PULSE WIDTH MODULATION USING A POTENTIOMETER

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Electronic systems for Biometrics and biosensing

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Acronyms

STM – STMicroelectronics

LED – Light Emitting Diode

USB – Universal Serial Bus

COM – Communication

DAC – Digital-to-Analog Converter

ADC – Analog-to-Digital Converter

ST – STmicroelectronics

IDE – Integrated Development Environment

HAL – Hardware Abstraction Layer

WB – WishBoard

ABS – Acrylonitrile Butadiene Styrene

LCD – Liquid Crystal Display

TDS –Tektronix Digital Storage

RMS – Root Mean Square

UL – Underwriters Laboratories

IEC – International Electrotechnical Commission

RoHS - Restriction of Hazardous Substances

DC – Direct Current

Wi-Fi – Wireless Fidelity

PC – Personal Computer

OS – Operating System

RISC - Reduced Instruction Set Computer

Arm - Advanced RISC Machines

RTOS - RealTime Operating System

IoT - Internet of Things

IPv6 – Internet Protocol version 6

TLS – Transport Layer Security

FAT – File Allocation Table

CMSIS - Cortex Microcontroller Software Interface Standard

RTX - RealTime Ray Tracing

Definitions

I. **Duty Cycle:** the percentage of time a signal remains high (active) within a complete cycle. A 0% duty cycle means the signal is always low, while a 100% duty cycle means the signal is always high. A 50% duty cycle results in the signal being high for half of the period and low for the other half.

II. **Pulse Width Modulation (PWM):** a technique used to control the average power delivered to an electrical load by varying the duty cycle of a periodic digital signal. It works by switching the signal on and off at a fixed frequency, adjusting the duration of the pulse width within each cycle.

III. **Potentiometer:** a three-terminal variable resistor that functions as an adjustable voltage divider. It consists of a resistive element and a sliding or rotating contact (wiper) that moves along the element to vary the resistance and control the output voltage.

1 OBJECTIVES OF THE REPORT

The objective of this report is to document the experimental activity on the use of the potentiometer for the control of pulse width modulation (PWM).

Specifically, through the use of a potentiometer, by varying the duty cycle of the PWM signal, the behavior of the system in response to the changes introduced by the user was understood and analyzed. The potentiometer, being a device capable of providing a variable resistance value, was used to modify in real time the ratio between the duration of the active pulse and the total period of the PWM signal.

During the laboratory sessions, the effects of the change in the duty cycle on the behavior of the signal generated through the use of an oscilloscope were analyzed.

2 HARDWARE

2.1 Components

2.1.1 STM32 Nucleo F091RC

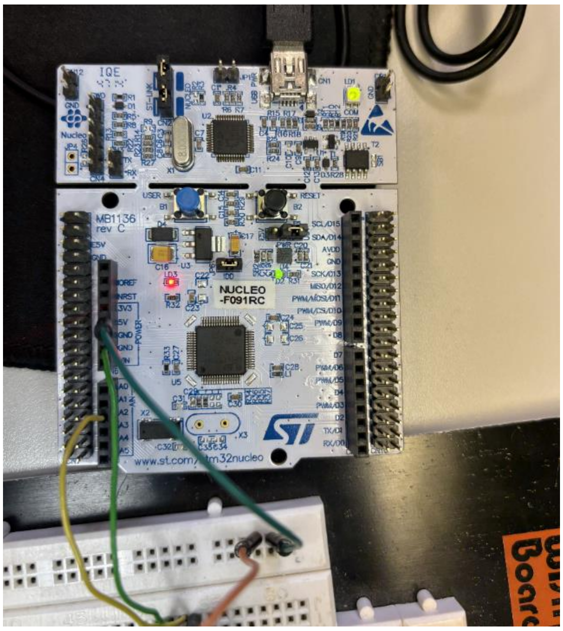


Figure 1: STM32 NUCLEO F091RC

The STM32 Nucleo-64 board provides users with a cost-effective and flexible way to experiment with new concepts and build prototypes by choosing from the various combinations of performance and power consumption offered by the STM32 microcontroller.

LEDs:

- LD1 (USB communication): Indicates the USB communication status, which is useful for viewing data activity or connections when debugging or using the Virtual COM port.
- LD2 (User LED): a customizable LED available to the user. It can be managed via software to report particular states of the application (e.g. error reporting, calculation activity, diagnostic blink, etc.).
- LD3 (Power LED): provides an indication of the power supply of the board, allowing you to quickly understand if the board is correctly powered.

