Ecole Nationale Supérieure d'Électronique, Informatique, Télécommunications, Mathématique et Mécanique de Bordeaux

Analog Electronics Project Report

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1. Introduction

As part of the unit PR206, the team carried out a project in Analog Electronics. The aim of the project is to create a working ventilator with speed control. The proposed project had 4 analog system steps. The first one is a Pulse Width Modulation (PWM) which controls the average power delivered and create a pulse signal. Next to that, an integrator will transform the pulse to a triangle which will create linear command. This command will regulate the motor speed of the ventilator. The third step will be to adapt the system to obtain a 5V supply. Therefore, tests will be led to check that everything is working correctly and the final step is design a fan to create the final product.

This project requires real engineering mindset because through almost a whole semester we will have to conceive our own electric circuits with well thought components values. The critical component for this project is the engine motor because it has predefined values that we cannot change. It means that it has a mandatory voltage and current supply and the team will have to deal with it. Ecological parameters have to be considered as energy consumption or components origin.Mainly, the ecological parameter is the current usage. Furthermore, the engine motor has to deliver a precise amount of energy to make our system function without destroying the connections between the components or the components themselves. Also a precise and optimal current and tension values were chosen for this ventilator to make everything work perfectly.

1.1. Tasks to Achieve

In order to conceive the project, the team fixed global tasks to complete which avoid to go off-track. Tasks aimed are :

1. Creation of the PWM circuit with simulations;
2. Creation of the integrator circuit for the linear command with simulations;
3. Tests with a breadboard;
4. PCB fabrication;
5. Final Rending.

1.2. Materials

The ventilator delivered to the team was the San Acer 120 model 9G1212P4H041 from the company SANYO DENKI, as shown in the figure 1. It has 4 cables. Red is 12V motor power. Black is GND. Brown is the PWM control input and yellow is the tachometer signal output.

Figure 1: DC Cooling Fan San Ace 120

2. Pulse Width Modulation (PWM)

As mentioned previously, the PWM generates pulses using a DC entrance of 5V. The decision which had been taken on making a full analog circuit made the team reject the use of a component named NE555, an integrated circuit that can be used to create PWM. So, the team started to search for a viable montage.

The PWM is used to vary the average output voltage by varying the duty cycle, meaning that the high time of the output signal changes in a period. Figure 2 shows how the duty cycle changes the average output voltage.

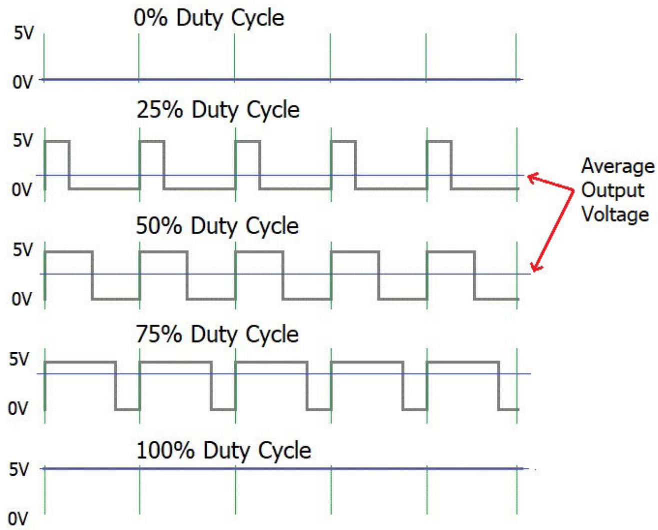

Figure 2: Duty cycle variation

2.1. Primitive PWM

The circuit for the PWM chosen is an astable multivibrator circuit that has a potentiometer for regulating the duty dycle, consequently resulting in a regulation of the motor speed. This circtuit is built with two NPN bipolar transistors with the reference BC547, with three resistors, a $10k\Omega$-potentiometer and two $100nF$-capacitors. The circuit is below:

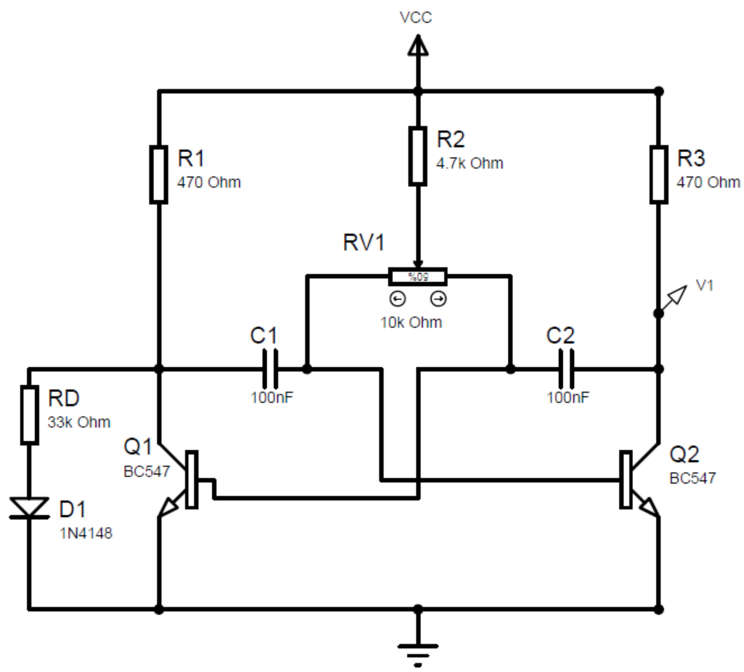

Figure 3: PWM circuit

2.1.1 Theoretical Analysis

In order to explain how the circuit works, the transistors will be considerate as switches, which are activated according to the base-emitter voltage and the calculations will be based on the traditional astable multivibrator, as shown in figure 4 (a). The analysis can be divided into 2 parts:

1. C2 before Q2 switches:
   The figure 4 (b) shows the case of C2 before Q2 actuates, considering that Q1 is saturated. In this case:

$$V_{C2} = V_{beQ1} - V_{CC} \tag{1}$$

2. C2 after Q2 switches:
   The figure 4 (c) shows the case of C2 after Q2 actuates, considering that Q1 is now a open switch. In this case, C2 will discharge until V_{beQ1}, because when this value is reached Q1 will saturate, repeating the process.

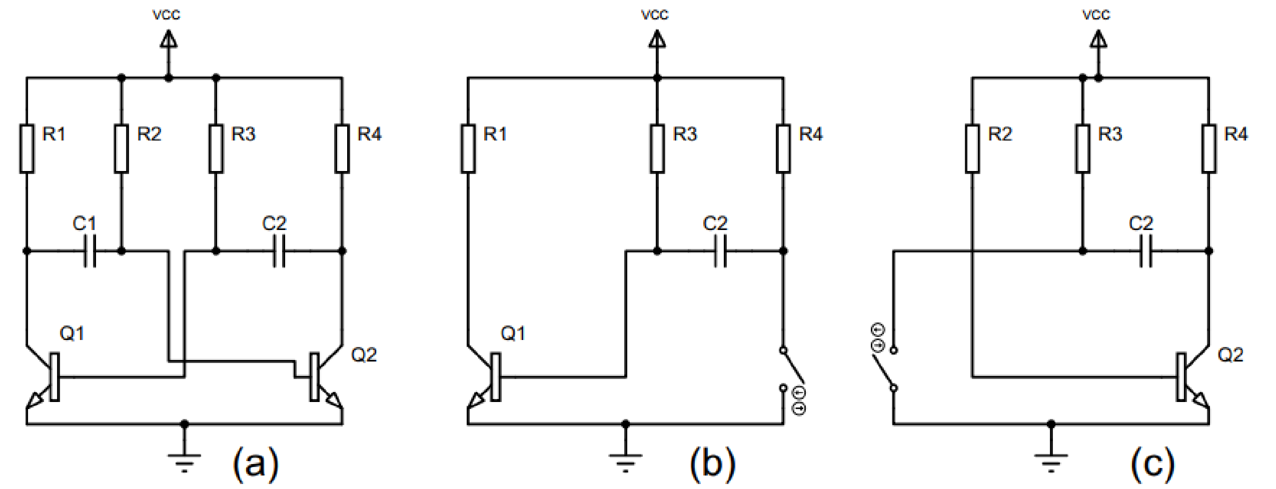

Figure 4: (a) PWM circuit for the theoretical analysis, (b) case 1 and (c) case 2

