Jørn André Mørck Gundersen

Analysis and Testing the Influence of Circuit Parameters on Serial Arc Detection

Master's thesis in Electric Power Engineering
Supervisor: Eilif Hugo Hansen
June 2023

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Abstract

Fire statistics indicate that electric fires are the leading cause of residential fires in Norway. As long as low voltage regulations are followed, protection should be provided against electrical fires caused by overloads and short circuits. A significant portion of the remaining fires are caused by series faults, including series arcing and resistance heating caused by loose connections, which are not detected with conventional protection equipment. To address this issue, a new type of protection device, called arc fault detection devices, has emerged in the market. These devices detect arcs by measuring the high frequency noise generated during an arc. However, previous research and theses have indicated that the signs used for arc detection can be obscured by different loads in the circuit.

During this thesis the influence of differen load and circuit parameters on the high frequency noise and the consequenses this have on the detection ability of arc detection devices from four devices from different manufacturers. The inclusion of these devices in the European electrical regulation is imminent, and before these devices are implemented in the Norwegian adaption these factors should be clarified. Due to this, the tests conducted in this thesis went beyond what is required by IEC 62606.

The results of the tests indicate that the signatures of series arcs are obscured if the arcing current is significantly smaller than the parallel load current in the circuit. Additionally, the inclusion of capacitance in parallel with the series arc fault was found to influence the detection ability of one of the devices. The same device also was troubled by having an electronic load, a switch-mode power supply, connected in parallel.

Furthermore the detection of different arc faults and the lower limits of disconnection was tested. The tested arc faults where contact arcing, electrical breakdown in air and arcing on char in a cable. The results demonstrated reliable detection of arcing on char and contact arcing, while detection of electrical breakdown in air exhibited more variability. It was also shown that all the tested devices met the requirement set by the test standard IEC 62606, although the specific threshold level varied across devices, ranging from 1.0A to 2.5A.

By shedding light on the influence of circuit parameters, loads, and various arc faults on the performance of arc fault detection devices, this research can contribute to the understanding of arc fault detection and the implementation of these devices in electrical installations. Further the results raise the question whether some of the devices sold in the market today may be too tuned for passing the requirements of the test standard, and if the test required by the test standard are adequate to verify the detection capabilities of the devices.

Sammendrag

Norsk brannstatistikk indikerer at elektriske branner er den ledende årsaken til boligbranner. Så lenge forskriftene for elektriske lavspenningsinstallasjoner følges vil beskyttelsen mot branner forårsaket av overbelastning og kortslutninger være overholdt. En betydelig del av de gjenværende brannene skyldes seriefeil, inkludert serielysbuer og resistiv oppvarming forårsaket av løse tilkoblinger. Disse feilene oppdages ikke av konvensjonelt beskyttelsesutstyr. For å håndtere disse feilene har nye vern kalt «arc fault protection devices», eller lysbuevern, kommet på markedet. Disse vernene bruker høyfrekvent støy med opprinnelse fra lysbuen til å oppdage feilen. Forskning utført tidligere har imidlertid indikert at den høyrefrekvente støyen kan skjules når ulike laster befinner seg i installasjonen.

Under denne oppgaven har påvirkningen av ulike laster og kretssammensetninger på den høyfrekvente støyen og konsekvense dette har på deteksjonsevenen til lysbuevern fra fire produsenter blitt undersøkt. Krav til bruk av disse nye enhetene er nært forestående i den førende europeiske standardiseringen, og før disse kravene innføres i den norske tilpasningen bør disse faktorene avklares. Testene utført i denne oppgaven ble derfor utført utover det som kreves av den europeiske testnormen IEC 62606.

Resultatene fra oppgaven indikerer at tegnene fra serielysbuer blir mindre målbare hvis lysbuestrømmen er betydelig lavere enn den parallelle laststrømmen i kretsen. I tillegg ble det funnet at tilkobling av kapasitive laster i parallell med den seriefeil belastede grenen førte til en dårligere deteksjonsevne for en av lysbuevernene som ble testet. Det samme lysbuevernet hadde også problemer med deteksjon av lysbuer når det var tilkoblet en elektronisk last i form av en likerettende strømforsyning i kretsen.

Videre ble det testet hvor gode lysbuevernene var til å oppdage ulike lysbuer og hva den nedre strømgrensen for utkobling var. De forskjellige lysbuene som ble testet var kontaktlysbuer, gjennomslag i luft og lysbuer på forkullet isolasjon i kabler. Resultatene viste pålitelig deteksjon av kontaktlysbuer og lysbuer på forkullet isolasjon, men variabel deteksjon av elektriske gjennomslag i luft. Resultatene viste også at enhetene som ble testet oppfylte kravet i teststandarden IEC 62606 til laveste deteksjonsgrense på 2.5A, men terskelen til de forskjellige leverandørene varierte fra 1.0A til 2.5A

Ved å belyse påvirkningen av kretsparametere, belastninger og ulike lysbuefeil på ytelsen til lysbuevernene kan denne forskningen bidra til forståelsen av lysbueoppdagelse og hjelpe i implementeringen av disse vernene i de norske tilpasningene av lavspenningsinstallasjon standarden.

Preface

This work presented in this thesis was conducted at the Norwegian University of Science and Technology (NTNU), Department of Electric Energy, in the subject group Power System Operation and Analysis. The work was carried out during the spring semester of 2023 and is based on a specialization project from the fall semester of 2022. It also represents the end of the two-year MSc program in Electrical Power Engineering.

The author's previous experience as an electrician undoubtedly influenced the choice of project. The subject was intriguing and is clearly an area of research worthy of attention. Fires caused by electric faults are a major cause of loss both in terms of money and human life. Any means that can help to further reduce fires should be looked at and understood.

The opportunity to plan and execute lab experiments was pleasant and made the final period of the MSc degree an enjoyable period of the education. In that regard I would like to thank Eilif Hugo Hansen, my supervisor during the project. I would also like to thank both Svein Erling Norum and Bård Almås from the service lab, and Morten Flå from the workshop at the institute for helping with the test circuits. Lastly, I have to thank the manufacturers, which I have chosen to keep anonymous, for willingly donating the arc fault detection devices that were tested during this master's thesis.

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Abbreviations

List of all abbreviations in alphabetic order:

- **AFCI** Arc Fault Circuit Interrupter
- **AFDD** Arc Fault Detection Device
- **DFT** Discrete Fourier transform
- **FFT** Fast Fourier Transform
- **FT** Fourier transfor
- **HF** High frequency
- **IFE** Institutt For Energiteknikk
- **IEC** International Electrotechnical Commission
- **MCB** Miniature Circuit Breaker
- **MS** Mega samples
- **NEK** Norsk Elektroteknisk Komite
- **NTNU** Norwegian University of Science and Technology
- **PVC** Polyvinyl chloride
- **RCCB** Residual Current Circuit Breaker
- **RSSI** Recived Signal Strength Indication
- **SMPS** Switch Mode Power Supply

Chapter 1

Introduction

This chapter presents the motivation for the work, description of the project, related earlier work, limitations of this project, the objectives and approach used to reach the objectives.

1.1 Motivation

Safety in electrical installations is a topic that still demands research. Although existing circuit protection devices, new installation material, and standards have improved the level of safety, fires that develop in electrical installations remain a problem. Protection devices such as fuses and circuit breakers help reduce the danger of short circuits and overloading, reducing the probability of fires. Residual current detectors have also become normal and are used to monitor installations for leakage current and reduce the impact of earth faults as both a source of fire and an electrocution.

The category electrical series faults has received increasing attention as a cause of fire in the last two decades. Traditional protection equipment does not detect series faults and the concern is that these faults are the source of numerous fires. Previous fire statistics from Norway have shown a large representation of series arcs as a source of fires originating from electrical installations. The accuracy of these observations has been called into question due to the low rate of fire investigations in Norway and the difficulty in determining the causes of fires without a thorough investigation. In 2016 new investigation practices concerning fire documentation were applied and because of this the specific cause of fires is no longer documented without an adequate investigation. The fire department no longer specifies what caused the fire, but the origin of fire is still specified. Even with these changes the more recent statistics do point towards typical series faults in a majority of electrical fires. Fire statistics from Norway (2016-2023) shown in Figure 1.1 indicate that fires caused by electrical equipment are the primary source of fires, with a higher rate of occurrence in the last 12 months.

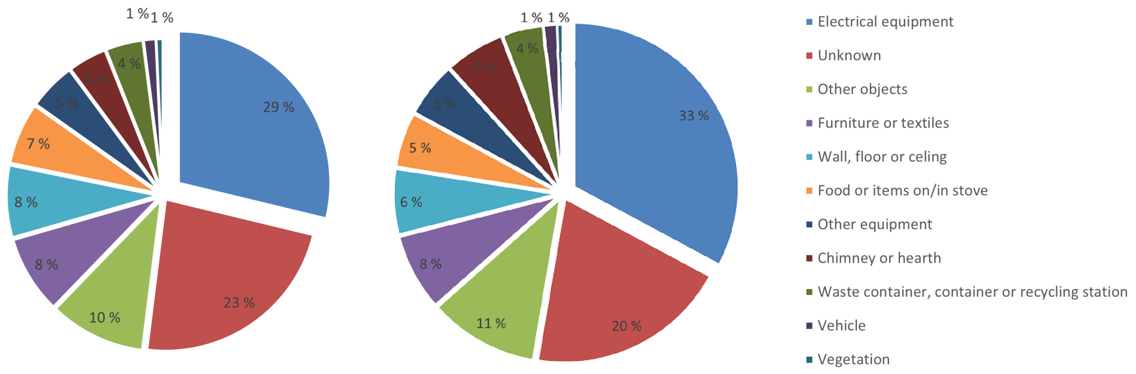


Figure 1.1: Fire statistics with avoided fires removed, Norway, left: 2016-2023, right: last 12 months

Over the last decade, manufacturers of low voltage protection equipment have developed and sold new devices called Arc Fault Detection Devices (AFDD's). Only a few countries and organizations have demanded the use of these devices in their standards and regulations, most notably several states in the USA. Never the less interest is increasing amongst other countries. In European countries covered by IEC standards, there is a push towards the implementation of these devices in the upcoming edition of IEC 60364 *Electrical Installations for Buildings.*

Some controversy exists regarding the efficacy of AFDD's and little information is published on the working principles of these devices. Some publications such as Institute for Energy Technology's(IFE) *"Status for Lysbuevern i Norge"* have pointed out several factors that should be looked into before a requirement for these devices is included in the Norwegian implementation of IEC 60364 *Electrical Installations for Buildings*, NEK 400[1]:

- The need for documentation of the fire preventive capabilities
- Published results from real-scenario testing
- The need for stricter test demands that better resemble real electrical installations in the standard IEC 62606

1.2 Project description

As concluded in the IFE report *"Status for bruk av lysbuevern i Norge"*, there are several aspects of arc fault detection that should be better documented, and documentation should be done before an eventual implementation in the Norwegian standard NEK 400. This master's thesis aims to further clarify whether arc faults can be obscured by circuit elements found in residential low-voltage installation, and how arc fault detection devices function during varying arcing conditions. Further answering the question *"Can detection of series arc be prevented by different circuit and arcing parameters?"*.

1.2.1 Related work

The topic of series faults such as series arcs and glowing connections has started to gain research traction in the last two decades. In particular, the research by John J. Shea on behalf of Eaton [2][3][4], and Peter Müller, Stefan Tenbohlen, Reinhard Maier, and Michael Anheuser on behalf of Siemens [5][6]. At the Norwegian University of Science and Technology (NTNU) two master theses were written on the topic in 2015 and 2016 using the first versions of AFDD's sold on the market. These dissertations were "Seriefeilvern som beskyttelse mot brann" by Maren Bjørnbakk Nilsen[7] in 2015 and "Testing av lysbuevern" by Markus Fagerås[8] in 2016. In 2018 a PHD was published by Jean-Mary Martel at the Technische Universität Ilmenau called "Series arc faults in low-voltage AC electrical installations"[9]. More recently a master thesis from Kungliga Tekniska Högskolan from 2022 written by Ghazal Alqabbani[10] can be mentioned.

1.2.1.1 Limitations

The work in this thesis is limited to series arc faults that occur in circuits that can be described as low voltage residential circuits. Therefore, the limitations of the projects extend to:

- Current limited to maximum 16A
- Voltage limited to 230 V
- The detection devices is located in the breaker at the start of the circuit, therefor commercially available arc fault detection devices (AFDD's) are used
- This master's thesis only considers series faults

1.2.2 Objectives

As a continuation of the work that was done in the specialization project, *Arc fault detection tests in residential installation scenario*[11] in the fall of 2022 by the author, the tests that are performed in this master's thesis are based on the questions that were presented in that project:

- What is the AFDD's lower current threshold for arc fault detecting?
- Does a low fault current to total current ratio influence the detection of arc faults?
- Can AFDD's detect glowing connections or the precursors to glowing connections such as contact arcing?
- Does electronic loads influence arc fault detection?
- Does parallel capacitance influence arc fault detection?
- Is arc fault detection influenced by the kind of arc that is produced?

1.2.3 Approach

To answer the question *"Can detection of series arc be prevented by different circuit and arcing parameters?"* and the sub objectives that lie within this question a series of laboratory tests have been performed. The tests were carried out with different circuit parameters and arc generating methods. To assess the effectiveness of AFDD's they were tested multiple times in different circuits. The detection rate and disconnection time were used as parameters to assess their performance. In order to evaluate the circuit parameter's ability to conceal a series arc fault, the AFDD's ability to detect the arcing and analysis of waveform recordings were used.

1.2.4 Contributions

By testing the AFDD's under conditions comparable to what is found in residential installations, the aim is to better qualify the performance of arc fault detection devices. This performance evaluation can be useful in the decision-making process about whether or not to implement these devices in the Norwegian version of IEC 60364 *Electrical Installations for Buildings*, NEK 400.

Chapter 2

Theory

This chapter presents theory and background on low voltage electric arcs, other series faults, low voltage protection equipment, the standard relating to arc fault detection in low voltage installations and theory on the mathematical transformation from time domain to frequency domain.

Several of the sections in this chapter are based on the theory chapter of the specialization project written by the author in the autumn of 2022 [11]. The sections that are reused and partially rewritten are:

- section 2.1 except subsubsection 2.1.3.3 and subsection 2.1.7
- section 2.2 in its entirety
- section 2.3 in its entirety
- section 2.4 except subsection 2.4.1

2.1 Electric arcs

Electric arcs are stable continuous electric discharges that connect across or through insulating mediums such as gases and polymers. The discharge produces an arc column made of plasma, which can exist as long as the energy provided to the arc is greater than the energy dissipated in the arc. This plasma column will give of a recognizable blue luminous glow that often is used to describe arcing. Arcs are classified as either in series with a load and having a current limited by the total impedance in the branch or in parallel with the circuit which gives a current only limited by the impedance of the preceding cables and power grid equipment. The stability and longevity of the plasma column separates arcing from sparking, where the more transient phenomenon is regarded as sparking [11].

The creation of arcs can be initiated in five ways. The five ways are described in the "Handbook of Fire Protection Engineering" [12].

- Sparks occur when the difference in voltage between two conducting materials that are separated by an insulating material is greater than the threshold voltage of the material. For gases, the voltage threshold is determined by Paschen's law.
- Separation or disconnection of a conducting bridge. As the conducting materials are separated, the current density in the conducting material will increase. Eventually, a liquid bridge is formed that evaporates as the temperature increases and ionizes the gap that is left open.
- Formation of a carbonized bridge in or on an insulating material between two conducting materials.
- The evaporation of a glowing, high-resistance, electrically conducting connection.
- The introduction of ionized gases between two conductors

To sustain an arc column, the energy provided to the arc has to be greater than the energy dissipated. Energy dissipation is dominated by heating of the plasma column. At low voltages, electric current is conducted in the arc through the travel of electrons between the cathode and anode and positive charge carriers traveling in the opposite direction. Thermionic field emissions from the cathode and ionizing collisions in the plasma provide the electrons and ions needed[9][13].

2.1.1 Series arcs

Arcs are categorized as series arc and parallel arcs, where arcing in series with a load is the definition of a series arc. When regarded as a lumped model, a series arc acts as an additional impedance in the circuit, and the total current in that branch will depend on the impedance of the arc and the additional loads. This limits the current in the branch, and thus the energy that can be dissipated by the arc. Series arcs in electrical installations are usually caused by loose connections or broken cables, but they are also caused by the function of some equipment such as brush motors, switching devices, and fluorescent lights. Other devices create an arc resembling waveform when used, as dimmers and certain types of two phase motors. Arc faults have undesired effects such as heat dissipation and the development of fires[3][11].

2.1.2 Parallel arcs

Parallel arcs occur parallel to the circuit and across other loads, thus short-circuiting the circuit. This leads to a reduction in the impedance of the circuit and an increase in current, which causes a high dissipated energy. Due to the energy dissipated in these arcs, it is necessary to quickly handle and disconnect them. Parallel arcs tend to occur due to damaged insulation, broken installation material, or intrusion of a conducting liquid such as water. If properly dimensioned, conventional protection equipment for low voltage installations will detect and handle these arc faults[11].

2.1.3 Non-contact arcing

Non-contact arcs are arcs caused by either voltage breakdowns in gases across an air gap or conduction across semi conducting paths like charred polymer insulation. Both categories of non-contact arcing demands a certain voltage to build up across the isolating gap for arcing to begin, but the mechanisms involved in the arcing are not equal. Both categories are described in more detail below[11].

2.1.3.1 Electrical breakdown

Discharges in air gaps can occur if the electric field across the gap is sufficiently high. The breakdown voltage for different gases at a specific gap distance and air pressure can be calculated by Paschen's law [9][11].

$$U_{breakdown} = a\frac{p \cdot d}{b + ln(p \cdot d)} \tag{2.1}$$

Where p is air pressure in atm, d is gap distance in meters, a and b are constants (for air, $a = 43.6 * 10^6 V/atm$ and $b = 12.8$). These kinds of breakdowns are caused by electron avalanches, which occur when free electrons are accelerated in an electric field. If the electrons obtain sufficient kinetic energy to dissociate the molecules in the air, they will further supply free electrons from atoms. These electrons can then be further accelerated, resulting in electron avalanches, decreased dielectric strength, discharges, and arcing[11].

At atmospheric pressure, the lowest voltage at which breakdown occurs in air is approximately 327V with a gap distance of $7.5\mu m$[14] as shown in Figure 2.1. In theory, the probability of a breakdown occurring in low voltage installations is very small, with only a few tenths of a millimeter air assumed to be sufficient to isolate the conductors. In practice, many factors can change the breakdown voltage, such as sharp electrode geometry, an inhomogeneous electric field, contamination of the electrode surfaces, high temperatures that result in thermionic emission of electrons, and ionized air [9][11].

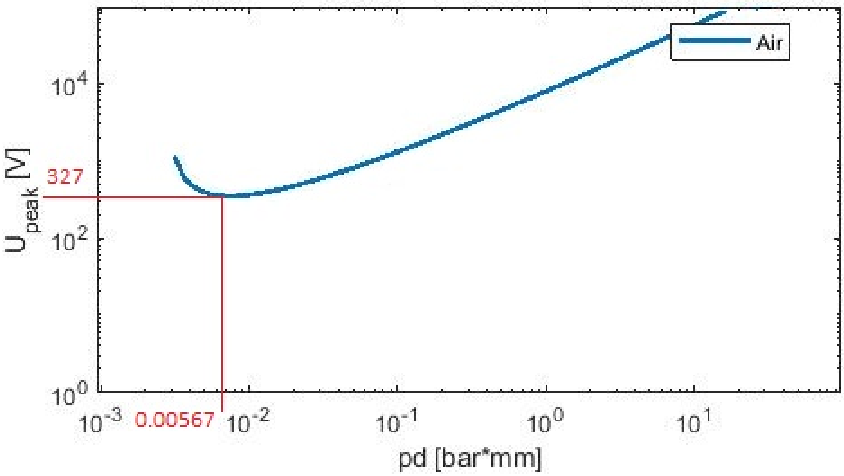


Figure 2.1: Plot of output from Paschen's law

2.1.3.2 Arc tracking

Creepage on char is a phenomenon that occurs when two conductors at different potentials are connected by a partially conducting track across an insulating material. The partially conductive track on the insulation surface can lead to the initiation of discharges[12]. This type of conductive track, also known as a "dry track", can be caused by an electrical fault or by harsh conditions[11].

Wet tracking can result in conductive tracks along an insulating material. Moisture or wet films along the insulating surface are conducting; current flow along this track can lead to evaporation of the water, which causes dry patches. Small discharges called scintillation's across these patches develop temperatures up to 1000 °C which can be enough to char the surface of the insulation[12]. This charring can act as a high-resistance conductor, causing additional heat development and charring. In general, the arc tracking process(current creeping onto char) is slow and takes a long time to develop [12][11].

Unlike for breakdown in air, breakdown voltage of creepage on char can not be determined by Paschen's law. Research has shown that voltages down to 24V is enough to initiate scintillation across polyvinyl chloride(PVC) insulation [12] and that the current required for carbonization can be as low as 0.15 mA for PVC cables [15][11].

2.1.3.3 Arc tracking in cables

For series arcing to occur in cables, damage must develop in one of the conductors of that cable. If one of the conductors gets severed but still remains close together, an environment for arc tracking on the insulation exists. Arc tracking can further lead to carbonization of insulation and ignition[9]. The behavior of such a fault can be characterized by three different current levels [9].

- Below 3 A, glowing connections are predominant and arcing is hard to achieve. Elevated temperatures over an extended time caused by glowing can lead to carbonization and igniting of the insulation.
- In the range of 3 to 10 A, the predominant phenomena are sustained arcing and insulation ignition.
- With currents above 10 A, the conductors are often welded back together by high energy, thus arcing stability becomes low.

2.1.4 Contact arcing

Contact arcing is an induced arc that can occur when breaking a current. Especially in switches and breakers, contact arcing is common. Contact arcing also occurs in loose connections and in plug and sockets when separated while energized. The current conducted between two contact points is not conducted through the whole contact surface. This is due to small irregularities on the surfaces that cause a limited number of contact points, as shown in Figure 2.2. When the contacts separate, there will eventually only be a very small surface that touches each other. When such a small surface carries the whole current, the current density becomes high and melting of this point can occur. This molten connection point can then evaporate and ionize the gap, creating ideal conditions for arcing to begin. Both breaking and making of the contacts are sources of degradation of contact surfaces, but neither is a fire hazard in particular. When contact arcing is caused by loose connections, it leads to surface degradation of the electrodes. Inside enclosures, arcing and bad connections can cause heat development that can further lead to fires[11].

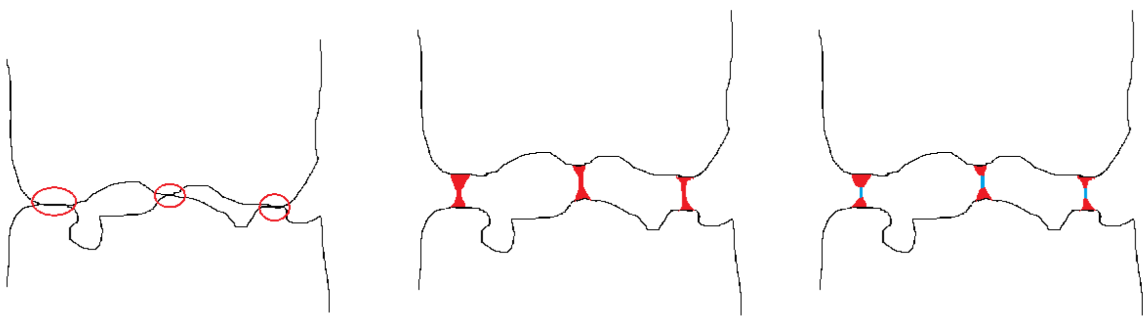


Figure 2.2: Typical contact surface, red rings mark contact spots for illustration

2.1.5 Static arcs

A static arc is an assumption that is often used. It is assumed that the relationship between the voltage drop and the current in the arc has a defined shape. This shape is called the static arc characteristic and is shown in Figure 2.3[13]. This characteristic applies to arcs that burn uninfluenced by physical obstructions in a gaseous medium. The characteristic is nonlinear consisting of a voltage drop that is high at low current and reduces as the current increases. The characteristic will vary depending on the gases in which it is burning, the electrode material and the length of the arc[13][11].