BUTTONs:

- USER: a programmable button that the user can read via software as input (e.g. to implement start/stop functions, mode selection or other events).
- RESET: allows you to reset the microcontroller returning it to its initial state. It is useful both in the development and debugging phases (quick reboot) and in situations where the software needs a hard reset.

BOARD CONNECTORs:

- Arduino Uno V3 connectivity:
    - Layout compatible with standard Arduino shields, simplifying the addition of existing modules or extensions (e.g. motor shields, Wi-Fi, various sensors...).

- ST morpho extension pin headers:
  - Provides full access to all microcontroller I/O pins.
  - Useful for those who need advanced features and want to take advantage of every single peripheral of the chip (e.g. DACs, multiple ADCs, serial interfaces, etc.).
  - Allows integration with ST-specific extension boards (e.g. shields or expansion boards).

FLEXIBLE BOARD POWER SUPPLY:

- ST-LINK USB V_{BUS}: using the USB port connected to the PC, the microcontroller is powered directly by the 5 V provided by the USB cable.
- External source (3.3 V, 5 V, 7 - 12 V): If your design requires more power or a different power supply, you can connect external sources with different voltage ranges.
- Power management access point: there is a test point dedicated to monitoring and measuring consumption.

USB INTERFACEs:

- Virtual COM port: allows you to communicate with the microcontroller via a virtual serial port, useful for logging, debugging, data exchange with the application on PC (e.g. serial terminals, PuTTy).
- Mass storage: the board is recognized as a storage unit (drive). It's a quick way to load firmware onto the microcontroller: simply drag and drop the binary or .hex file into the dedicated folder.
- Debug port: using the integrated ST-LINK programmer/debugger (on board), it is possible to program and debug the microcontroller directly from the IDE (e.g. KeilStudioCloud, or others) without the need for external programmers.

HAL SOFTWARE:

- HAL library: Simplifies access to peripherals through high-level functions, reducing programming complexity. Ready-to-use starting software is available to test functionality (e.g. reading sensors, managing displays, etc.).

2.1.2 Breadboard Wish Board no.108J

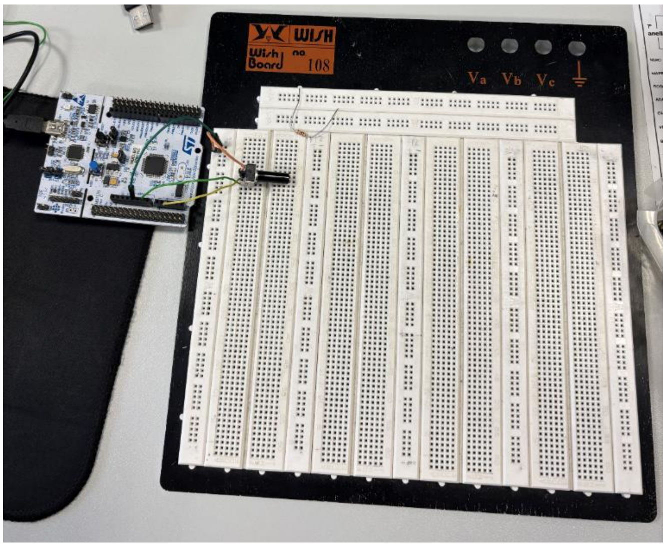


Figure 2: Breadboard WB n. 108J

The WB-108J breadboard is an experimental solderless plate (sometimes simply called a "protoboard" or "breadboard") designed for fast prototyping of electronic circuits. The Wish Board 108J falls into the category of "full-size" breadboards (240x260x31 mm), providing a large enough area for small/medium-sized projects. Allows you to insert components (e.g. resistors, capacitors, sensors, or others) without the use of a soldering iron.

Its structure includes four main terminal strips, each with a capacity of 640 terminal holes. Each terminal block is in turn divided by a groove that electrically separates the horizontally short-circuited terminal holes.

In addition to these terminal blocks, the breadboard has seven distribution strips with a total of 700 contact points (distribution holes), which are useful for the distribution of power lines and ground signals. These strips are arranged along the sides of the breadboard and make it easy to wire positive and negative supplies. The distribution holes of each strip (or power bar) are electrically connected vertically, thus generating a single node that extends along the column. In addition, the strip itself is divided into two sub-portions, usually labeled with "+" and "−" (or with distinct colors and symbols) allowing two different supply voltages to be kept separate.

The four integrated connection clamps allow the breadboard to be easily connected to external devices such as power supplies or measuring instruments. The main structure of the WB-108J is made of ABS plastic, which is an insulating and durable material.

