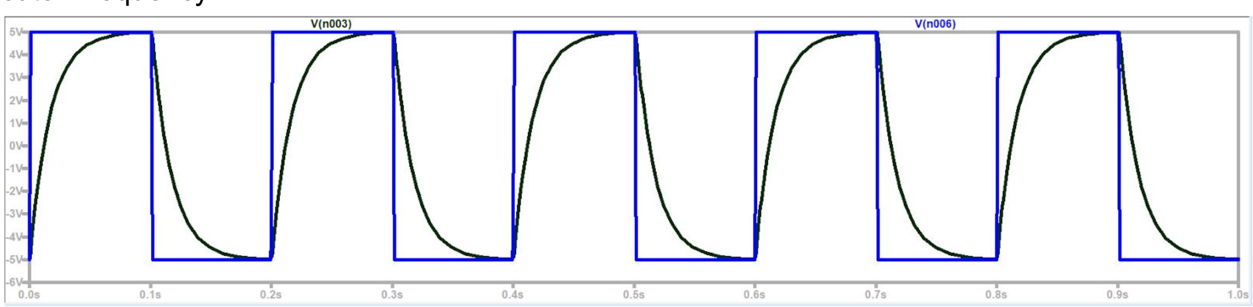


Figure 23: Low Pass Filter Output at low frequency (Black)

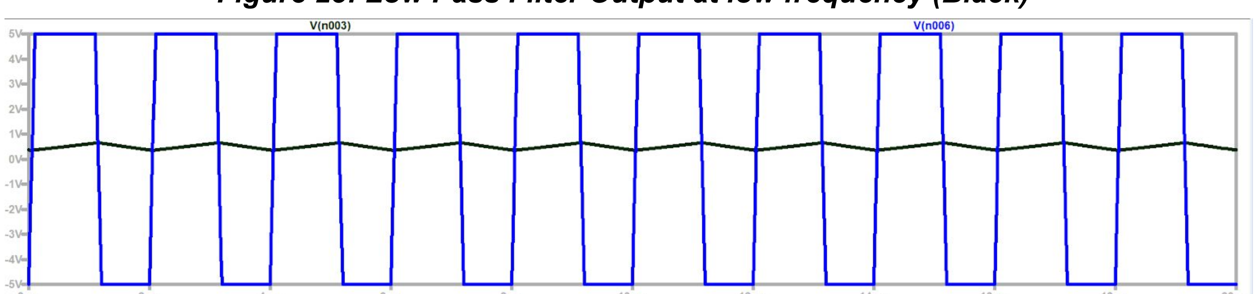


Figure 24: Low Pass Filter Output at high frequency (Black)

LED [3]

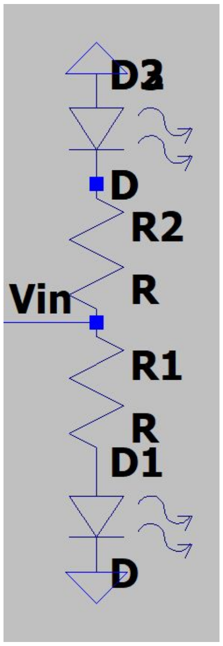


Figure 25: LED output juncture.

The red LED used at the end is the output that the user sees. Both LEDs are the same type to ensure consistency in terms of LED parameters. From the data sheet, the forward voltage is 2.2V and the reverse voltage is 5V. These two parameters are guaranteed by the circuit designs if the power supply to the comparator op amp is at least 5V. The LEDs are placed in opposite orientations so that only one LED will turn on. The resistor in series with each LED are current limiters so any arbitrary small value will do. In theory, there can be a scenario where both LEDs will both be off if the input to the comparators are equal, however that is extremely unlikely as noise will ensure that one value will be greater than the other so this scenario can be safely ignored in the design as a factor to consider.

From all these components we can represent the output signal as:

$$V_{final} = \{\, 5V \;:\; if \int_0^t MQ9_1(t) * dt > \int_0^t MQ9_2(t) * dt$$

$$-5V \;:\; if \int_0^t MQ9_1(t) * dt < \int_0^t MQ9_2(t) * dt$$

$$0V \;:\; if \int_0^t MQ9_1(t) * dt = \int_0^t MQ9_2(t) * dt \,\}$$

Where the time frame $0 \rightarrow t$ is controlled by the monostable vibrator whose equation is: $V_c(t) = -5e^{\frac{-t}{.94}} + 5$ (solution to equation 1). And the function $MQ9(t)$ is representing the voltage signal outputted by the sensor. The $-\frac{1}{RC}$ the component of the integral is equivalent on both sides of the inequality so we can ignore it.