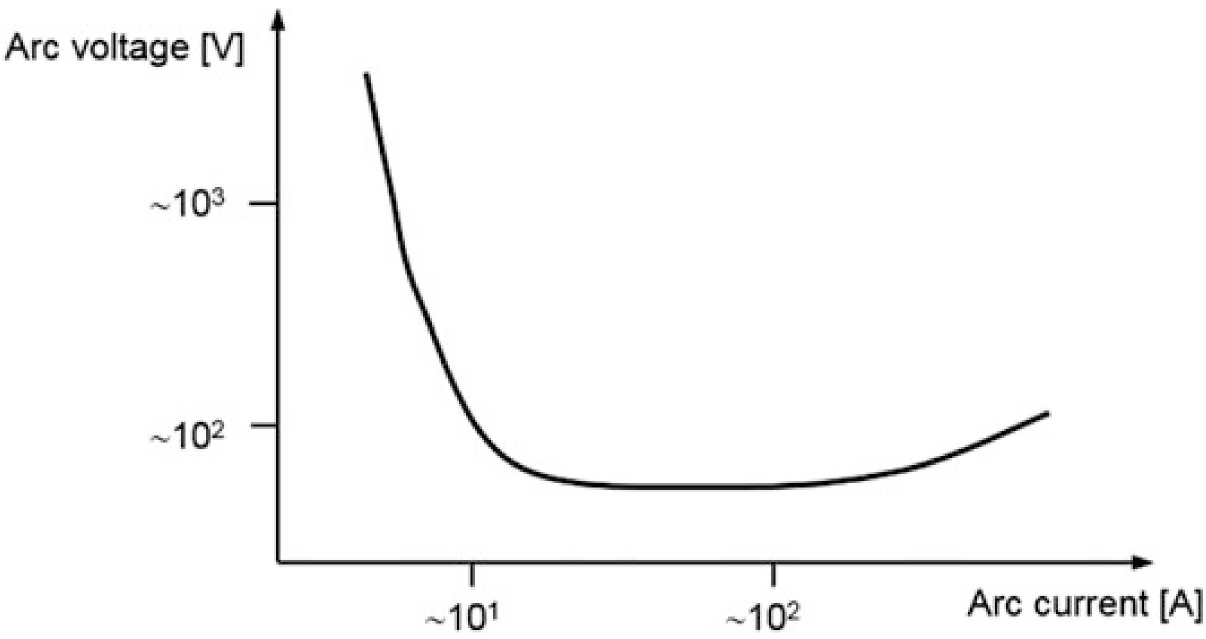


Figure 2.3: Typical static arc characteristic of an arc burning in a gas gap at atmospheric pressure or higher. Scaling is approximate and varies with gases and materials of the electrodes[13]

The static arc is characterized by three regions. The cathode region, which typically has a voltage drop between 8V and 20V, the arc column, which typically has an electric field strength between 8V/cm and 30V/cm, and the anode region, which typically has a voltage drop between 2V and 6V [13][9]. The voltage drop at the different regions depends on the electrode materials. The model shows that for short arcs, most of the voltage drop occurs in the cathode and anode regions, and these govern the minimum arc voltage necessary to sustain the arc [9][11].

2.1.6 Arc stability

One defining factor for arcs caused by electrical breakdown is arc stability, also known as "arc persistence". Arc stability indicates how many half cycles the arc is sustained for in a time period. The count of half cycles in which arcing occurs during a set period of time determines the arcing stability. As shown in Figure 2.4, the number of half periods with and without arcing sums up to an arc stability of 60%[9][11].

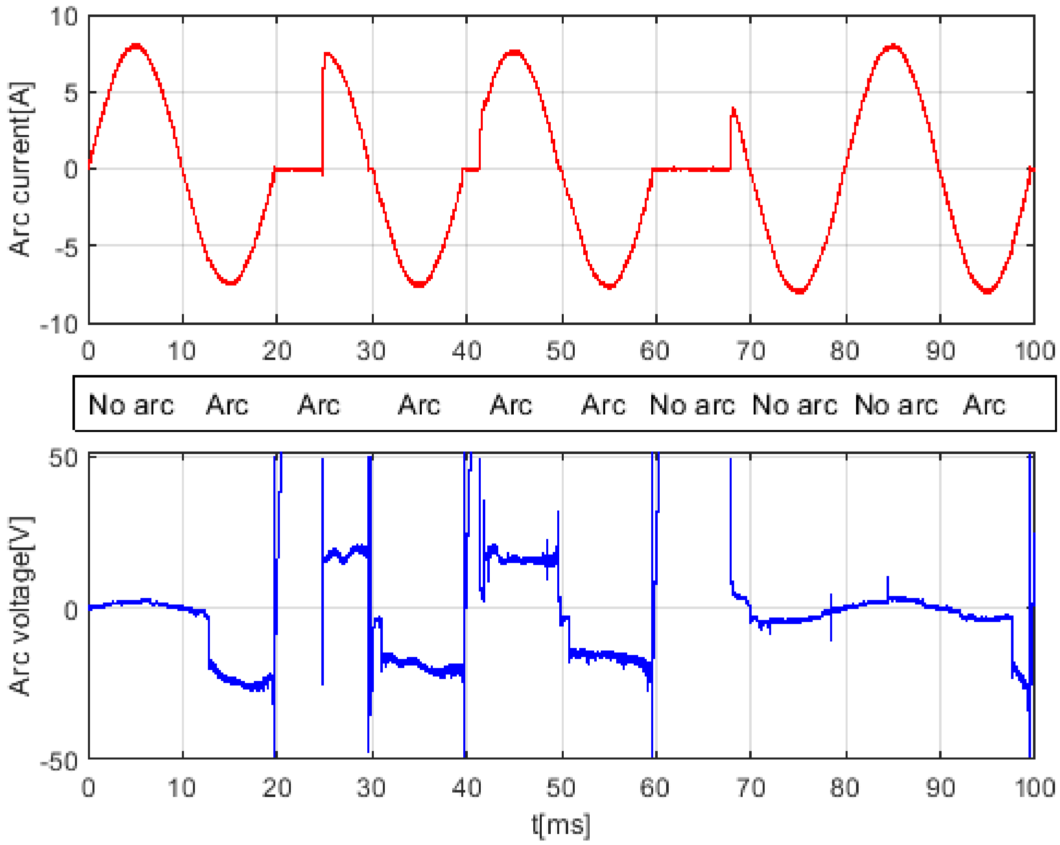


Figure 2.4: Determining arc stability in a time window of 0.1s. Figure show arc stability of 60%

2.1.7 Arc energy

The energy dissipation of the arc can be found simply by Ohm's law and using the time duration of one half period. Even though the resistance of the arc is nonlinear the power can be calculated from measurements of the voltage drop and the current in the arc.

If we use a normal residential installation in Europe as a starting point, a voltage of 230V and a current ranging between 0.5A and 20A are assumed, with a 50Hz fundamental frequency. Each half period would take 10ms, and each second would include 100 half-periods. The arcing voltage is further assumed to be 40V, in accordance with the assumptions of the test standard IEC 62606[16]. This gives an arc energy per half period ranging from 0.2J to 8.0J and 20J/s to 800J/s for continuous arcing.

For contact arcing and no contact arcing between to uninsulated electrodes, the previous is enough to calculate the arc energy. When arcing tracking occurs in cables, the potential energy stored in the insulation must also be taken into account. Heating the insulation will cause evaporation and decomposition of the insulation, leading to ignitable gases. One half-cycle of arcing could be enough to ignite the gases and the potential for combustion increases.

Using PVC as an example, when decomposed into gas it would contain primarily CO_2, but also some part H_2 and hydrocarbons such as C_2H_4 and C_2H_6 [2]. Furthermore if hydrogen is used as an example, assuming a circular fireball with diameter of 5 cm. The heat of hydrogen combustion is 141.8 kJ/g and the hydrogen density is 0.089 g/l at 0 °C[2]. The volume of gas is:

$$V_{gas} = \frac{4}{3} \cdot \pi \cdot r^3 = \frac{4}{3} \cdot \pi \cdot (2.5\ cm)^3 = 65.45\ ml \tag{2.2}$$

And the energy released becomes:

$$E_{gas} = 141.8\ kJ/g \cdot 0.089\ g/l \cdot 65.45\ ml = 820.3J \tag{2.3}$$

If this, although unrealistic, complete combustion is assumed to happen every half-cycle, the energy per second becomes 82 kJ/s. Although an unrealistic example, it shows how much higher the energy is when an arc occurs in a cable compared to an arc in air between two uninsulated conductors.

2.1.8 Time domain behavior

The time-varying characteristics of the voltage and current of the arc are characterized by the ignition and extinction of the arc. To establish an arc, the electric field strength must exceed the breakdown strength of the medium. This applies to both arcs in air gaps and arcing on char. The arc can persist as long as sufficient energy is delivered to the arc, but as the current reaches its zero crossing, the arc extinguishes. This behavior can be observed in a plot of current amplitude as a function of time, as illustrated in Figure 2.5. A characteristic shoulder can be observed on several occasions when the current reaches zero amplitude, indicating that the circuit is left open, as the voltage has to build up before electrical breakdown of the gap occurs. The length of the shoulder depends on the gap length and the breakdown strength in the gap[11].

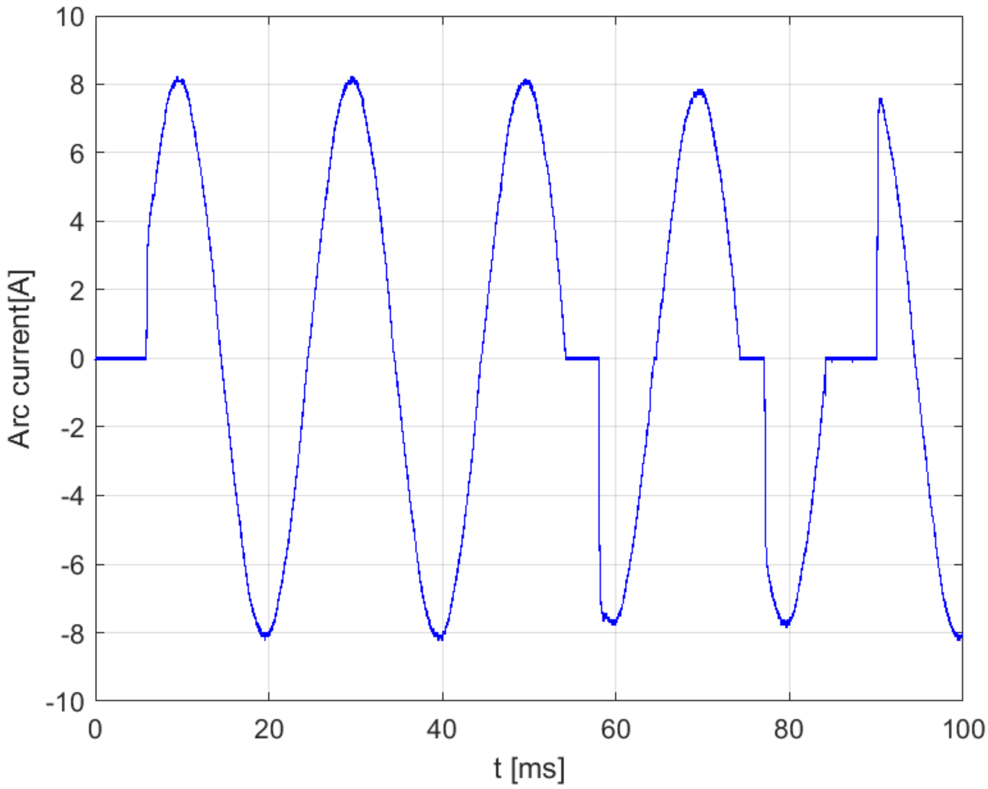


Figure 2.5: Characteristic series arc current waveform. Characteristic shoulders at the current zero crossing

With the occurrence of an arc, the voltage across the gap behaves in a way determined by the breakdown strength of the gap and the voltage drop across the arc. The voltage peaks before the voltage reaches an amplitude that exceeds the breakdown strength of the gap. When the arc is burning, the voltage drop is stable before it peaks again at arc extinction, when the current is close to zero. A recording of arc voltage and arc current is shown in Figure 2.6. It can be observed that when the arc does not ignite (prolonged zero crossing of the current), the circuit is considered open, and the arc voltage goes out of the measured area and is assumed to be 325V peak.

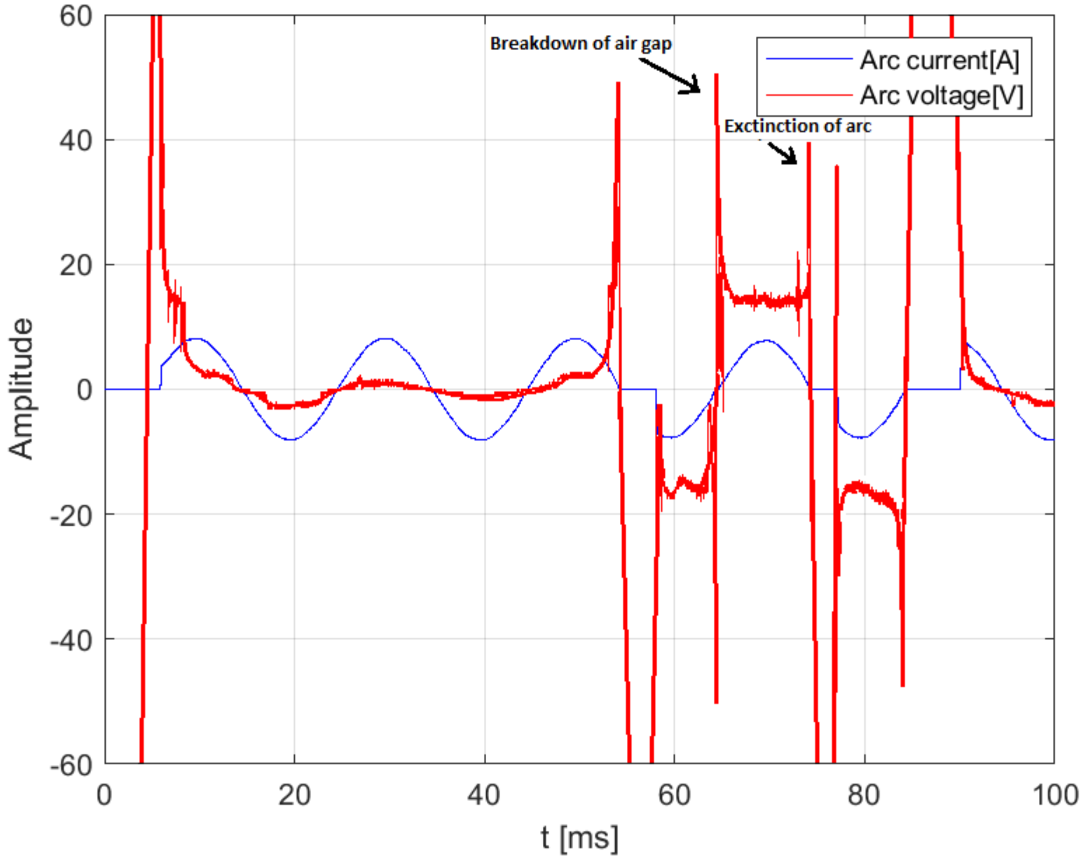


Figure 2.6: Arc voltage across air gap recorded with differential probes, breakdown of air gap and extinction of the arc is highlighted

2.1.9 Frequency characteristics

When arcing occurs in a circuit, it causes an elevation in specific frequencies. By analysis of the measured current with Fourier transformation, P. Müller et al[6] made a representation of the arc current amplitude spectrum. Three distinct frequency areas are noteworthy; the third harmonic of 50 Hz, 150 Hz, has a distinct peak during arc conditions. The spectrum between 100Hz and 1.5 kHz is generally elevated and the spectrum from 2kHz to 5kHz experiences an increased amplitude. The spectral analysis of the series arc current performed by P.Müller et al[6] is shown in Figure 2.7[11].

In addition to the characteristics mentioned above, an electrical breakdown in a gap will produce HF noise in the current. Different phenomena are proposed to be the sources of HF noise in the current. Fractal geometry and cathodic arc root movement that leads to localized breakdowns of the interface between the cathode and plasma are the most favored [4].

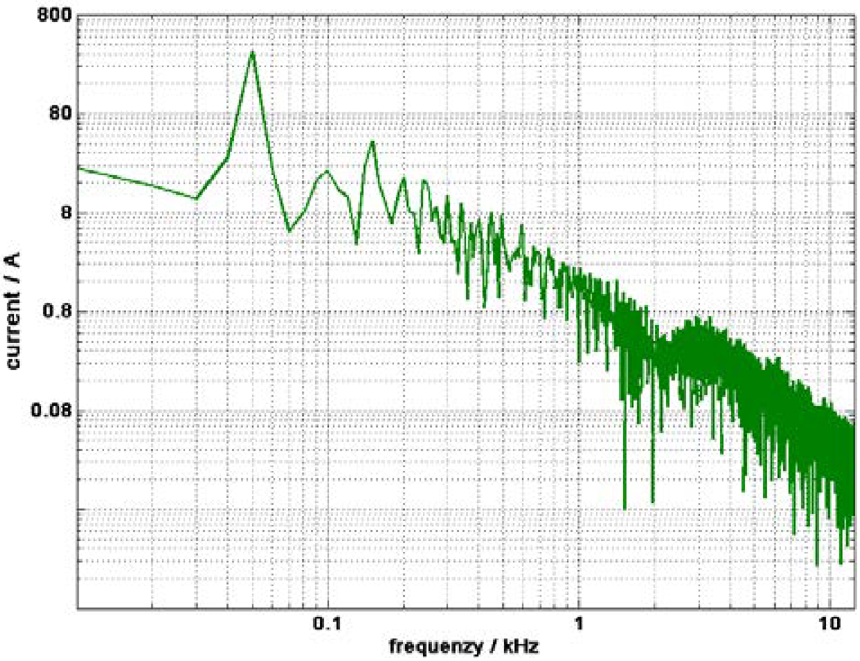


Figure 2.7: Spectral analysis of a series arc current. The highest peak is the fundamental frequency 50Hz. The peak at the 3rd harmonic and the increasing amplitude from 2 to 5kHz is distinguishable [6]

Siemens has shown that the power content in the frequency spectrum of an arc is spread over a much larger frequency band than measured by P. Müller et al. in their research [17][6]. Figure 2.8 shows the background noise and arcing noise in a frequency band ranging from DC to 25MHz. It can be observed that the power in the frequency band from arcing is distributed relatively uniformly, with peak values ranging from -35dBm to -50dBm for this specific measurement. The background noise, on the other hand, has specific peaks and troughs, with a peak of -50dBm at 15MHz and the lowest values of -80 dBm from 19MHz to 25MHz. This highlights that an advantageous frequency band to measure for HF noise caused by arcing would be 19MHz to 25MHz.

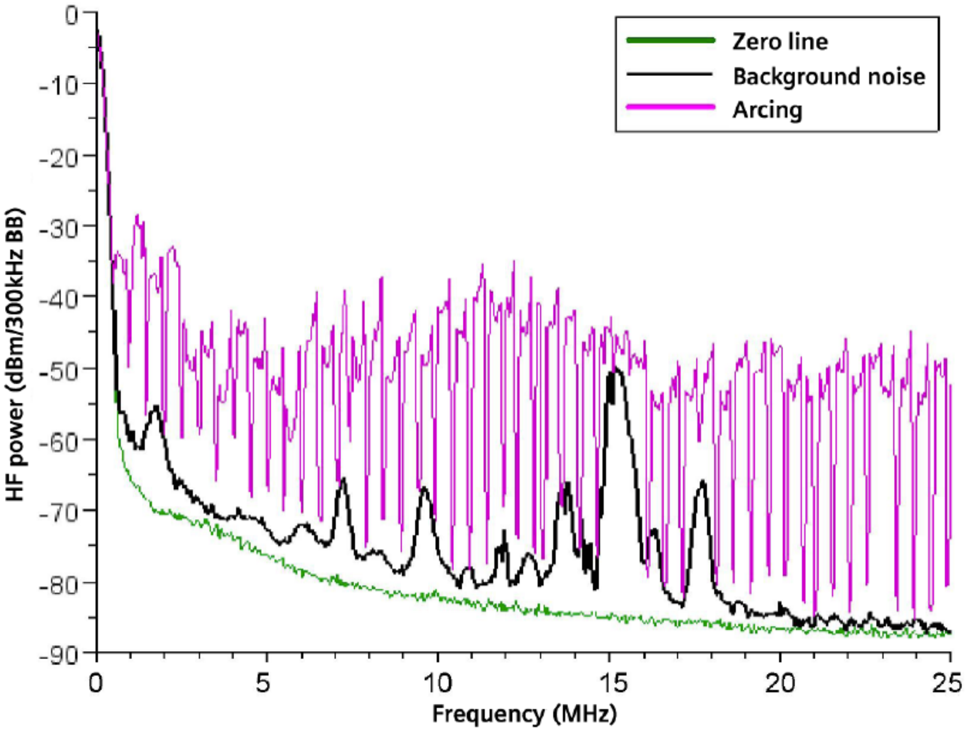


Figure 2.8: Background noise as registered by Siemens in residential installation [17]

2.2 Series faults, glowing connections and resistance heating

Apart from series arcs, the category series faults also includes bad connections which lead to resistance heating and glowing connections. A series fault in a contact can be caused by a variety of factors. Examples include manufacturing defects, faults during installation, and environmental influences. The mechanisms in the build-up to overheating of an electrical connection are complex, as illustrated in Figure 2.9. The initial causes are shown as; repeated current cycling, surges in current, vibrations, and work hardening.

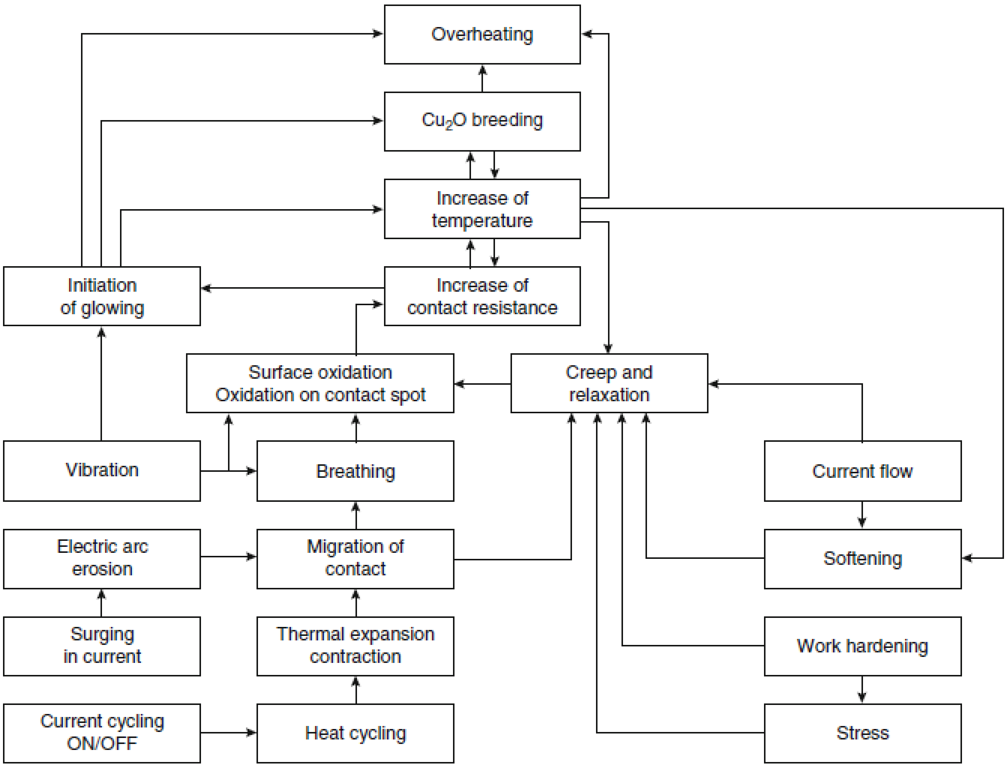


Figure 2.9: Mechanisms for overheating at electrical connections as outlined by Kuroyanagi et. al. [18]

Even though overheating can occur on it's own from a bad connection, the severity grows if glowing is initiated in the contact as well. The glowing connection acts as a nonlinear resistances where low current leads to high voltage drop and increased current decreases the voltage drop. Examples of this behavior for glowing between copper and brass or iron are demonstrated in Figure 2.10. It also shows how high the power dissipation in the glowing connection can become, and its dependence on the current[11].