2.1.3 Bourns Rotating Potentiometer PTV09A-4225F-B502

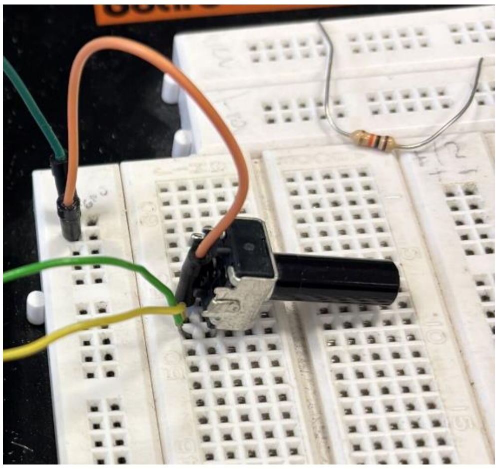


Figure 3: Potentiometer PTV09A-4225F-B502

The PTV09A-4225F-B502 potentiometer from the PTV09 series is an electronic component with a carbon resistive element and an insulated shaft. The device is RoHS compliant.

Electrically, it has a linear or audio response, with a standard resistance range of 1 kΩ to 1 MΩ and a resistance tolerance of ±20%. The maximum residual resistance is 500 Ω or 1% of the nominal value. The potentiometer can operate with a maximum voltage of 20 V DC and 50 V AC.

As for environmental characteristics, the device can operate in a temperature range of -10°C to +50°C.

Mechanically, the mechanical angle of rotation is 280° with a tolerance of ±10°.

The potentiometer guarantees an operating life of 10,000 cycles. For welding, the component can be subjected to a maximum temperature of 300 °C for up to three seconds.

2.1.4 Two Channel Digital Real-Time Oscilloscope: TEKTRONIX TDS 210

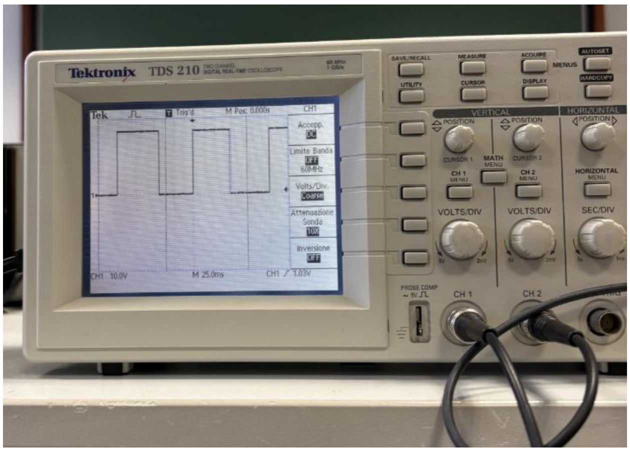


Figure 4: Tektronix Oscilloscope TDS 210

The Tektronix TDS 210 is a digital oscilloscope with two input channels, designed for the analysis of signals up to 60 MHz of bandwidth. Thanks to a sampling rate of 1 GS/s, supported by a memory of 2500 points per channel, it allows you to observe waveforms in real time with a good level of detail, especially if we consider the wide range of horizontal scales, ranging from 5 ns to 5 s per division with the possibility of zooming. On the vertical edge, the signal amplitude can be adjusted from 2 mV to 5 V per division, providing considerable flexibility for measurements on both low and medium amplitude signals.

Trigger functions include modes based on the front (Edge), video signals or external sources; there is also a practical "Trigger View" function for a more precise adjustment of the trigger. Waveform storage options are available to stop and save the current track, or resize it vertically and horizontally. The user also has the option to retain up to two reference waveforms for later comparisons.

The acquisition mode can be set to simple sampling, average or peak detect, while the signal can be represented with dot or continuous line (Vector) display. A set of automatic measurements, including period, frequency, RMS value of a single cycle, average value and peak-to-peak, supported by sliders and autoset commands, as well as the "Math" function for more advanced operations, facilitates data analysis. The backlit LCD screen, measuring 11.5 by 8.6 centimeters, offers good readability and makes this instrument suitable for different light conditions.

On the safety side, the UL 3111.1 and IEC 1010 certifications attest to its compliance with the standards in force. Dimensions and weight, respectively 30.5 cm wide, 15.1 cm high, 11 cm deep and 2.9 kg, contribute to making it sufficiently compact and transportable.