Considering the capacitor discharge equation, where $V_C = V_{beQ1}$ and the initial value $V_0 = V_{beQ1} - V_{CC}$, it is possible to calculate the output voltage high or low time:

$$V_C = ((V_0 - V_{CC}) - V_{CC})e^{\frac{-t}{\tau}} + V_{CC} \tag{2}$$

$$V_{beQ1} = ((V_{beQ1} - V_{CC} - V_{CC}) - V_{CC})e^{\frac{-t}{\tau}} + V_{CC} \tag{3}$$

$$V_{beQ1} - V_{CC} = (V_{beQ1} - 2V_{CC})e^{\frac{-t}{\tau}} \tag{4}$$

$$e^{\frac{-t}{\tau}} = \frac{V_{beQ1} - V_{CC}}{V_{beQ1} - 2V_{CC}} \tag{5}$$

$$\frac{-t}{\tau} = ln(\frac{V_{beQ1} - V_{CC}}{V_{beQ1} - 2V_{CC}}) \tag{6}$$

Considering that $V_{CC} >> V_{beQ1}$

$$t = -ln(\frac{-V_{CC}}{-2V_{CC}})\tau \tag{7}$$

$$t = -ln(\frac{1}{2})\tau \tag{8}$$

$$t = ln(2)\tau \tag{9}$$

The values for the components C2 and R3 control the high time of the output voltage, designated t_1:

$$t_1 = ln(2)R_3C_2 \tag{10}$$

The values for the components C1 and R2 control the low time of the output voltage, designated t_2:

$$t_2 = ln(2)R_2C_1 \tag{11}$$

Fixing $C1 = C2 = C$ and considering that the period T is equal to $t_1 + t_2$:

$$T = ln(2)C(R_2 + R_3) \tag{12}$$

To control the Duty Cycle, the potentiometer RV1 in figure 3 changes proportionally to the relation between R2 and R3, and the sum of the resistance between each terminal of the potentiometer and the center pin is always constant. In the case where the potentiometer is in the central position, $R3 = R2$, $t_1 = t_2$ and the duty cycle will be 50%. If the potentiometer is positioned close to 0°, the Duty Cycle is approximately 0% resulting the minimum speed of the motor, because the low time t_2 is much longer than the high time. If the potentiometer is positioned close to 360°, the Duty Cycle is approximately 100% resulting the maximum speed of the motor, because the high time t_1 is much longer than the low time.

2.1.2 Simulations

Simulations were performed on this montage on Proteus software. The results obtained are illustrated below:

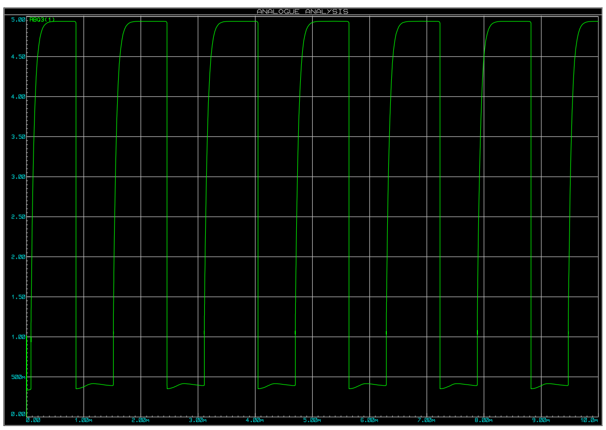

Figure 5: Simulation of the PWM with potentiometer set at 3.7 k

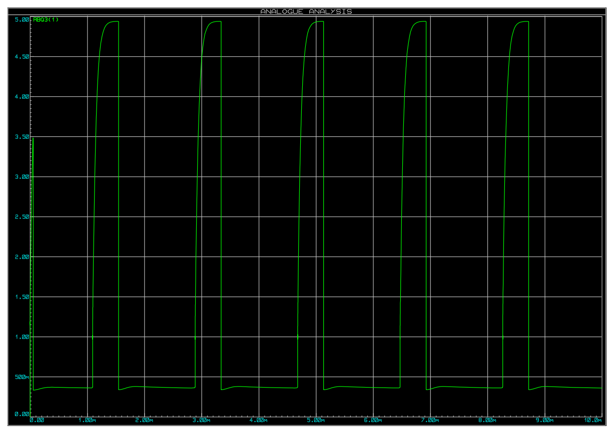

Figure 6: Simulation of the PWM with potentiometer set at 8k

On this simulation, the PWM response fluctuates with the potentiometer value. However, there are curves at the beginning of each pulse resulting from the capacitor loading. Hence, with those results it was straightforward to measure the frequency of the system. Using the cursors on Proteus simulation the frequency found was roughly about $636.9Hz$.

2.1.3 Practical Results

The test on the first circuit was concluding because an almost perfect squared signal was obtained. Furthermore, when the potentiometer value was modified, the frequency of the PWM at the output change. Nevertheless, the load of both capacitors could be seen on the graph. That was an issue that had to be solve.

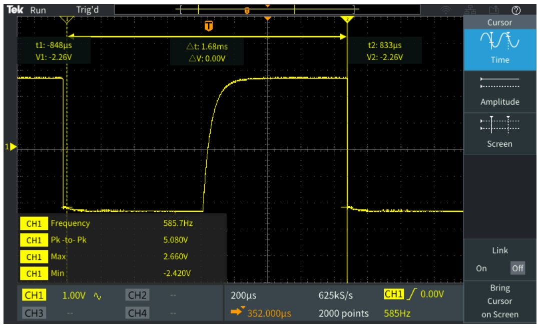

Figure 7: Graph of the primitive PWM voltage output throughout the time

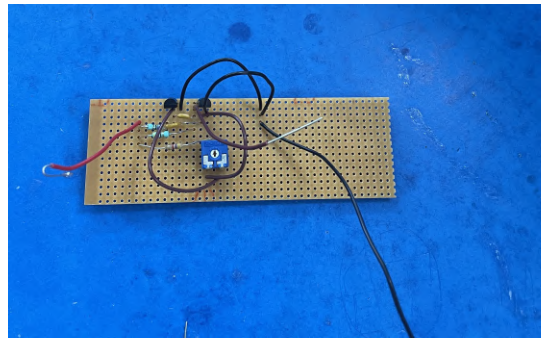

Figure 8: Wiring of the primitive PWM on the breadboard

On this first graph, the value of the peak-to-peak voltage is $5V$. It was the aimed value of our output so the team was satisfied about the result. As predicted with the simulation, on the oscilloscope appears the load of the capacitor of the PWM resulting from the change of each transistor operation mode. Nevertheless, the displayed curve was conclusive and could be used as such. However, a decision had been made to compensate the loading phenomenon in order to create a perfect square related to a real PWM.

On the second picture, there is the montage of the primitive routed PWM which was created on a breadboard.

2.2. Comparison between theoretical, simulated and practical results

The comparison between the frequencies for a 50% duty cycle obtained can be seen in Table 1.