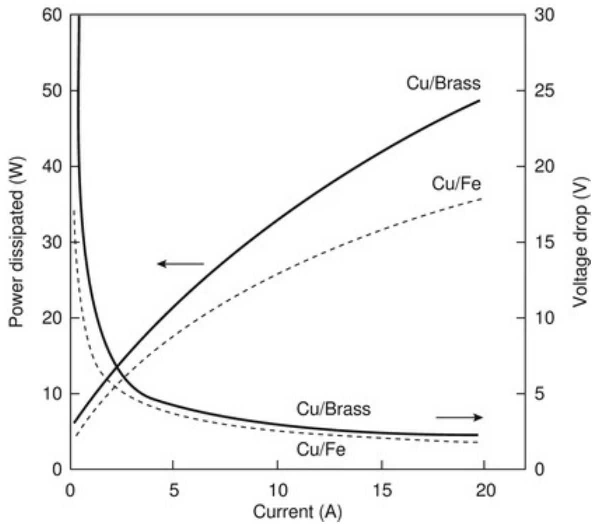


Figure 2.10: Power dissipation and voltage drop across glowing connections between copper and other metals [19]

The nonlinear behavior does mean that the resistance in the connection changes with the amplitude of the current. This is shown in Figure 2.11 and causes spikes in resistance and a voltage drop across the connection, similar to what is seen during series arcing. The nonlinear behavior also causes the power dissipated in the connection to become higher when glowing is initiated.

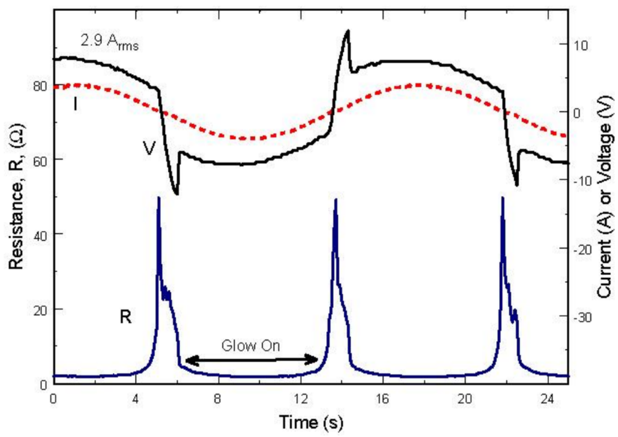


Figure 2.11: The dynamic resistance, and saw tooth shape of the voltage in a glowing contact at $2.9A$ current is shown in red [20]

According to J. Shea and X. Zhou [21] glowing can occur in virtually any electrical circuit with voltages down to 115 V and currents as low as 0.25 A rms. It is assumed to be the make-and-break occurrences in a loose connection that initiates the glowing and it's contributed to heating of the interface between the materials caused by series arcing. The series arcing and heating creates a copper oxide(Cu_2O, CuO) with the non-linear resistance behavior. Sustained vibrations and arcing are believed to accelerate the oxidation process [21][22][11].

2.3 Protection equipment

2.3.1 Traditional detection principles

The Norwegian regulation on electrical low voltage installations, FEL (Forskriftt om elektriske lavspenningsanlegg) is the governing document that ensures responsible safety when planning, building, changing and maintaining electrical low voltage installations[11]. In this document, the protection of humans, livestock, and properties is required to be protected against overcurrents and fault currents. These requirements are stated in Chapter 5, §20 to §30 [23]. NEK 400[24], further suggests how the installation can be built to comply with the regulation. All circuits in Norwegian low voltage installations are protected accordingly so that standard switchgear found in low voltage residential installations has overcurrent functions that offer overload and short circuit protection, but also functions that protect against earth faults[11].

Ordinary protection equipment consists of miniature circuit breakers (MCB) with trigger characteristics regulated by IEC 60898-1 for short circuit and overcurrent protection and IEC 61009-1 for residual current circuit breakers (RCCB) for earth fault protection. These devices include thermal-influenced bimetallic strip for long-term overcurrent protection, electromagnetic tripping using a solenoid for short circuit protection, and a differential transformer ensuring current balance for leakage current detection. None of these detection principles are able to detect arcs that occur in series with a load. Faults such as series arcing appear only as a small decrease in current seen from the perspective of protection devices [11].

2.3.2 Arc fault detection principles

The best documented detection principle is that used by Siemens [17]. The patent for this technology was filed in 1992 by Fredrick K. Blades [25]. These devices have the ability to detect both parallel arcing and series arcing by using two different measurements and algorithms. Figure 2.12 shows the measurement principle used by the Siemens 5SM6 arc fault detection unit.

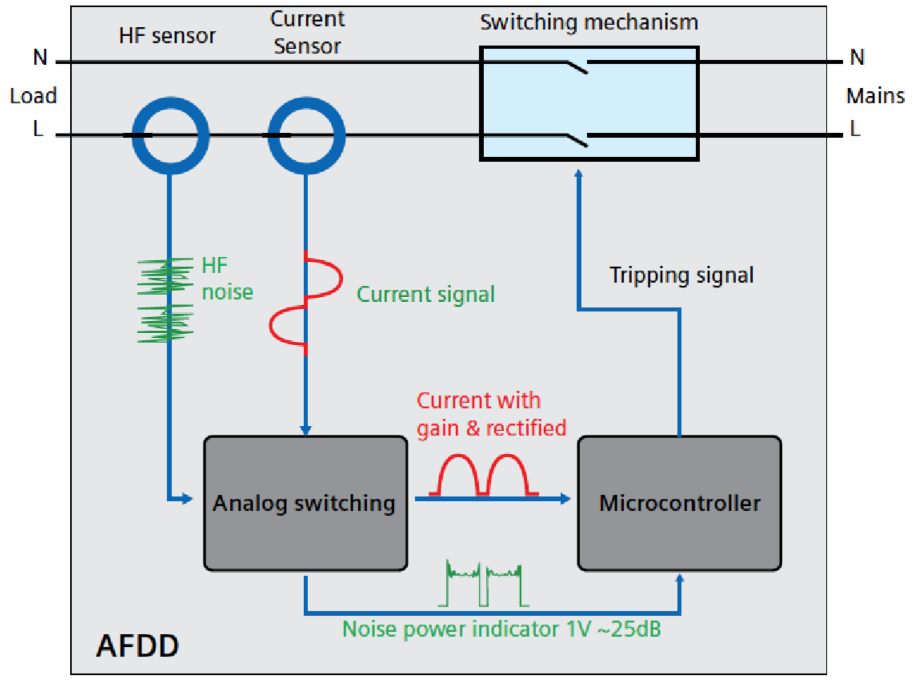


Figure 2.12: Principle schematic of the Siemens 5SM6 AFD unit [17]

The first signal is a measurement of the 50Hz current that records changes in the amplitude and the rate of change of the amplitude. It also keeps track of current zero crossings to make a mask of a number of previous cycles [26]. The second signal measured is the HF noise in the current that originates from the arc. Figure 2.13 shows how the frequency spectrum changes over time during one period of arcing. The lack of amplitude in the frequency spectrum from the arc during the zero crossing can be used to define the background noise from the HF noise.

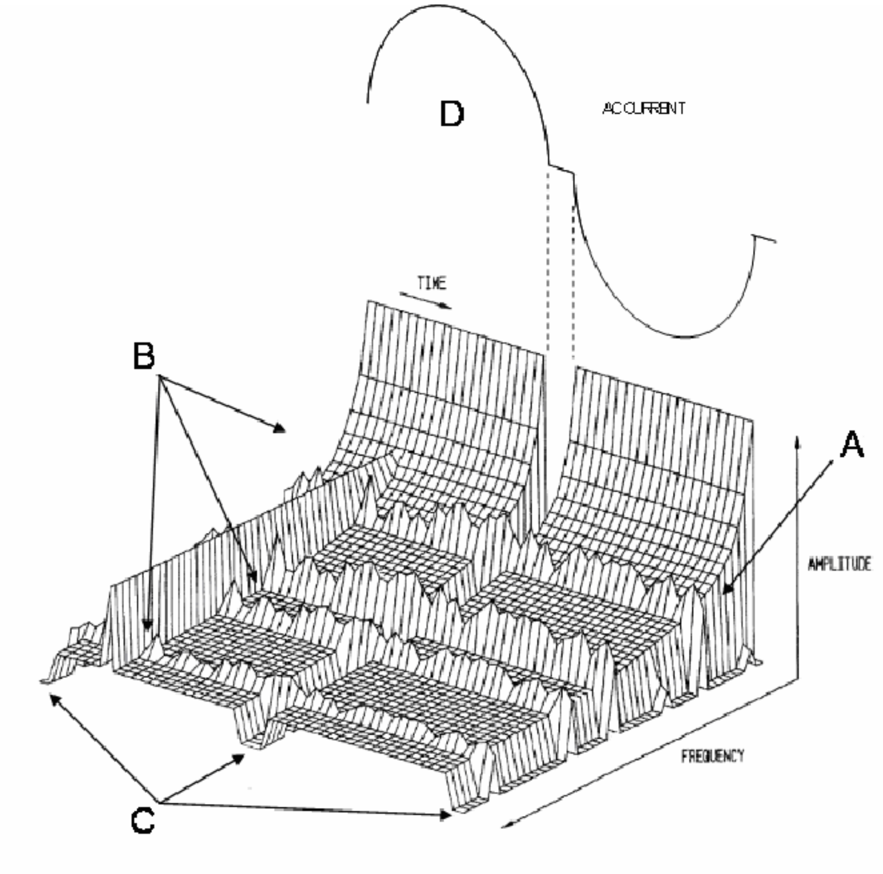


Figure 2.13: Illustration of frequency behaviour of an arc through time, **A** Frequency spectrum, **B** Elevated frequency bands, **C** gaps in the frequency band where current is zero, **D** Arc current. [26]

For detection of series arcing, the 50 Hz current is used to make a zero crossing mask to track the background noise level. The background noise level is stored to remove it from the HF noise present when the arc is conducting current. Zero crossing gaps are also used to differentiate between arcing and HF noise from other appliances or equipment that produce consistent noise. The HF signal is converted to a received signal strength indicator (RSSI) through analog processing. The absolute value of the differentiated RSSI is then compared to the periodicity of the zero crossings. If the periodicity of the differentiated RSSI is in sync with the periodicity of the zero crossing mask and the amplitudes of the RSSI and the absolute value of the differentiated RSSI surpass the threshold G2 and G4 arcing is registered and an integrator is incremented. The integrator increments until it reaches the interruption threshold or is reset due to an abnormal signal, typically an interruption in the RSSI amplitude. The detection algorithm used by Siemens as explained is shown in Figure 2.14.

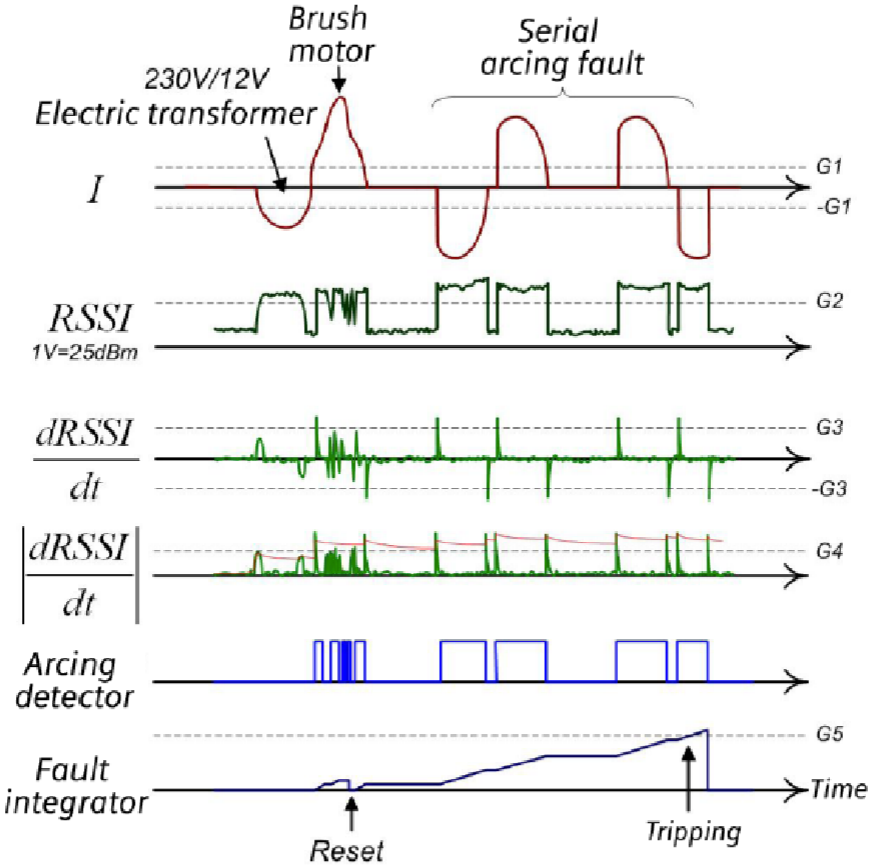


Figure 2.14: Signal processing for assessing series arcing faults [17]

In the detection of parallel arcs, the RSSI is used together with a differentiation of the current. Both the differentiated current and the RSSI need to be above their respective threshold at the same time before arcing is registered. An arc registered will increase the fault integrator and eventually cause disconnection.

2.3.3 Discrimination of arc resembling currents

One issue with the detection principle that was reviewed in the previous section is the distinction between real and hazardous series arcs and current from the equipment that can resemble arcs. To solve this problem, Siemens have constructed different criterion that has to be met. These criteria are shown in Figure 2.15 and contain a current limit, a stability limit, synchronization with current zero crossings, a background noise limit, and a duration limit[17].

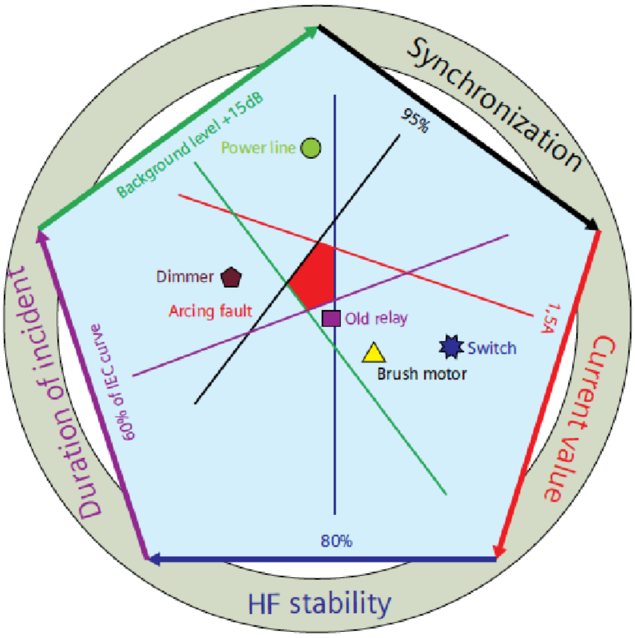


Figure 2.15: Factors that distinguish an arc from a arc resembling load[17]

2.3.4 Factors that can influence arc detection

Several factors have previously been suggested to affect the detection of HF noise caused by arcing. The relevant factors with reference to the originators of the theory are further shown below.

2.3.4.1 Parallel loads

The issue of detecting an arc in a parallel circuit when the total current is much larger than the arc current was discussed by P. Müller et al [5]. In cases where the two currents differ greatly, the signs of the arc become less noticeable. This is a plausible situation in a residential setting, where a fault may occur in one branch of a circuit with a small load current, while other branches contain high-load appliances, such as heaters. If the fault is located in such a way that the total load current does not pass through it, the ratio of fault current to total current would be small.

2.3.4.2 Reactive loads

The use of reactive loads such as highly inductive or highly capacitive loads influences the current in the circuit. Both types of loads introduce a phase shift between the current and the voltage, lagging for inductors and leading for capacitors. This phase shift can alter when the arc ignition and extinction occurs in comparison to the zero crossing of the current[11].

The problem with creating a very phase-shifted inductive current is that the relationship between inductance and resistance needs to be low, with high inductance and low resistance. This causes a very large current to flow, which is not very likely in a residential circuit protected with maximum 20A. So this type of fault is regarded as unlikely, and if it were to occur, the overload protection or short circuit protection would probably handle it.

High capacitance could more likely occur as a part of the installation as capacitive compensation, capacitance of cables, or filtering equipment in electronic loads. Several experiments have already been performed with capacitive loads, amongst which P.Müller et al[5], M.Fagerås[8] and A. Alqabbani [10].

When P. Müller et al[5]. tested arc faults with a $20\mu F$ capacitor in a parallel branch, they found the effect of the capacitor to be small. The expected result was that the capacitor would have a greater impact on the high-frequency noise generated by the arc, and it was concluded that further investigation was needed. One of the potential causes for this was mentioned to be the current probes, which were only designed for frequencies up to 200 kHz. The theory was that capacitance in parallel with the arcing branch would act as energy providers to the fault, thus supplying the high frequency components when the arc ignites and masking the arcing signs from being detected[11].

M. Fagerås[8] did experiments with AFDDs from two different manufacturers, using a circuit with a parallel connected capacitor. He found that AFDDs from one manufacturer were unable to detect series arcing when the circuit was tuned to a cutoff frequency below 41.44kHz. When the capacitance was adjusted to $0.22\mu F$ the device managed to detect all arcs. This shows that a very defined cut-off limit affected this device. The cutoff frequency was determined to be 43.24kHz, however, it appears that the nonlinear resistance of the arc was not taken into consideration. P. Müller et al[5] stated that the cutoff frequency of such a filter is hard to calculate due to the nonlinearity of the arc resistance[11].

A. Alqabbani [10] discovered during testing of AFDDs with arcing in loose connections and loose contact sockets that some devices had difficulty detecting arcs when resistive and capacitive loads were connected. The loads used for these tests were computer chargers and an LCD display, which are typical loads with capacitive filters. This indicates that there still exist some uncertainty regarding the performance of AFDD's when capacitive loads influence the arc current.

2.3.4.3 Arc influenced factors

Different arc sources develop different levels of HF energy as discussed by J. Martel [14] and M. Bjørnbakk[7]. It is shown that when arcing occurs between a carbon electrode and a copper electrode, the HF energy released differs depending on which electrode works as the cathode. When the graphite electrode is the cathode, the arc energy is measured to be less than when the copper electrode is the cathode. The theory is that the broadband HF current is created from arc root instabilities on the cathode surface caused by a high current density. In nonthermionic emitting materials such as copper, this effect is greater than in thermionic emitting materials such as graphite[14].

2.4 General requirements for AFDD's (IEC 62606)

The general requirements and test procedures for arc fault detection devices are defined in IEC 62606 also reffered to as *the test standard* in this thesis. This standard defines how to verify the operation of the devices sold in the market, the tripping characteristics of the devices, and the conditions that they should be able to sustain. The main task of the AFDDs is to detect and clear series and parallel arc faults that can occur in electrical installations. By reducing the fault time, the accumulated fault energy and the duration of thermal stress are reduced, reducing the risk of fire, as illustrated in Figure 2.16[9].

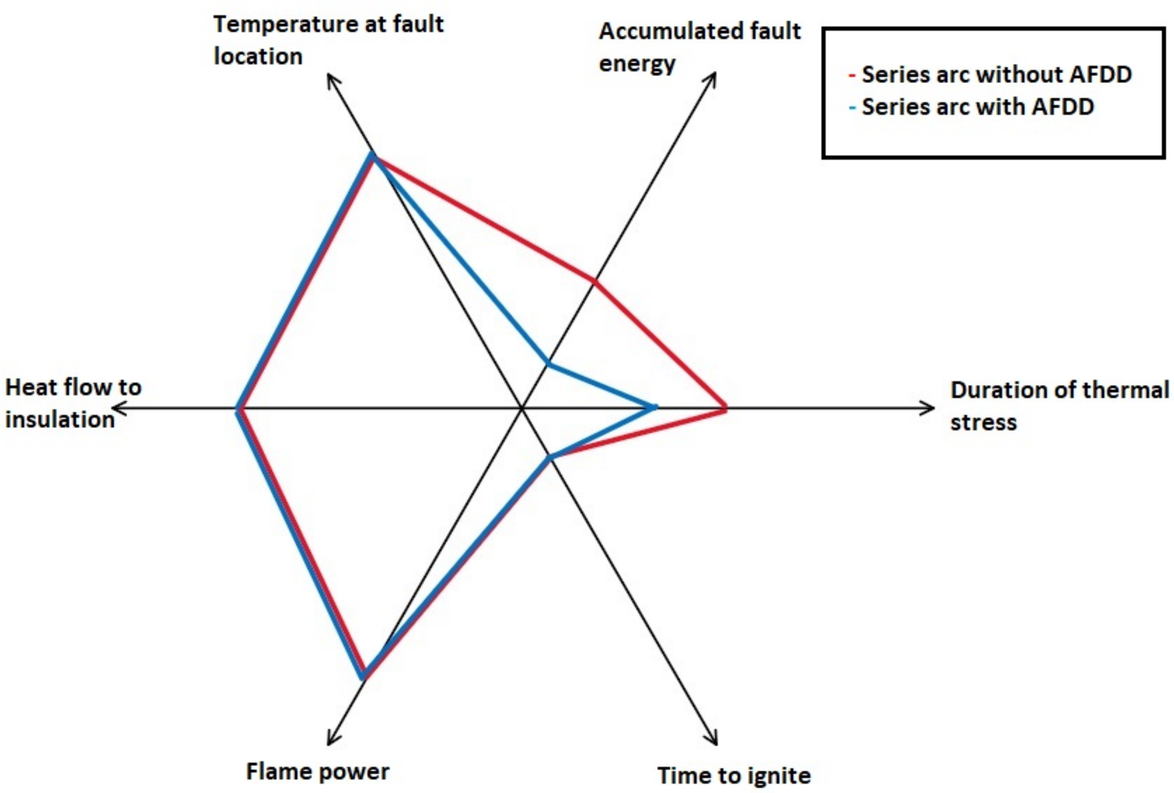


Figure 2.16: Change in hazard parameters when arc fault protection is used during series arcing in a cable. Inspired by J. Martel[9]

2.4.1 Fire curve

The energy required to ignite PVC insulation is in the range of 100J to 800J [9]. Due to this energy requirement, the reference value for the tripping characteristic in IEC 62606 5.3.7.1 is chosen as 100J[9]. Assuming an arc voltage of 40 V, the maximum break time t_b is defined by the following relations [9].

For $I_{arc} \leq 20A$:

$$t_b = \frac{100J}{40V \cdot I_{arc}} = \frac{2.5A}{I_{arc}}\ s \tag{2.4}$$

For $I_{arc} > 20A$:

$$t_b = 0.12\ s \tag{2.5}$$

This ensures that the device disconnects before the arc energy reaches 100J. It is important to note that the current used in the tripping characteristic is the current running in the circuit after the arc is initiated and not the load current.

When using an arc generator with a carbon electrode to produce an arc, the energy of the arc is considered to be in the range of 2.5 times lower than for a preconditioned cable sample[16]. The clearing time is adjusted to 2.5 times the values of IEC 62606 5.3.7.1. Table 2.1 show the standard clearing times and extended clearing times for the use of an arc generator at 230 V, together with a graphical representation of both characteristics in Figure 2.17. As Table 2.1 also shows, the minimum current required by IEC 62606 5.3.7.1 to cause disconnection is 2.5A[16].