Integration

The first stage of the circuit is power delivery. We have a 5V wall adapter that converts the 220V AC from the wall into 5V for our circuit. These circuits step down the high AC voltage to a value between 5V and 12V AC. In our case this is done with a 26:1 primary to secondary turn ratio. That AC voltage is then rectified with a bridge rectifier to convert it to DC. That DC voltage is then sent through a linear 5V regulator that powers our circuit. Figure 19 shows the output of our wall adapter transformer.

Figure 19: Voltage output of wall adapter.

Afterwards we have the Low Pass Filter that sends a trigger to our monostable multivibrator. We imagine we have a pressure plate that cars can drive by on. That is a frequency which we want to trigger our circuit on. We chose the corner frequency to be 10Hz as that is the upper maximum of how many cars can pass in one second in a city. The Low Pass Filter also makes our circuit sensitive to lower frequencies, and therefore more realistic car traffic models. After the corner frequency we have a roll off of -20dB/Decade. This means that our circuit does not trigger on anything more than roughly 25Hz. Figure 23 shows the output of our filter at a low frequency.

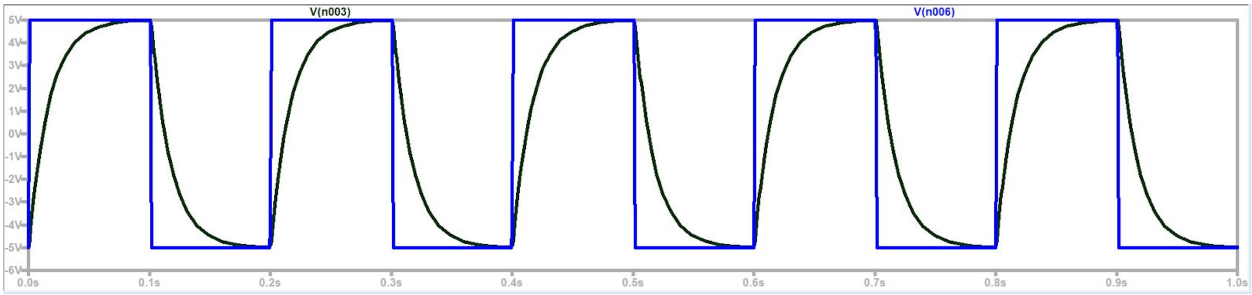


Figure 23: Low Pass Filter Output at low frequency (Black)

The negative edge of the filter output is sent to the monostable multivibrator as the trigger pulse that starts the rest of the circuit.

The next stage of the circuit is the monostable multivibrator implemented with a 555 timer, which produces a high signal of approximately 4.5V when an external trigger is set off that sends a 0V signal into the trigger pin of the 555 timer and an output of a low signal of 0V when input to the trigger pin is greater than 0V. The output of the 555 timer is connected to the two MQ9 to turn them both on and off simultaneously and control the time that they are both on to sense their respective air quality. The time that the monostable multivibrator's output remains high, when an external trigger of the 555 goes off, is determined by the time the capacitor C2 reaches ⅔ of the source voltage to the 555 timer (LTSPICE Schematic). In our circuit, we used a single pulse as the trigger for ease of testing and 5V as the source of the 555 timer since this is easily accessible through the wavegen. When the pulse-trigger shuts off to start the 4.5V output, the source, R3, and C2(LTSPICE Schematic) form an RLC circuit and to find the voltage of the capacitor simply boils down to solving the differential equation

$$\frac{dV_{c2}}{dt} + \frac{1}{R_3C_2}V_{c2} = \frac{V_{source}}{R_3C_2}$$

For our design, we chose R_3 and C_2 values such that the time that the monostable multivibrator is outputting its high signal is approximately 1.1 seconds.

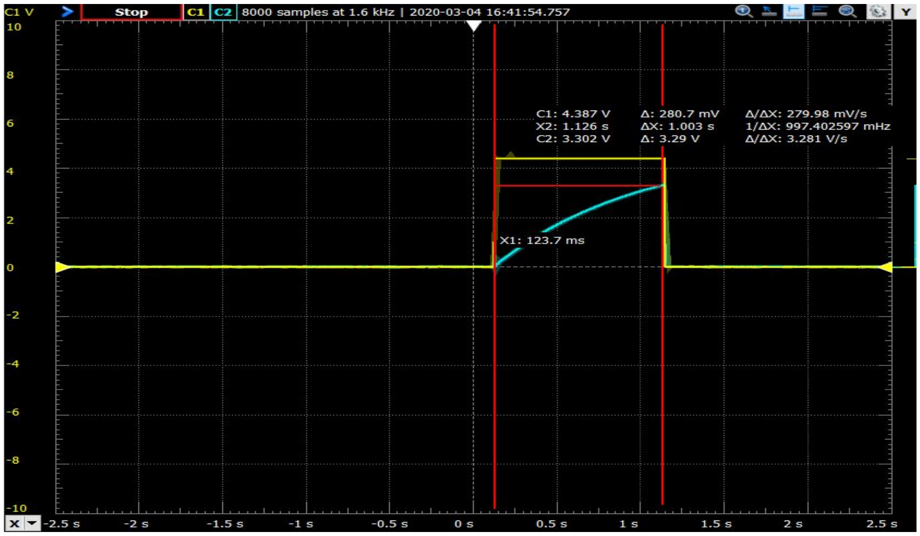


Figure AA: BLUE is the voltage over C2 in the monostable multivibrator and YELLOW is the on time of MQ9 which is also the 555 timer's output.