Theory	Simulation	Practical
743,8 Hz	636,9 Hz	585,7 Hz

Table 1: Comparison of the frequencies obtained

It can be seen that the values obtained are in the same order of magnitude. The difference between the values is due to the fact that in theory the transistor model used for the calculations was a simple switch, while in reality the dynamic behavior of the transistor takes into account parasitic capacitance and resistance, for example. Simulation considers a more complex model of the transistor compared to theory, that is why the simulated value is closer to the practical value.

For the amplitude of the primitive PWM output signal, the theoretical, simulated and practical values are close, being 5 V, 4.99 V and 5.080 V respectively.

2.3. Free Wheeling Diode

During this project, a motor was used to convert electric energy into mechanic energy. This latter was present in the provided fan. A motor is a very sensitive component which has a high sensibility on voltage fluctuations. The designed PWM varies between high and low level states. Thus, when the system fails to the low level, the voltage is cut off. This interruption results from once the switching element switches, here the transistor. Once the switching element activates then an extremely high voltage spike because of the stored energy within the resistor comes into view across the switching element terminals in switch OFF or ON condition so, it may destroy the switching element. The free wheeling diode brings safety in the PWM. Whenever the tension plummets, the diode operation mode changes to ON and keeps the energy of the circuit inside creating a new path for the current. In consequence, the amount of current reduces as it turns into the montage. This free-wheeling diode is of paramount importance in order to keep in safety some components such as the transistors or the engine motor in the fan which are fragile.

To sum up, this free-wheeling diode is a simple safety for the PWM. The montage is below:

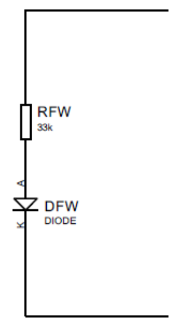

Figure 9: Free-Wheeling Diode Schematic

It is noticeable that the montage is straightforward. Nevertheless, a component design had been made for this circuit.

2.3.1 Theoretical Analysis

At first glance, the team thought about the type of diode that might be used. Firstly, a Zener diode was considered because it conducts in both ways. However, due to the avalanche zone, our output signal would be deformed. Hence, a simple diode was selected because the main goal was to verify if the current goes in the good direction. Moreover, the peak reverse voltage of the PN diode is lower than the Zener, therefore it is more appropriated to select for a PN diode.

Afterwards, the team chose the resistance that would keep the energy of the PWM. A great resistance value was aimed. However, the resistance has to be low value enough in order to allow the current to go across it. Yet, the value of $33k\Omega$ was selected.

2.3.2 Simulations

This free-wheeling diode was then merged with the previous PWM montage. The behaviour of the PWM output might remain unchanged because none active components had been added to the output. Nonetheless, the output behavioral within each state commutation might become more stable. The simulation was performed and the results are displayed below:

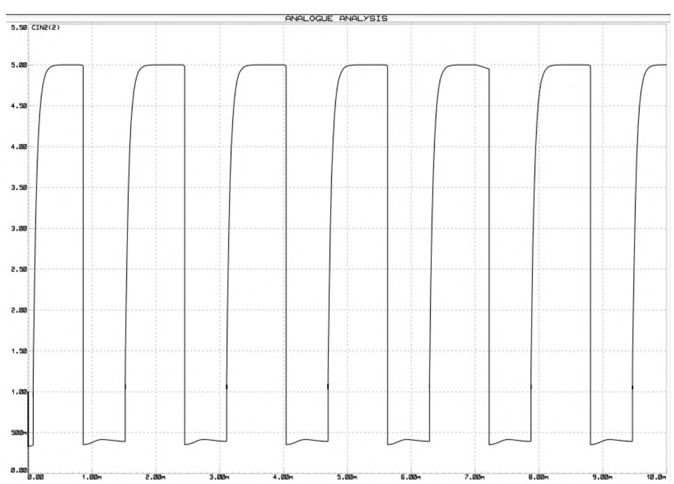

Figure 10: Output Signal with the Free-wheeling Diode

This chart foregrounds the fact that the free-wheeling have none impacted the PWM. It is used for safety purposes.

2.3.3 Practical Results

In this part, the aimed goal was to highlight that the diode is working on each rising and falling edge of the PWM output. The purpose was to show the commutation time of the diode. Below, the results of the practical results performed:

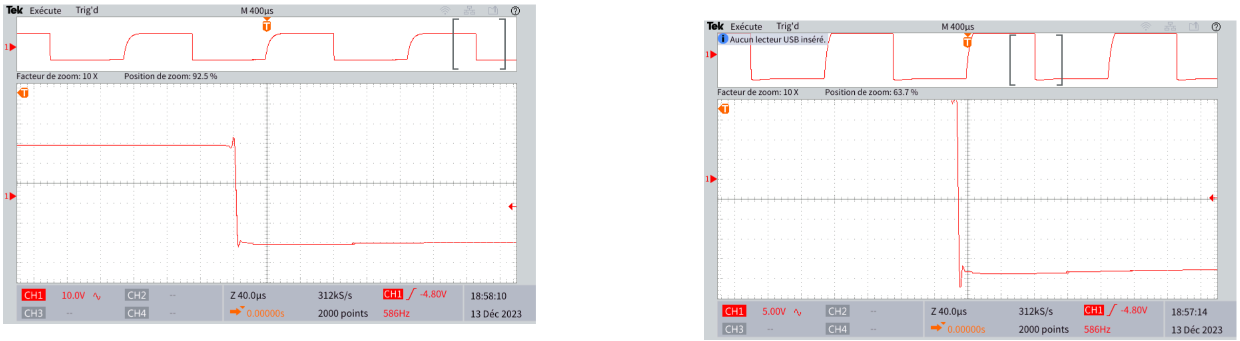

Figure 11: Free-Wheeling Diode working

On the charts above, the commutation time of the diode working has been emphasized. This is a proof that the free-wheeling is working. Furthermore, the output signal remained intact as predicted in the simulation on Proteus.

2.4. First Stage Amplifier

The team kept in mind the fact that on the output signal there was a striking loading time of the capacitors. Yet, the team reflected on possible solutions to fix that. The outcome of this reflection resulted of adding an amplifier stage to deform the signal and recreate it across a counter reaction.

2.4.1 Theoretical Anaysis

From now on, the main point was to design this amplifier. Considering that the PWM mainly provides voltage to the fan, a voltage amplifier had to be created. There were plenty of possibilities for this amplifier but a counter reaction was selected to serve this purpose. This counter reaction is amplified by a common emitter montage with a resistor upon the collector. The montage is below:

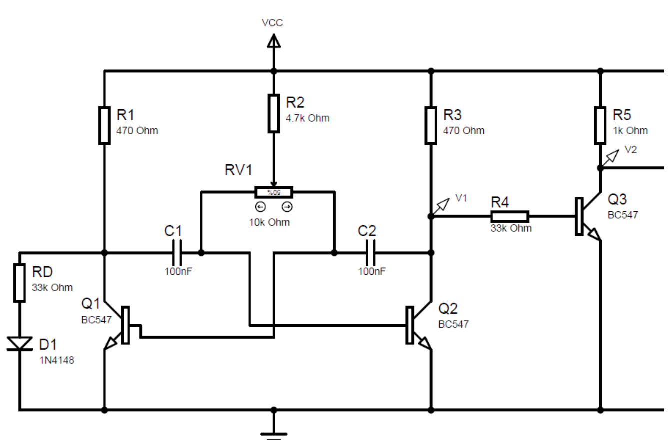

Figure 12: PWM and first stage amplifier circuit

On this schematic, on the base, $33k\Omega$-resistor is present, its main goal is to decrease the current that goes into the base. An important base current is harmful for the transistor. However, the base current has to be high enough to saturate the transistor. On the data sheet, it is written that the minimum gain β is equal to 110.

