Master Thesis

Czech Technical University in Prague

F3

Faculty of Electrical Engineering
Department of Measurement

Arc detector in DC grids

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MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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II. Master's thesis details

Master's thesis title in English:

Arc detector in DC grids

Master's thesis title in Czech:

Detektor jiskření ve stejnosměrných sítích

Guidelines:

Design and develop a prototype of a DC arc detector for DC power grids. Use fully digital signal processing solution based on a microcontroller (e.g., STM32H4). Use suitable current to voltage converter and desing analog conditioning path for analog to digital converter. Use industrially standardized communication to transfer results between prototype and central unit. Design and evaluate signal processing algorithms using Matlab or Python.

Bibliography / sources:

[1] Horowitz and Hill: The Art of Eletronics
[2] Carmine Noviello: Mastering STM32
[3] STmicroelectronics datasheets
[4] Jerald G. Graeme: Applications of operational amplifiers

Name and workplace of master's thesis supervisor:

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt Student's signature

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I would like to thank my favorite people for existing in my life and providing me with love and support.

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Declaration

I hereby declare that I worked out the presented thesis independently, and I quoted all the sources used in this thesis in accord with Methodical instructions about ethical principles for writing an academic thesis.

In Prague, 20. May 2023

Abstract

In this thesis, the problem of DC arc detection was discussed, with a focus on designing an arc detection prototype. It points to a hardware design on a protoboard and a software approach that uses Fast Fourier Transform for computing. For communication, an industrial protocol will be used.

Keywords: DC arc, detection, Microcontroller, DC arc, Fast Fourier Transform

Supervisor: Ing. Ondřej Fidra

Abstrakt

V této práci je diskutována problematika detekce DC výbojů, se zaměřením na vývoj prototypu. Práce ukazuje návrh hardwarové části na prototypovací desce a softwarové detekci založené na fourierově transformaci. Pro komunikaci bude použit průmyslová sběrnice.

Klíčová slova: Detektor DC jiskření, Mikrokontrolér, DC oblouk, Fourierova Transformace

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Chapter 1

Introduction

Throughout the years, the need to use alternative sources of energy has been steadily increasing and DC power supply has found its way into many new energy systems such as solar power, electric vehicles and the aerospace industry. Whether it is low or high voltage level systems, using a DC power has proven to be an exciting concept with many advantages and disadvantages, giving room for more improvement and exploration. One of the main challenges in employing a DC power supply is the occurrence of DC electric arc and the hazardous behavior it entitles.

An electric arc can be explained as a self-sustaining discharge of electricity with energy and, if not detected and extinguished on time, can lead to serious hazards. Electric arcs can occur with AC and DC, whereas AC arcs have been widely researched due to the different approaches to the detection and cancellation of the phenomenon. DC arcs, on the other hand, are much more complicated to be recognized and extinguished because the current does not pass through zero (as in the case of AC), they last and burn longer and are generally extinguished only when the power source is cut off. Another challenge for the detection of arcs is their occurrence in large systems or remote locations, which can also be compromised due to noise in various electric components. Additional problems occur from the fact that the arc occurrence is happening very fast in time, which shows the need for fast and accurate detection.

The field of research on DC arcs is still relatively new and most papers are focused on researching DC grids in photovoltaic systems, being the most common use of DC electricity. Meanwhile, other systems using DC power supply can not use the same detection methods and algorithms and demand a different approach in research and development, that can be universally used in various DC systems.

Chapter 2

Aims

This thesis aims to provide a solution for the detection of DC arcs by developing and designing a prototype that will independently provide arc detection and monitoring. The detector will be consisting of a data acquisition and data processing circuit, accompanied by communication with an external device, which will provide arc monitoring. The design of the arc detection device and the performance evaluation will be tested with artificially generated arcs, whereas the arc generation was out of scope for this study.

It details the process of developing and testing an arc detection and monitoring device, whereas the system can be divided into three interconnected parts. The first part is the signal acquisition part, which will convert the current to voltage in an artificial arc setup, pre-process the signal and deliver it to the microcontroller. The second part is signal processing, where the detection is happening, which is connected to the third part of the system, the communication part, which will pass in arc occurrence information. These three parts complement each other and it is vital that each works in accordance with the next one. During the designing and testing stage, each part should be developed in consideration of the others since only due to their synergy can the device successfully detect a DC arc occurrence.

2.1 Device

The fully operational device has to fulfill the following requirements :

- Gather current and voltage data
- Process current and voltage data
- Send information about the processed data

In order to successfully gather information, the device has to have some sort of sensor, which will collect current or/and voltage data, and an electrical circuit that will initially pre-condition the signal. This involves operational amplifiers and Analog Digital Converters (ADCs) which will enhance and improve the signal, as well as deliver it digitally to the microcontroller. Detecting DC arcs demands speed, so the emphasis in the processing part will be on a fast microcontroller, which should have good computing power. Connecting to the third part, the microcontroller should also be equipped with a communication protocol that will swiftly report arc occurrence to an external device or computer.

Chapter 3

Electric arc

An electric arc is a discharge of electric current across a gap in a circuit. While flowing through a nonconductive medium such as air, a thermally ionized column of gas (called plasma) can be observed, usually seen as visible light. [14][10]

Electric arcs can occur in AC (alternate current) and DC (direct current) systems. The main difference between these two systems is in the polarity; AC polarity changes its direction while DC remains constant. Since the polarity in AC systems has a periodic zero current crossing, this enables the recognition of distinct arc features. On the other hand, DC systems have different arc characteristics and behavior and demand a different approach to analyzing them.

DC power supply implementation has been increasing every year, being used for both domestic and industrial purposes. These systems can vary in scale, complexity, and voltage range, as well as the conditions in which they operate and the length of time. Weather conditions and time have the biggest influence on these systems, leading to deterioration and wear (loose connections, exposed wires, insulation aging, and grounding faults) which subsequently could lead to the occurrence of DC arcs.

Compared to AC, DC arcs are more dangerous since they last and burn for a longer period of time with high temperatures, which can lead to serious fire hazards and damage to the entire system, as well as to injury of human operators who work close by. Since DC arcs are generally only extinguished by cutting off the power supply, it is essential to properly analyze their behavior and characteristics. [10][17]

3.1 DC arc characteristics

The main classification of DC arcs is based on the location with respect to the load, so they can be divided into series and parallel DC arcs (Figure 3.1, adapted from [3]). Parallel arcs do not occur through any loads and happen usually from line to line or line to ground. Series arcs occur when the current passes through the arc and the serial-connected load. Series arc faults are considered to be more dangerous, but also harder to distinguish than parallel arcs. [18][10]

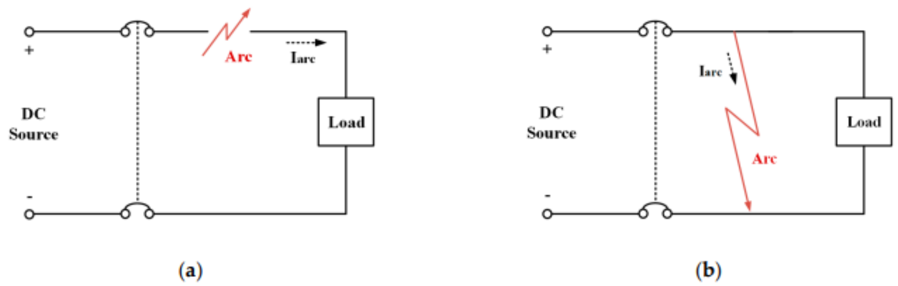

Figure 3.1: Arc faults: a) series arc fault b) parallel arc fault

DC arc characteristics can be physical and electrical. Physical characteristics are arc sound, arc light, and electromagnetic radiation signals. Many early arc detection methods were based on these phenomena and required specific sensors, antennas, and acquisition systems. The main problem with these detection systems is the different types of noise they also pick up, which interferes with the data collection. The electrical characteristics are changes in current and voltage, which are usually easier to detect, but the problem lies in the fact that these changes can occur without the presence of an arc. Properly detecting these features can be computationally demanding and time-consuming. [5]

The current arc research is focusing on electric characteristics, especially on the change of current in the time and frequency domain, since it's the most promising characteristic for feature extraction. In order to examine DC arcs, researchers usually use a simple hardware setup whose most important components are the DC power generator and movable electrodes, which are able to simulate different voltage and current levels, as well as arc lengths. In

[18], the author focuses on series arcs, varies these three characteristics, and records the results with an oscilloscope. That resulted in Figure 3.2 (adapted from [18]) where the author observes that the arcing process is characterized by a fall of current and rise of voltage in the beginning. In [12] series arc

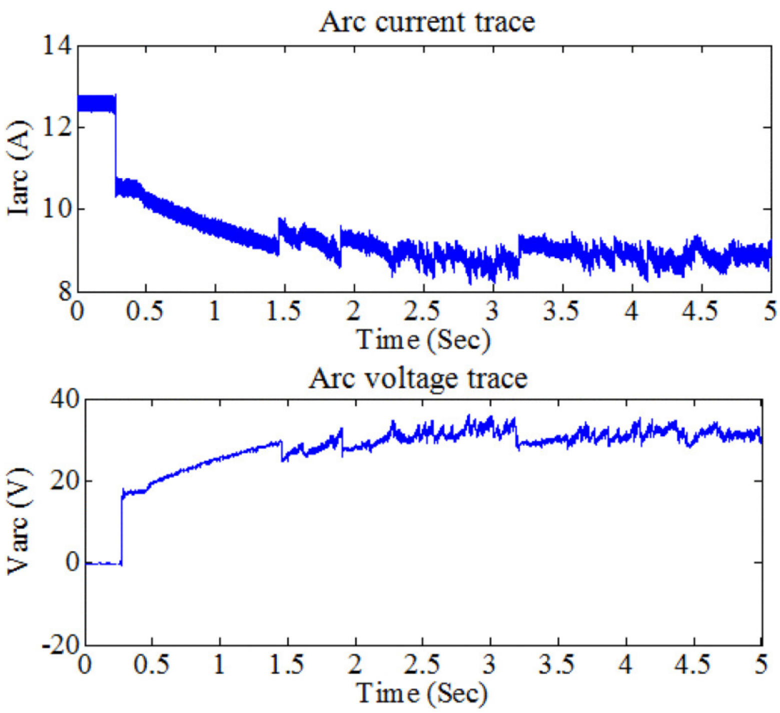

Figure 3.2: Voltage and current characteristic curve in serial DC arc occurrence

faults in micro-grids were tested and different speeds of electrode separation should simulate different fault scenarios. The conclusion was the same as in [18]: the start of an arcing event is characterized with a drop of current and a rise of voltage with time and that was symptomatic for various speeds of separation. In [19] the author explores the average value and standard deviation of current in series and parallel arc fault and comes to the conclusion that the current average in series arc decreases while in parallel increases compared to normal state, but that it is not enough for arc detection since it can be a false trigger. The standard deviation of current was examined in both the time and frequency domains and proved to be higher, while it was also observed that the occurrence of arc causes an increase of the spectrum in the frequency domain. In [17], the focus was on electromagnetic radiation, and the existence of a characteristic frequency was noted, whose amplitude is significantly bigger than the noise. However, these tests were conducted on a photovoltaic system so they may not be true for other DC systems.