2.2 Circuits

2.2.1 Potentiometer

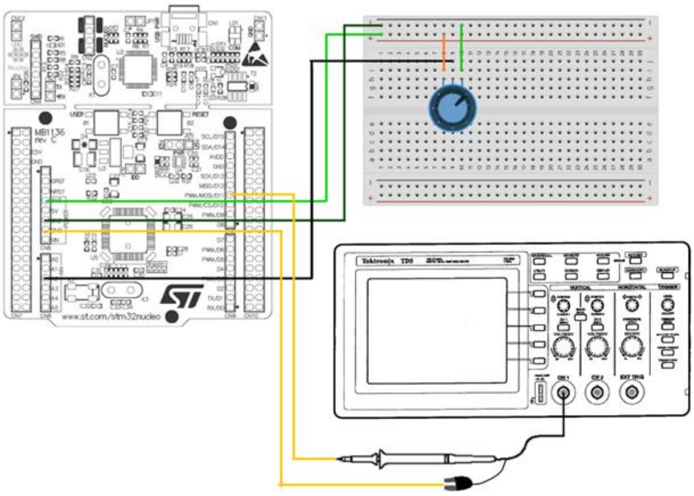


Figure 5: Circuit Diagram For PWM Visualization

To test the operation of a potentiometer and monitor the PWM output of the microcontroller, the following connection diagram was made:

- **Connecting the breadboard:**
  - The distribution strip was connected to the 3.3V line at the "+" contact point and to the GND at the "–" contact point.
- **Connecting the potentiometer:**
  - The potentiometer power terminal has been connected to the "+" contact point via orange cable.
  - The ground terminal has been connected to the contact point "–" via green cable.
  - The output of the potentiometer (center pin) has been connected to pin A1 of the microcontroller, which acts as an analog input for reading the variable voltage generated by the potentiometer adjustment.
- **Connecting the Oscilloscope:**
  - The oscilloscope's ground clamp was connected to a microcontroller GND to ensure a common reference.
  - The oscilloscope probe was connected to the PWM output pin of the microcontroller, allowing the amplitude-modulated signal to be displayed on the oscilloscope display.

3 FIRMWARE

3.1 MBED OS

Mbed OS is an RTOS operating system developed by Arm and designed for embedded devices based on Cortex-M microcontrollers. Provides a complete, IoT-optimized development environment, with support for connectivity, security, and efficient energy management.

This operating system offers an RTOS kernel that allows for multitasking task management, thread synchronization, and efficient use of system resources. It adopts an event-driven programming model, which is especially suitable for low-power devices. It also integrates network stacks and communication protocols such as IPv6, TLS/DTLS, MQTT, and CoAP, making it easy to connect with cloud services and edge devices. The native file system manager supports several formats, including FAT and LittleFS, which are optimized for use with flash memory. Communication security is ensured by the Mbed TLS encryption library, which is designed to operate on resource-constrained devices.

Mbed OS is compatible with a wide range of development boards based on Arm Cortex-M microcontrollers and offers an ecosystem of ready-to-use drivers for different peripherals and sensors. Integration with the Mbed Cloud framework facilitates remote deployment and management of IoT devices.

Keil Studio is the IDE provided by Arm for programming embedded applications on Mbed OS. This platform includes advanced tools for writing, compiling, and debugging code, with support for CMSIS (Cortex Microcontroller Software Interface Standard) and the Arm libraries for Cortex-M microcontrollers. The system supports programming in C/C++ and offers advanced real-time debugging, simulation, and hardware emulation capabilities. With the integration of Arm Compiler 6, it enables the generation of optimized code to reduce power consumption and improve performance. In addition, the implementation of Keil RTX RTOS ensures efficient thread and resource management, improving the reliability of embedded applications. The debugging and tracing system allows a detailed analysis of the software's behavior, allowing the optimization of critical applications.

3.1.1 Potentiometer

```
#include "mbed.h"
#include <cstdio>

// Define an analog input pin (A2)
AnalogIn analog_value(A2);

// Define a PWM output pin (D11)
PwmOut output(D11);

int main(){
    float meas;  // Variable to store the measured value

    // Set the PWM period to 0.1 seconds
    output.period(0.1);

    while(1){
        // Read the analog input (returns a value between 0.0 and 1.0)
        meas = analog_value.read();

        // Set the PWM duty cycle based on the measured value
        output.write(meas);

        // Convert the value to millivolts (assuming a 3.3V reference)
        meas = 3300 * meas;


        // Print the measured value in millivolts
        printf("%0.1f \r\n", meas);
    }
}
```