Therefore, on the circuit, on the collector a $1k\Omega-$resistor had been set because it is the easiest to control:

$$I_C = \frac{5}{R_5} = 5mA$$

Because the transistor is a NPN bipolar, to reach a saturate operation mode,

$$I_B \geq \frac{I_C}{\beta} \iff I_B \geq 4.5 \times 10^{-5}mA$$

From now on, it was straightforward to deduce the resistor value with a Kirchhoff's law keeping in mind that the PWM output $V_E = 5V$.On the data sheet $V_{BE_{sat}} = 9mV$. So

$$V_{R_4} = -V_{BE_{sat}} + V_E - 5 + V_{R_3} \implies V_{R_4} = 1.45V$$

Thus, knowing that $V_{R_4} = 1.45V$, with the Ohm formula, $R_4 = \frac{V_{1.45}}{4.5\times10^{-5}} = 32k\Omega$, only $33k\Omega$-resistor were available.

The choice to use bipolar transistors instead of MOSFETs was based on the bibliographies studies (Transistors in Pulse Circuits and Laboratory Manual for Electronics via Waveform Analysis). In these references, all astable multivibrator circuits found are composed of bipolar transistors. The simulated and practical results show that using bipolar transistors the project goals were achieved.

2.4.2 Simulations

Before proceeding to the practical experiments the team did some simulations of the circuit on Proteus. Here are the results:

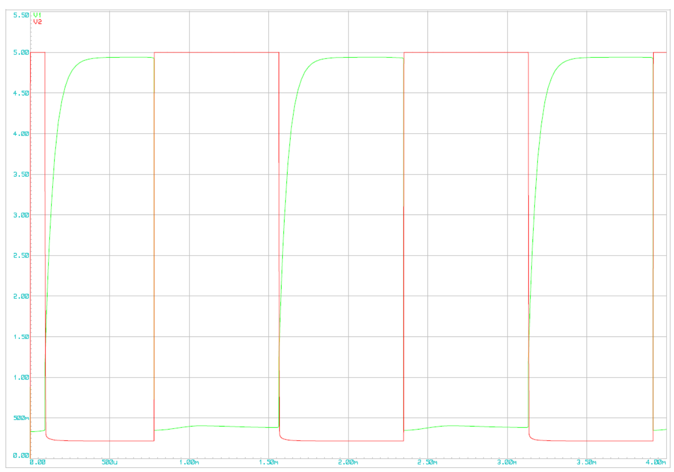

Figure 13: Contrast between the previous output and the new one

The results were dramatically convincing. Thus, the team proceeded to practical tests using a breadboard.

2.4.3 Practical Results

From now on, some experiments were performed to verify the montage designed. The new PWM was wired and the results are displayed below:

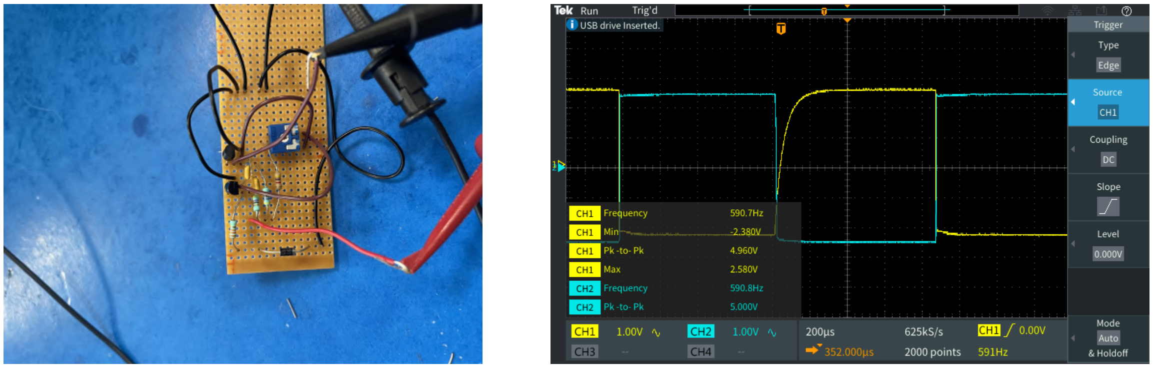

Figure 14: PWM with enhancements simulations

It is striking that those charts reveal an important improving of the output. While before the output was blurred by the loading phenomenon of the capacitors, now it looks almost like a PWM output. However, there is phase of 90 on the received signal.

2.5. Second Stage Amplifier

Actually, this undesirable angular phase is the whole point of the this second stage amplifier. The purpose is to wire a montage that will invert the signal without affecting it.

2.5.1 Theoretical Analysis

The point is to merge this so call amplifier to the previous one. The aim was to create a 2-stage amplifier montage using the 90-degree phase of each one to delete the inversion. To reach this goal, again a common emitter montage using a counter reaction was used. There is none resistor on the base of the transistor bipolar though. Indeed, here the usage of a resistor to reduce the current to a low level is unnecessary because on the collector output of the previous stage the current is low. Therefore the second amplifier has a straightforward architecture using only a counter reaction with a $1k\Omega$-resistor on the collector. The output of the final PWM will be taken between this resistor and the collector. This would be the final montage. The schematic is below:

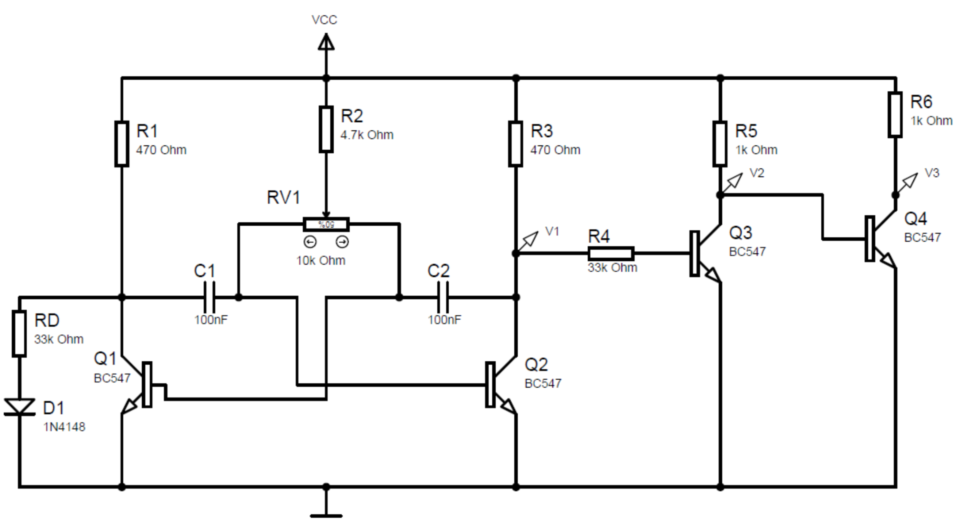

Figure 15: Final PWM

2.5.2 Simulations

The efficiency of the montage was checked by a test performed on Proteus:

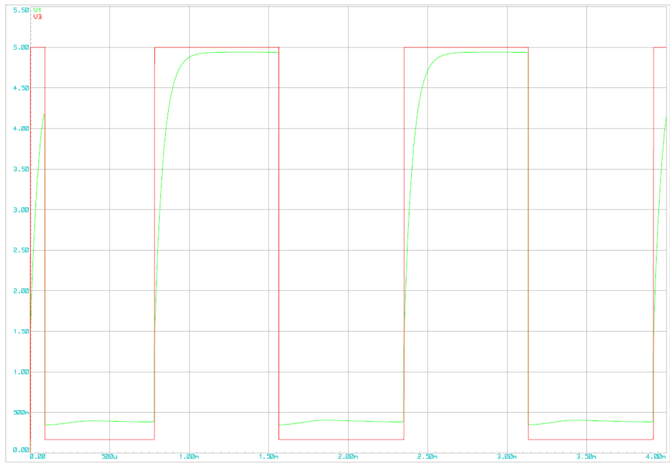

Figure 16: Nuance between first and final version

It is noticeable that this new PWM is drastically more efficient than the first one proposed. The output showed above is nearly a perfect square.