Further investigation in other literature proves that the best way to approach DC arc fault detection is to investigate the behavior of current and voltage, both in frequency and time domain, and focus on characteristic features that differ from normal operation mode.

3.2 DC arc fault detection

Detection of DC arc faults is still relatively not researched nor is there a universal and simple approach for detection. Most research papers agree that the best way to go is to extract some specific features of current and (or) voltage, analyze them in the time and frequency domain and then apply a specific detection algorithm that will be able to differentiate these features from a usual operating mode and noise. In [18], the author explores the differential current

$$I_{dif} = I_{max} - I_{min} \tag{3.1}$$

in the time domain and the RMS value of the current in the time-frequency domain. The author concluded that using both features for detection seemed the proper way to go, even though it meant more complex computing. Choosing the right time window for feature extraction and DWT (discrete wavelet transformation), which is done by passing the signal through low pass and high pass filters, along with down-sampling by 2 [18]. With both values exceeding the threshold value a predefined number of times, an alert is given that arcing exists.

In [15] Wavelet transformations (WT) have been explored further and compared to standard Fast Fourier Transformation (FFT). WT proved to be more effective in distinguishing the arc signal from a non-arcing event, especially in real-time detection, where a precise time stamp can be set. In [10] an advanced machine learning (ML) approach was used to process current features in the time and frequency domain in order to improve diagnostic accuracy and optimize system performance. The proposed model was not tested in real-time or with the presence of noise in the system, so it can not be used with real arc occurrences. In [5] autocorrelation was used and proved to be more effective than FFT, especially in consideration of background noise, but the data was tested on an arc model and not in real-time.

Other papers and research mostly go in the same direction as the ones mentioned above. Short and fast Fourier transformation as well as wavelet transformations are used in order to obtain arc fault information from both frequency and time domain. Machine learning is also getting more use in detecting arc faults, but still has ways to go since it is rarely tested in real-time applications. The focus also seems to be mostly on photovoltaic systems, since they are the most popular systems using DC power and on series arc fault detection. DC arc fault detection is a demanding task due to the arc's chaotic nature and unpredictability of occurrence, as well as the size of some DC power systems and the costs that inevitably follow.

Chapter 4

Hardware

Detection of current arcs starts with the right hardware choice, which will successfully measure the current signal and pre-process it so it can be analyzed in the microcontroller. Different components can be used for each of the data acquisition steps. It is important to make a schematic to ensure the best possible output signal for digital processing. The original idea is to make a rather universal prototype that will offer different data acquisition components, shown in Figure 4.2. The signal acquisition part will have 3 different sensors and will be connected to the signal preconditioning, where it will be amplified or filtered. The third part will be the analog to digital converters which will convert the signal for processing in the microcontroller. After the arc is detected, the information is sent further in the data monitoring part.

All parts need to work cohesively and have a function of interchangeability between them so the whole process provides the user a mean of simply connecting the desired current source and getting information about arc occurrence. In this chapter, all of these parts will be described individually, in the sequence in which the signal travels, as well as the chosen schematic for them.

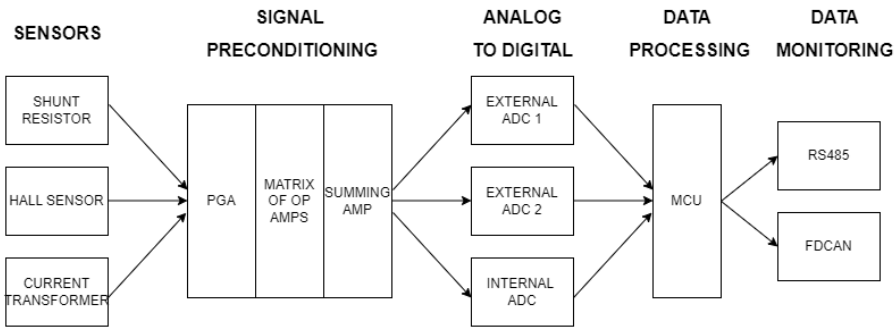

Figure 4.1: Block diagram of the arc detecting prototype

4.1 Sensors

As mentioned in the chapter Electric Arcs, the best features to detect are current and voltage; to do that, we use different sensors. In this project, a shunt resistor, current transformer, and Hall-effect sensors were planned to be used.

The electrical shunt resistor is a device that directs the current through a low-resistance path, enabling it to flow at an alternative point in the circuit. By making an indirect measurement of the voltage drop across the resistor, the current can be calculated with reference to Ohm's law, where the voltage drop corresponds directly with the current passing through. [7]

The shunt resistor to be used in this paper is FHR 4-2321, with the following characteristics :

- Resistances from 0.001Ohm to 50Ohms
- Power Rating to 40Watt
- Resistance Tolerances to ±0.1 %
- Very Low Inductance
- Load Stability to 0.1 % [13]

Shunt resistors are relatively simple to include in circuitry, more so on a PCB, due to their small size and uncomplicated way of operating. In Figure 4.2

we can see the chosen resistor in combination with a voltage follower. The output of the op-amp is going to a sensor switch which will be used to choose between sensor inputs.

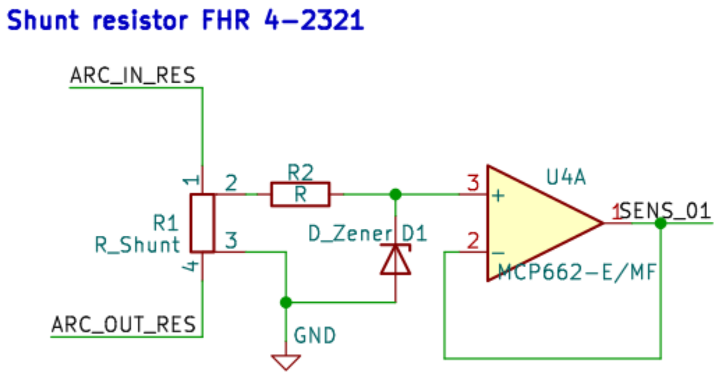

Figure 4.2: Shunt resistor schematics

The current transformer is considered to be an instrument transformer, scaling down the high currents to a much smaller one, by producing an alternating current in their secondary winding, proportional to the measured current in the primary winding. In this way, monitoring current is possible in a much safer way since current transformers can reduce the current levels from thousands of amps to a standard output of 1 or 5 amps. In Figure 4.3 (adapted from [11]) we can see the circuit of a current transformer with an ammeter, which is generally used in pairs. The transformer is calibrated usually for a specific type of ammeter, in order to provide the maximum secondary current corresponding to a full-scale deflection on the ammeter.

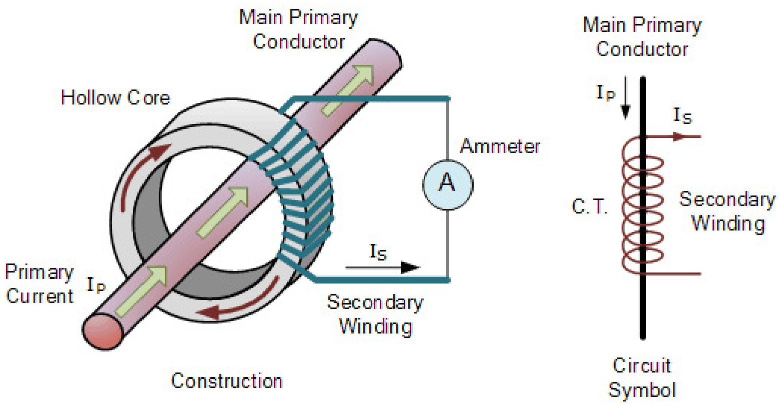

Figure 4.3: Current transformer typical use

By increasing the number of secondary windings, Ns, the secondary current is smaller than the current in the primary circuit - as Ns increases, Is goes down by a proportional amount. In other words, the number of turns and the current in the primary and secondary windings are related by an inverse proportion. A current transformer, like any other transformer, must satisfy the amp-turn equation, and the turn ratio is calculated as follows [11] :

$$T.R. = n = \frac{N_p}{N_s} = \frac{I_s}{I_p} \tag{4.1}$$

and we get the secondary current :

$$I_s = I_p \frac{N_p}{N_s} \tag{4.2}$$

The chosen current transformer is from Wurth Electronic, the 7492540 series with the following characteristics :

- Input 40 A
- 1 MHz frequency range.
- 1:40 transfomer ratio
- can be used as a ´voltage divider

In Figure 4.4 we can see the chosen schematic for the current transformer, which operates with a voltage divider, serving as an offsetting ground. The output is again going to the sensor switch.

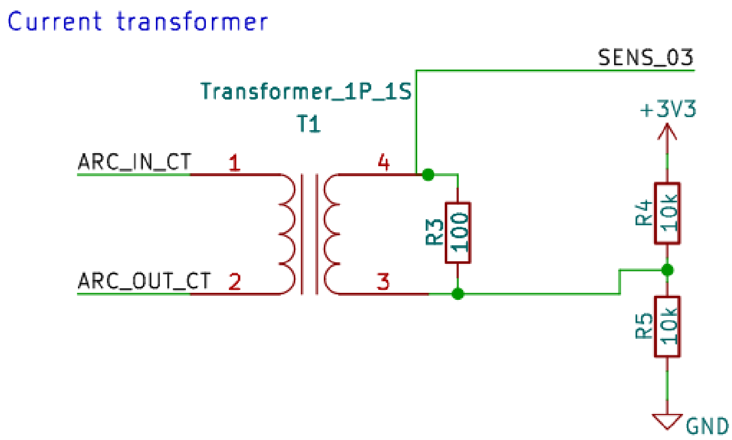

Figure 4.4: Current transformer schematic

Hall effect sensors are usually used to measure the direction and intensity of the magnetic field, which can be used for indirect measurement of current too. Measuring the magnetic field that is created by the current flowing in the wire provides a safer way for measurement due to the galvanic isolation between the Hall sensor and current. There are two ways to implement Hall sensors: in an open and closed loop. In the open loop setting (Figure

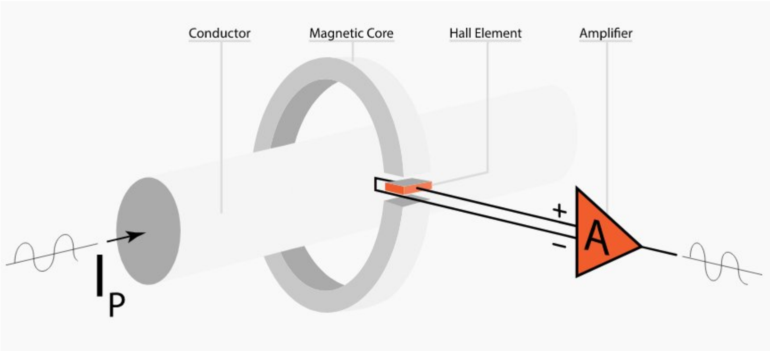

Figure 4.5: Hall current sensor in open loop

4.5 (adapted from [2])), current flows through a conductor that is inside a magnetic core, creates a magnetic field inside the core, which is then measured by the Hall sensor placed in the core air gap. The output of the Hall sensor is a voltage proportional to the core magnetic field which is also proportional to the input current. In a closed loop however (Figure 4.6 (adapted from [2]))