Figure 6: Firmware For Reading The Signal Of A Potentiometer And PWM Adjustment

The code uses the Mbed library to capture the value of a potentiometer connected to pin A2 and adjust a PWM signal on pin D11 accordingly. The <*cstdio*> library is included to allow the use of the *printf function*, which will be used to display the scanned data. The variable *analog_value* is declared as an *AnalogIn* object associated with pin A2, allowing analog values between 0 and 1 to be read. The output object is instead declared as *PwmOut* and assigned to pin D11, which will be used to generate a amplitude-modulated signal.
Within the *main* function, the *float* meas *variable is declared*, which will be used to store the value read by the potentiometer. Next, the PWM signal period is set to 0.1 seconds, thus determining the frequency of the output signal. The code then enters a loop, in which at each iteration the analog value from pin A2 is read via *analog_value.read()*, returning a normalized number between 0 and 1. This value is assigned to the PWM signal via *output.write(meas),* so that the duty cycle of the PWM signal is proportional to the position of the potentiometer.
The read value is multiplied by 3300 to obtain the corresponding voltage in millivolts. Finally, the voltage value is printed on the serial console, allowing you to monitor in real time the variation of the analog voltage generated by the potentiometer.

4 RESULTS

4.1 Potentiometer

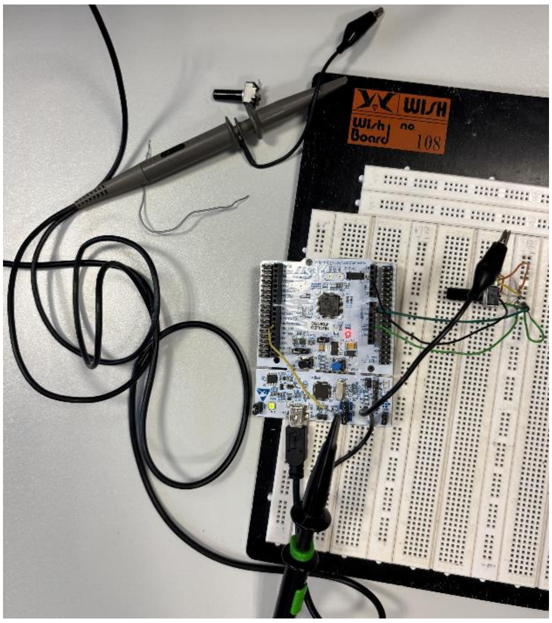


Figure 7: Photo Of The Circuit With Microcontroller, Potentiometer, BreadBord and Oscilloscope Probe

The goal of this exercise was to perform Pulse Width Modulation (PWM) (Def. II) using the microcontroller, a potentiometer, and an oscilloscope.

The potentiometer is a variable resistor that can be used to generate an analog voltage value depending on the rotation of a knob it is equipped with (Def. III). This value is then read by the microcontroller and used to change the PWM signal duty cycle.

The modulation obtained is the result of converting the voltage into a duty cycle that can vary from 0% to 100%, depending on the position of the potentiometer. If the potentiometer is in the minimum position, the duty cycle will be close to 0%, which means that the signal will be mostly low. On the contrary, if the potentiometer is at maximum, the duty cycle will be close to 100% and the signal will be predominantly high. For intermediate positions, the pulse width is intermediate, as it was possible to observe from the tests carried out.

The code (Figure 6) used to carry out the acquisition allows the microcontroller to read the value of the analog input A2, i.e. where we connect the output of the potentiometer, to convert it into a value between 0 and 1 and use it to vary the pulse width of the PWM signal output on pin D11, which we will detect through the oscilloscope probe. The PWM signal frequency has been set with a period of 0.1 seconds, which corresponds to a frequency of 10 Hz.