2.5.3 Practical Results

Once the theory allowed us to perform practical test. The wiring process of the final PWM took place. Afterwards, a bunch of verifications were proceeded. The relevant images are showed below :

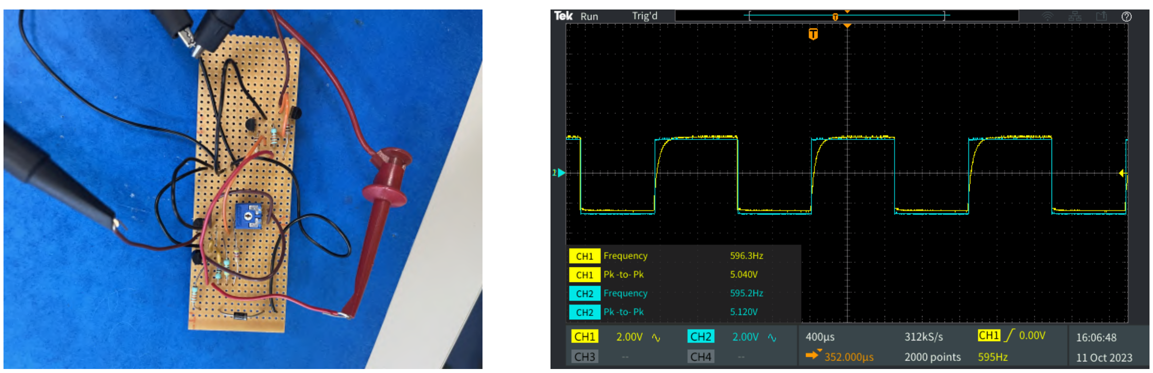

Figure 17: PWM with enhancements simulations

Finally, according to the group a PWM was designed and conceived. The whole conception was tough and demanding. The team figured out that a PWM conception is not only a bunch of hard equations contrary to what we thought but there is a true engineering approach upon the components, the wiring and also the voltage and current values.

3. Integrator

3.1. Initial Analysis

The first step of the project was successfully accomplished. That means, the system generates a square sign with a duty cycle from 1 to 100 per cent. Nevertheless, the square signal which will be injected in the fan engine is low in current though and hard to control. What are the solution to overcome this controllability issues. It this straightforward that an integrator is the best solution for this problem. The purpose of the integrator is to transform the PWM output signal to a linear triangle command giving to the system more efficiency, controllability.

However, it is important to take in consideration that this integrator might give us an unwanted gain, neither an input nor output impedance and also a voltage offset. That is why, there is a key consideration to give to the components. At first glance, the team wanted to use bipolar NPN and PNP transistors for the integrator.

Nevertheless, it might bring a lot of noise into the system but also an unnecessary complexity during the wiring process. Therefore, a active integrator using a TL071 was used. The TL071 was a good and an efficient choice because it is flexible and easy to find in our store. Furthermore, it has a straightforward usage and it was already used in other practical classes. That is why the team decided to design an active filter with an amplifier, passive and active components.

To conclude this part, a classic integrator using a resistor and a capacitor in parallel and an TL071 amplifier seemed to be the better choice.

3.2. Theoretical Analysis

First of all, the team had to go across the conception of the resistor and the capacity. The output frequency of the PWM was about $600Hz$. Thus, the team proceeded to the components value calculus which is detailed afterwards. The montage of the classic integrator is below:

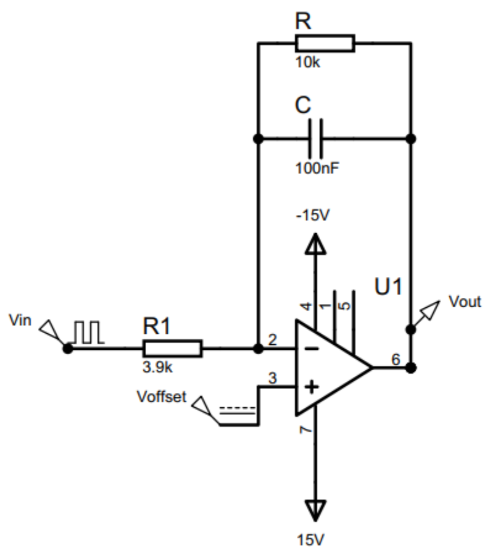

Figure 18: Integrator circuit

If the frequency is roughly $600Hz$, the integrator bandwidth might be nearly $1kHz$. That is why, a cut frequency has to be set nearby $1kHz$. Thus, if the capacity is set at $100nF$,

$$f_{-3dB} = \frac{1}{2\pi RC} \Leftrightarrow R = \frac{1}{2\pi f_{-3dB} C} = 10k\Omega \tag{13}$$

The resistor R1 is used to adjust the gain and a voltage is inserted into the positive input of the operational amplifier to adjust the offset and make the output voltage more similar to the input voltage in terms of voltage range. The values for the V_{offset} and R1 were adjusted with simulation in the Proteus software.

3.3. Simulation

The simulation results for the circuit in the figure 18 is shown in figure 19. In this case, the R1 were chosen as $3.9k\Omega$ to have a gain of 2.5 approximately and the V_{offset} is 2.5 V. The integrator circuit creates the triangular signal with the square signal as input

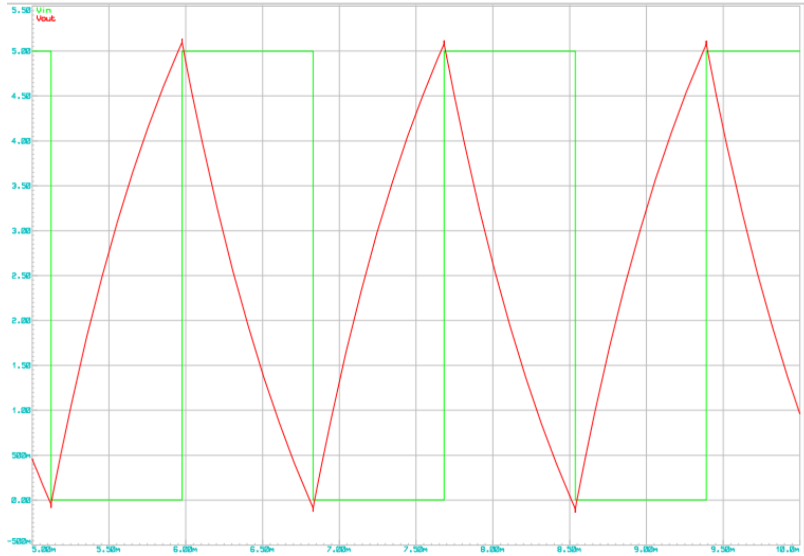

Figure 19: Integrator simulation results

3.4. Usability and Discussion

During the development of the project, we tried to find bibliographical references for controlling motors with the triangular sign instead of the square sign. However, we did not find books or articles that cited the advantages of controlling the speed of a DC motor using a triangular signal. So, the group asked for guidance from Professor Pierre Melchior, who is a specialist in the area of control engineering. It was then found that the triangular signal would have an advantage in reducing the motor's current consumption, but in cases of power motors, where the current demanded is bigger than 1A. In the case of the motor used, the current consumption is around $100mA$. It was found that the use of the triangular signal to control the speed of a DC motor has no advantages for low consumption motors. Therefore, it was decided to eliminate this stage of the project with the approval of the responsible teacher.