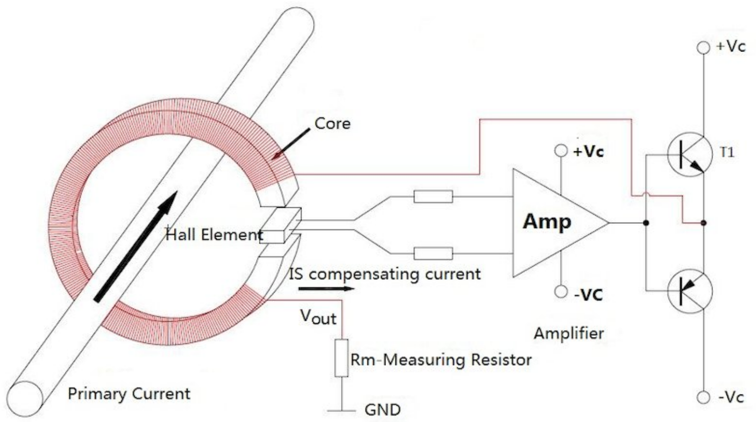

Figure 4.6: Hall current sensor in closed loop

negative feedback is introduced as a secondary winding, driven by the output of the feedback. In this way, the current through the secondary winding is adjusted so that the total magnetic field of the core is equal to zero. Both of these approaches have their advantages and weaknesses. Introducing negative feedback reduces non-linearity and gain errors and becomes unaffected by drift in sensor sensitivity, offering better accuracy and more robustness. On the other hand, the open-loop concept uses fewer components and has a lower power consumption, lower price, and is faster. [2] In this project, the Hall sensor that was planned to be used is ACS712 due to the following characteristics :

- ±2.5% Total Accuracy
- precise and low offset
- low noise
- output voltage proportional to the measured DC current

Device accuracy is also optimized due to the close proximity of the magnetic signal to the Hall transducer. Its small footprint makes it ideal for including on a PCB. [1] On Figure 4.7 we can see the schematic for the sensor, with its output going to the switch.

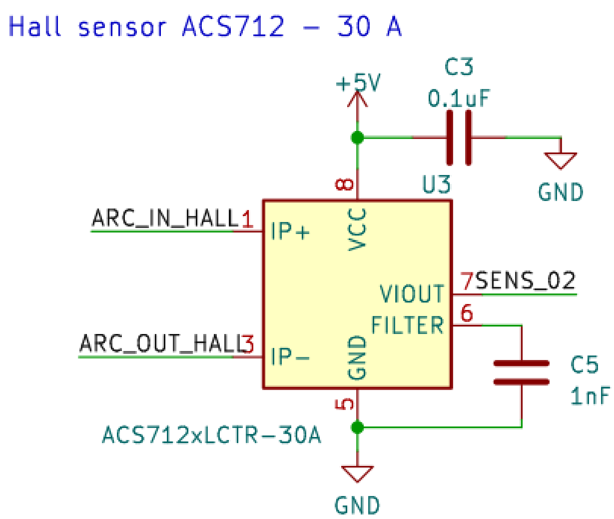

Figure 4.7: Hall current sensor schematic

4.2 Pre-conditioning of signal

Signals, that the sensor produce, are usually weak analog signals in danger of being buried in noise. In order to deliver a signal that can be recognized by the microcontroler, the signal needs to be pre-conditioned with amplifiers, analog filters, and ADCs. This in-between circuitry consists of a Programmable Gain Amplifier (PGA), a matrix of operational amplifiers that will be used for filter construction, and a summing amplifier which is sending the preconditioned signal to the ADC.

Programmable gain amplifiers (PGA) are electronic amplifiers whose gain can be controlled via an external signal. This is very useful, particularly in a multi-sensor environment, where different sensors may require specific gain or amplification. The chosen PGA is MCP6S91/2/3, which can be configured for gains from +1 V/V to +32 V/V and is optimized for high-speed, low offset voltage, and single-supply operation with rail-to-rail input and output capability. [6]. In Figure 4.8 we can see the sensor switch in a form of a pin header, where the output is going to the PGA. The PGA is controller with the SPI communication, provided from the microcontroller, whereas the output of the PGA is going to the filters section.

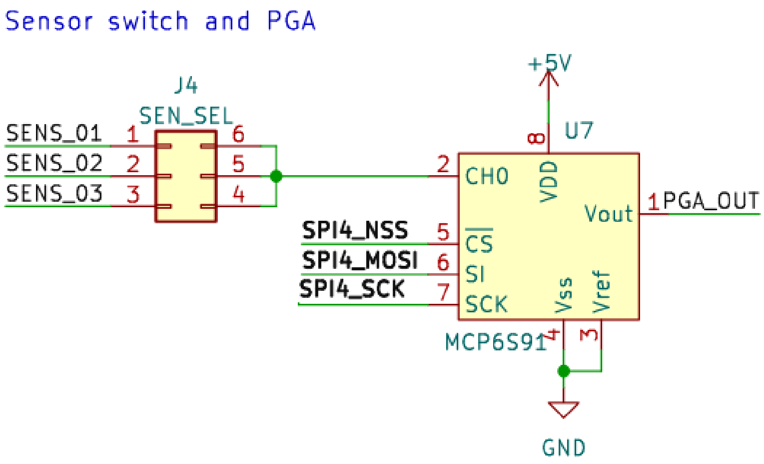

Figure 4.8: PGA and sensor switch schematic

The analog filters are the next part in the signal path which will serve to reject certain unwanted frequencies. Since this will be a universal board, the design of the filters is also universal and the user can decide which one will they construct, as well as which filters will be used via a pin header. In Figure 4.9 we can see the design for the universal filter which enables the construction of low pass, high pass, and band pass filters. The left side, before the amplifier, will serve as a low/high pass filter with the right side being disregarded. The user will choose which filter to choose and accordingly construct it. If there is a need for a band pass filter, both sides will be used - a combination of a high pass filter on the left side and a low pass on the right makes a band pass filter.

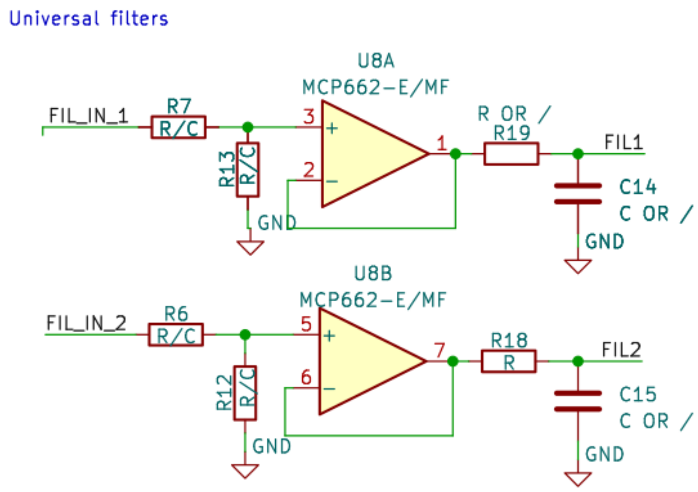

Figure 4.9: Universal analog filter schematic

The output of the filters is a summing amplifier which will prepare the signal for the ADC. It is a simple amplifier with different interchangeable resistors.

4.3 Analog Digital Converters

The Analog Digital Converter (ADC) is an integral part of data acquisition, by transforming analog input signals into digital output signals, which will be subsequently used in data processing. Choosing an ADC is dependent on the speed and resolution needed for the task, as well as power consumption and dynamic performances. The pre-conditioned analog and continuous signal arrive at the ADC input, where it is quantized and periodically sampled. This produces a discrete digital signal that can be used in further processing. It is essential that this process is performed fast and accurately since that is the main element in timely arc detection. Since DC arc detection is a matter of speed and accuracy, MAX11102 has been chosen for the task with the following characteristics :

- Resolution 12-bit
- Fast and low power
- Supply from 2.2 V to 3.6 V

- Throughput from 0.03 Msps to 3 Msps
- Serial clock frequency from 0.32 MHz to 32 MHz
- Dual channel input [4]

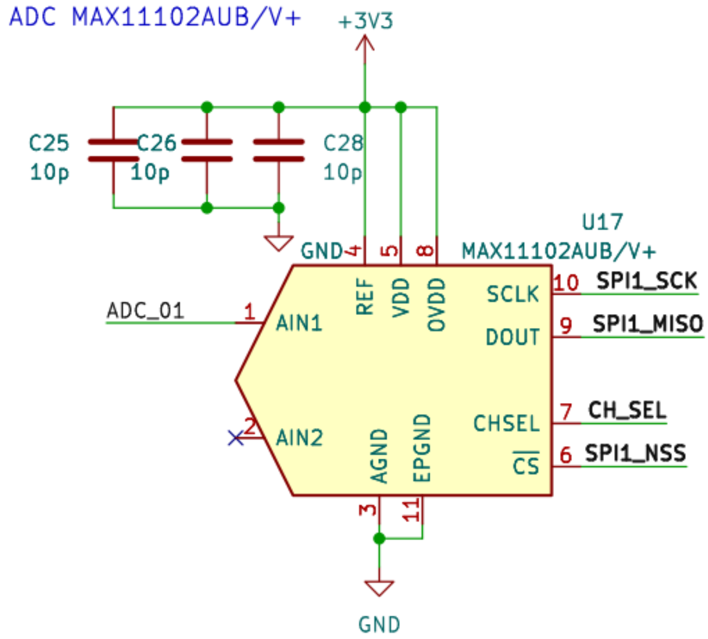

Figure 4.10: MAX11102 schematic

MAX11102 comes small in size, which makes it ideal for incorporation on a PCB (printed circuit board). In Figure 4.10, the schematic is shown, where the ADC is controlled by the SPI communication with only one input channel.

The second ADC is LTC2323-12 which is a 12-bit, low-noise, high-speed ADC with single and differential input. In Figure 4.11 we see the schematic for this ADC, where the ADC is controlled by SPI, with one input channel. In order to test out the performances of specific ADCs, there will be a pin header to change between them, with the internal ADC of the microcontroller as one of the options.