Table 2.1: Table of standard clearing times according to IEC 62606 5.3.7.1 [16], and calculated extended clearing times when arc generator is used for testing

Arc current	**2.5 A**	**5 A**	**10 A**	**16 A**	**32 A**	**63 A**
Maximum break time	1.0 s	0.5 s	0.25 s	0.15 s	0.12 s	0.12 s
Extended break time	2.5 s	1.25 s	0.625 s	0.375 s	0.3 s	0.3 s

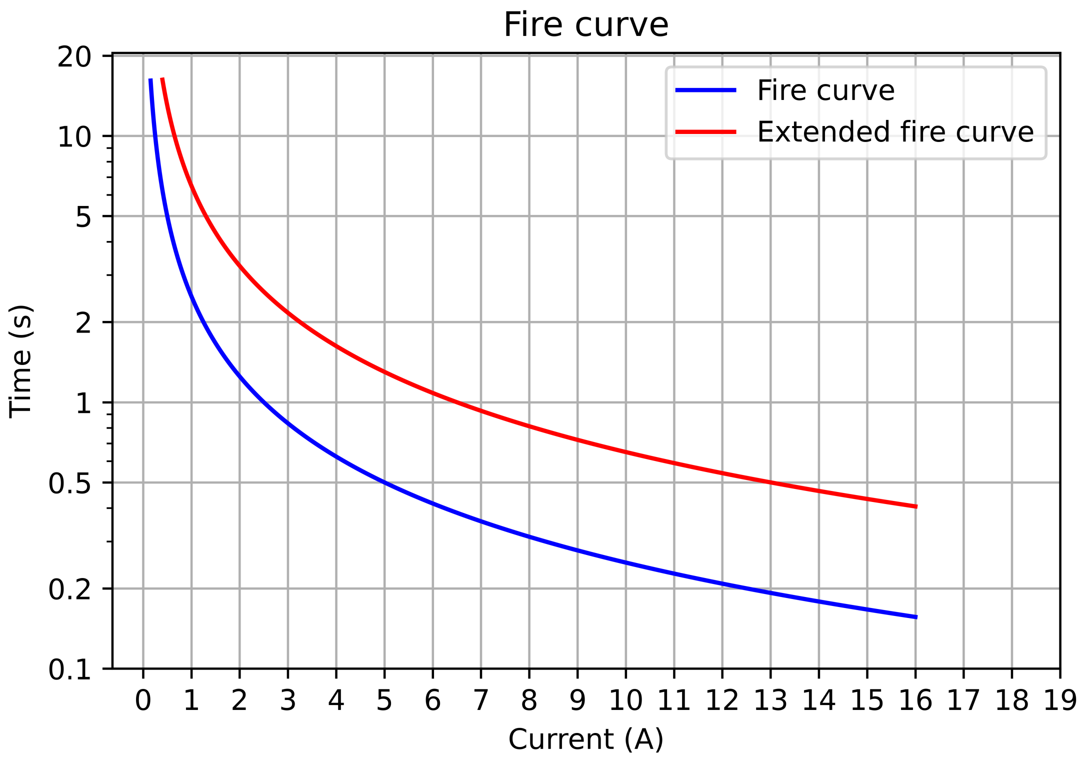


Figure 2.17: Plot of the "fire curve" in blue and the extended clearing times for use with the arc generator in red according to IEC 62606 5.3.7.1

2.4.2 Arc generating methods

Chapter 9 in IEC 62606 specifies what kind of arc source can be used during the tests. According to chapters 9.9.2.6 and 9.9.2.7, there are two viable ways: a preconditioned cable specimen or an arcing generator[16].

2.4.2.1 Preconditioned cable specimen

One of the ways that an arc can be created according to IEC 62606 chapter 9 is a preconditioned cable specimen. This cable specimen must be prefabricated following the specifications stated in the standard chapter 9.9.2.6, which involve insulation material, number of conductors, and high-voltage conditioning [16]. An illustration of the cable sample is shown in Figure 2.18. High voltage conditioning is performed to create a charred path between the two conductors, which will later become an arc path when a low voltage potential is applied across it[11].

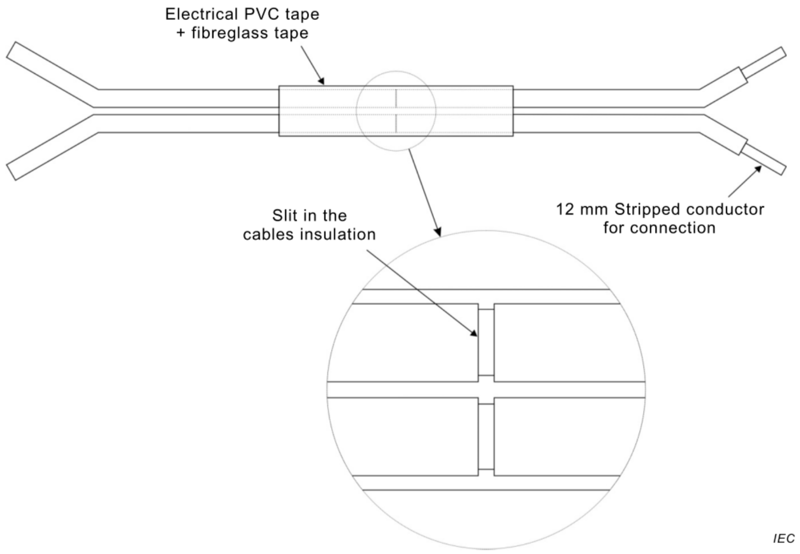


Figure 2.18: Illustration of the cable sample used in arc tests [16]

2.4.2.2 Arc generator with carbon electrode

The arc generator consists of one stationary and one laterally moving electrode. One of the electrodes should be a 6 mm ± 0.5 mm diameter carbon graphite rod and the other electrode a copper rod with equal dimensions[16]. The arc is generated by first having the two electrodes in contact and then moving one of the electrodes laterally to make an air gap between them[11]. Figure 2.19 shows an illustration of the arc generator.

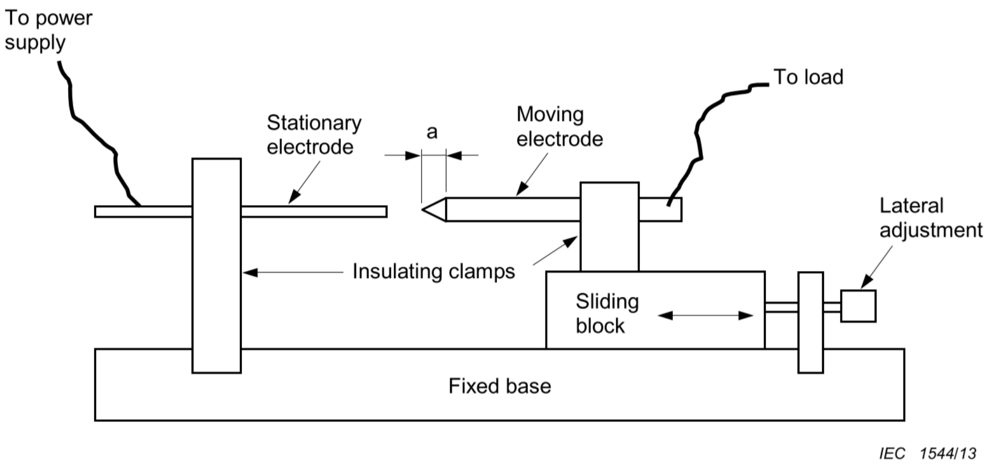


Figure 2.19: Illustration of the arc generator with one copper and one carbon-graphite electrode [16]

2.5 Frequency transform

2.5.1 Fourier transform

The Fourier transform is a mathematical operation that can be used to make a representation in the frequency domain of events that are recorded in time. For example, if used on a function, the Fourier transform represents the frequencies present in the function. For use on recorded time series with equally spaced samples, the Fourier transform is known as a discrete Fourier Transform (DFT), and to make the calculation less computationally intense, several algorithms under the name Fast Fourier Transforms (FFT) are used to calculate the DFT.

The amplitude and phase of a frequency component of the function $f(x)$ at frequency $\frac{n}{P}$ can be found in the complex number c_n that is found with the formula for the Fourier series coefficients, here in Euler's form:

$$c_n = \frac{1}{P}\int_P x(t) \cdot e^{-i2\pi nt/P} dt \tag{2.6}$$

Where P is the period of the function and i is the imaginary unit. Extension of this provides the continuum of frequencies found in the function and is called the Fourier Transform:

$$\mathcal{F}[x(t)] = X(\omega) = \int_{-\infty}^{\infty} x(t) \cdot e^{-i\omega t} dt \tag{2.7}$$

$X(\omega)$ is called the spectrum of x(t) and x(t) is a real signal dependent on time in seconds, ω is the angular frequency $2\pi\ f$ where f is the frequency with unit $s^{-1} = Hz$. $|X(\omega)|$ has the unit of $amplitude\ of\ x(t) \cdot s = amplitude\ of\ x(t)/Hz$ meaning what ever unit the measured signal has per frequency interval [27]

In digital signal processing, DFT is used to compute the frequency domain of a finite signal sampled with equally distanced samples recorded in time. The DFT transforms N sampled values x_n into N different complex values X_k representing the frequency domain. The new values are defined by the discrete representation of Equation 2.6:

$$\mathcal{F}[x_n] = X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-i2\pi\frac{kn}{N}}, k = 0, ..., N-1 \tag{2.8}$$

This definition is used in the FFT package [FFTW], which is used further in Matlab in this thesis. For digitally recorded time-dependent signals the values are always real, as a consequence the output X_k follows the relationship [27]:

$$X_{N-k} = X_k^* \tag{2.9}$$

Here, $*$ is the complex conjugate.

2.5.2 Nyquist-Shannon sampling theorem

To capture all the information in a continuous-time signal and represent them as discrete-time signals, the sample rate of the continuous signal has to be sufficient. The Nyquist-Shannon theorem states that a signal that contains a maximum frequency of B Hz can be completely reconstructed if it is sampled at more than $2B$ samples per second [28]. If the signal contains frequencies above B the reconstructed signal can contain imperfections that are known as aliasing. To avoid aliasing, undersampling of the signal, a lowpass filter should be used to contain the frequencies within what can be captured at the sampling rate that was chosen.

Chapter 3

Equipment and method

This chapter describes the analysis methods used to analyze the data, the methods used to verify the tests, and some of the equipment used in this thesis.

3.1 Analysis methods

3.1.1 Measurements

To be able to detect HF noise caused by arcing, the recording device used must be able to sample the signal with a sample rate according to the Nyquist-Shannon sampling theorem displayed in subsection 2.5.2. If the measurements used by Siemens, shown in Figure 2.8 in subsection 2.1.9 is correct. It should be possible to distinguish between a current recording when arcing occurs and the current when arcing does not occur. This could also indicate if any of the circuit topologies tested disturb the high-frequency signals from the arc.

To be able to display frequencies up to 25MHz the sampling rate must be minimum twice this frequency. This means that the current must be recorded with a minimum sampling rate of 50 Mega samples per second (MS/s). It also requires measuring probes with a frequency response that can capture the higher frequency without distorting the measurement.

To obtain the same frequency amplitude spectrum weighting, every recording must be equal in length and sample rate. If this is not done, more data processing must be done. Thus, frequency domain recordings were standardized to 10 periods, with an equal trigger point and sample rate. This was also beneficial to avoid bias in the frequency amplitude spectrum. The motivation being that if only one period was used, that single period could be a bad representation of the arcing and influence the results. When 10 periods are used, it should display a more general frequency content representation.

3.1.2 Amplitude spectrum

The amplitude spectrum of a series of time samples describes how the amplitude in the frequency components of that signal is distributed. This is used in this thesis to measure the amplitude of the frequency components in the current. The amplitude spectrum of a measured current or voltage is implied to have the same unit as the measured signal [27].

To acquire the amplitude spectrum, the recorded signal is Fourier transformed with a DFT as presented in subsection 2.5.1, this acquires a complex signal X_k that includes information about the amplitude and phase of the signals in the frequency domain. By finding the absolute value of each sample and dividing it by the amount of samples N we get a two-sided amplitude spectrum of the time domain signal that compensates for the proportionality of $|X_k|$ to the number of samples N [29].

$$S_k = \sum_{k=0}^{N-1} \frac{1}{N} \cdot |X_k| \tag{3.1}$$

S_k is the two-sided spectrum that includes the frequency components below the Nyquist frequency and the mirrored frequencies above that follow the relationship of Equation 2.9. For the computation package [FFTW], the vector $z_i,\ i = 0 \dots N-1$ follows:

$$z_i = \Re\{X_i\},\ 0 \ \le\ i\ \le\ N/2 \tag{3.2}$$

$$z_{N-i} = \Im\{X_i\},\ 0 < i < N/2, \tag{3.3}$$

The amplitudes of the two-sided spectrum are uniformly distributed around the Nyquist frequency, and for signals sampled from the time domain, the rest are redundant [29]. Therefore, only the single-sided spectrum is used. For even N the single-sided spectrum $P_{ss,k}$ is represented as:

$$P_{ss,k} = \begin{cases} S_k, & ,\ k = 0 \\ 2 \cdot S_k, & 0 < k < N/2 \\ S_k, & ,\ k = N/2 \end{cases} \tag{3.4}$$

S_k is the dual-sided spectrum and N is the number of total recorded samples. The rest of S_k is not used and can be discarded.

The script used in Matlab for the calculation of the single-sided power spectrum is attached in Appendix C

3.1.3 Spectrogram

A spectrogram visually represents a signals frequency spectrum as it changes over time. This is useful for seeing changes in the HF noise as the current reaches current zero crossing and to see changes in the HF noise with different circuit parameters. The method used to display the spectrogram is a Matlab function called *pspectrum.* This function can compute a time-dependent spectrum of a nonstationary signal, which indicates how the total power of the signal is distributed amongst the frequency components as they change with time. The signal is divided into segments of equal length, and each segment is windowed with a window function. The spectrum is then computed by Fourier transforming each segment to obtain the short-time Fourier transformed signal. The limit on the frequency band possible to represent depends on the sampling frequency and the resolution depends on the window function that is used. If high time resolution is desired, a narrow window is necessary[30].

3.2 Methode

3.2.1 Comparing performance

To asses the performance of the AFDD's, their detection rate and disconnection times are presented. The detection rate is defined as how many times the AFDD's did detect arcing and disconnected within the set time limit during the 10 tests that were performed. The disconnection time is defined as the time the AFDD's used to detect and disconnect the circuit. Both parameters indicate if the arc was hidden from the AFDD, or if the AFDD could detect the arcing independently of circuit conditions.

3.2.2 Comparing of waveforms

The comparison of waveforms is performed to look for signs that could indicate if the current measured by the AFDD's has changed as a consequence of the circuit parameters. Different waveforms were compared according to the parameter that was changed. A comparison between the total current during arcing measured with the largest value and the smallest value of the change should indicate how the waveform changes with an increasing value of that particular parameter. Comparison of the arcing waveform without the parameter and arcing with the parameter should indicate how the parameter changes the waveform.

3.2.3 Comparing amplitude spectrum

Comparing the amplitude spectrum is performed to examine how the amplitudes of the frequency components of the waveform behave under different circuit parameters. Comparison between the total current during arcing with the largest and smallest parameter values will indicate the influence of the parameter value. Comparison of the amplitude spectrum during arcing with and without the parameter indicates how the particular value influences the amplitude of the different frequency components.

3.2.4 Comparing spectrograms

The spectrogram is used to indicate how the HF noise changes with different parameters. Comparison of the spectrogram with and without the parameter indicates that the parameter changes the detectability of the HF noise change. Comparison of the total current during arcing with increasing value of the parameter indicates how the value of the parameter changes the detectable HF noise. Below is a description of how to read these plots.

Figure 3.1 shows the measured arc current and the total current during arcing with a cable sample. The most interesting aspect is the difference observed in the amplitude of the noise power, indicated by color. When looking at the left figure, the measurement is done in the arc branch; the vertical lines in the plot show a lower noise power, which corresponds to the current zero crossings and half periods of the current. The periodicity is shown at the bottom of the figure and shows a much higher power corresponding to the fundamental frequency and the odd harmonics. The spectrogram clearly shows that there is an elevated HF noise when the arc is ignited and that it is reduced when the arc is extinguished. This clearly corresponds to the theory from section 2.3. In the right plot, the plot is from the total current measured at the same time. The same signs of change in noise power is not noticeable, indicating that the signs of current zero crossing are masked and that the detection principle of the AFDD's can be influenced.

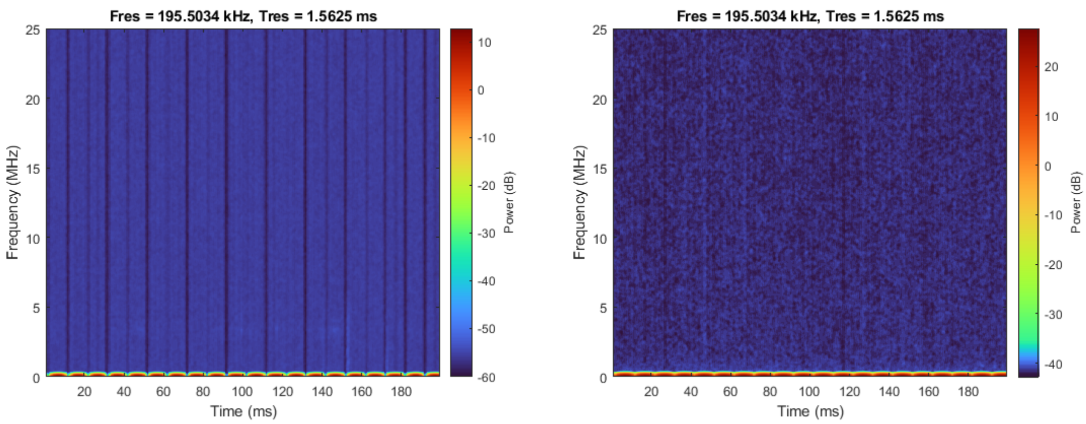


Figure 3.1: *Left side:* Spectrogram of measured arcing branch, 2.5A arcing current, cable sample used to generate the arc.
Right side: Spectrogram of measured total current, 12.5A, cable sample used to generate arc

Figure 3.2 shows the same as Figure 3.1 but with an arc generated by the arc generator. The arc generator produces a noticeable higher power when the arc is ignited, which can be observed as the light blue lines occurring right after zero crossing. This elevated power can be noticed at frequencies up to 20MHz, and is more noticeable in one of the half-periods which corresponds with the theory of subsubsection 2.3.4.3. A reduction in the frequency power at current zero crossing can be noticed between 20MHz and 25MHz. The right plot shows the total current measurement, and similarly to the previous figure, the total current shows fewer signs of zero crossing than the arc current measurement, although some signs can be observed. The reduction of HF noise corresponding with current zero crossing is not noticeable, but the same elevation in power that was observed in the arc current measurement can be observed as an elevation in power at the 4-5MHz line.

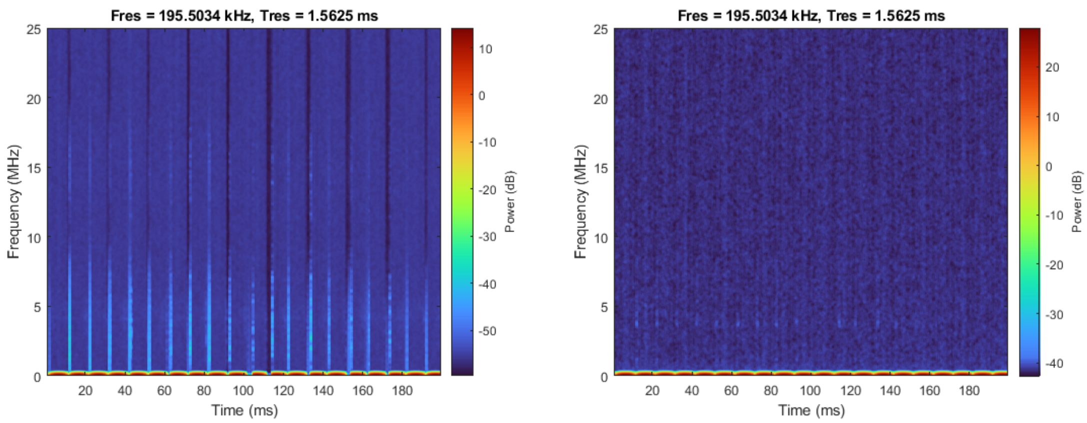


Figure 3.2: *Left side:* Spectrogram of measured arcing branch, 2.5A arcing current, arc generator used to generate the arc.
Right side: Spectrogram of measured total current, 12.5A, arc generator used to generate arc

3.3 Equipment

This section displays and explains the general equipment that was used in the different tests that were performed during this thesis. Much of the same equipment was used for several different tests. Pictures of the loads, enclosure and control system for the cable sample are found in Appendix B. Tables that show the parameters of the oscilloscope and measuring probes are also found in the same appendix.

3.3.1 Arc generator

The arc generator used in the experiments is shown in Figure 3.3. This arc generator conforms to the requirements of IEC 62606 9.9.2.7. During the tests, one copper electrode and one graphite electrode were used, but different electrode materials, such as brass or steel, can be used to replicate an arc between different materials.

To ensure consistent performance, the copper electrode was kept clean and sharp, and the graphite electrode flat. When the carbon electrode started to wear, measures were taken to restore it back to its original shape. Since continuous arcing without abruptions was the goal, the following method was used; the test began with the arc generator electrodes in contact with each other. Then, the electrodes were gradually moved away from each other, simulating a series arc fault in the circuit. The gap between the electrodes was further adjusted using the handle of the arc generator. To ensure a consistent distance between the electrodes, the same amount of adjustment was repeated for each test.

The difficulty in maintaining the arc varies with the current. This is due to the alteration in arc power at different currents. At low currents, there is less arc energy, which makes it easier to put out the arc by increasing the distance too much. If the arc was extinguished due to an excessive distance adjustment, the test was repeated to ensure continuous arcing.

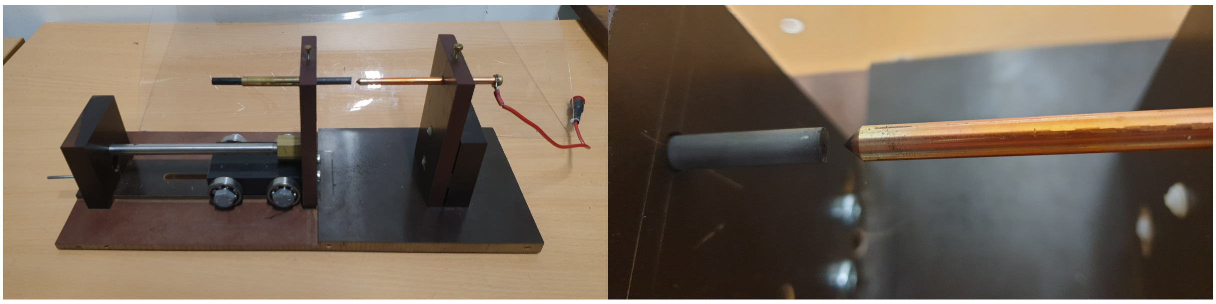


Figure 3.3: Picture of the arc generator.

3.3.2 Cable sample

Another method for arc generation suggested in the test standard IEC 62606 is the use of preconditioned cable samples. The cable samples that were used were made by Siemens and made according to the specifications of IEC 62606[16].

When the electrical grid is used as a power source, the voltage reduction suggested in IEC 62606 is complicated to achieve. Instead of adjusting the voltage, the resistance can be adjusted. The resistance was adjusted so that the current before arcing was a bit higher than the expected arc current, compensating for the voltage drop. This ensured that the arcing current was equal to the expected value. The resistance in the circuit was adjusted according to the following relationship:

$$R = \frac{U_{grid} - 40V}{I_{arc}} \tag{3.5}$$

The test standard IEC62606 states that the cable sample should be replaced after every test performed[16]. To introduce some variance in the arcing and imitate real varying conditions, the cable sample was re-used several times. The cable sample was used to make arcs until visible arcing signs could no longer be observed in the oscilloscope recording. To ensure that multiple tests could be performed with the same sample, the maximum arcing time was limited to 4 seconds to avoid too much degradation of the sample. A picture of a cable sample after some tests is shown in Figure 3.4. This time was chosen to be well beyond what is required by the standard IEC 62606, seen in Table 2.1 in Figure 2.17.

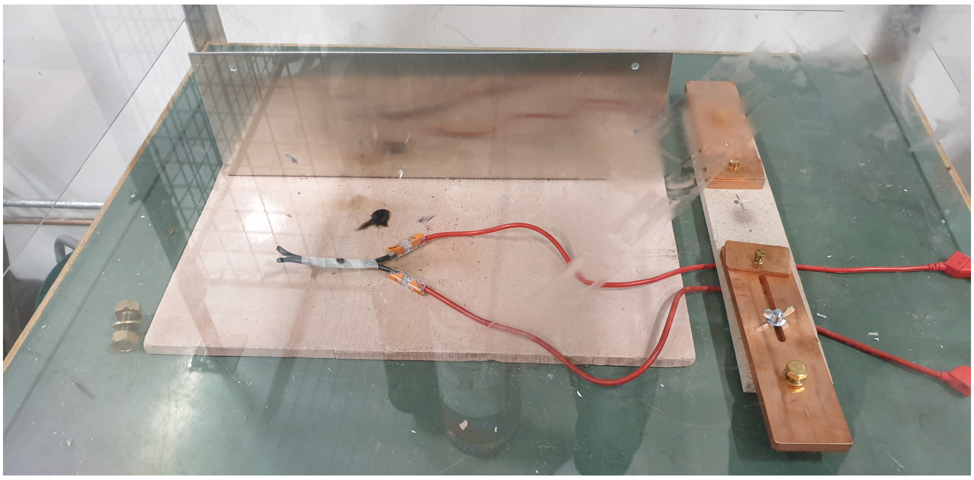


Figure 3.4: Pictures of cable sample casing and connections used

The degradation of the cable sample leads to an observable change in the arc current waveform as shown in the right side of Figure 3.5, but to a lesser extent in the total current waveform when the total current in a parallel circuit was measured as shown in the left side of Figure 3.5. The total current in the circuit consisted of the arc current at 5.0A and a parallel load current of 10.0A. The use of the cable sample as done in these tests is a clear departure from the test standard that should be taken into account when reading the results.