4. PCB Implementation

Now that the team was sure that all the components worked correctly, it was the time to create the final PCB of the project. The process of the creation of the board is the key part of the project. It is a summary of what the team achieved throughout the whole project. If something is not properly designed or do not function in a good way it will be immediately reflected on the board and make our whole system unusable.

As a quick introduction of what is below, this part will explain the layout designed on Proteus. Afterwards, it will illustrates each step of the PCB fabrication. Finally, the performed PCB tests.

4.1. Design

The team gave up on the integrator and used only a PWM for the ventilator control. The layout of our PWM was mad on a $12cmx12cm$ board. For the layout on Proteus, the width path was $T50$. This width is intentionally set at an important value in order to keeping safe the paths, avoiding possible damage that would make it impossible for the PCB to function. Indeed, if the path selected is too narrow, they are prone to be destroyed by the current and make the board useless.

At first glance, the team wanted to use a ground plane in order to avoid some parasites behaviors of the circuit. However, the supervisors of the project explicitly recommended us to give up on this idea due to the small size of the project and the eventual bad outcomes that it could create. Therefore, a design was made considering those parameters. The montage below is what the team use afterwards, it keeps the ground plane though :

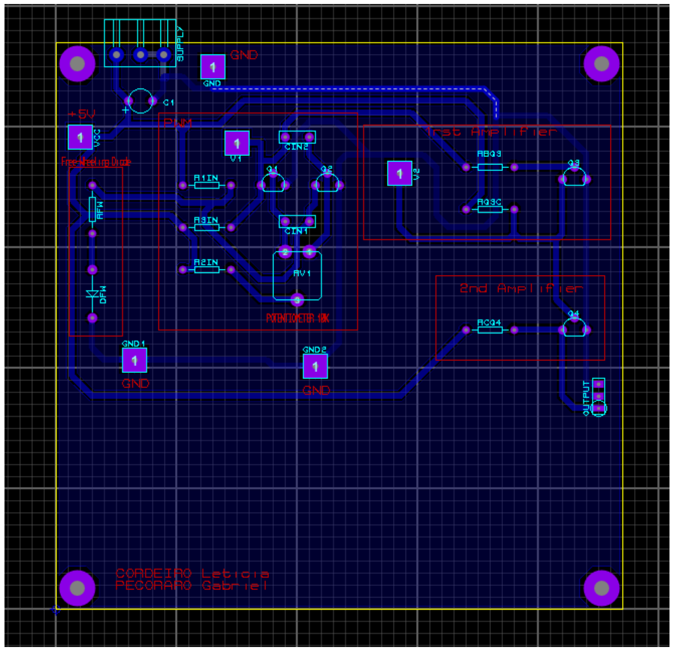

Figure 20: Layout of the PWM

On this layout, a distinction between each part as been made in order to facilitate the tests and the debugs on the board. Moreover, it was also mandatory.

4.2. Fabrication

Now that the layout is done, the team can proceed to the fabrication of the PCB card. Thus, the USB key that contained the layout of the project was brought to Ms Bedenes so he could print it. Afterwards, those printings were given to Ms Micouleau to create the copper of the PCB. The creation of the PCB is a 5-step chemical procedure. First of all, the card is inserted into an UV machine that reveal the the paths copper. The machine is below :

Figure 21: UV machine

However, the UV only burn the path under the chemical material that cover the whole card. That is why, wearing all the protection equipment, to reveal all the copper paths of the card a sodium hydroxide solution was use. The purpose of this step is to remove the protection part of the PCB by revealing all the paths. To achieve that, after dipping the card into the chemical solution, this latter was scrub with a napkin many times. Here is the sodium hydroxide solution :

Figure 22: Chemical that reveals the path

When all the protection part was removed, it was the time to engrave the paths with a special machine that spring distilled water on the card. The PCB card had to be cleaned with normal water after it went out of the machine.

Figure 23: Machine that engraves the card

Figure 24: Place where the card was washed

Finally, the last step of this PCB craft was to cut the border of the card, it was straightforward to do this because there is a machine at school that does that:

Figure 25: Machine that cuts the border

4.3. Tests

To confirm the functioning of the PCB, practical tests were carried out with the following assembly:

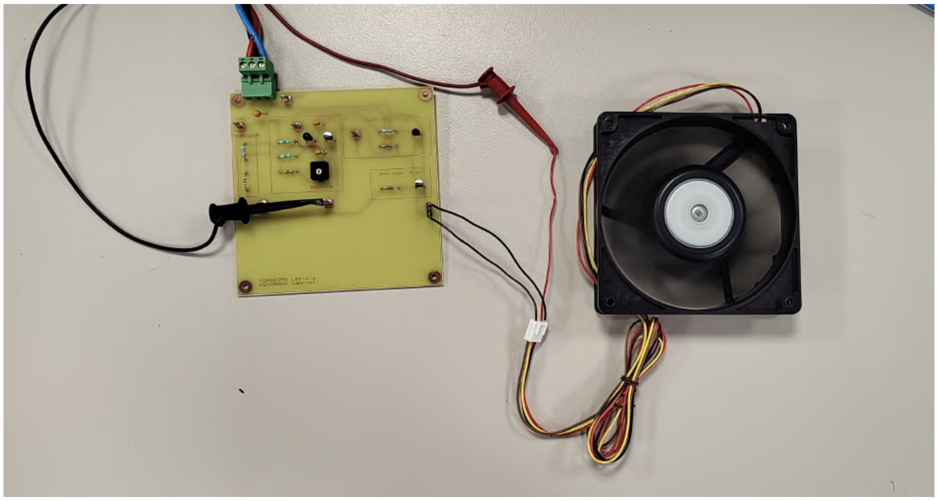

Figure 26: PCB tests

Before connecting the output signal to the motor, each stage of the circuits was tested to verify its correct operation. The practical results were satisfying, as they were similar to the simulations and practical results previous obtained with a breadboard.

5. Tachometer

As the proposed objectives were completed before the project deadline, a bonus part was proposed to the team, which consisted of an interpretation of the data from the motor's tachometer.

A tachometer measures the rotational speed of the fan's motor. The unit of measurement for fan speed is often Revolutions Per Minute (RPM). Tachometers are commonly used in cooling fans to provide feedback on the fan's performance. This data can be used to create a feedback control system.

5.1. Theoretical Analysis

Initially, readings of the tachometer signal were taken using the oscilloscope. It was noted that there were noisy. The motor datasheet shows that for correct sensor reading, a pull-up resistor is required, as shown in figure 27.

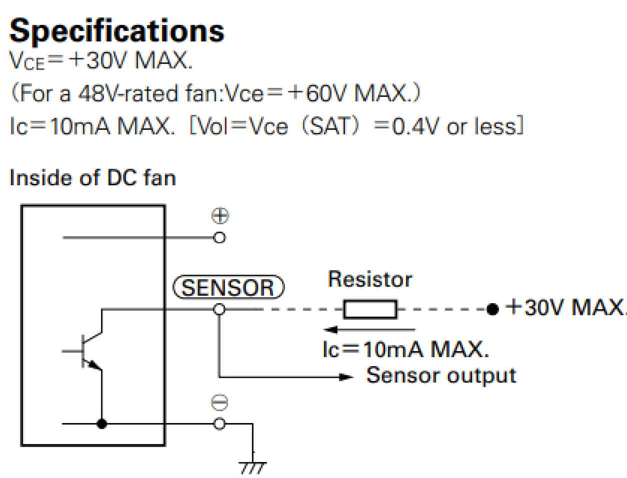

Figure 27: Datasheet information about the pull-up resistor for the sensor

The chosen power supply was 12 V and to limit the current to approximately 1.2 mA, a $10k\Omega$ pull-up resistor was chosen.