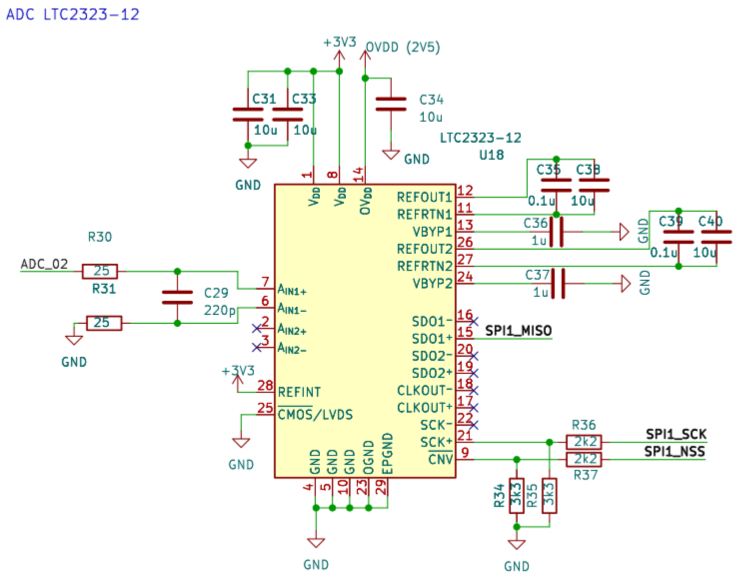

Figure 4.11: LTC2323-12 schematic

4.4 Microcontroler

The main component of arc fault detection is the microcontroler, which will be used for signal processing and detection. Since the task of arc detection is a demanding one, the controller needs to be carefully chosen, so it can meet the high requirements of computing power and minimal computing time. For this project, the controller STM32H743ZI2 (or Nucleo144), from the company STM Electronics, has been chosen for its high-performance Arm® Cortex®-M7 32-bit RISC core operating at up to 480 MHz, high-speed embedded dual-bank flash memory, as well as an extensive range of enhanced I/Os and peripherals connected to APB buses, AHB buses, 2x32-bit multi-AHB bus matrix and a multi-layer AXI interconnect supporting internal and external memory access. [8] An overview of all the controller features is shown in Figure 4.12 (adapted from [8])

Figure 4.12: STM32H743ZI2 components diagram

The most important peripherals that will assist in the detection of arcs are SPI and CAN peripherals, where the ADC peripheral was used for testing purposes.

4.4.1 ADC

The STM32H743 has 3 16-bit successive approximation analog-to-digital converters, where each can have up to 20 multiplexed channels. With efficient low-power mode, there is a very low consumption at low frequency. It is fast, with a high overall performance, and can manage single or differential inputs [9]. In Figure 4.13 (adapted from [9]) the internal ADC block diagram can be seen. The ADC is used to sample the incoming signal from the summing

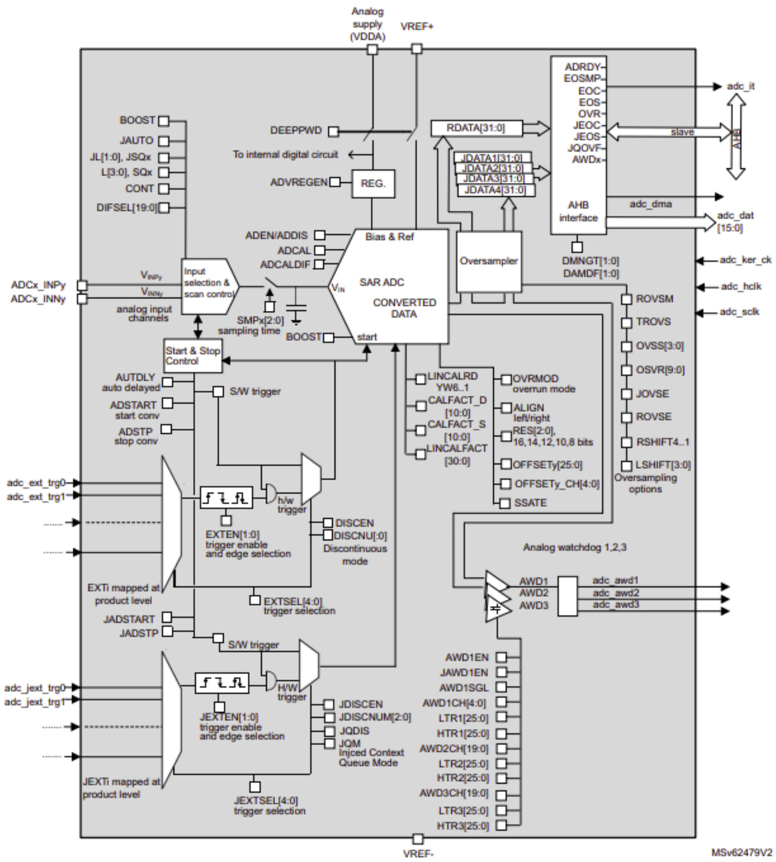

Figure 4.13: Internal ADC block diagram

amplifier and provide a digital signal for the microcontroller. In this paper, the internal ADC was mostly used for initial testing purposes but will not be used for the main data acquisition sequence.

4.4.2 SPI

The serial peripheral interface (SPI) can be used to communicate with external devices while using the specific synchronous protocol. It supports half-duplex, full-duplex, and simplex synchronous serial communication with external devices and can be configured as a master or a slave. It has a multi-master or multi-slave mode capability, can go from 4-bit up to 32-bit data size selection, and programmable clock polarity and phase which proved to be useful in this project [9]. The block diagram of SPI communication is shown in Figure 4.14 (adapted from [9]). In arc detection, it is used as a master in communication with the ADC and PGA, providing a communication clock signal to both of them, which regulates the speed of the ADC and CS pins input, so the sampling can be done or in the case of the PGA, the gain instructions can be sent. With the PGA, it is used as a transmitter for the desired gain, while with the ADC it is used as a receiver for the incoming data from the ADC. In this paper, two SPI peripherals are used and more about them can be found in the chapter Software.

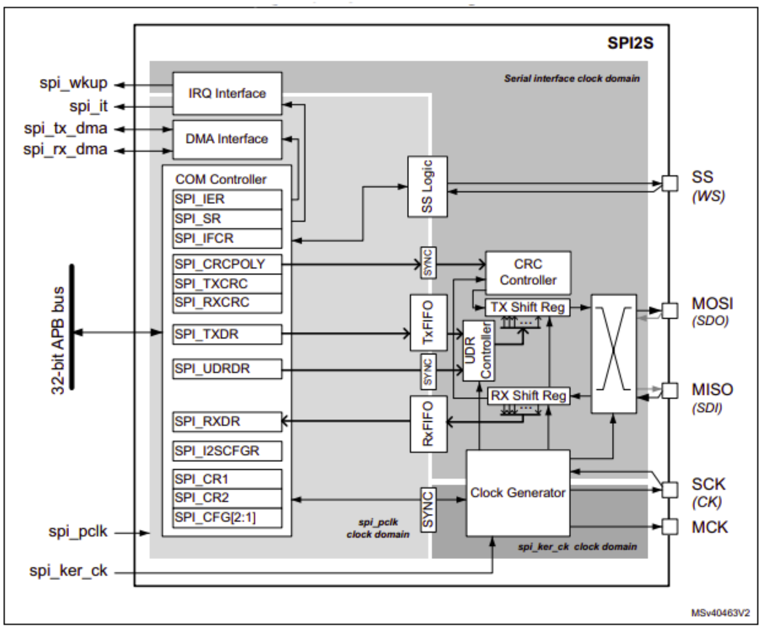

Figure 4.14: SPI block diagram

4.4.3 CAN

Controller Area Network (CAN) is a communication standard used for communication between the microcontroller and another device in the same local network, without the presence of a host. CAN can be seen as a serial bus system, where information is serially transmitted to all the participators in the system, but there is a priority in sending which must be respected. It is mostly used in the automotive industry but can be used in any other application where communication is message-based. In STM32H743ZI2, a newer type of CAN module is present, the Flexible Data Rate Controller Area Network (FDCAN), which adds additional features that the original CAN didn't have, but still supports the older CAN versions. FDCAN supports max. 64 data bytes, has separate signaling on the reception of high-priority messages has modules on this specific controller as well as two configurable receive FIFOs and a configurable transmit FIFO / queue. [9])

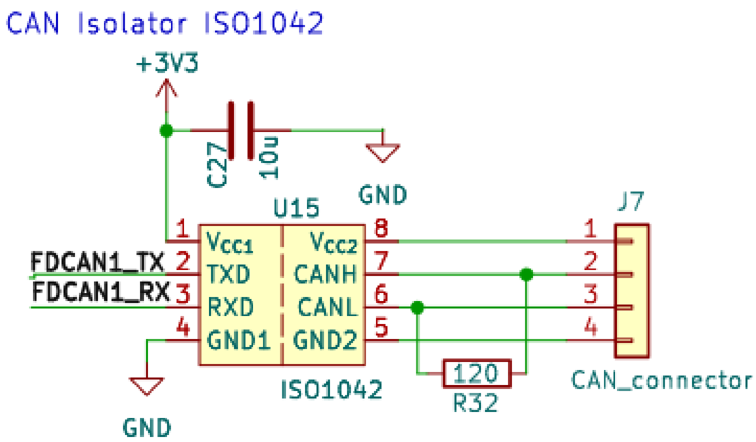

Figure 4.15: ISO1042 diagram

For devices to be in the CAN bus, they need to have a CAN transceiver, which can be already a part of the controller or can be an external chip. Since the chosen controller does not have an integrated transceiver, an isolated CAN transceiver will be used. The chosen one is ISO1042, shown in Figure 4.15. On the left side is the connection to the Tx and Rx of the microcontroller and on the left side are the pins for the CAN bus, which will be used for information to be sent.

4.4.4 USART

Universal Synchronous Asynchronous Receiver/Transmitter or USART is a type of hardware that enables a certain device to establish communication using the serial protocol. Serial communication enables sending each bit of data one at a time, which means that both the sender and receiver have to agree on the way the data is sent. The difference between synchronous and asynchronous In asynchronous communication, only one data line is used to send data from the sender to the receiver. The sender and receiver do not have a shared synchronization signal so they have to be manually configured in advance. With synchronous mode, both data and a clock line are used to send the data, where both the controller and the peripheral are synchronized at the same data rate which enables continuous data sending [16]). STM32H743ZI2 supports both asynchronous and synchronous data sending, where in Figure 4.16 (adapted from [9]) the block diagram of the communication can be seen.

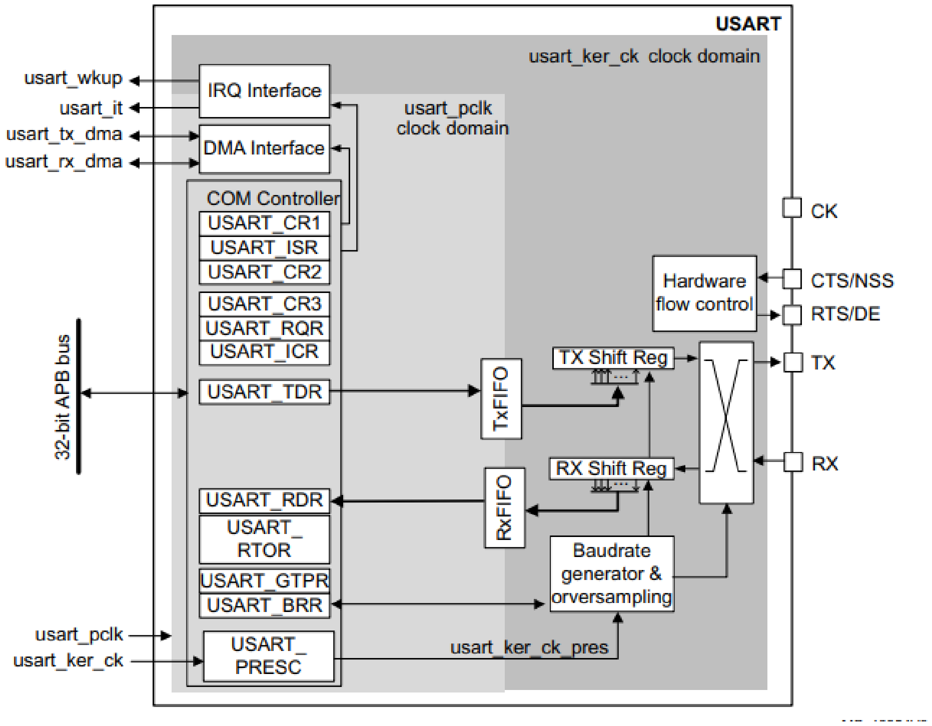

Figure 4.16: USART block diagram

It supports full duplex data exchange with asynchronous data sending and synchronous master/slave mode and clock output/input for synchronous communications. In order to communicate with an external device, it needs a transceiver that will send the data to an external device and in this case, MAX485 will be used. It is a low-power transceiver, where each part contains one driver and one receiver. In order for the data to be received at the peripheral end, another one of these transceivers needs to be connected. USART was also initially used for testing purposes since it was essential for sending data to a serial monitor and serial plotter, which proved to be very important for debugging.