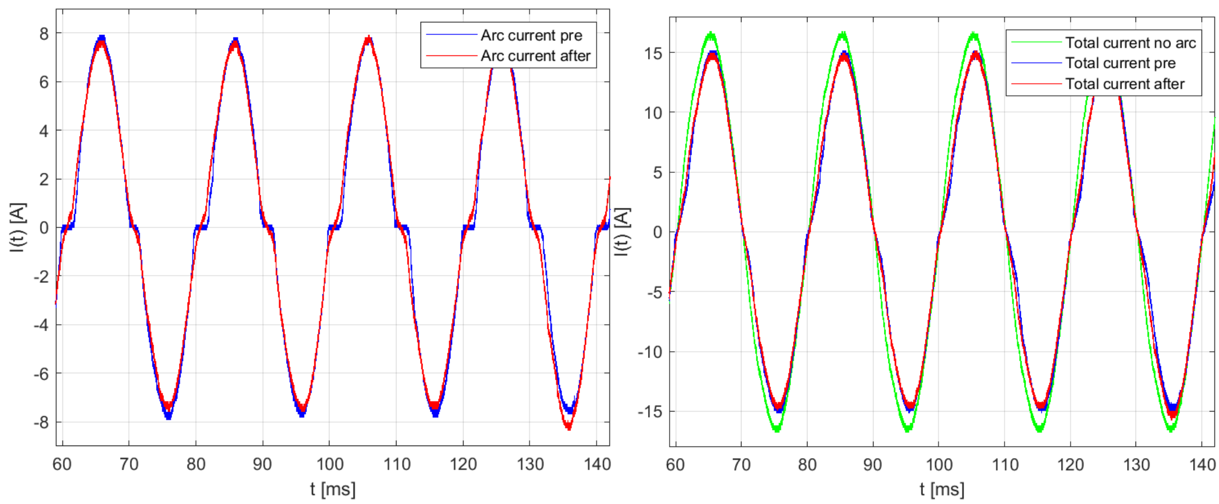


Figure 3.5:
Left side: Arc current from a new and used cable sample.
Right side: Total current from a new and used cable sample compared

3.3.3 Contact arc generator

To produce contact arcs, a solenoid connected to a solid-state multifunction timer was used. To establish contact, two stiff copper conductors were used as electrodes; one of them was attached to a platform and the other to the solenoid. As the solenoid oscillated up and down, the conductors varied between being in contact and making a gap. With this setup, it was possible to break and make the circuit at a frequency of 10Hz. This setup failed to achieve adequate arc stability due to the extended open-circuit period, which caused the gap between the conductors to become too long, resulting in the arc being extinguished. To ensure a shorter air gap, shorter open-circuit times, and consistent current flow, a loop was made on the conductor attached to the solenoid. This provided two contact points, one at the top position and one at the bottom position. The distance between the contact points also became short enough to maintain the arc and the make-and-break frequency was increased to about 20Hz. The finished system is shown in Figure 3.6.

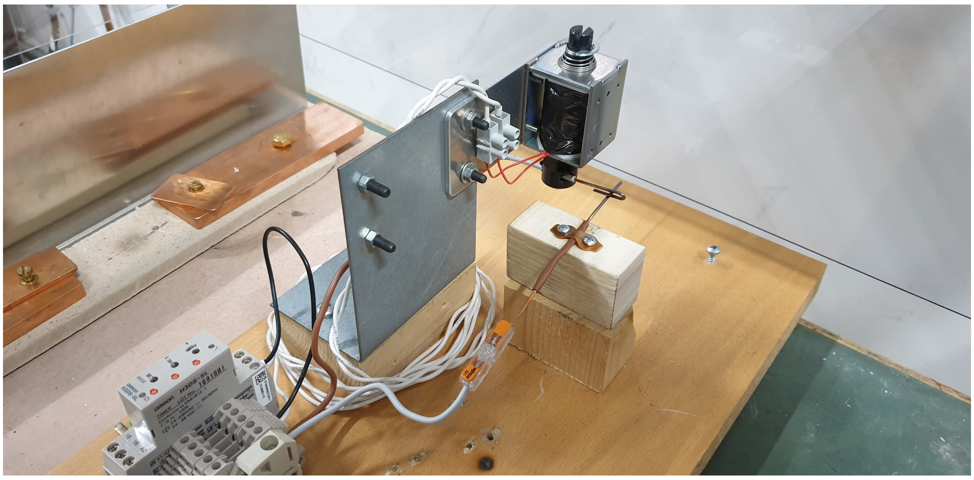


Figure 3.6: Picture of the contact arc generator used to make contact arcs

3.3.4 Switch mode power supply and high current load

The parameters of the switch-mode power supply(SMPS) are shown in Table 3.1. The power supply was used as a means of disturbances in the total current and had to be sufficiently loaded to do so. A high current resistance was used as the load for the power supply, with a load resistance of 0.133 Ω the steady state DC current from the power supply was 52.6A corresponding to an AC current of 2.2A. When the load resistance was further reduced to see if a higher current could be achieved on the AC side, the power supply reduced the voltage. Thus, the same current of 2.2A was measured on the AC side. A picture of the SMPS and the high current load is found in Appendix B.

Table 3.1: Parameters of the switch-mode power supply

Model	iMP4 - 2D0 - 2D0 - 00
Harmonic distortion	In accordance with EN61000-3-2
Power factor	0.99 typ.
Supply voltage (AC)	85 - 265 V
Maximum rated current (AC)	12 A
Output voltage (DC)	3.5 - 7.0 V (series connected modules)
Maximum rated output current (DC)	60 A

Chapter 4

Verification of function and testing at low currents

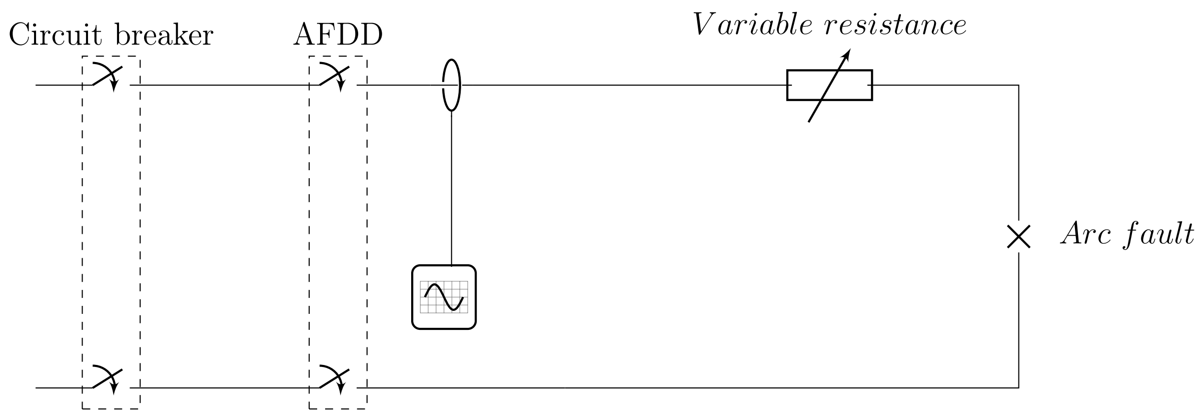
This chapter presents the test setup, measuring procedure, results and discussion from the verification test and the testing of lowest current threshold of the AFDD's.

4.1 Background

The test standard IEC 62606 declares that the devices must act according to the characteristic shown in subsection 2.4.1 and the AFDD standard IEC 62606. This characteristic follows the fire curve. To verify that the devices operate correctly and to test their behavior on currents below the threshold for the minimum current 2.5A. If the arc current is below this minimum threshold, no disconnection is required according to IEC 62606[16]. Manufacturers are free to set a lower limit, and J. Martel proposed the recommendation to change the test standard limit to 1.0A in his PHD dissertation[9]. The recommendation was based on his own tests where ignition of cable samples had been possible with currents as low as 1.0A [9]. This test was performed to determine the minimum arcing current threshold each manufacturer has chosen for their devices and to validate the devices for further use in this project.

4.2 Test setup

The test setup for function verification and low current testing consisted of the arc source, in this case only the arc generator was used. Arcing in the preconditioned cable samples was found to be unreliable for currents below 2.0A in preliminary tests. The load used for these tests was only the three-phase load with adjustable resistance. The actual current in the circuit was controlled with measurements from the oscilloscope. A diagram of the test circuit is shown below.



Circuit no.1: Test circuit for verification and low arc fault current tests

4.3 Measuring procedure

Measurement of the disconnection characteristic is based on the requirement that devices act within the required time at a specified current level. Current measurements and disconnection times were recorded with the oscilloscope. When the arc generator is used to test the requirements of IEC 62606 - 5.3.7 the allowed time before disconnection is 2.5 times greater than the time when using a charred cable sample [16]. Each measurement consisted of visible sparking/arcing and inspection of the recording on the oscilloscope to check for missing half-periods. If several missing half-periods occurred, the result was not used and the test was repeated.

For currents below 2.5A, 10 measurements were made of each device. The maximum arcing time was decided to be 15.0s and if disconnection had not occurred within this time, the test was deemed a failure. For currents between 2.5A and 15.0A, five measurements were made. As a result of wear on the electrodes, long periods of arcing were undesirable at higher current levels. Since the allowed arcing time at 3.0A arcing current, as seen in Figure 2.17, was 2.0s, the test was deemed a failure if the arcing time exceeded 5.0s.

4.4 Results

4.4.1 Low currents (0.5A-2.0A)

At lower currents, the arcing consisted mainly of spark-like behavior. The sparking waveform is visibly different from more typical arcing waveforms. Sparking was identified by a quicker reignition, thus not creating as long current zero time and as fast change in current when the re-strike occurs. Both the sparking and arcing waveforms mentioned above can be seen in Figure 4.1. The second and third periods consist of the sparking waveform and the rest of the periods of more characteristic arcing. The recording is from a 2.0A arc current, where the arc was generated with the arc generator.

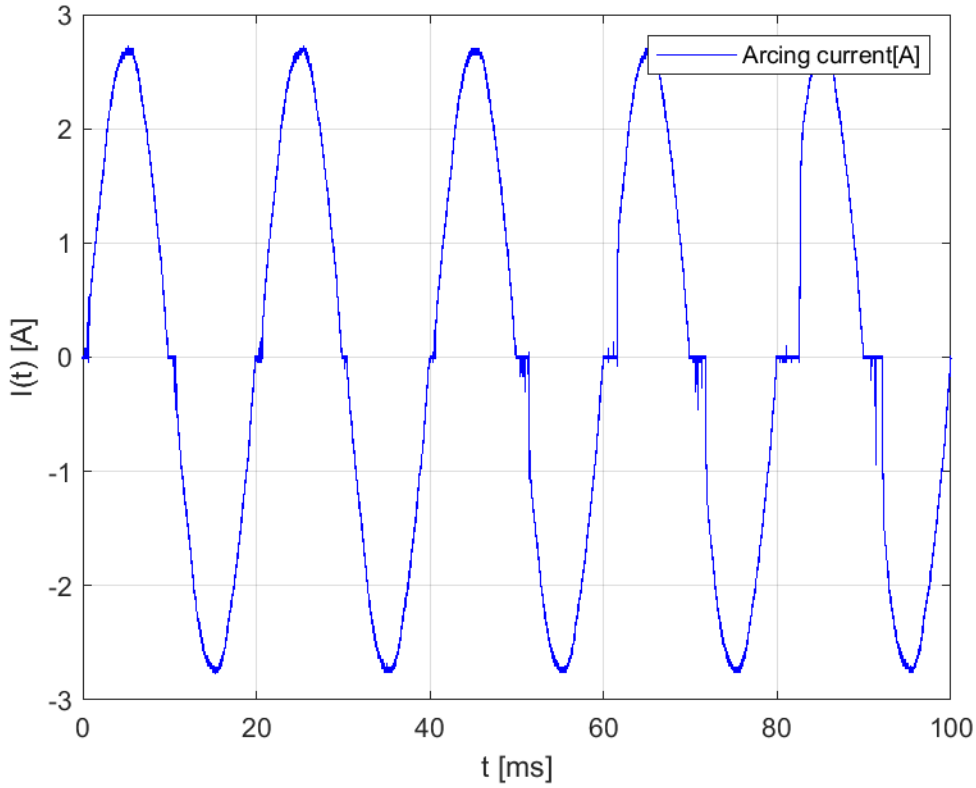


Figure 4.1: Sparking and arcing waveform at 2.0 A when the arc generator was used. Notice the short current zero crossing in the second and third period which was typical sparking signs.

More characteristic arc waveforms were often noticeable right before the sparking/arcing was extinguished when the air gap became too large and also at reignition when the electrodes were brought together again. Keeping the more typical arcing constant at low currents was shown to be hard and required fine adjustment of the electrode distance.

Time measurements were recorded at each current level and then plotted to see the characteristic and compare it with the fire curve. The diagram with all the measurements from the tests with currents below 2.5A is shown in Figure 4.2. For these tests, it is worth noting that none of the tested devices disconnected on 0.5A. Device 1 had consistent disconnection times below the time threshold. Device 2 did not detect arcs or disconnect for currents below 2.5A. Device 3 only detected arc when the arc current was 2.0A and above, but the disconnection times at this current were consistent. Device 4 detected an arcing current of 1.0A and above and had disconnection times below the time threshold for all currents except for 2.0A. At 2.0A it had three disconnections above the time threshold of the characteristic.

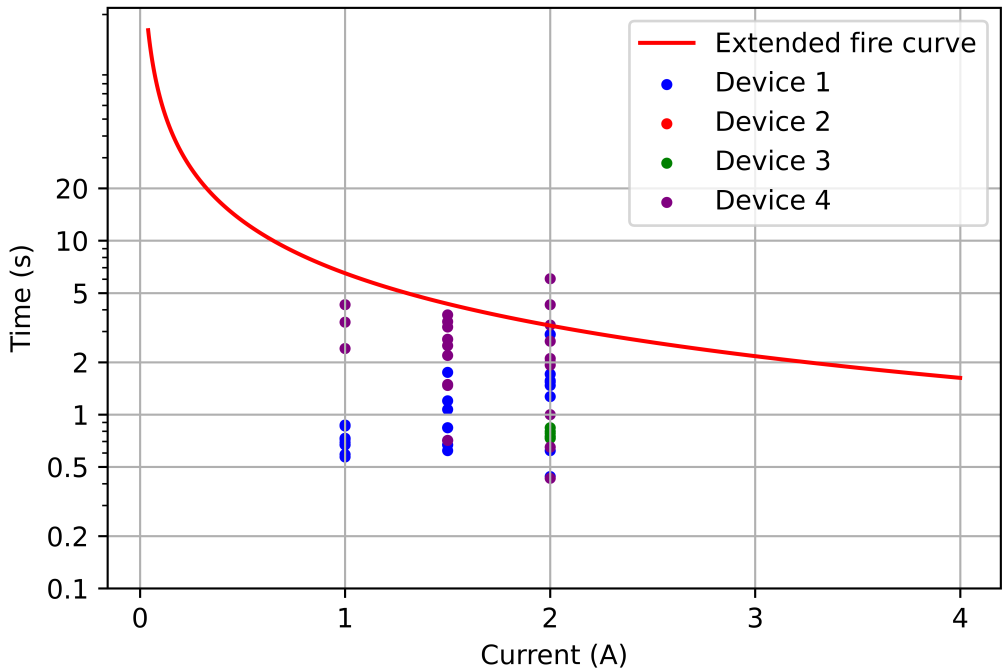


Figure 4.2: All measurements of disconnection times with currents below 2.5A, the arc generator was used as an arc source.

4.4.2 Higher currents (2.5A-15A)

When currents were produced in the range of 11.0A to 15.0A, the exact current level was difficult to maintain at a set level due to heating of the load resistance. Therefore, it was decided not to measure each current level in this range. Instead, only measurements of 11.0A and 15.0A were made. As a result of the shorter disconnection time requirements, the allowed arcing time for these currents was kept at 5.0s. This also helped reduce the wear of the electrodes. In particular, the copper electrode became blunt fast and the continued arcing caused a lot of wear and heating of the electrode.

For currents measured above 2.0A, the diagram is shown in Figure 4.3. Device 1 had mostly consistent disconnection times between 0.5s and 1.0s, which did not decrease with increasing currents. This caused several instances of disconnection above the time threshold. Device 2, which did not disconnect at a current below 2.5A, started to function as expected at 2.5A and disconnected consistently below the time threshold with a decrease in allowed arcing time for increasing arc currents. Device 3 disconnected consistently below the time threshold and had a decrease in time for increasing current. Device 4 had varying disconnection times and several disconnections above the fire curve threshold.

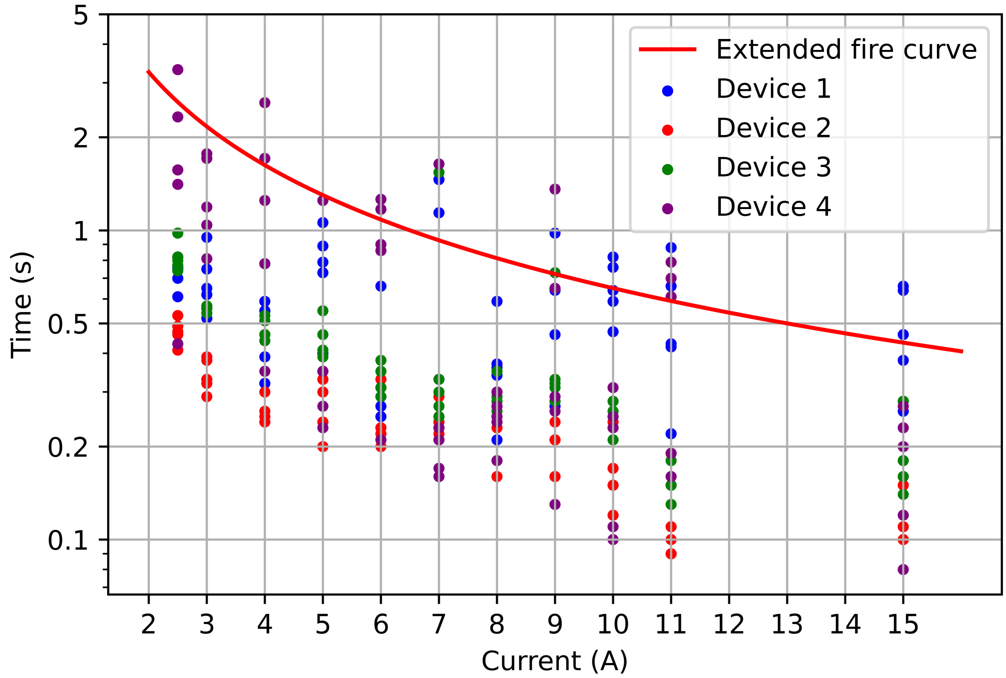


Figure 4.3: All measurements from disconnection time tests with currents above 2.5A, where the arc generator was used as arc source

4.4.3 Average disconnection times

The average disconnection times were calculated from the results of the previous tests and are plotted in Figure 4.4. When considering average times, the plot shows decent performance for most devices. Device 1 had an average time above the threshold for both 10A and 15A tests. The plot of average times also shows that Device 1 had a somewhat constant time characteristic regardless of the current. Device 2 had consistently fast disconnection times when the current was greater than 2.5A, but currents below 2.5A were not detected. Devices 3 and 4 had consistent average times below the threshold set by the fire curve.

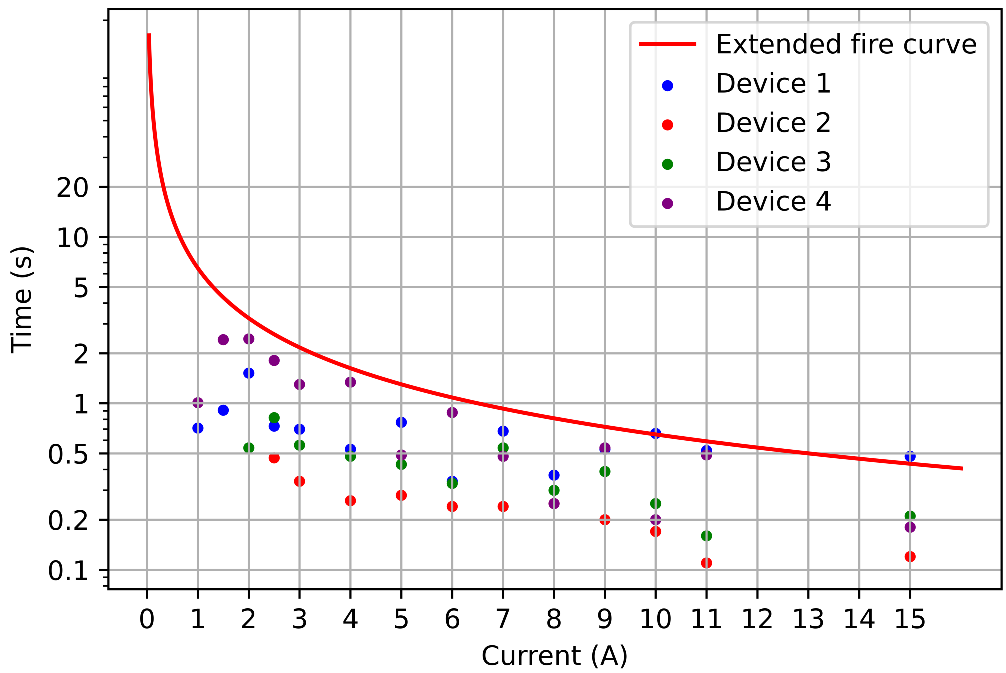


Figure 4.4: Plot of the calculated average disconnection times

4.4.4 Number of failed detection's

All devices had several instances in which they did not disconnect within a reasonable time of arcing. For currents below 2.5A, this time was set to 15.0s and for currents above 2.5A, this time was set to 5.0s. The goal was to get 10 disconnections for currents below 2.5A and five disconnections for currents above. For currents above 2.5A, each time a device failed to disconnect, another test was performed. Table 4.1 gives a overview of how many tests and failures occurred in current below 2.5A and how many tests had to be performed to obtain five valid time measurements on currents above 2.5A. This shows that there is some variability in the detection of arcs produced with the arc generator for all devices.

Table 4.1: Table of the number of times the devices failed to disconnect at different current levels

Arc current	Device 1	Device 2	Device 3	Device 4
0.5 A	10/10	10/10	10/10	10/10
1.0 A	0/10	10/10	10/10	7/10
1.5 A	0/10	10/10	10/10	0/10
2.0 A	0/10	10/10	3/10	0/10
2.5 A	0/5	0/5	0/5	0/5
3.0 A	0/5	0/5	0/5	0/5
4.0 A	0/5	2/7	3/8	0/5
5.0 A	3/8	3/8	0/5	2/7
6.0 A	2/7	2/7	0/5	0/5
7.0 A	0/5	0/5	2/7	2/7
8.0 A	0/5	1/6	1/6	4/9
9.0 A	0/5	2/7	2/7	3/8
10.0 A	0/5	0/5	3/8	3/8
11.0 A	1/6	1/6	0/5	0/5
15.0 A	0/5	0/5	0/5	0/5

4.4.5 Consistently fast disconnection when arc was extinguished with re-ignition

An important observation regarding arc detection is that both Device 3 and Device 4 consistently detected the arcs when the arc was extinguished and then re-ignited. This behavior seems to be part of the algorithm that detects arcs. The arcing time had no influence on this behavior; if the arc was extinguished and not able to reignite itself without moving the electrodes closer, then moving the electrodes closer and reigniting the arc these two devices disconnected consistently.

4.5 Discussion

When the devices were tested at a current below 2.5A, it was apparent that some of the devices had a lower threshold current than others. In this regard, Device 1 and Device 4 had the lowest disconnection threshold and acted on currents down to 1.0A, which was the lowest current tested. Device 3 had a 2.0A threshold but detected only 7 out of 10 arcs at this current level. Device 2 did not act on currents below 2.5A.