As the tachometer signal contained a lot of noise, an active high-pass filter was designed after the pull-up resistor R1 composed by the operational amplifier, C1, R2 and R3, as shown in the figure 28. After measurements on the oscilloscope, it was found that the cutoff frequency for the high pass filter would be approximately 18.5 kHz. As we want unity gain, R2 will be equal to R3. Defining the capacitance C1 as 10nF, for the resistor R3 we have:

$$f_c = \frac{1}{2\pi R3C} \Leftrightarrow R3 = \frac{1}{2\pi f_c C} = 860\Omega \tag{14}$$

The components D1, C2 and R4 make up an envelope detector to detect the change in state of the tachometer signal. The final signal of this circuit could be used, for example, at the input of a micro-controller which, by detecting the time between pulses, could calculate the engine RPM in real time. In this part, for the values of the components we have:

$$\tau = RC \Leftrightarrow f = \frac{1}{RC} \tag{15}$$

Fixing C2 = 100nF,

$$R4 = \frac{1}{18.5k100n} \leftrightarrow R4 = 540\Omega \tag{16}$$

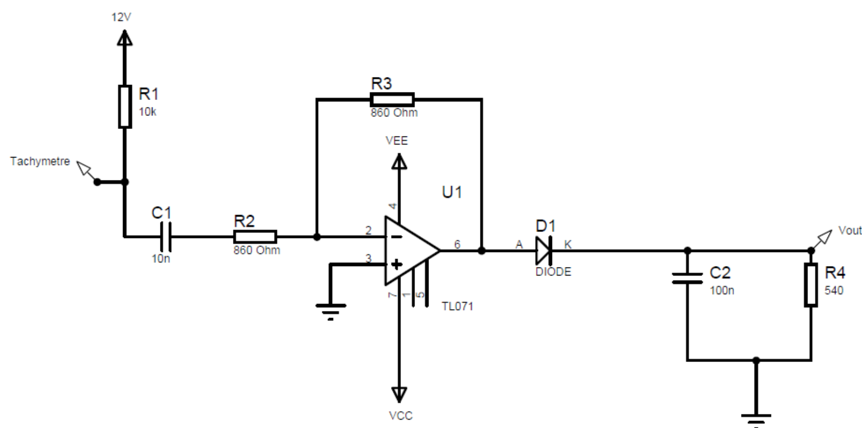

Figure 28: Circuit to process tachometer data

The datasheet of the DC Cooling Fan San Ace 120 also contains an approximate RPM calculation based on the tachometer signal, shown in figure 29.

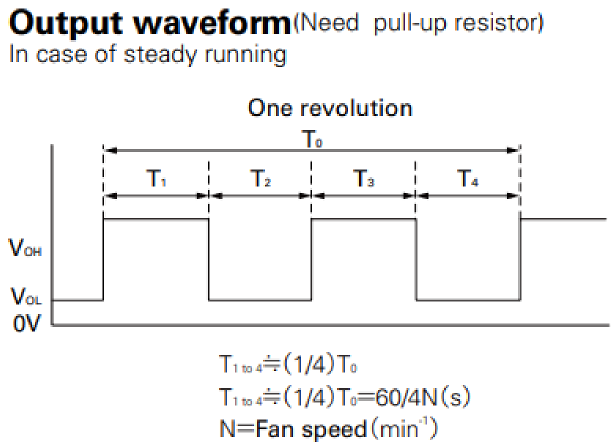

Figure 29: Datasheet information about the RPM measurement

5.2. Practical Results

For different duty cycle values at the motor input, the tachometer output with the pull up resistance and the output of the complete circuit were measured, as will be shown in the next figures. The red curve is the input PWM, the green signal is the tachometer signal and the blue signal is the output of the complete circuit. The figure 30 shows the results for a 20% duty cycle.

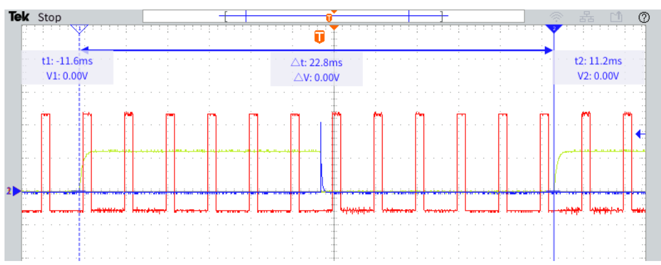

Figure 30: Practical results for the tachmeter data with 20% duty cycle

Based on the datasheet, it is possible to calculate the motor RPM, where T_0 is the entire period measured:

$$T_1 = \frac{T_0}{2} = \frac{60}{4N} \leftrightarrow N = \frac{260}{4T_0} \leftrightarrow N_{20\%} = 1316RPM \tag{17}$$

The figure 31 shows the practical results for a 50% duty cycle. In this case:

$$N_{50\%} = 1923RPM \tag{18}$$

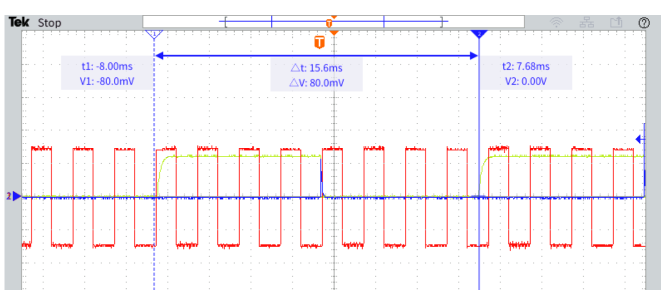

Figure 31: Practical results for the tachmeter data with 50% duty cycle

The figure 32 shows the practical results for a 80% duty cycle. In this case:

$$N_{80\%} = 2419RPM \tag{19}$$

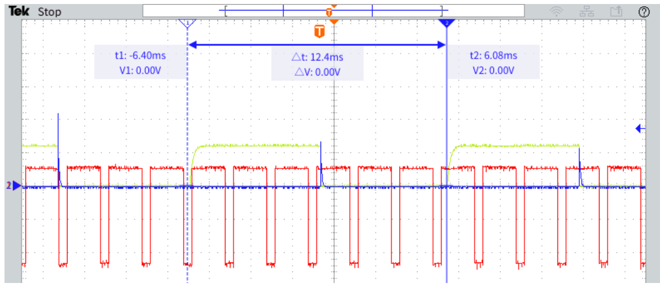

Figure 32: Practical results for the tachmeter data with 80% duty cycle

6. Conclusion

For this project, all proposed objectives were fulfilled because the speed of a DC motor is controlled through an analog PWM circuit designed and dimensioned by the team. In addition to the initially proposed objectives, the motor tachometer signal was also analyzed to calculate the RPM.

During the development of the project, some difficulties were encountered, such as the choice of the circuit for the PWM, the theoretical reflection on the linear control of the motor with a triangular signal and the signal processing with noise for the tachometer.

Many skills could be learned from this project, for example: analysis and deduction of equations for an astable multivibrator circuit, simulation with Proteus, practical laboratory skills, designing and building a PCB and oral presentation of the project in English.

To sum up, this project allowed the team to see what a conception in a real engineer life looks like. It gave us an important amount of knowledge about analog electronics but also about team working. All the topic proposed to each group were interesting. Recognition to Mr Lagoug, our supervisor, who helped us and gave us key advices to carry out this project until the end and to avoid us to go of track.

7. References

1. Fontaine, G. (1971). Transistors in Pulse Circuits (1st ed.). Philips Technical Library. Red Globe Press London. https://doi.org/10.1007/978-1-349-00166-8. Chapter 7: Astables Multivibrators.