4.5 Prototype realisation

In the following chapters and subsections, the prototype will be referred to as ARCUS, its name derived from the word arc. The block diagram of the realized prototype is shown in Figure 4.17, where the author chose a simplified setup that will ensure correct data acquisition and processing, but compromise on some of the interchangeability and measuring range. In Figure

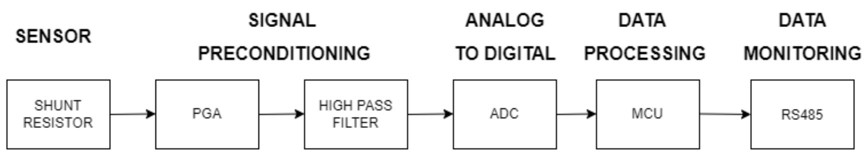

Figure 4.17: Block diagram of the realized prototype

4.18 the schematic of ARCUS is shown, with the hardware parts mentioned above. The input current enters the shunt resistor, followed by the adjacent voltage follower. The output is going to the PGA, which will amplify the signal if needed and send it further to a high pass filter (which will be an optional element if the low-frequency noise is affecting the measurements significantly). The high pass filter cutoff frequency should be between 1 and 2 kHz, but in the end, the chosen one was 1592 Hz, which was calculated after using a 1 kOhm resistor and 0.1 uF capacitance. After cutting off the lower frequencies, the signal is sampled by the ADC and sent further to the MCU.

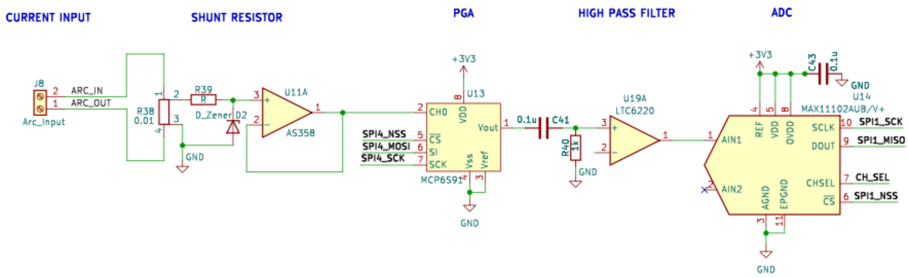

Figure 4.18: Schematic of the prototype

The communication, which is serving as arc detection monitoring, will be conducted with USART. It proved to be a reliable communication protocol since the goal was to provide a way of monitoring arc detection.

Chapter 5

Software

DC arc detection is dependent on both the right hardware but also on the right software which will analyze the input data and successfully detect an arc occurrence. STM32H743ZI2 is using C language for programming and the STMCubeIDE development platform for writing and implementing code. For assistance with data interpretation and visualization, Python and Visual Studio Code were used.

5.1 Data processing

In order to start making initial data interpretation, an arc measurement was made with an oscilloscope and saved to "csv" type of file. The measurement consists of an initial state with no arc, that escalates into an arc. Since the file has a sampling rate of 20 Msps, the file was transformed into a binary file, to ensure faster loading and manipulation, and plotted on Figure 5.1. In this figure, we can see the distinctive regions of no arc and arc, which will be used for later processing. Since there is a very high number of samples in the original file, the data will be resampled at another sampling frequency, which has two benefits: the data is visually more clear to analyze and we can simulate the available sampling frequency of the ADC (shown on Figure 5.2). In this Figure, we can see the characteristic voltage and current behavior of an arc, where the amplitude of voltage decreases and the amplitude of current increases - indicating a parallel arc.

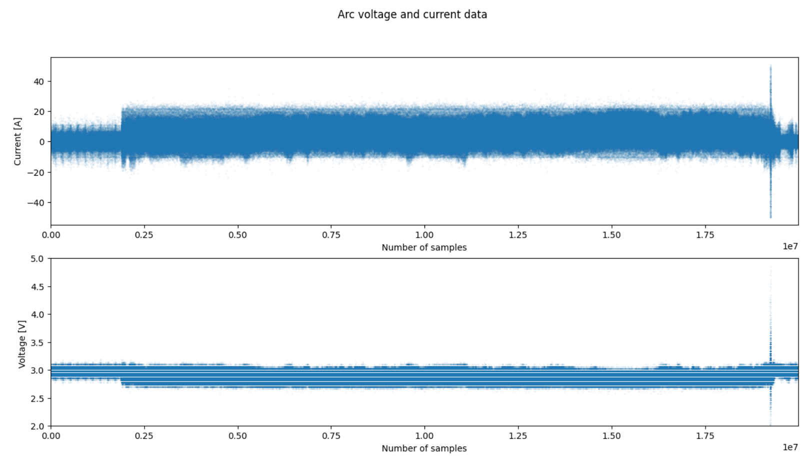

Figure 5.1: Arc current and voltage plot

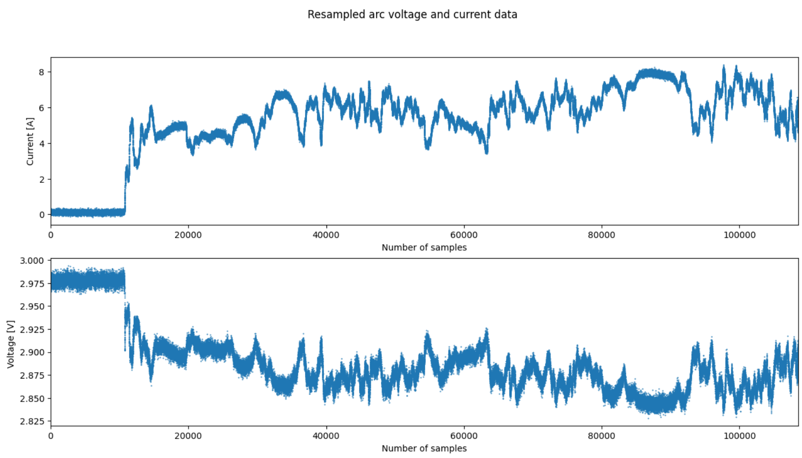

Figure 5.2: Resampled arc current and voltage plot

The next step was to split the input data into two parts: the part we know is without an arc and the one with arc, with the same number of samples in both sets. After splitting the parts, Fast Fourier transformation can be done on both sets of data and visualize the characteristic frequency spectra. In Figure 5.3 both arc and no arc voltage and frequency spectra can be seen. The top plots show the resampled signal and the change in amplitude that occurs with arc existence, where the voltage of the arc has a higher amplitude than the one without. The bottom two plots show the characteristic frequency spectra of no arc and arc occurrence where both have a fairly similar frequency distribution and position of peaks, but not the same. In Figure 5.4 arc and no arc current and frequency spectra are shown, where the behavior in the frequency domain is almost identical for both occurrences. The difference between them is more visible in the upper two plots, where the amplitude of the arc current is slightly lower than the amplitude of no arc current. On all 4 frequency plots, noise can be observed in the low-frequency region (below 2000 Hz).

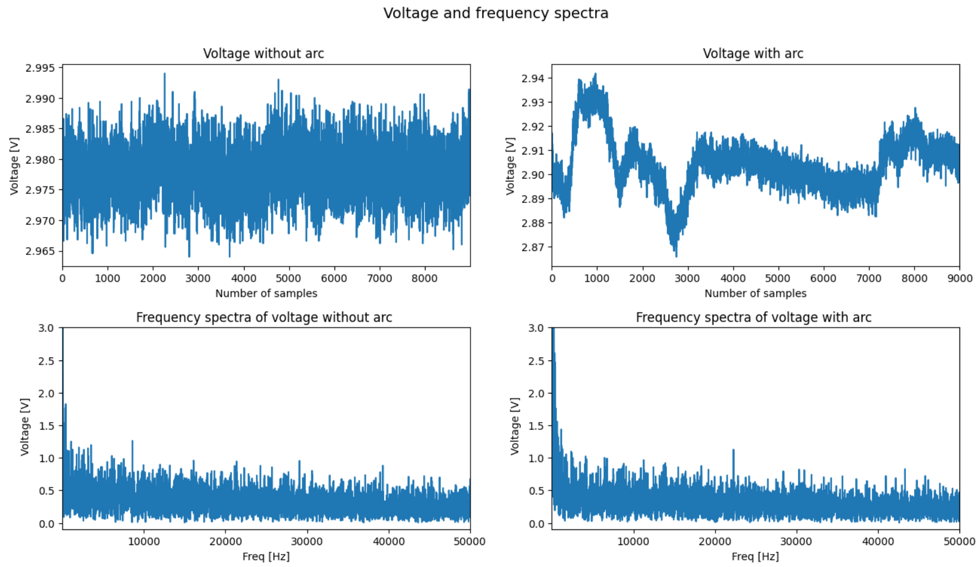

Figure 5.3: Arc and no arc voltage behavior and frequency spectra

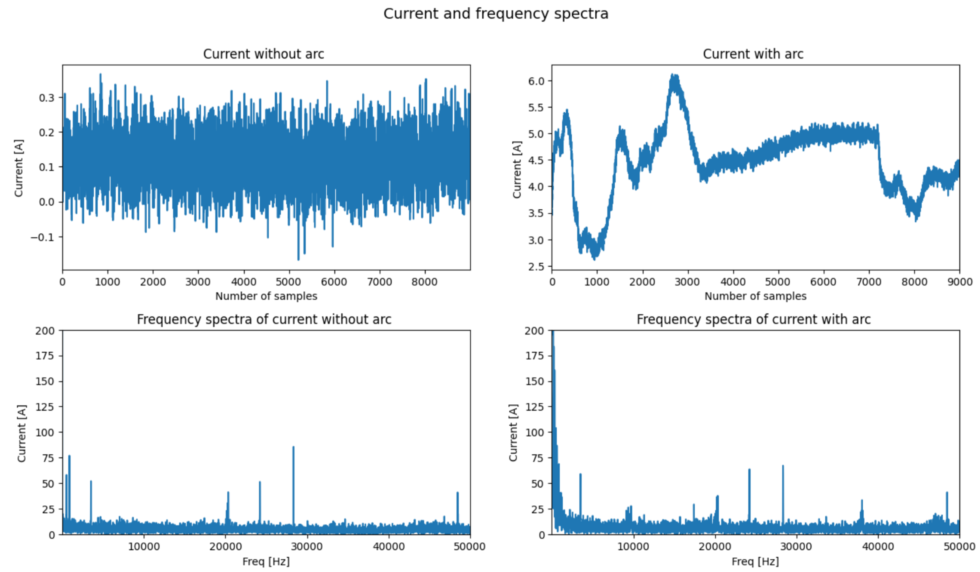

Figure 5.4: Arc and no arc current behavior and frequency spectra

It is clear from these plots that additional measurements should be conducted, where one measurement will contain no arc, and the second arc data and analyze separately. The new measurements were made with a shunt resistor and an oscilloscope, where one set was done with 10 V input and the other with 5 V. A DC/DC step-up was also used, in order to simulate frequency dependency on a load. Both sets of data were analyzed since the protoboard was designed to withstand up to 10 A. In Figure 5.5 the shunt current with no arc can be seen, whereas in Figure 5.6 shunt current with an arc can be seen. It is notable to say that the arc measurements contain smaller and bigger no-arc regions, so data with mostly arc regions should be chosen for further analysis. The same observed low-frequency noise is still