The output of the monostable multivibrator powers the second stage of the circuit, the two MQ9 sensors simultaneously. Their AC outputs are fed into the third stage of the circuit, the two independent inverting integrators that sums up their instantaneous AC readings over the period that the MQ9s are powered by the monostable multivibrator high output. The output of the individual inverting integrators are governed by the equation:

$$V_{output} = \frac{1}{RC}\int_{0}^{t} V_{in} dt$$

In our design, for both inverting integrators, the resistor value was chosen to be 3 megaohm and the capacitor value was chosen to be 1uF. This was to ensure amplification remained consistent between the two outputs of the inverting integrators. These values were chosen because this will "amplify" the integration output by $-\frac{1}{3}$ to prolong the time to saturate the limit on the op amp since we are limited by a ± 5V supply to power the op amp. We chose the optimal amplification from the parts kit. There is no resistor bigger than 3 megaohms and the next biggest capacitor (4.7μf) value will reduce the signal to around 0.07 of its integration value which is too small. Putting resistors in series to further reduce the integration output was not considered since it would take up more breadboard space which was scarce considering the entire circuit. The output of the two integrators are then fed into a single comparator. The output of the comparator is to a where that splits off into two independent diodes with opposite orientation as pictured in figure BB.

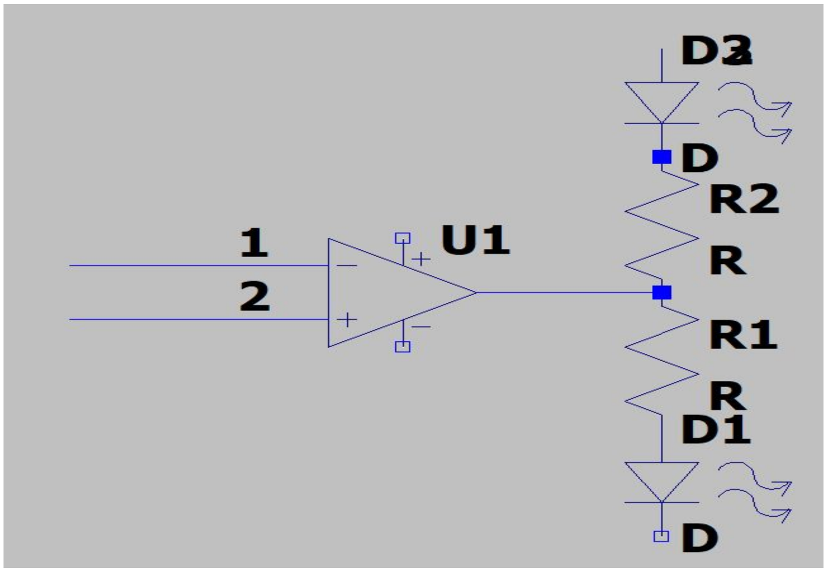


Figure BB: Orientation of the diodes and diode-input associativity

The inverting integrator, whose output is connected to the positive input terminal of the comparator op amp, is associated with the LED that has the orientation that goes from positive to negative due to the fact that when MQ9 that is associated with input 1 sense more pollution, the inverting integrator will yield a lesser value relative to input 2. This will make input 2 to have a greater value than input 1 so the comparator will send out the positive supply voltage. Since LED D1 is oriented positive to negative, the positive supply voltage will turn D1 on while D2 is off since its orientation is negative to positive. The opposite is true when the MQ9 sensor that is associated with input 2 senses more pollution. Thus, to summarize, the MQ9 sensor, whose AC output is connected to the inverting integrator whose output is connected to positive input to the comparator, is associated with the LED that is in the positive to negative orientation. The other MQ9's inverting integration's output that connects to the negative input of the comparator is associated with the LED that is in the negative to positive orientation. The LEDs are in opposite orientations to only allow one LED to turn on at a time, and the LED that turns on is associated with the MQ9 that sensed the least pollution over the period of time determined by the monostable multivibrator. In our physical design, we placed the LED near their associated MQ9 sensor for virtual ease to determine which MQ9 sensor is currently reading the least polluted levels.