2. Craig, E.C. (1994). Astable Multivibrator. In: Laboratory Manual for Electronics via Waveform Analysis. Springer, New York, NY. https://doi.org/10.1007/978-1-4612-2610-9_15. Chapter 14: Astable Multivibrator.

8. Annex 1: PCB

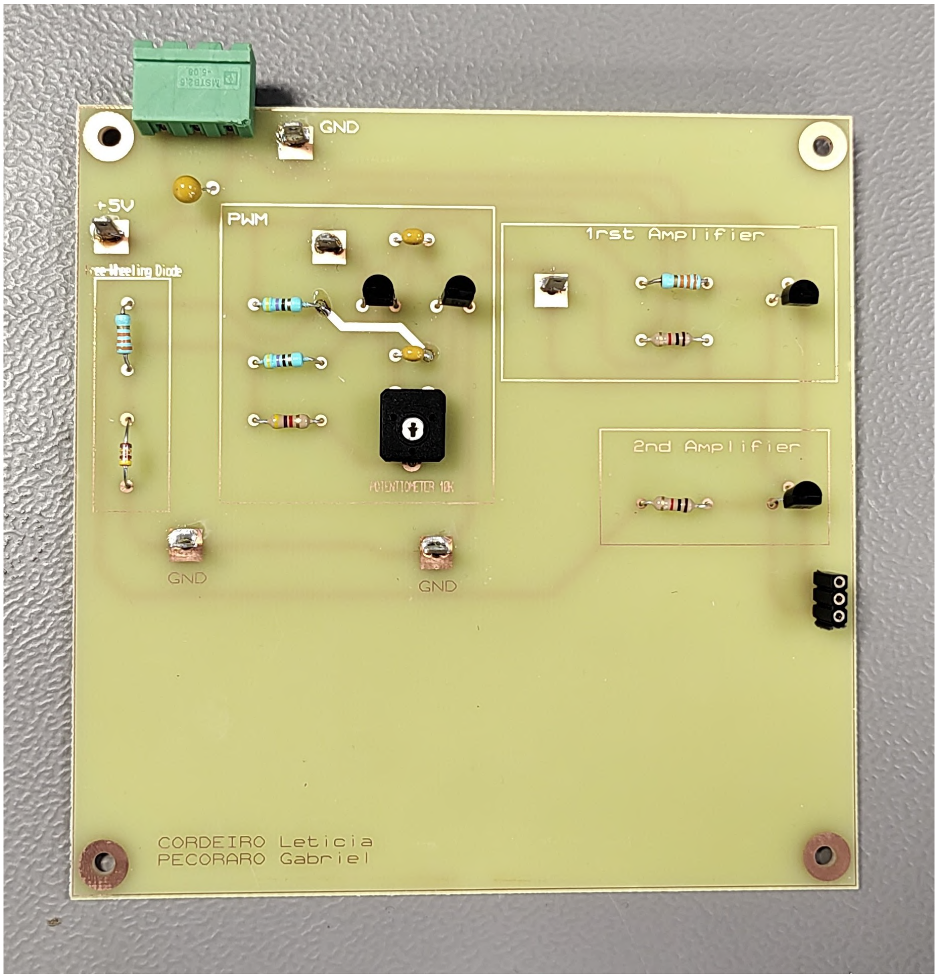

Figure 33: PCB top layer

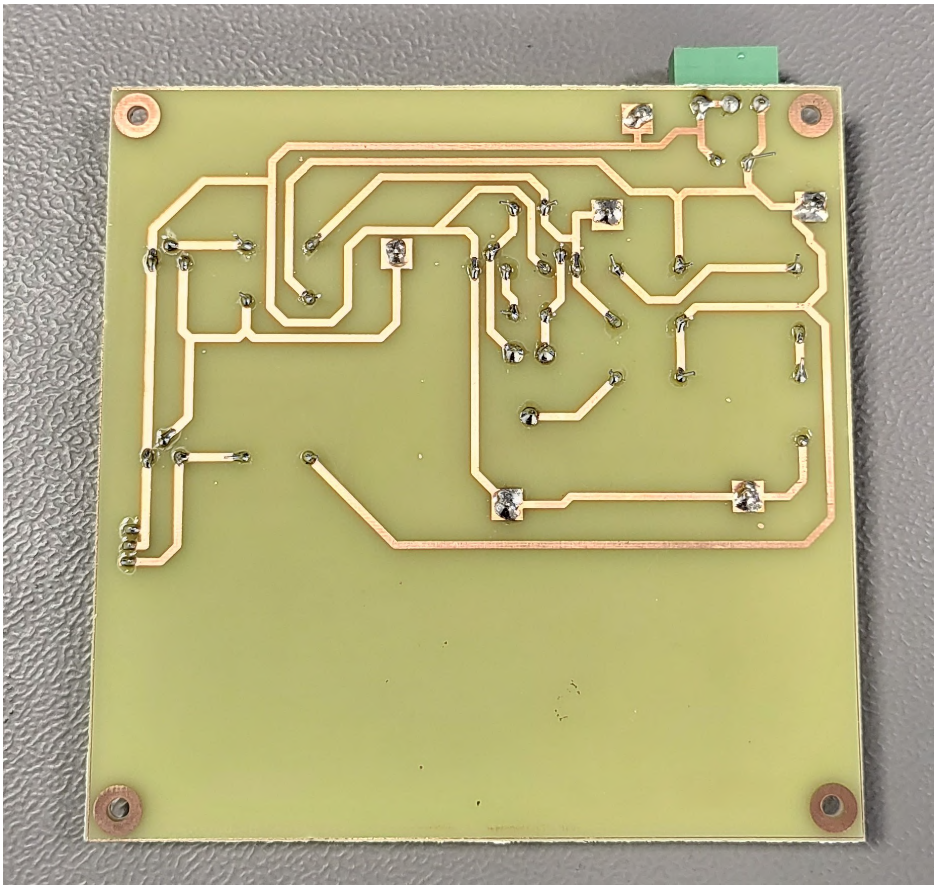

Figure 34: PCB bottom layer

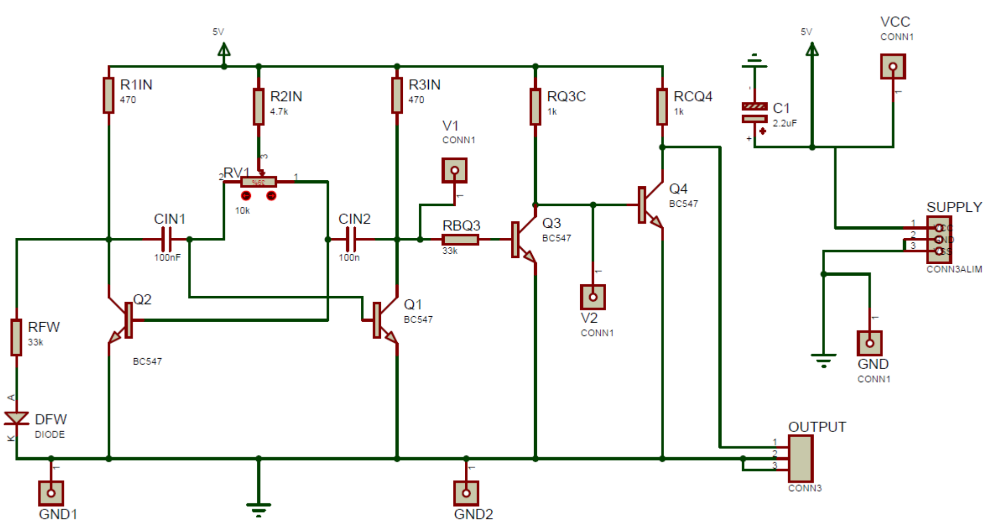

Figure 35: Schematic for the PCB