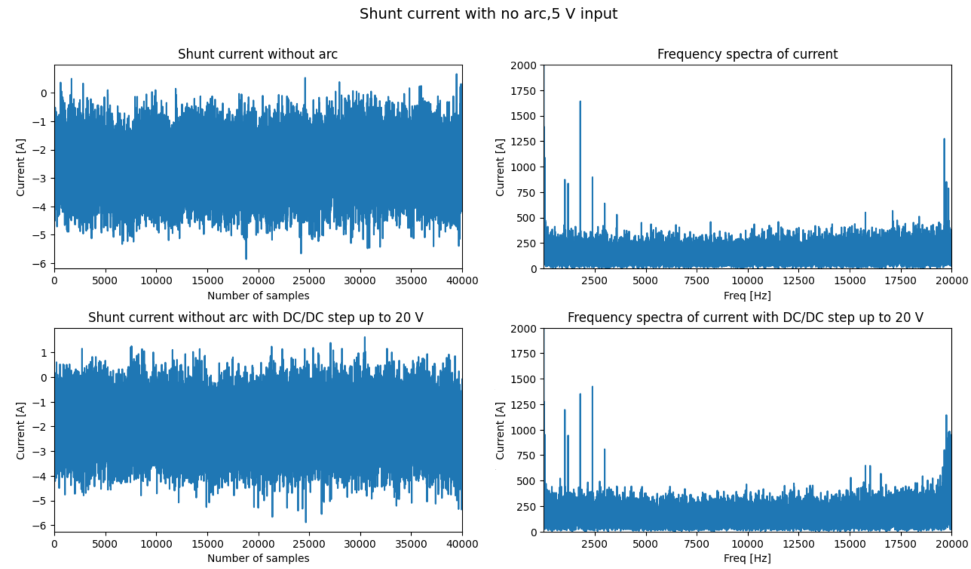

Figure 5.5: Shunt current behavior and frequency spectra without arc

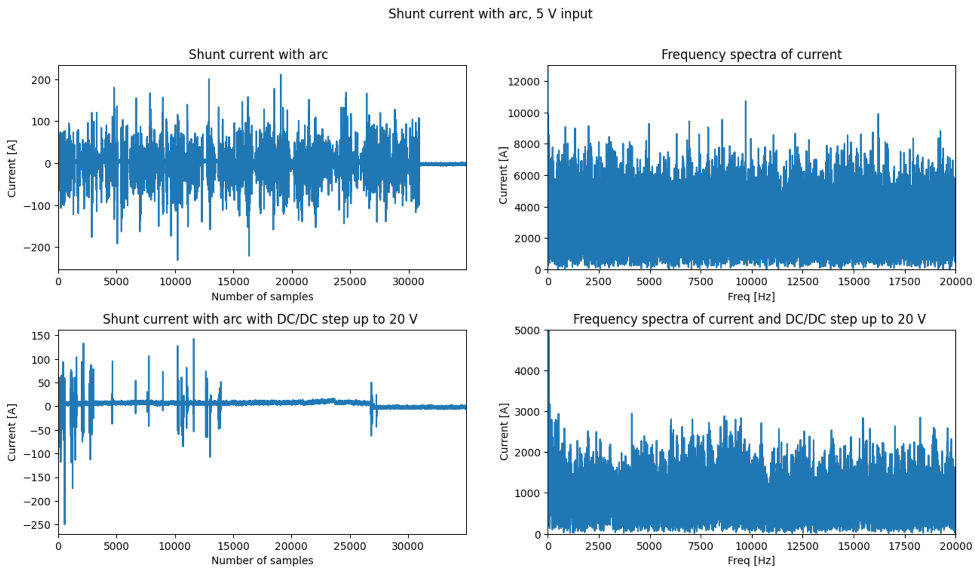

Figure 5.6: Shunt current behavior and frequency spectra with arc

present so a digital high-pass filter is used in further calculations, to eliminate the influence of this noise. This noise is mostly present in the region below 2000 Hz again, so a filter between 1 kHz and 2 kHz should be constructed. After applying the filter on the same set of data, shown in Figure 5.7 and

Figure 5.8, it can be seen that most noise in the low pass region has been eliminated in the arc data sets, alongside the DC offset, but not in the no arc data sets. Another approach should be used in order to eliminate the influence of noise and that approach will be described in the next section.

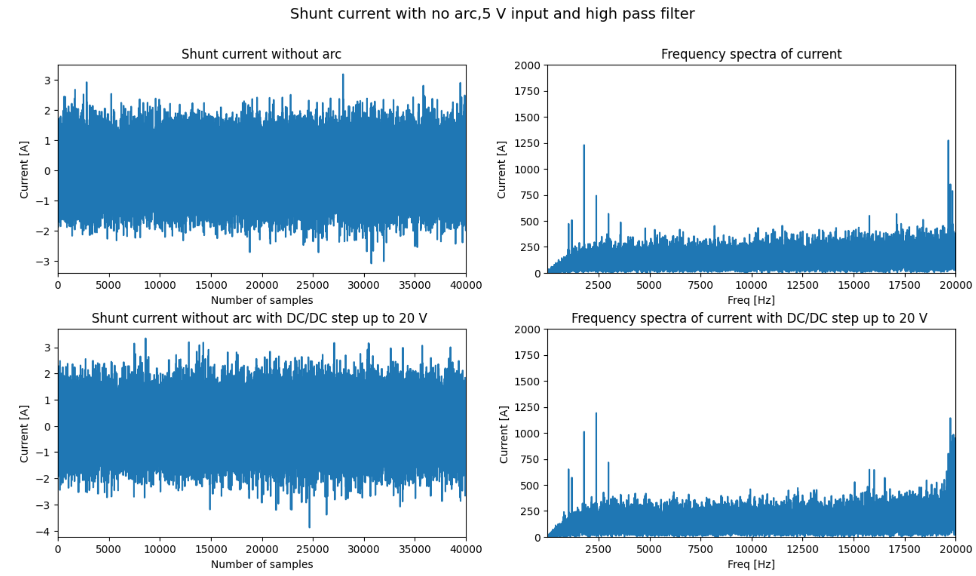

Figure 5.7: Shunt current behavior and frequency spectra without arc and with high pass filter

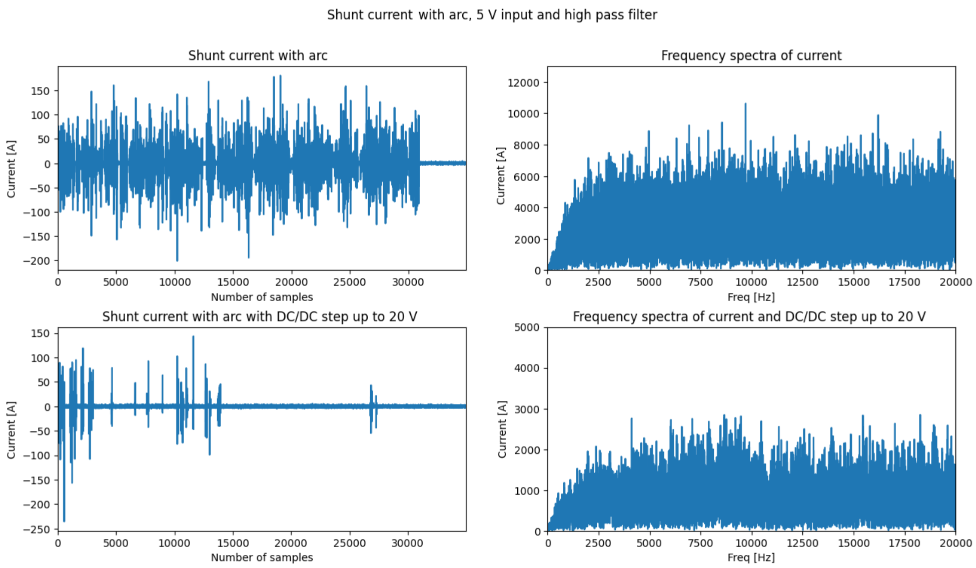

Figure 5.8: Shunt current behavior and frequency spectra with arc and with high pass filter

5.2 Development of detection algorithm

The first step in the development of the detection algorithm is to compare the non-arc and arc current frequency domains. Visual comparison of the frequency plots in Figure 5.7 and Figure 5.8 shows a difference in the amplitude of the frequency data, where the amplitude of the arc is higher than the one of no arc. As suggested in the previous section, using a low pass filter does not entirely remove the unwanted peaks. In order to minimize the influence of the noise on the data, it is clear that the noise peaks need to be removed so that the true data is shown. The function for peak or unwanted noise removal first goes through the no arc data, in order to find the positions of peaks - the frequencies at which they occur. After that, it goes through the same data, with the peak position information, finds the peaks, and assigns them a zero value. In Figure 5.9 the result of the process can be seen, where the peaks from the top plot have been removed and on the bottom plot, we have a stable signal floor.

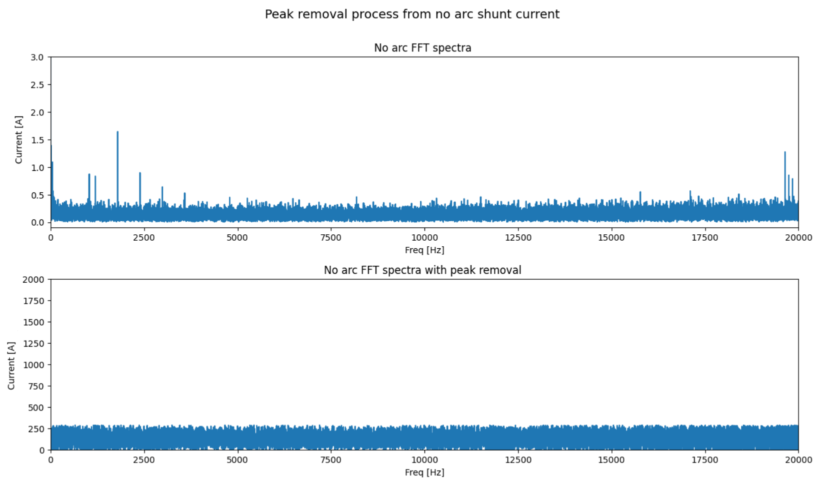

Figure 5.9: Peak removal comparison in shunt current with no arc

The same thing is done for the arc data, we find the same peaks in the data set with known arc existence and remove all the peaks that represent the noise accompanying the arc. In Figure 5.10 the results of the peak removal can be seen in both sets of data, wherein the arc region a stable signal floor is left. In this Figure, we can also observe the difference in amplitude in no arc and arc data, which will be the basis of the detection algorithm. The first step is to use only absolute values of the FFT and then sum the whole frequency spectra. The results of this process are shown in Figure 5.11, where we can clearly see that the sum of no arc data sets is smaller than the sum of the arc data sets, by a big margin.