The IEC 62606 standard for arc fault detection devices requires that devices operate at fault currents of 2.5A and above when there is a series arcing event in the circuit. Despite this, there have been proposals to have an even lower current threshold than 2.5A. J.Martel proposed in his dissertation [9] that the threshold should be reduced to 1.0A due to his observation of ignition of cable samples at this current level. The reason for using 2.5A as the disconnection threshold could be to avoid certain cases of false disconnections and to discriminate equipment that has arc resembling waveforms. These tests showed that some of the manufacturers have chosen a lower threshold than what IEC 62606 demands and then use other methods to discriminate arc resembling loads and equipment.

Testing devices with the arc generator to verify correct operation showed that when devices detect arcing, the time to disconnect is mostly within the times demanded by IEC 62606. On some occasions, Device 1 and Device 4 had times that exceeded the standard, but when averaging the times, the results were mostly within or very close to being within. For further testing in this project, these results were determined to be satisfactory to continue using these devices.

A more concerning observation is the number of times the devices did not detect arcing. All devices had several instances in which arcing was not detected. This could be assigned to the test method of only arcing for 5.0s, with longer arcing times allowed, more devices could possibly disconnect within the assigned time. In addition, the occurrence of "sparking" because of a short gap between the electrodes could be a reason for the number of failed disconnections. One of the observations was that many of the devices did not detect the "sparking" as an actual arc. If a less stable arc with several missing half-periods was accepted in the tests, especially Device 3 and Device 4 would probably have less undetected arcs due to the observation of these devices disconnecting consistently when the arc was extinguished then re-ignited.

Chapter 5

Small arc fault current to parallel current ratio

This chapter presents the test setup, measuring procedure, results and discussion from the small arc fault current to parallel current test.

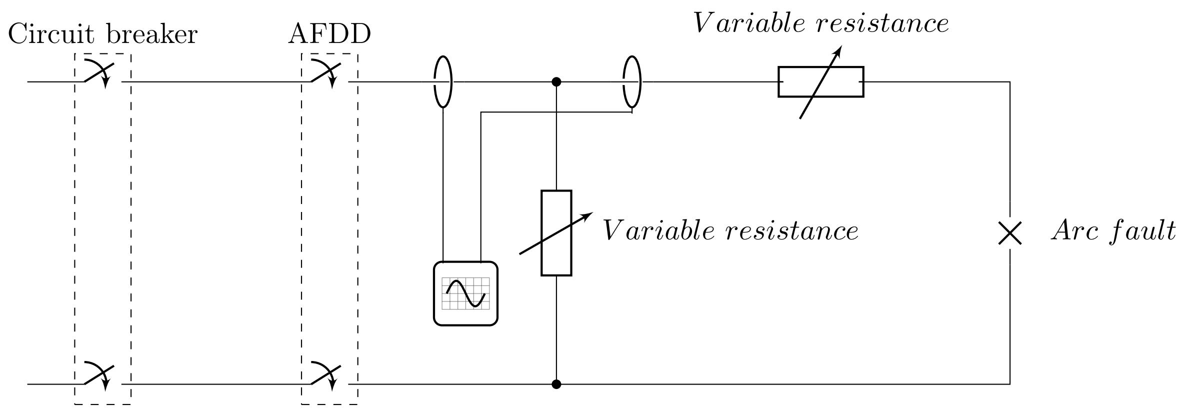
5.1 Background

The signature of an arc can easily be observed in the current waveform when monitoring an arc fault in a resistive series circuit. However, the introduction of other loads in parallel branches can cause the arc signature to become less prominent, as noted by Petter Müller et al. [5].

To gain insight into how the devices behave in a complex load environment, it is beneficial to test them during several different load conditions. One of the conditions that is of special interest is where high currents flow through the non-faulted branches and low currents flow through the faulted branch. This is one example of a situation that AFDD's can encounter in residential buildings with multiple loads connected to the same circuit at the same time.

5.2 Test setup

The measurement setup for this test consisted of two variable loads that allowed adjustment of the arc current and the parallel load current. The adjustable three-phase load was used as a variable load for the series arc fault, and one or two of the single-phase loads were used as a parallel branch load. Two different arc-generating methods, the arc generator and charred cable samples, were used. The oscilloscope was used to record disconnection times and waveforms for further analysis. The test circuit is shown in Circuit no.2.



Circuit no.2: Test circuit to test different arc/load current ratios

5.3 Measuring procedure

The goal of the experiment was to verify that the device could detect and react to a series arc fault that occurs in a parallel branch of a circuit. The current in the parallel branch and in the arc was adjusted to check several current ratios. The current ratios chosen for the test are shown in Table 5.1. The arc current was not tested below 2.5A which is chosen as the minimum threshold according to IEC 62606[16].

Table 5.1: Table of arc current to parallel branch current ratios used during testing

Arc current	**Parallel branch current**	**Total current**	**Ratio**
2.5 A	10.0 A	12.5 A	0.25
2.5 A	5.0 A	7.5 A	0.50
5.0 A	10.0 A	15.0 A	0.50
5.0 A	5.0 A	10.0 A	1.00

5.3.1 Arc generator tests

For each current ratio, each device was tested a total of 10 times. The first device was tested repeatedly five times, before the next device was tested five times. Then all devices were tested five more times in the same order. The arcing current waveform and the total current seen by the device were recorded using an oscilloscope. The oscilloscope was also used to keep track of disconnection times.

When creating an arc with the arc generator, the maximum arcing time was chosen to be 15.0s. If the arcing continued for longer, the test was deemed as "failed to disconnect". Continuous arcing was the goal; if the arc was extinguished because of the excessive distance between the electrodes, the test was re-done. The test was carried out as described in subsection 3.3.1. If the device tested did not disconnect for 15.0s, the distance between the electrodes was gradually increased until the arc was extinguished, and then the distance was again decreased until the arcing reoccurred. This was to see if the device did disconnect on reoccurring arcs.

5.3.2 Charred cable sample tests

When arcs were created with the charred cable samples, a total arcing time of 4.0s was chosen. If arcing persisted for long periods the samples would catch fire. When the cable samples caught fire, they were often destroyed and no longer capable of making arcs. As a result of a limited number of samples, a shorter time was chosen, so several tests could be performed with the same sample. According to IEC 62606 and the fire curve explained in subsection 2.4.1, with an arcing current of 2.5A the AFDDs should disconnect in 1.0s, and at 5.0A in 0.5s when using preconditioned cable samples, therefore a time of 4.0s should be acceptable to consider whether the device would disconnect or not.

5.4 Results

5.4.1 Waveform comparison

The introduction of a parallel load made the arcing characteristics less prevalent when measuring the total current in the circuit. However, there is a noticeable change in the waveform even at the lowest arc current to total current ratio, which becomes more apparent when the ratio increases. Figure 5.1 shows a side-by-side comparison of a 0.25 ratio and a 1.0 ratio arc to total current ratio. For both cases, the characteristic shoulder is not visible in the total current, but a clear increase in current amplitude is apparent when the arc ignites. It is also apparent that the arc burns all the way until the current reaches the next zero crossing.

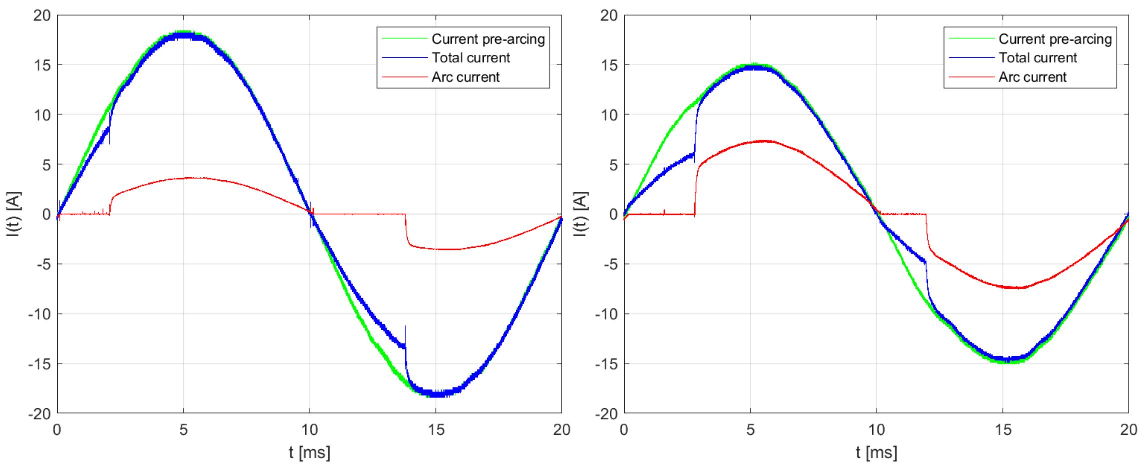


Figure 5.1:
Left side: Plot of oscilloscope recording of 2.5A arc current and 12.5A total current (0.25 ratio) during arcing when the arc generator is used.
Right side: Plot of oscilloscope recording of 5A arc current and 10A total current (1.0 ratio) during arcing when the arc generator is used

The difference between typical arcing and sparking is noticeable when comparing the waveforms in Figure 5.1 and Figure 5.2 where the last show one period of sparking. When sparking occurs, the change in the total current waveform is small and difficult to notice. Sparking was a typical outcome when using the arc generator and trying to keep the arc for 15.0s without extinguishing it.

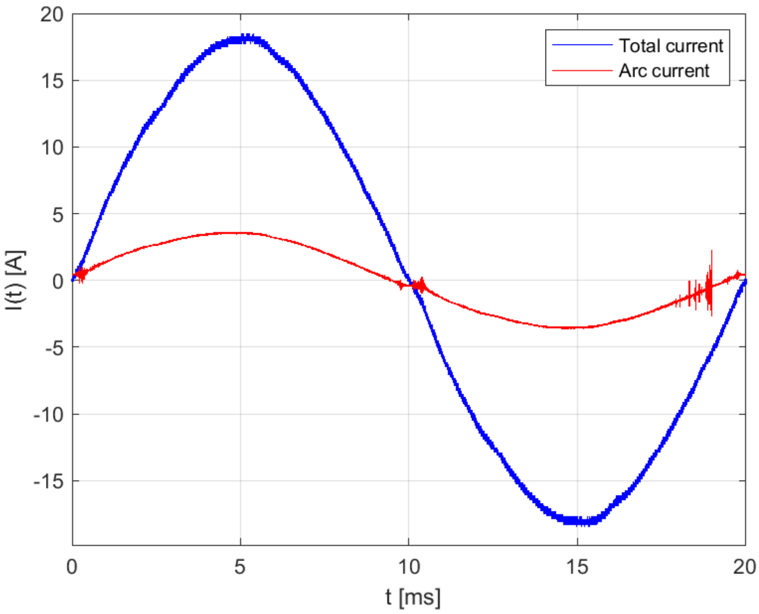


Figure 5.2: Plot of a oscilloscope recording of one period spark current 2.5A and total current 12.5A during sparking

Figure 5.3 shows a comparison of the waveforms for an arc current to total current ratio of 0.25 and 1.0 when arcing was generated from a preconditioned cable sample. It can be seen that the arc current has a different behavior when the cable sample is used and when the arc generator is used. The amplitude of the total current also changes more when using the cable sample. When comparing the actual disturbance in the total current waveform during arcing, it is less noticeable when the cable sample is used, but with increasing ratio the increase in current when the arc ignites becomes more noticeable. At least for the lowest of the arc currents it is apparent that the arc extinguishes before the total current reaches zero, for the higher arc current, this behavior is less noticeable.

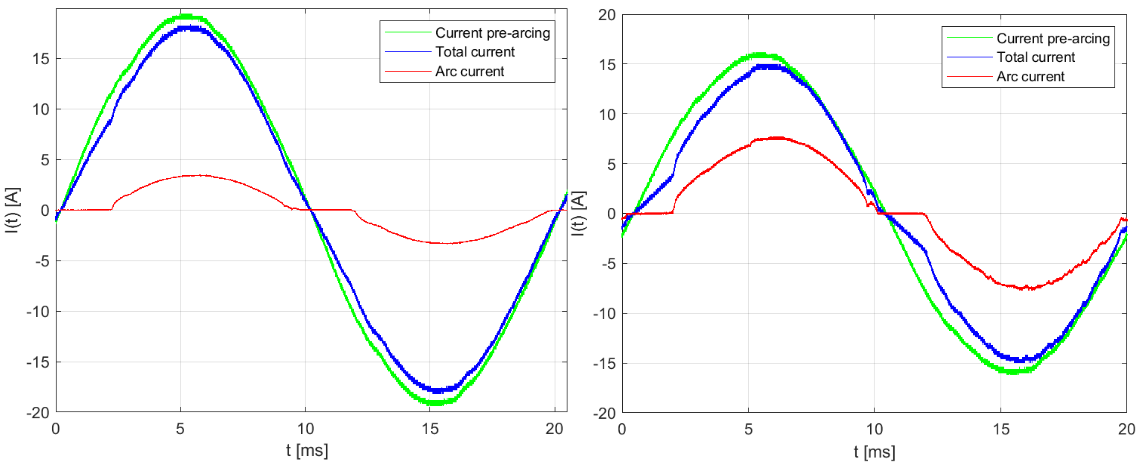


Figure 5.3:
Left side: Plot of oscilloscope recording of 2.5A arc current and 12.5A total current (0.25 ratio) during arcing when a preconditioned cable sample is used.
Right side: Plot of oscilloscope recording of 5A arc current and 10A total current (1.0 ratio) during arcing when a preconditioned cable sample is used

5.4.2 Frequency spectrum comparison

The frequency spectrum of the current ratio tests gives an indication and a baseline for how the amplitudes of the frequency content change. For comparison, the 0.25 and 1.0 ratios are used because these are the highest and lowest current ratios tested. A comparison of the total current before and during arcing with both ratios is also shown.

The comparison of arcing with the two different current ratios is shown in Figure 5.4. Small differences in amplitude were noticeable in the 5th, 7th and 9th harmonic, where the 1.0 current ratio had higher amplitudes. For the current ratio of 1.0, a slight elevation in the frequency band between 1kHz and 10kHz was also noticeable. In the high frequency band above 100kHz the amplitude is indistinguishable.

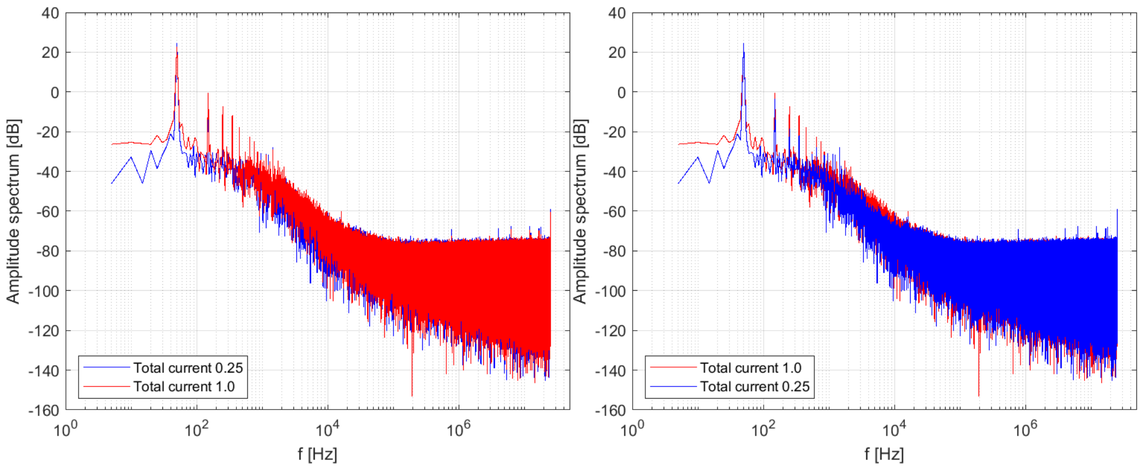


Figure 5.4:
Left side: Plot of frequency amplitude spectrum, measured total current with arcing from cable sample with current ratio 0.25 and 1.0.
Right side: Same as left side with reverse order of plots

The comparison of the frequency amplitude spectrum before and during arcing with both current ratios is shown in Figure 5.5 and Figure 5.6. Both frequency amplitude spectra showed general elevated amplitudes between 100Hz and 2kHz, but the higher ratio gave a larger difference. Large difference is especially noticeable in the 3rd harmonic. The 1.0 ratio also showed elevated amplitudes for higher frequencies, up to 10kHz. The high frequency band above 100kHz was indistinguishable in both cases.

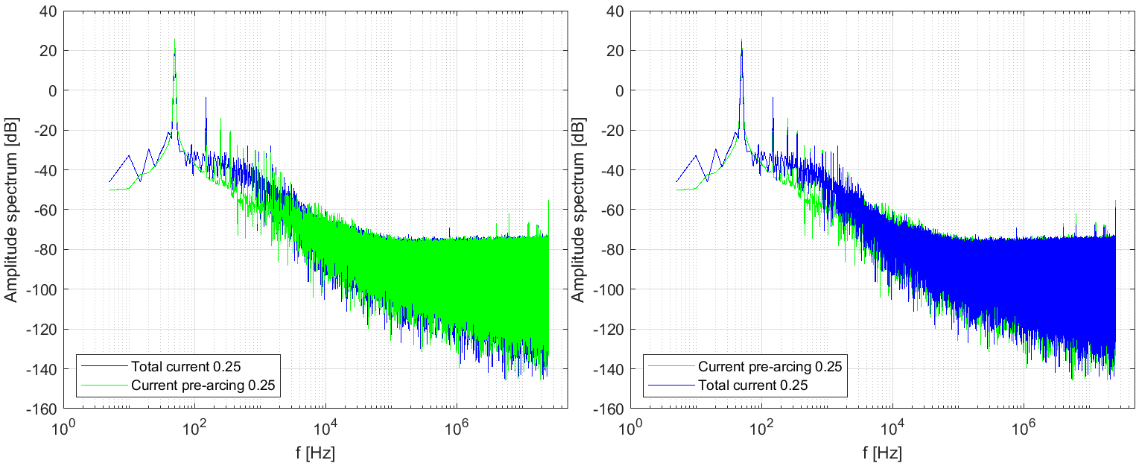


Figure 5.5:
Left side: Plot of freq amplitude spectrum, current before arcing and measured total current with arcing from cable sample with current ratio 0.25.
Right side: Same as left side with reverse order of plots

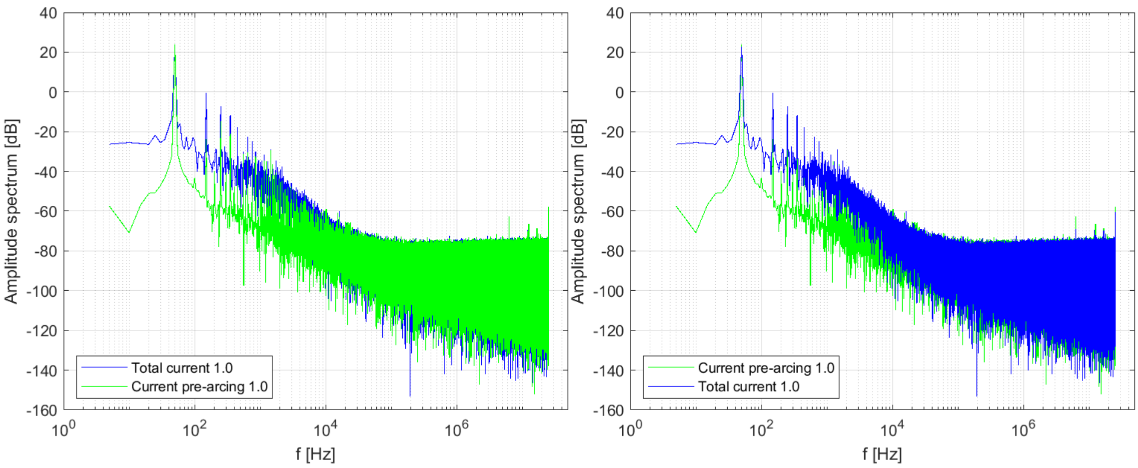


Figure 5.6:
Left side: Plot of freq amplitude spectrum, current before arcing and measured total current with arcing from cable sample with current ratio 1.0.
Right side: Same as left side with reverse order of plots

The same plots, but when the arc generator was used, are shown in Appendix A.

5.4.3 Spectrogram

Spectrograms showing the frequency power in the arc current and total current of 10 periods are shown in Figure 5.7. The figure on the left shows the current ratio 0.25, and the figure on the right shows the current ratio 1.0. The arcing current of 0.25 has noticeable decreases in HF power at zero crossings, and it's more noticeable in one of the half periods. The current ratio of 1.0 showed weaker signs of zero crossings than the 0.25 ratio. Neither of the figures of total current shows clear signs of current zero crossing or difference in the noise power corresponding to zero crossings.

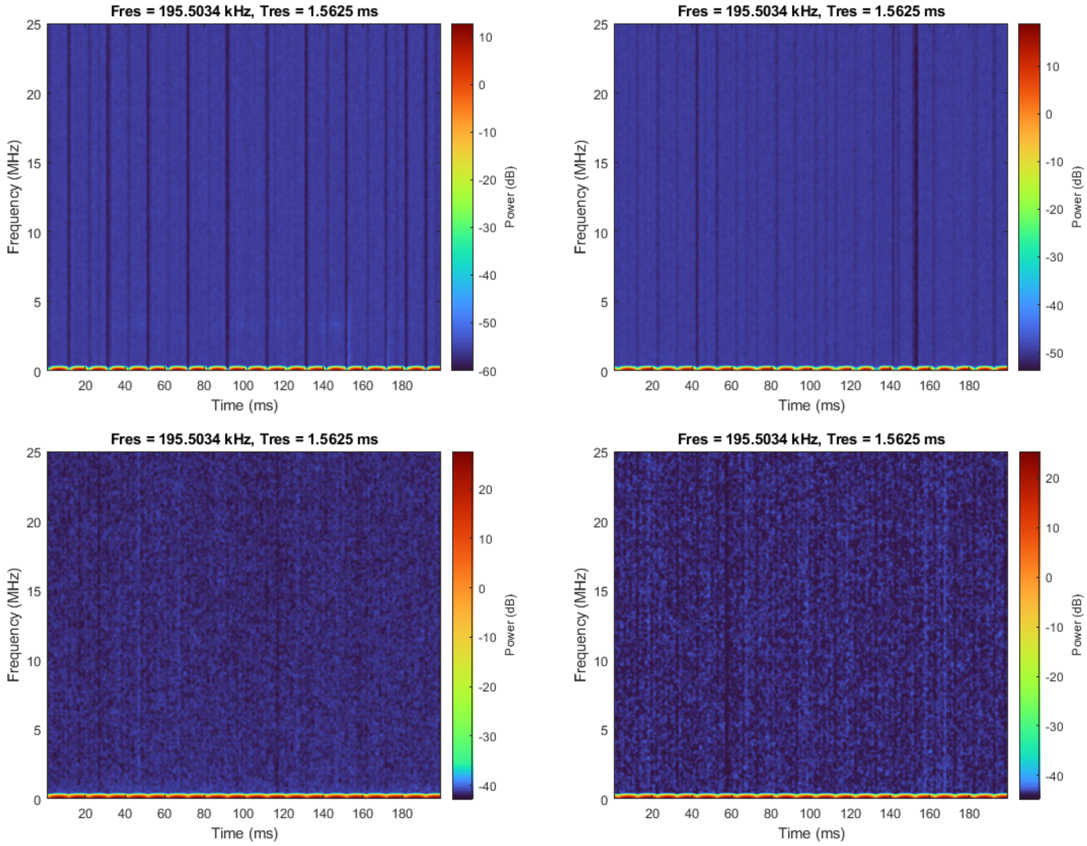


Figure 5.7:
Left side: Spectrogram of frequency power, arc current and total current measurements from current ratio 0.25 with arcing from a charred cable sample.
Right side: Same type of spectrogram but with current ratio 1.0

5.4.4 Performance of the AFDD's, arc generator

As shown in Table 5.2, the test results exhibited substantial variation in the ability of the devices to detect the series arcs produced by the arc generator in this test configuration. This is also evident in the average disconnection times shown in Table 5.3. In the calculation of the average disconnection times, only the recorded times were used when the devices actually disconnected.