Operating Conditions:

The circuit, as expected, does not operate well in all environments. Outside of environments that would cause mechanical failure of our circuit there are scenarios that can pose a challenge for our circuit.

Where the Circuit Fails to Work:

The largest problem/area that our circuit fails to operate predictably in is when the period integration is larger than ~3 seconds. This is because the present coefficient of our integration ($\frac{1}{RC}$) is not small enough to prevent the Op-Amps from reaching the saturation voltage (+/- 5V). If both integrators reach the saturation voltage we cannot accurately tell which of our sensors is providing the favorable output. We can solve this by supplying a higher voltage to the Op-Amps.

In addition our circuit has two sensors that, in theory, are to be placed a block's distance at minimum to compare the air pollution between two streets. However, our circuit is not up to that level yet. It is possible for us to get 50ft of wire and connect the sensor to our circuit, but over wire resistance to our main circuit, that would bring the signal drastically down and destroy its integrity. We can potentially solve this with a transformer as in power transmission lines, on a much smaller scale.

Current Operating Conditions:

As it stands now the circuit has defined operating conditions on where it works optimally. All chips, and Op-Amps are supplied from 0V-5V. From the transformer that supplies main power to our circuit, that must be hooked up to 120V-240V AC 60Hz (RMS values). In addition our filter is a Low Pass Filter that has a corner frequency of 10Hz, thus our circuit operates best at low frequencies.

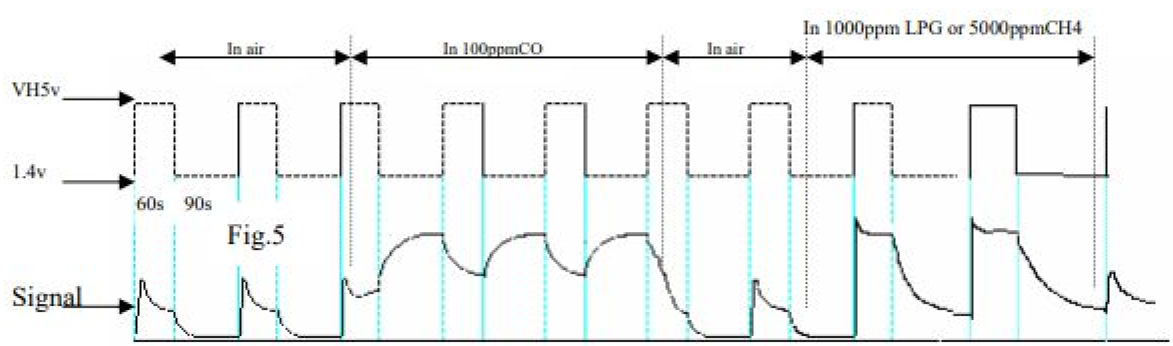


Figure 10: MQ9's signal output for various settings

And as shown in Figure 10 above the MQ9 sensor works well in normal air, or in 100ppm CO and 5000ppm CH4. Under these conditions, the circuit works both in simulation and in practice.

Limitations and Tradeoff:

Our circuit is limited in what is able to do. It can detect CO and CH4 very well, and outputs a clean signal for the listed concentrations of the gas. However, we cannot integrate our signal for over 2-3 seconds as it reaches the saturation voltage. Furthermore until changes are made, we cannot place the sensors far apart, like we would like to, due to wire resistance. So we made the tradeoffs of integrating for a shorter amount of time, and having one of the sensors as a simulated input. The main drawback of this issue is that our readings, while accurate, are not as robust as they could be.

There is a low vs high frequency trade off in the selection of the cut off frequency. In our design we choose frequency cutoff (below ~10hz) to trigger the sensors. There is a trade off in the frequencies of the updates on the LED where low frequencies mean more updates and a higher frequency meaning less updates. So with more updates, the results are more up to date and hence more trustworthy and where less update means the results might be not accurate. The trade off above is also present in the filters being used. Low pass updates more while high pass updates less.

The trade-off of using external pulse triggers is that the integration time of the 555 can be obsolete when the frequency of the pulse trigger is greater than the period of the 555 timer. So each trigger will not allow the 555 timer to run its full course.

How we can Improve:

The circuit is already planned to be improved and we list some of those improvisations here. Primarily we want to increase the period of integration. In addition to changing our RC values for the monostable vibrator we want to decrease the $\frac{1}{RC}$ coefficient of our integrators, so choosing larger capacitors and resistors would work. We want to increase the physical distance between the two MQ9 sensors. For that we might be able to use a transformer to preserve the signal integrity of our sensors if the voltage drop across the wire is too large. Instead of having the circuit powered from a wall outlet, our modeled transformer design should work on a larger grid such as NYC's grid. NYC is a 3 phase system. We can get a high enough voltage if we take the difference between 2 sine waves 120 degrees out of phase to power our circuit.

References

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