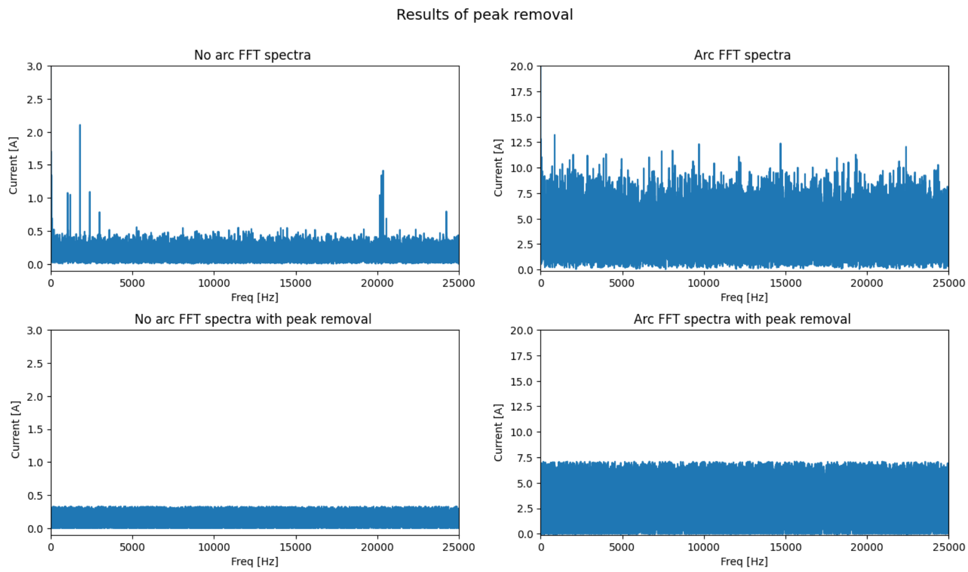

Figure 5.10: Peak removal results comparison in shunt current with and without arc

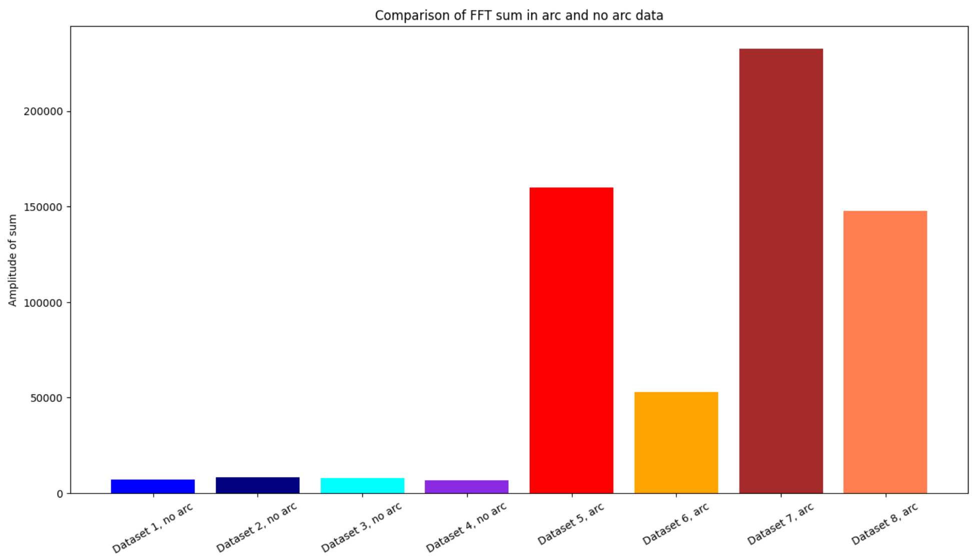

Figure 5.11: Sum comparison in shunt current with and without arc

The next part is to make an arc threshold. After first sampling the no arc data, the threshold will be calculated which will be the double sum of the no arc data, and then we compare every new data to the threshold. The algorithm was tested on 23 data sets and On Figure 5.12 we can see 4 different data sets and the effectiveness of the algorithm. The chosen data set is represented with the blue color and it shows the sum of the no arc and arc through time. The green line is the calculated threshold and the red line is showing where the arc is. If there is an arc, the red line goes to one, whereas no arc sends it back to zero. Some data sets have very mixed arc and no arc region, but the algorithm is successfully detecting even those.

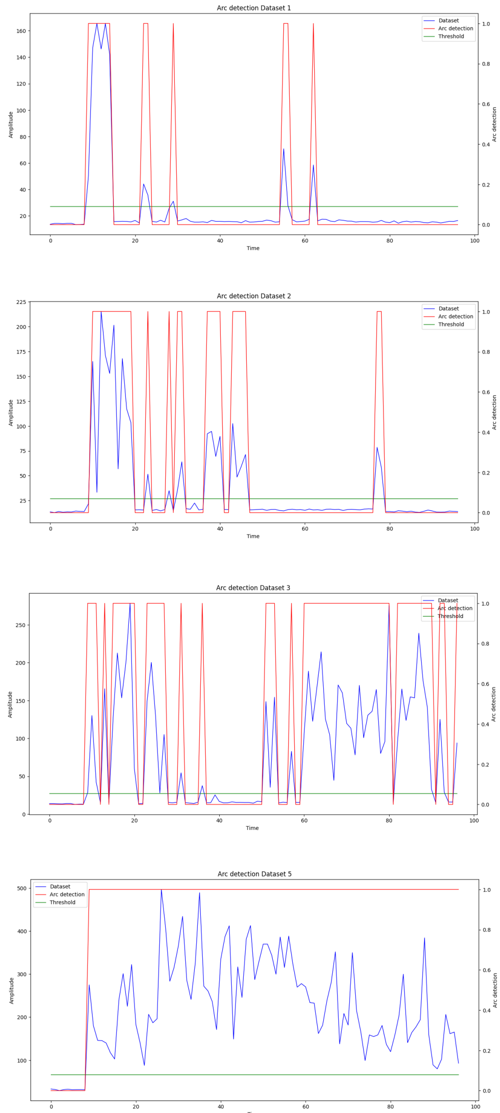

Figure 5.12: Arc detection

5.3 Data processing and detection algorithm in STM32

Developing a mock sampling and detection script in Python served as a basis for developing the code for STM. Essentially it is the same program structure but written in C language, which is a very fast programming language but does not have all the functions that Python provides. On top of that, STMCubeIDE has no way to visualize data from a serial port or a serial plotter, which was solved by sending data with USART to a Python script in Visual Studio Code and plotting it or for simpler debugging purposes to a serial monitor program named Putty. The STM32 program can be divided into two parts, where the first part communicates with external hardware and ensures the success of the data acquisition and the second part is responsible for processing the data and realizing the detection algorithm.

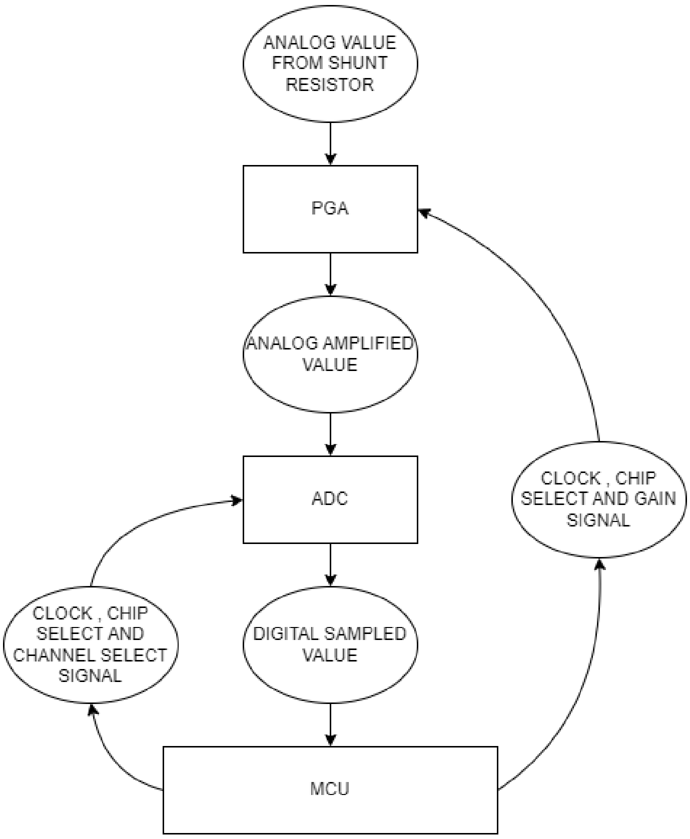

Figure 5.13: DC Arc detection diagram

The first part of the program is dealing with data acquisition since the PGA and the ADC are getting their control signals from the MCU. In Figure 5.13 the data acquisition diagram can be seen, where the MCU sends clock, chip select, and gain signal to the PGA first, where the gain can be later corrected, depending on the incoming signal. The output of the PGA is an analog value, which goes to the ADC. To the ADC, clock, chip select, and channel select signals are sent, to convey the sampling information and the result is a buffer of digital values which can be used for processing in the MCU. These values can be considered as "raw" values from the ADC and need to be additionally manipulated in order to partake in the arc detection process since the FFT needs current or voltage values in a meaningful scope.

In Figure 5.14 the DC arc detection diagram can be seen and the logic behind it. Arc detection starts with incoming data from the ADC, which needs to be converted into "meaningful" data that can be used for the FFT. After conversion to voltage data, the real FFT is done and the result is a buffer with real frequency spectra values. The next step is to check whether the arc detection threshold is set and if not, the peak detection threshold is set, the peaks are eliminated and then the arc detection threshold is set. After a new incoming data buffer, the peaks are again eliminated and the sum of the filtered FFT data buffer is done. That sum is then compared to the arc detection threshold and if the sum is bigger than the threshold, there is an arc, and a warning message appears. If there is no arc detected, the whole process starts anew from the incoming ADC buffer.