Device 1 consistently disconnected when exposed to a 2.5A arc current, but failed to disconnect at a higher current of 5.0A, and it did not disconnect during re-strikes of the arc. Device 2 disconnected in only 8 out of 20 tests at a 5.0A arc current, but consistently disconnected when a recurring arc was introduced, except for two instances at a 2.5A arc current and a total current of 7.5A. Device 3 disconnected in 8 out of 10 tests at a 5.0A arc current and a total current of 15.0A, and in 6 out of 10 tests at a 5.0A arc current and a total current of 10.0A. However, in the remaining two test scenarios, the device did not disconnect until after the arc had been extinguished and then reoccurred, but it did so consistently. Device 4 showed significant variability in disconnection times, occasionally disconnecting at every current ratio. In cases where it initially failed to disconnect within the first 15.0s, it eventually disconnected when the arc was extinguished and then reoccurred.

It is notable that all devices except Device 1 demonstrated the ability to disconnect when the arc was extinguished and then reoccurred, highlighting the devices' operational characteristics.

Table 5.2: Table of disconnection results when using the arc generator. Table showing the number of times the AFDDs disconnected out of 10 tests

Ratio	**Device 1**	**Device 2**	**Device 3**	**Device 4**
0.25 (2.5A/10A)	6/10	0/10	0/10	3/10
0.50 (5.0A/10A)	0/10	5/10	8/10	4/10
0.50 (2.5A/5.0A)	10/10	0/10	0/10	6/10
1.00 (5.0A/5.0A)	0/10	3/10	6/10	8/10

Table 5.3: Table of average disconnecting times when using the arc generator as arc source

Ratio	**Device 1**	**Device 2**	**Device 3**	**Device 4**
0.25 (2.5A/10A)	7.25 s	-	-	9.23 s
0.50 (5.0A/10A)	-	0.68 s	0.25 s	6.65 s
0.50 (2.5A/5.0A)	0.55 s	-	-	5.52 s
1.00 (5.0A/5.0A)	-	0.20 s	0.24 s	3.46 s

5.4.5 Performance of the AFDD's, charred cable sample

The results of the cable sample test are shown in Table 5.4 and the average disconnecting times in Table 5.5. The average disconnecting times were calculated from the recorded times when the device disconnected correctly. When using the cable sample, average disconnecting times were generally faster and all devices disconnected more frequently. Device 1 did disconnect in most current ratios. The only two times the device did not disconnect was at 2.5A arc current and 12.5A total current. Device 2 had the most varied results. The only current ratio that gave consistent disconnecting was at 5.0A arc current and 10.0A total current. For a current ratio of 0.5 with a 5A arc current and a 10 A parallel branch current, this device did not detect the arc once. Devices 3 and 4 had consistent disconnecting for all tests. This is in large contrast to the tests where the arc generator was used.

Table 5.4: Table of disconnecting results when using a cable sample. Table showing the number of times the AFDDs disconnected out of 10 tests

Ratio	**Device 1**	**Device 2**	**Device 3**	**Device 4**
0.25 (2.5A/10A)	8/10	6/10	10/10	10/10
0.50 (5.0A/10A)	10/10	0/10	10/10	10/10
0.50 (2.5A/5.0A)	10/10	8/10	10/10	10/10
1.00 (5.0A/5.0A)	10/10	10/10	10/10	10/10

Table 5.5: Table of average disconnecting times when using cable sample as arc source

Ratio	**Device 1**	**Device 2**	**Device 3**	**Device 4**
0.25 (2.5A/10A)	0.21 s	0.35 s	0.15 s	0.10 s
0.50 (5.0A/10A)	0.17 s	-	0.14 s	0.09 s
0.50 (2.5A/5.0A)	0.24 s	0.54 s	0.24 s	0.13 s
1.00 (5.0A/5.0A)	0.68 s	0.11 s	0.24 s	0.10 s

5.5 Discussion

5.5.1 Waveform comparison

The recording of the waveforms shows clear differences between the arc produced by the arc generator and the cable sample. When the arc generator is used to produce arcs in the parallel circuit, the signs of the arcing are clearly visible in the total current waveform even at a low ratio of arcing current to parallel load current. Foremost, the reignition of the arc is visible as a quick change in the total current amplitude.

One problem with using the arc generator was apparent when trying to maintain high arc stability. Many of the half-periods will be arcing with very short current zero crossings, which the AFDD's did struggle to detect. It is difficult to be certain of how arcs behave when occurring naturally in installations, but arcing across an air gap between a carbon electrode and a copper electrode in a similar way to how the arc generator is operating is probably less likely.

When the cable sample was used as the source of arcing, the change in the total current waveform was less visible than when the arc generator was used. Even though the sign in the time domain waveform was less visible, further testing showed that the devices reacted much more predictable and had less problems with the detection of these arcs than the arc generator. The most notable change in the total current is the decrease in current amplitude caused by the increased impedance across the charred track in the cable sample. The voltage drop across the cable sample was much more noticeable than in the air gap. This observation agrees with the theory of static arcs shown in section 2.1 which states that the minimum voltage drop in an air gap can be attributed to the 8V cathode drop and the 2V anode drop compared to the 40V drop across arcing on char as mentioned in subsection 2.1.7. It can be observed that the arc current also hits current zero earlier than the total current, in contrast to the arc from the arc generator, which burns until the total current reaches current zero.

5.5.2 Frequency spectrum comparison

The frequency amplitude spectrum comparisons generally showed an increase in the odd harmonic frequencies and a general increase in all frequencies between 50Hz and 10kHz with increasing arc current. In the more interesting frequency band above 100kHz there was no noticeable difference between arc current ratios or between arcing and no arcing. This means that no difference in the frequency band between 20MHz and 25MHz could be seen. This can indicate that the HF noise difference is either totally concealed by the parallel load current or a problem with the approach.

An elevation was expected at higher frequencies caused by an increased noise level when arcing occurred, in accordance with the theory of subsection 2.1.9 and Figure 2.8. Another possible reason is the local presence of background noise. The laboratory area and university campus may be exposed to elevated levels of background noise caused by nearby machines and equipment. If this is the case, the elevated background noise can drown out the noise signature of the arc.

A problem with the approach can be the way DFT is calculated. Because there is no time representation, the DFT only shows the distribution of the amplitudes contained in the 10 periods of the waveform. If the background noise amplitudes and the noise amplitudes from the arc are similar in magnitudes and occur in the same frequency range, they cannot be distinguished by this method.

5.5.3 Spectrogram comparison

When the spectrogram was used to represent the frequency power, the zero crossings of the current were clearly identifiable by the change in HF noise. Zero crossing was more noticeable when the 2.5A arc current was measured, and one of the half-periods was more distinct. Because the zero crossings were more noticeable at a lower arc current, it may indicate that less HF noise is produced with increasing current, but it could also be caused by more wear on the cable sample when the higher current was measured. When the total current was examined, the total current did not show the same clear correlation between zero crossing and reduction in noise power for any of the current ratios. It was expected to see clearer signs of zero crossings in the 1.0 ratio due to a higher arc current and lower parallel load current than in the 0.25 ratio. This does indicate that the reduction in noise was hidden from what the AFDD measures in both cases.

5.5.4 AFDD performance

When the arc generator was used as the arc source in this parallel setup, the detection rate was surprisingly low. Only one of the devices obtained a 100% detection rate at one current ratio, that was Device 1 at a current ratio of 0.5 with an arc current of 5.0A. All other current ratios for all devices had several instances in which the devices did not detect arcing and all devices except device 4 had current ratios where arc was not detect at all. The disconnection times also varied, and devices 1 and 4 had instances of very long disconnection times. The arc generator test results presented in this chapter must in general be found to be unsatisfactory.

The results of the test when using the cable sample were quite different. Device 1 had only two instances where arcing was not detected. Device 2 had the worst results of all devices in this test. Especially strange was the fact that this device did not detect any arcing at a current ratio of 0.5 with an arcing current of 5.0A, which was one of the current ratios that had good performance in the previous test. It also did not disconnect in two of the other circuit configurations. Device 3 and Device 4 operated as expected when arcs were made with the cable sample.

In general, the results from the arc generator tests are not good enough. Especially since the arc generation method used is one of the proposed methods from IEC 62606 and the current levels are within the range that the devices should operate at. These results must be seen in context with how the arc generator was used, and no other explanation can be found then that the many periods of "sparking" have caused these results. Because arc stability was prioritized, the outcome when the arc generator was used was arcs with a short zero time. This "sparking" was shown in the previous test to be hard for the devices to detect. As the results of this test show, the inclusion of a parallel load did not make the arc easier to detect. The result of Device 2 in the subsequent test when a cable sample was used as the arc generating method reinforces the perception that the performance of this device was not satisfactory.

Chapter 6

Contact arcing and glowing connection

This chapter presents the test setup, measuring procedure, results and discussion from the contact arcing and glowing connection test.

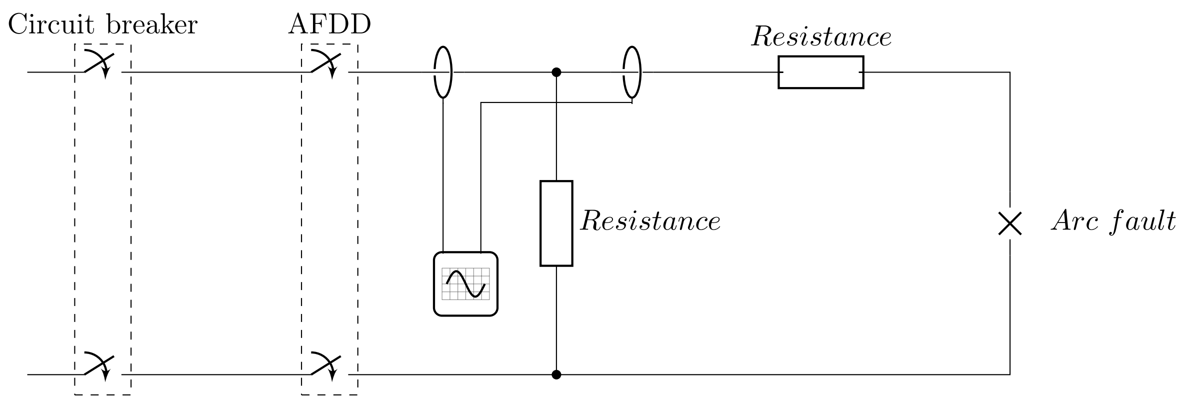
6.1 Background

The characteristics of a glowing contact differ from those of an electric arc, so the detection of such faults poses a unique challenge for AFDDs. This is particularly relevant as AFDDs are advertised as fire preventing devices. Series faults, such as glowing connections, have been suggested to be one of the causes of electric fires [12][22].

In addition to detecting glowing contacts, it is important to determine whether the devices can identify precursor signs that precede the formation of such contacts. Because series arcs is assumed to be initiating the glowing process, as mentioned in section 2.2, it should be possible to detect this precursor with an AFDD. Testing the ability of devices to detect these precursor events can provide valuable information on their performance under real-world conditions.

6.2 Test setup

To make contact arcs, a solenoid was connected to a solid state multifunction timer with a flicker function of the type Omron H3DS-SL. This timer was used to cause the solenoid to oscillate at a frequency of around 20 Hz, which in turn moved one conductor into contact with another conductor, resulting in multiple make-and-break operations. More information about the contact arc generator and a picture of the contact arc generator is shown in subsection 3.3.3. The first test involved only a series arc limited by a 42 Ω load, resulting in a current of 5.0 A. In the second test, the same arcing branch was used in addition to a parallel connected load with equal resistance, leading to a arc current to parallel load current ratio of 1.0. Using this ratio makes the results comparable to other results in the thesis. A diagram of the test circuit is shown in Circuit no.3.



Circuit no.3: Test circuit to test with contact arcing and glowing connection

6.3 Measuring procedure

These tests were performed to determine whether the devices tested could detect series arcing caused by make-and-break operations, as well as if a glowing contact could be detected. Each AFDD was tested 10 times with a 5A arc current, which has been shown in previous experiments to be sufficient to create and sustain glowing contact, as reported by M. Bjørnbakk [7] and J. J. Shea [20]. The current was measured with current probes connected to an oscilloscope, and the tripping times were acquired from the recording. The recording was also examined to determine the stability of the arc and whether there was constant current running in the circuit. For this test, the frequency spectrum was not analyzed.

6.4 Results

6.4.1 Glowing contact

During this test, a glowing connection was observed several times, but only for a short period of time. When the conductors were sufficiently oxidized, glowing contacts could be formed. However, because of the make-and-break operations, the glowing could not be maintained. Even if the contact arc generator was stopped in the closed position after the observation of a glowing connection, the glow would disappear. It was found that decreased make-and-break frequency would result in longer time before the glowing occurred.

6.4.2 Waveform comparison

During contact arcing, the waveform of the arcing current behaved similarly to that of the arc generator used in other experiments. One period comparing the arc waveform, the total waveform and the total waveform without arc is shown in Figure 6.1. When the gap between the two conductors was too small, it often resulted in a more spark-like phenomenon that did not cause the devices to trip. To ensure consistent arcing, a sufficient distance was necessary, however, too much distance caused too many missed periods for the devices to detect arcing. During testing, it was observed that when about 8 periods in a row were missing, none of the devices would act on the arcing. The number of missing periods causing failure to trip differed somewhat between the different devices.

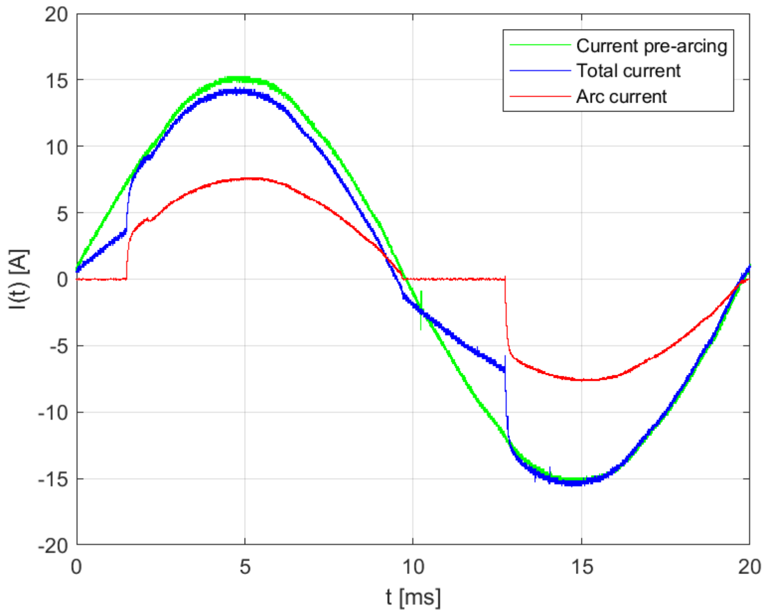


Figure 6.1: Comparison of recorded contact arcing waveforms with an arc current of 5.0A and a total current of 5.0A

Typical arcing stability during a test is shown in Figure 6.2. This figure shows an arc stability of approximately 50%. This was generally the arc stability obtained for all tests performed. Some half-periods are missing completely, but most show signs of arcing or sparking. This figure was recorded during the testing with a parallel load included.

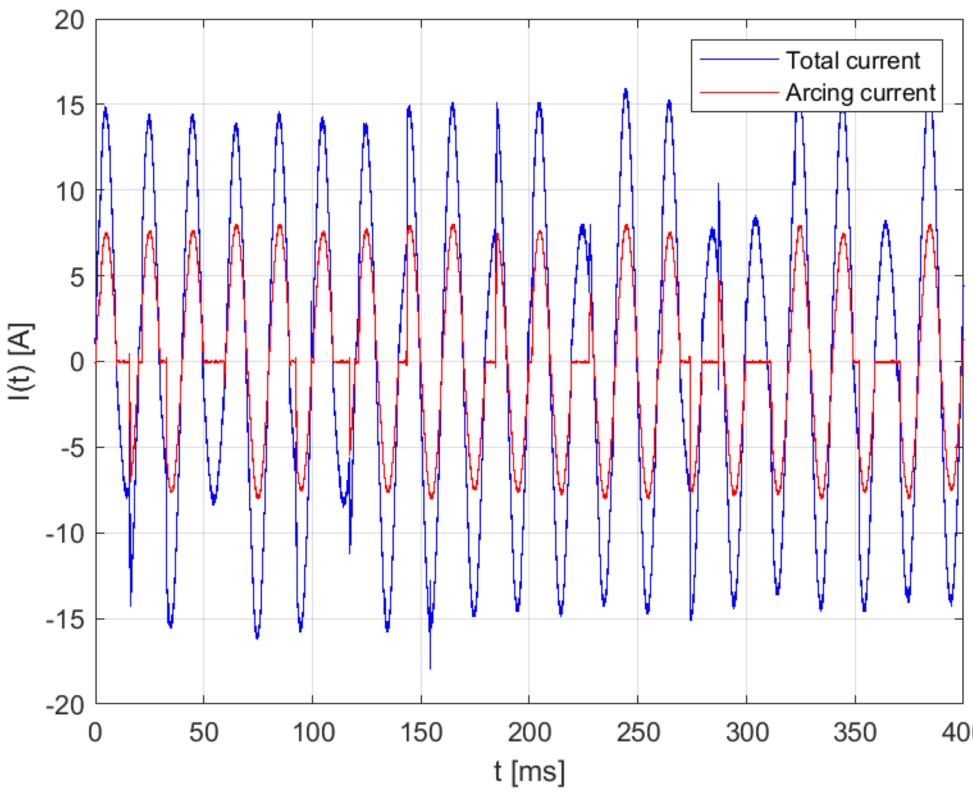


Figure 6.2: Typical arcing stability obtained with the contact arc generator

6.4.3 Disconnection times

The disconnection times when testing devices without a parallel load are presented in Table 6.1. Generally, the disconnection times varied and Device 1 did not detect and respond to contact arcing performed in this test. Devices 2 and 3 disconnected on most tests, but both had two cases where arcing was not detected. Device 4 disconnected on all occasions of arcing. A glowing contact point was observed during the tests with the longest disconnection times, but the glow could not be sustained because the continuous vibration disrupted the oxidization bridge.

Table 6.1: Table of recorded disconnection times for contact arcing tests without parallel load

Test number	**Device 1**	**Device 2**	**Device 3**	**Device 4**
1.	-	4.44 s	2.35 s	0.65 s
2.	-	-	1.06 s	1.28 s
3.	-	-	1.34 s	3.13 s
4.	-	40.0 s	0.46 s	1.49 s
5.	-	1.46 s	8.66 s	0.97 s
6.	-	0.46 s	5.74 s	32.0 s
7.	-	0.44 s	-	1.34 s
8.	-	0.49 s	-	7.60 s
9.	-	0.42 s	3.98 s	2.74 s
10.	-	0.50 s	1.40 s	7.98 s

When a parallel load was added to the circuit, all devices behaved more consistently. All devices disconnected during each test at a more appropriate time according to the fire curve and characteristic from IEC 62606. The characteristic is presented in Table 6.2. Device 1 had some instances with disconnection times greater than 1 s, which was the longest times across all devices for this test.

Table 6.2: Table of recorded disconnection times for contact arcing tests with parallel load

Test number	**Device 1**	**Device 2**	**Device 3**	**Device 4**
1.	0.37 s	0.14 s	0.36 s	0.27 s
2.	1.20 s	0.39 s	0 28 s	0.20 s
3.	0.26 s	0.18 s	0.75 s	0.23 s
4.	1.57 s	0.18 s	0.43 s	0.24 s
5.	0.87 s	0.21 s	0.50 s	0.23 s
6.	0.37 s	0.13 s	0.21 s	0.16 s
7.	0.55 s	0.13 s	0.72 s	0.29 s
8.	3.14 s	0.70 s	0.25 s	0.25 s
9.	1.88 s	0.22 s	0.50 s	0.20 s
10.	2.62 s	0.41 s	0.32 s	0.26 s

6.5 Discussion

6.5.1 Glowing connection

Because the glowing contact could not be sustained with the test setup that was used, testing if the devices could detect only the glowing contact was not possible. It was expected that the glowing contact could be maintained but, as mentioned in the results, the glowing contact disappeared when the generator was stopped in the closed position. This was probably caused by the contact pressure between the conductors, and no solution was found to solve this problem during the testing. Either way, considering the observed events in this test, it seems apparent that glowing contacts commonly appear during contact arcing and appear relatively fast when contact arcing is occurring. It was observed that increasing the frequency of the arcing events would lead to a faster occurrence of a glowing contact spot.

6.5.2 Waveform comparison

It was apparent from the waveform recordings during contact arcing that the shape of the arc current would have similarities to the arc current generated from the arc generator using a carbon and a copper electrode. The same issue of insufficient arc stability also arose when the contact arc generator was used, but this was resolved by forming a loop on one of the electrodes.

6.5.3 AFDD performance

The tests show that when tested with only the contact arc generator and no parallel load, the results varied. Device 1 did not detect arcs at all, and the other devices had varying disconnection times. This is probably caused by either the varying arc stability or the lack of a constant current running in the circuit. There was a large improvement in the detection of arcing and disconnection times when the parallel load was connected. The parallel load connected in the circuit ensures that a constant current flows through the device, probably making the make-and-break action and arc stability of the contact arc generator less problematic.

The performance of the devices toward contact arcing when a parallel load was connected in the circuit was consistent, and most of the devices had fast disconnection times. Device 1 was the only device where disconnection times greater than 1.0 s were observed. The results are mostly comparable to the previous test with a current ratio of 1.0 when the charred cable sample was used. This test has shown the ability of devices to detect rapid contact arcing when there is constant current flowing in the circuit. It has also highlighted some problems with arc detection when there is no constant current running in the circuit.

In addition, it is obvious that the frequency of the arcing has an impact on the severity of the fault. If the arcing frequency is low, the fire hazard is lower than if the arcing occurs frequently, as is apparent from subsection 2.1.7. During the test setup some preliminary tests where done to check how often the make-and-break action had to be performed for the devices to act. With about 8 periods or 16 ms between make and break actions, the devices would not detect the arcing. More periods between each arcing incident also caused the devices to allow longer times before disconnection occurred. This observation indicates that the AFDD's probably would not detect typical arcing in bad connections, where the frequency of arcing could be low.

Chapter 7

Disturbing load, parallel capacitance

This chapter presents the test setup, measuring procedure, results and discussion from the parallel capacitance test.

7.1 Background

Both P. Muller et al.[5] and M. Fagerås[8] have mentioned that capacitive loads and elements in the circuit can influence the ability of AFDD's to detect arcs. Testing devices with several different levels of capacitance in parallel should clarify whether this causes problems for any of the devices with regard to detecting arcs and, in that case, at what capacitance level it becomes a problem.

M. Fagerås showed in his thesis[8] that some of the devices he tested encountered problems when he tested with parallel capacitance in the circuit. That test was performed several years ago, and this new test should uncover if this problem still persists or if changes have been made to deal with it. It will also contain more manufacturers of AFDD's to see if others have similar problems.

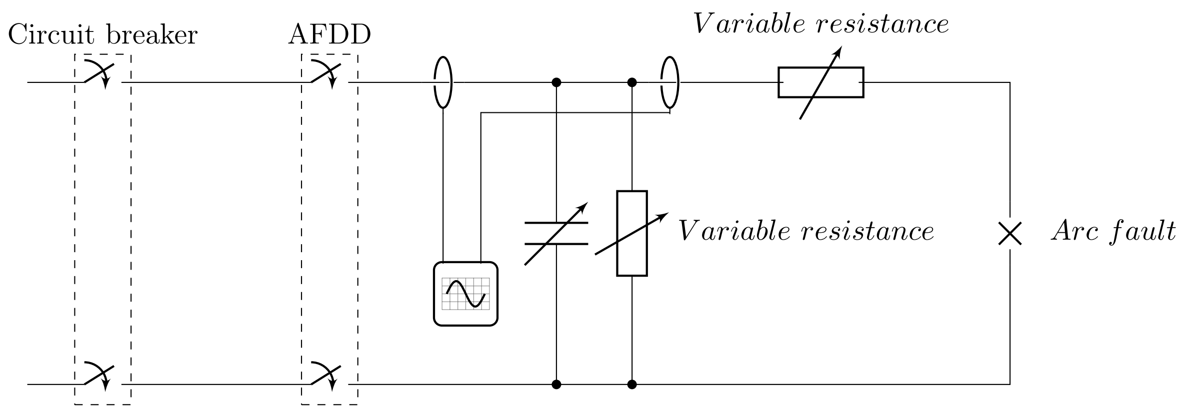
7.2 Test setup

When this test was planned, it was chosen to use a measurement setup similar to that of *small arc fault current to load current ratio test* from section 5.2. This made it possible to make comparisons between the results of both tests. An arc current of 5.0A and a parallel branch current of 5.0A were used.