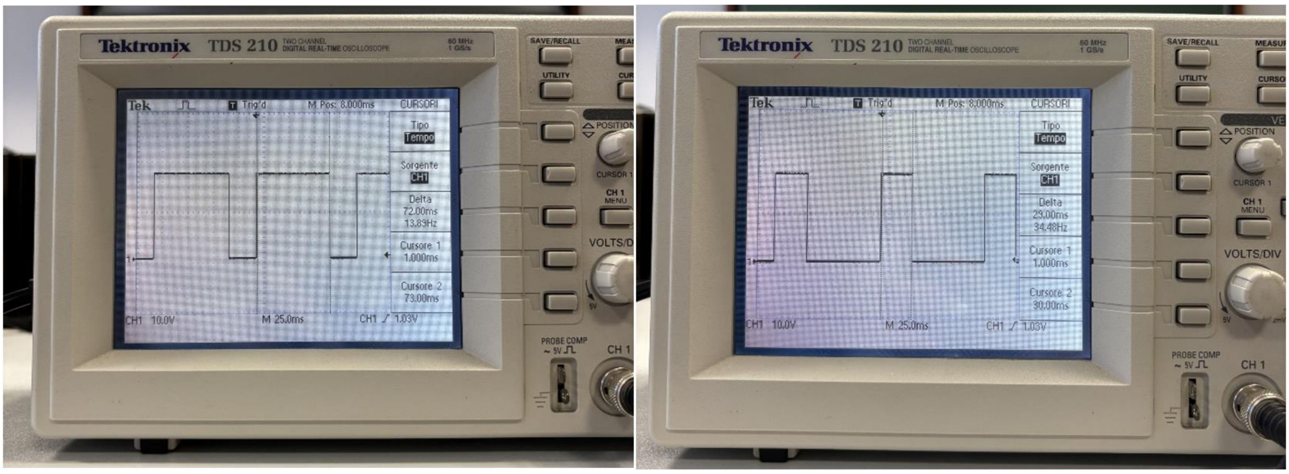
We then connected the CH1 channel of the oscilloscope to the output pin D11, which is the pin on which the PWM signal is produced, through a probe to view the generated signal in real time and analyze the variations based on the position of the potentiometer.

The first acquisition, which we can observe in *Figure 8* (a), it showed a square wave with a high duty cycle. At this time, the potentiometer was already in an intermediate position, supplying a voltage to pin A2.

At this point, we rotated the potentiometer to see how the system reacted to the change in the A2 analog input. After adjustment, we made a second acquisition with the oscilloscope, in *Figure*

8 (b), and we noticed a noticeable change in the duty cycle, which was smaller than the previous measurement.

This confirms that the microcontroller has read the new potentiometer value and adjusted the duty cycle accordingly, reducing the period when the output signal is high.



(a) (b)

Figure 8: Examples Of PWM With Different Duty Cycle

5 CONCLUDING NOTES AND POSSIBLE OBSERVATIONS

5.1 Observations

During the acquisition and analysis of the signals with the different sensors, some problems emerged that influenced the quality of the data and, therefore, the results obtained.

One of the main problems concerned the oscilloscope (Figure 9), which during the analysis carried out with the potentiometer coupled with the measured signal. Coupling occurs when the oscilloscope unintentionally introduces a change to the signal it is measuring, for example due to imperfectly matched impedances or electromagnetic interference.

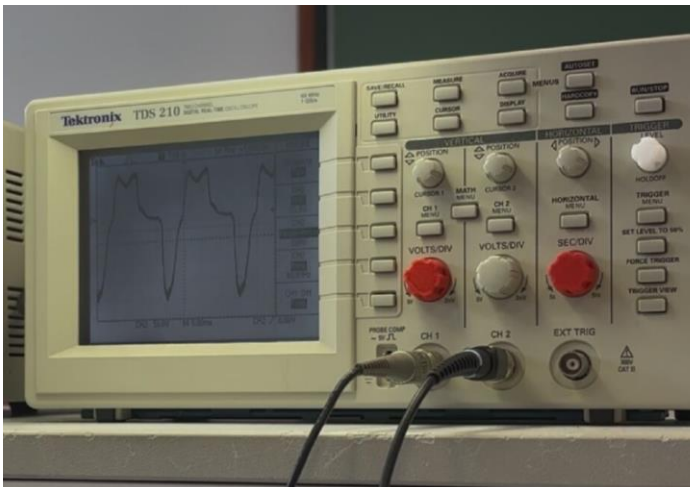


Figure 9: Example Of Distorted Signal On The Oscilloscope

5.2 Conclusion

The experience conducted has made it possible to analyze the behavior of PWM modulation as the duty cycle varies, experimentally verifying the variations of the square wave through the oscilloscope. It has been observed that by increasing the duty cycle, the duration of the active phase of the signal increases, while by decreasing it, the active phase is reduced.

The use of the oscilloscope proved essential to accurately visualize the signal trend and to measure the characteristic parameters of PWM, such as frequency and working ratio. These results confirm the theory that PWM modulation allows effective control of the power delivered to a load.

In conclusion, the experiment demonstrated the importance of the duty cycle in determining the behavior of the PWM signal and highlighted the role of the oscilloscope as an indispensable tool for the analysis of time-varying signals.