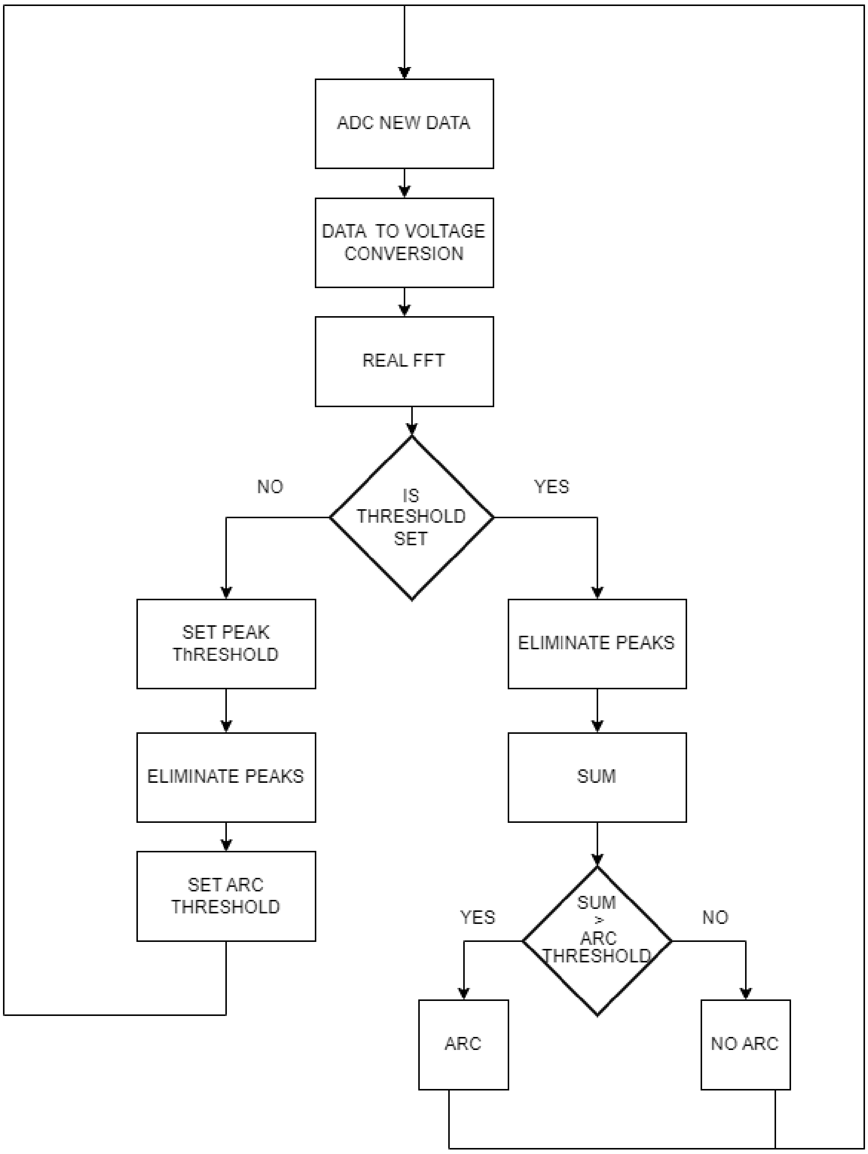

Figure 5.14: Data acquisition diagram

Chapter 6

Results

The result of this thesis is a DC arc detection prototype, which consists of a hardware part, realized on a protoboard, which connects to the software part described in the section Data Processing and detection algorithm in STM32. This part describes the realized prototype and the achieved results.

6.1 The device

For assembly, a protoboard was used, which will be able to sustain currents up to 10 A. Measuring higher currents is not that advisable, but still could be done. The concept of the design is that the STM32H743 will be on top of the protoboard and all the components are on the side of it, showing the path of the signal from the input screw terminals until the ADC output that leads to the microcontroller. All the components except for the shunt resistor are removable, which makes debugging and testing easier. In Figure 6.1 the finished prototype can be seen, with the STM32H743 on top. A pin header is added between the filter output and ADC input, so the ADC and the detection can be tested with an external signal from a signal generator. The final part is the serial communication converter module for RS485, seen in the lower right corner, which serves as a serial communication port to the desired destination.

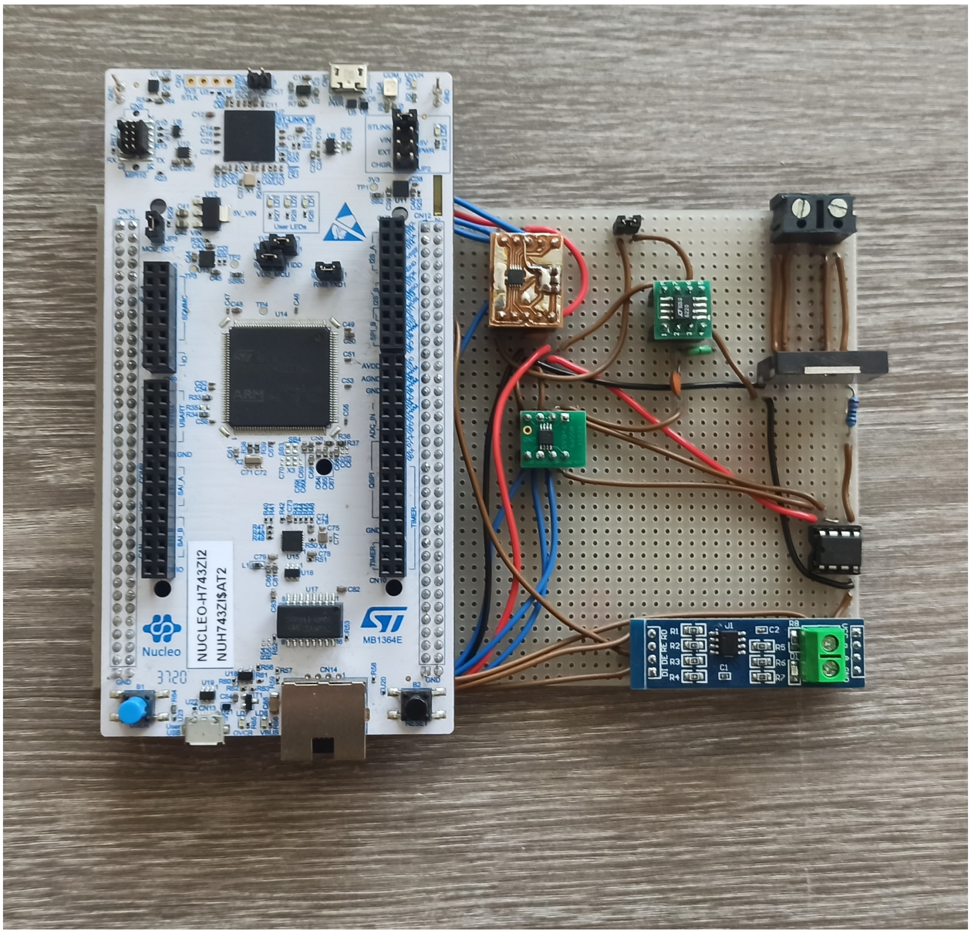

Figure 6.1: ARCUS detector

6.2 Detection results

As mentioned in the section 5.2, the detection algorithm has proven its effectiveness theoretically using Python and Visual Studio Code. Using Fourier transform and the frequency domain showed much more information about the incoming data and the changes occurring with the presence of an arc. Implementing this algorithm in the hardware did not turn out to be as robust as we expected. The data acquisition part fulfilled its intended purpose and the result is shown in Figure 6.2. The beginning and the end show the no arc part, which was used to set the threshold for detection, whereas the parts with the higher amplitude clearly show the occurrence of an arc. This example shows what a short arc event looks like, as well as a sustained arc. The applied algorithm was able to detect the arc, differentiating between the no arc and arc regions, but it failed in certain scenarios.

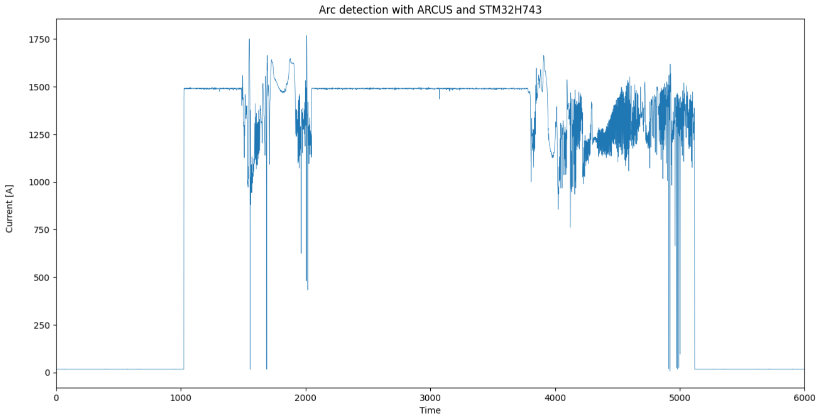

Figure 6.2: ARCUS detection result

Due to the lack of shielding, the measurement was accompanied by a very high noise amplitude, which could not be compensated with the current hardware setup. The no arc and arc signal was buried in the presence of noise, so the algorithm would not detect a change in amplitude between these 2 occurrences. This posed a problem since the threshold was wrongly calculated due to the presence of noise and it could not detect an arc successfully since there was a small difference between the no arc and arc data. In order to amplify the signal, the PGA gain setting was set to the highest, but it was not able to amplify the signal enough for it to be more detectable. With the current setup, the ADC was able to sample at a maximum 50 kHz frequency which was not high enough for this detection. Higher sampling rates should be applied to differentiate better between the signals.

One of the problems was also the use of the protoboard, which was not designed to sustain high current applications, so the used voltage and current had a limit of 5 V and 15 A, which was not enough high to be detected. No matter the amplification gain, it was still too small to be detected in the presence of much bigger noise.

The detection algorithm is based on a very simple threshold crossing and to get this threshold, we are using a calibration period in the beginning. This calibration period is currently only a single measurement and it is not enough to make this algorithm detect more robustly. It should be run over a longer period/measurements and repeated after a specified time interval in order for it to be updated.

Chapter 7

Conclusions

This thesis provides a comprehensive study that aims to design and develop a prototype of a DC arc detector using digital signal processing in a microcontroller. The hardware part of the prototype was designed to capture and enhance input data, with all the components realized on a protoboard. The software part provides a mean to analyze arc data and to detect an arc occurrence with a generated warning of arc detection with an industrial serial communication protocol.

Within the thesis, the detection algorithm has proven successful with theoretical experiments, but the implementation of it with the chosen hardware experienced trouble with accurate detection. The influence of the noise was very high and the signal was not strong enough to be properly distinguished and interfered with the detection algorithm. Another limitation of the algorithm was the amplitude of the current that was analyzed since the use of a protoboard put a maximum on it.

Despite this limitation, this thesis provides a solid foundation for future research and development in arc detection technology. It proved that focusing on both hardware and software was essential in the entire design process in order to eliminate the influence of noise. In future applications, the hardware should provide a relatively noiseless data acquisition, while the detection algorithm should provide a robust detection method.

7.1 Future work

Future studies of this topic should focus on eliminating the noise in the analog system that is used in data acquisition. The influence of the noise should be better compensated and the focus should shift to enhancing the signal in comparison to the noise - the SNR (signal-to-noise ratio). The sampling rate of the ADC should be increased to get data from a higher frequency domain and the use of filters should be more studied and tested. The board should also be realized as a PCB (Printed Circuit board) with its own power supply and redesigned to a smaller scale so it can be used in different applications.

Software-wise the detection algorithm should be improved with a different calibration setup so the detection threshold is improved accordingly with data change. Additionally, the focus should be on a more universal device that will function in any arc occurrence setting, even in high-noise environments.

Appendix A

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Appendix B

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