The different circuit parameters used in the tests are shown in Table 7.1 and a circuit diagram of the test circuit below the table. To produce arcs, preconditioned cable samples were used, controlled by the relay box and two switches, as shown in Appendix B. To record the current as seen by the AFDD's, an oscilloscope with current probes was used. A diagram of the test circuit is shown in Circuit no.4

Table 7.1: Table of currents, resistance and capacitance used when testing for capacitance masking of series arc

Arc current	**Parallel current**	**Total resistance**	**Capacitance**
5.0 A	5.0 A	20 Ω	8 μF
5.0 A	5.0 A	20 Ω	400 nF
5.0 A	5.0 A	20 Ω	200 nF
5.0 A	5.0 A	20 Ω	100 nF
5.0 A	5.0 A	20 Ω	80 nF



Circuit no.4: Test circuit for parallel capacitive masking

7.3 Measuring procedure

This test was performed to see if the parallel capacitance in the circuit interfered with the ability of AFDD's to detect and disconnect on series arcs. Disconnection times were recorded for each test and each device was tested for each capacitance value a total of 10 times. The devices were tested five times in succession and then further tested five more times. To record the disconnection times and perform a further analysis of the time and frequency domain, an oscilloscope with two current probes was used. To limit the wear on cable samples, the maximum arcing time was limited to 4.0s.

7.4 Results

7.4.1 Waveform comparison

The left side of Figure 7.1 shows a comparison between one period of the total current before arcing occurred, the total current during arcing without capacitance, and the total current during arcing with a capacitance of 80nF. The right side of Figure 7.1 shows the same comparison, but with a capacitance of 8μF. These capacitance levels are respectively the lowest and highest capacitances used during testing. By comparing the waveform of subsection 5.4.4 with the same current ratio, with the highest and lowest capacitance levels, any changes due to capacitance should be observable. When this comparison was performed, it showed no clear difference in the current waveform. The shoulder caused by the current zero crossing also shows a behavior similar to the previous test, with a less noticeable shape. There is still a clear decrease in the amplitude of both waveforms.

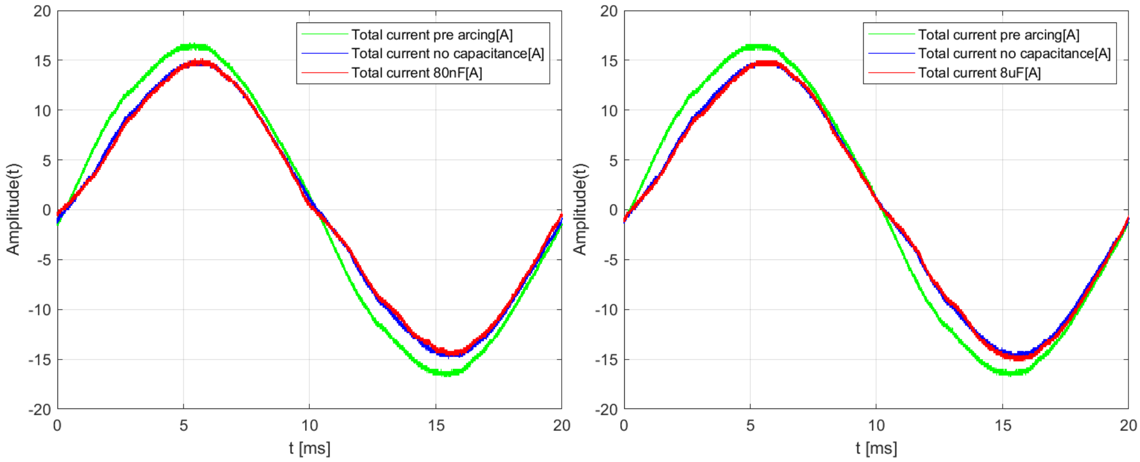


Figure 7.1:
Left side: Plot of oscilloscope recording of 5A arc current and 10A total current (1.0 ratio) with a 80nF capacitor in parallel, during arcing with a charred cable sample.
Right side: Plot of oscilloscope recording of 5A arc current and 10A total current (1.0 ratio) with a 8μF capacitor in parallel, during arcing with a charred cable sample

The total current during arcing will naturally vary some from period to period. Therefore, the comparison of one period is not necessarily the most informative way of comparing. Figure 7.2 shows a four-period comparison of the total currents during arcing with no capacitance, 8μF and 80nF connected in parallel. The comparison of the four periods further shows that there is no clear visible difference between the total current with different capacitance levels.

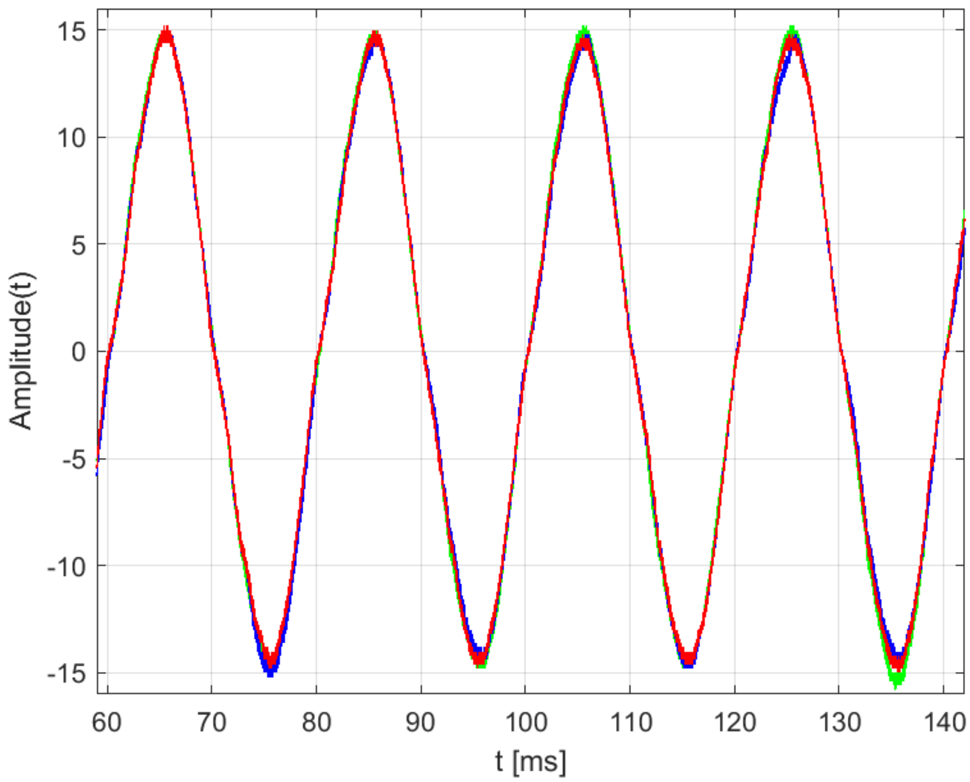


Figure 7.2: Comparison of 4 periods of the total current while arcing. Green is without capacitance, blue is with a 8μF capacitor and red is with a 80nF capacitor, legend was omitted for visibility

7.4.2 Frequency spectrum comparison

When looking at the power spectrum distribution in Figure 7.3 which compares the highest with the lowest capacitance, it is apparent that the 1st harmonic 50 Hz, 3rd harmonic, 5th harmonic and 7th harmonic contains the largest amplitudes in the current. For frequencies between 1kHz and 70 kHz, the amplitudes are reduced and reach the zero point of approximately -75dB, which continues until a frequency of 25 MHz, the threshold for the sampling rate that was used. It is apparent that both spectrum's are similar in shape and have equal characteristics, and there are no observable differences caused by the change in capacitance.

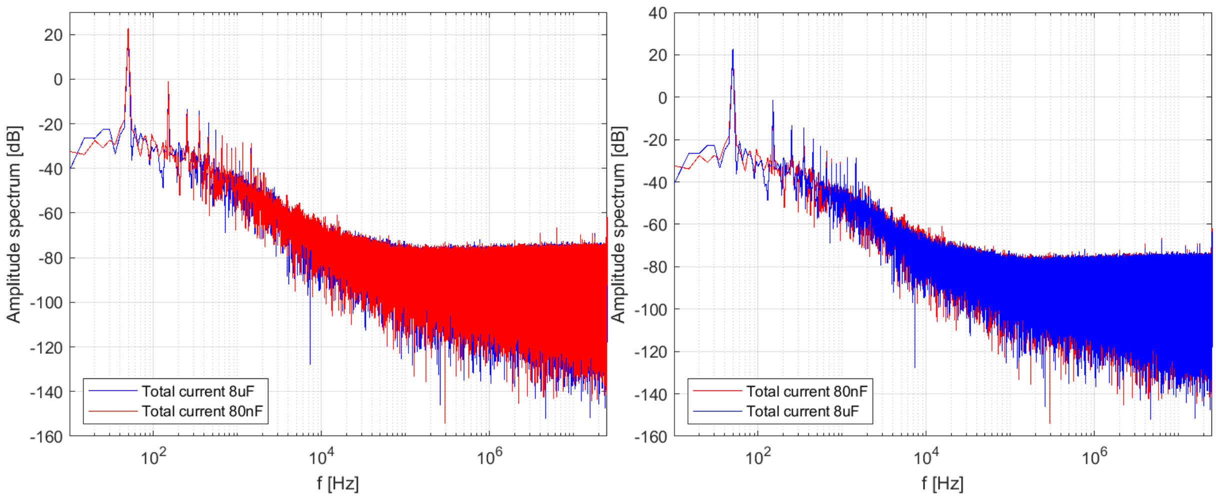


Figure 7.3:
Left side: Frequency spectrum comparison of the total current in the circuit when arcing occurs with 8μF capacitor and 80nF capacitor.
Right side: Same as left side with opposite order

In addition, a comparison between the total current with the two different capacitances and the total current of the same circuit without capacitance is made in Figure 7.4 and Figure 7.5. This further shows very little difference between arcing without capacitance in the circuit and arcing with capacitance in the circuit. There is no apparent cutoff in the frequency spectrum and there are no other signs of noise filtering.

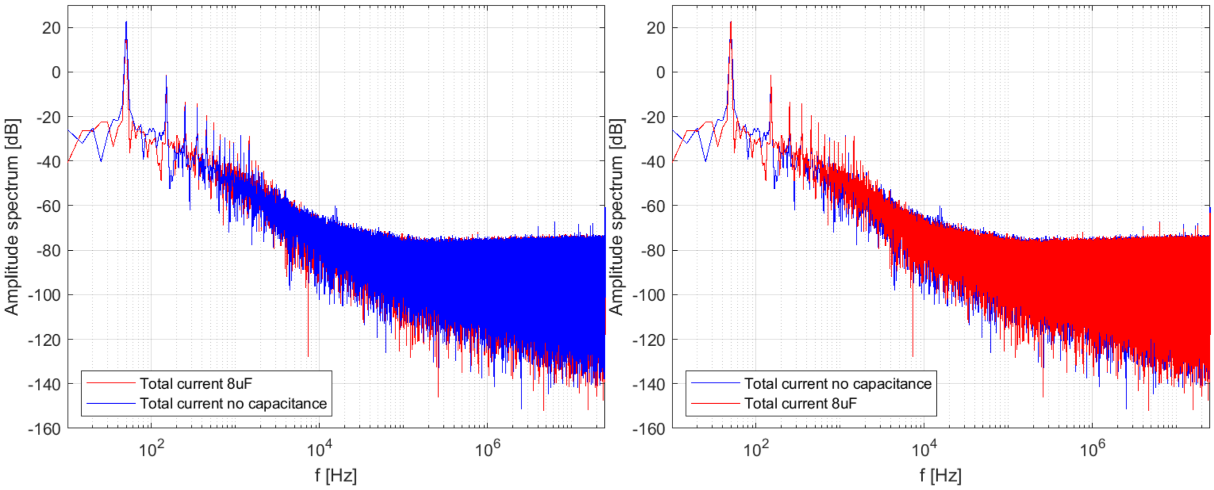


Figure 7.4:
Left side: Frequency spectrum comparison of the total current when arcing occurs with no capacitance in the circuit and with a 8μF capacitor.
Right side: Same as left side with opposite order

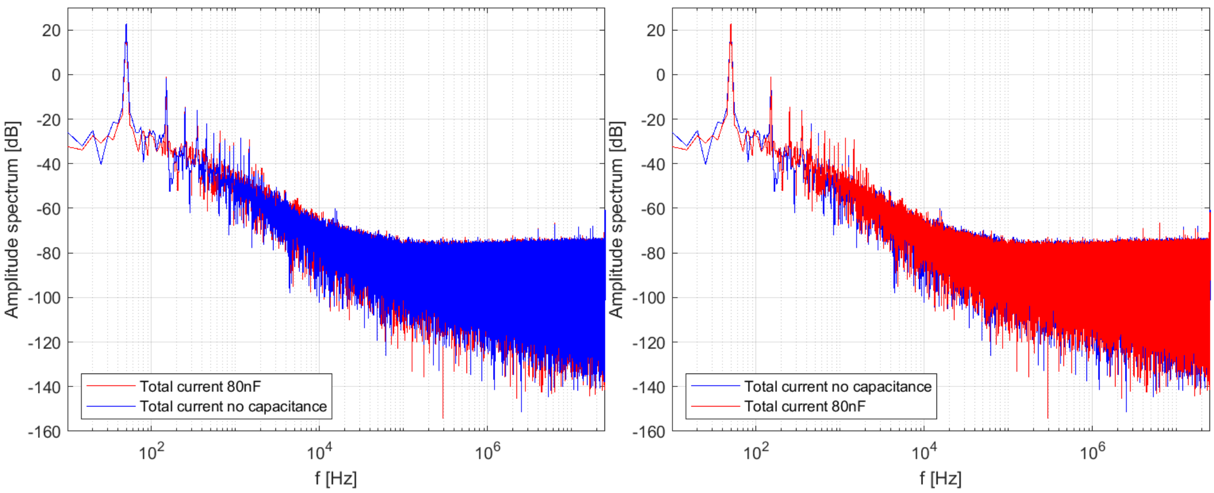


Figure 7.5:
Left side: Frequency spectrum comparison of the total current when arcing occurs with no capacitance in the circuit and with a 80nF capacitor.
Right side: Same as left side with opposite order

7.4.3 Spectrogram

Spectrograms showing the frequency power in the arc current and the total current of 10 periods are shown in Figure 7.6. The figure on the left shows the current ratio 1.0 and a 80nF capacitor in parallel, the right shows the same current ratio but with an 8μF capacitor in parallel. Both figures in the top row are measurements of arcing current, which clearly shows that the noise decreases when the zero crossing occurs, this is not visible in the bottom figures. The figures in the bottom row are of the total current and show a decrease in detectability of the change in HF noise. The figures of the total current have a slight change in the color map in the attempt to make any slight sign more visible, but no change in the frequency power is noticeable in correspondence to the zero crossing of the half periods seen in the bottom of the figures.

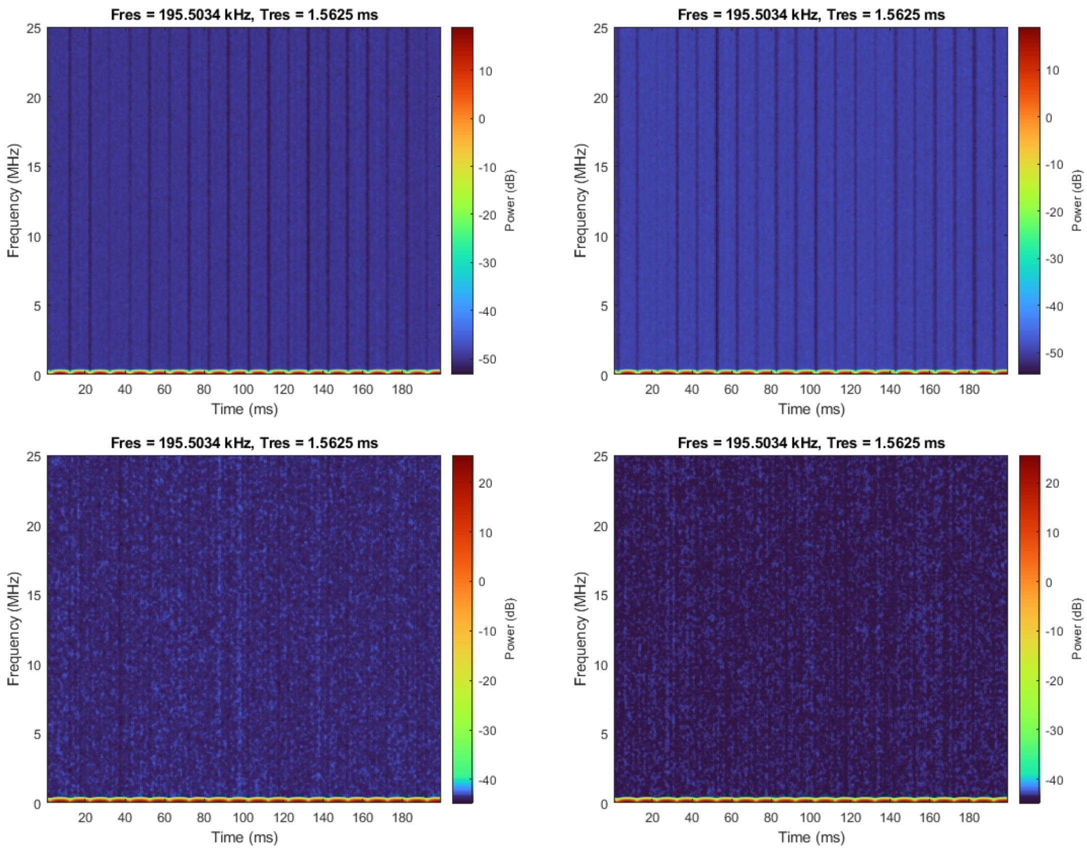


Figure 7.6:
Left side: Spectrogram of frequency power, arc current and total current measurements from current ratio 1.0 and 80nF capacitor in parallel with arcing from a charred cable sample.
Right side: Same type of spectrogram but with a 8μF capacitor in parallel

7.4.4 AFDD performance

Table 7.2 shows the number of times the device disconnected during the 10 tests conducted on each capacitance level. The only device that failed to disconnect during the test was Device 2, so the decision was made to perform the same tests on a new device from the same manufacturer. The new device had characteristics identical to those of the previous device and showed similar behavior. The last column of the new device was left empty because tests without capacitance were not performed with this device.

Table 7.2: Table of number of times the device detected arcs during 10 tests with each capacitance value. Failure to detect was chosen as a disconnect time longer than 4 seconds

Capacitance	Device 1	Device 2(a)	Device 2(b)	Device 3	Device 4
8 μF	10/10	6/10	7/10	10/10	10/10
400 nF	10/10	6/10	8/10	10/10	10/10
200 nF	10/10	6/10	8/10	10/10	10/10
100 nF	10/10	7/10	9/10	10/10	10/10
80 nF	10/10	10/10	8/10	10/10	10/10
0	10/10	10/10	-	10/10	10/10

The average disconnect times calculated from the recorded disconnect times are shown in Table 7.3. The test was carried out with different capacitance levels in the circuit. The results are compared with the results of the *Small arc fault current to parallel load ratio* test from subsection 5.4.4. Average disconnection times were calculated using only the successful disconnections of the devices.

The results show that Device 1 exhibited a reduction in average disconnection time when a capacitance was introduced in the circuit compared to the results of the test without capacitance. However, these disconnection times do not appear to have any correlation with the increase in capacitance. The average times also had a larger variation than expected.

In contrast, Device 2 exhibited an increase in the average disconnection time upon the introduction of a parallel capacitance. However, the average times varied randomly with the different levels of capacitance and showed no clear relationship between an increase in capacitance and an increase in disconnection times. To address the fact that the device failed to disconnect on several occasions, a second device with identical characteristics from the same manufacturer was tested. The new device exhibited shorter average disconnection times on all tests, but, as mentioned, it also had several instances of failure.

Devices 3 and 4 were found to be unaffected by the presence of capacitance in the circuit. Their average disconnection times remained constant irrespective of the capacitance level, similar to that of the test without capacitance.

Table 7.3: Table of average disconnection times during 10 tests with each capacitance value, the times without capacitance are from the *Small arc fault current to parallel current ratio* test with equal current ratio

Capacitance	Device 1	Device 2(a)	Device 2(b)	Device 3	Device 4
8 μF	0.12 s	0.39 s	0.18 s	0.21 s	0.09 s
400 nF	0.37 s	0.49 s	0.29 s	0.21 s	0.09 s
200 nF	0.17 s	0.95 s	0.11 s	0.21 s	0.09 s
100 nF	0.17 s	0.95 s	0.11 s	0.21 s	0.09 s
80 nF	0.28 s	0.38 s	0.10 s	0.21 s	0.09 s
0	0.68 s	0.11 s	-	0.24 s	0.10 s

7.5 Discussion

The detection of series arcs by measurement of HF noise in the current and identification of arcing based on elevated power levels in this noise seems to be the main method used by AFDD's. Series arcs develop noise in a broad frequency spectrum up to 1 GHz, as mentioned in section 2.3. This identification method is speculated to be vulnerable to influence from circuit elements, such as capacitors, that store and release energy. Rapid changes in energy can be provided by the capacitor and therefore possibly mask the series arc fault from the arc detecting device.

Earlier dissertations like M. Fagerås[8], and G. Alqabbani[10] have conducted experiments with capacitances or capacitive equipment in order to find influence on the detection rate and if any eventual cutoff frequencies cause detection failure. These tests showed that some manufacturer's AFDD's were sensitive to the influence of capacitance or capacitive equipment, but they did not look further into why they were influenced.

7.5.1 Waveform comparison

Efforts were made to examine the oscilloscope recordings to look for any detectable variation in the waveform and high-frequency noise measured by the AFDD's when capacitance was included. Comparison of total current waveforms during arcing with different capacitance values did not show any noticeable difference. It was expected to show some signs of discharging from the capacitor during the decreasing half of each half-period, but this was not noticeable. The reason could be that there simply is not enough energy stored in the capacitance to make a noticeable difference between the two loads. It could have been beneficial in regards to this test to remove the parallel branch and use lower resistance, then perform a new test to better see if the capacitance then would have a larger impact on the waveform. This would make the test case less realistic with regard to real loading scenarios, but it could better display any impact.

7.5.2 Frequency spectrum comparison

M. Fagerås[8] suggested that the parallel capacitor in the circuit acts as a lowpass filter, this type of analysis can demonstrate whether this assumption is correct. If the suggestion is correct, it was expected to see a reduction in the amplitude spectrum after the cutoff frequencies of the circuit. A simple assumption would be that the resistive elements of the circuit are constant, which is not entirely true, with the obvious error being the resistance of the arc. If following the assumptions of M. Fagerås, the cutoff frequency would only change with different levels of capacitance as the resistance would be constant. Comparing the largest capacitance with the smallest capacitance should give an indication of whether the capacitance in the circuit acts as a lowpass filter or not, or influences detection of arcing in any other way.

A Fourier transform was performed to make the frequency spectrum representation of the recorded waveform to look for this change in high-frequency noise. In the results obtained from the FFT it was hard to notice any difference when the capacitance was changed. This agrees well with the observations of P. Müller et al[5] shown in subsubsection 2.3.4.2. Nor could they detect any change in the frequency spectrum when capacitors were connected in parallel to the arcing fault. One point that was raised was the frequency response of the current probes that they had used. For the experiments carried out in this test, the current probe used was chosen to be able to measure an adequate frequency.

There is still a possibility that the FFT transform of recordings from an oscilloscope is not optimal when looking for changes at high frequencies. Although the measuring equipment used should be adequate, there was still a lot of high-frequency noise noticeable in the recorded waveforms. When studying the recorded files, it was noticed that the amplitude could fluctuate between 50 and 200 mA from sample to sample depending on the amplitude. This deviation in amplitude certainly could have an impact when transforming to the frequency domain.

7.5.3 Spectrogram comparison

As shown in section 2.3 the frequency spectrum from 20-25 MHz is used for detection purposes because the background noise level is lower and the noise produced by the series arc can be distinguished. When the arcing current was transformed and viewed as a spectrogram, the cutoff in HF noise could have been visible. This was not the case, as seen in the results section. The arcing current figures show clear signs of change in the noise amplitude when zero crossings occur, but the noise level does not decrease at a specific frequency. In addition, it was not possible to detect the zero crossings and the corresponding change in HF noise in the figures of the total current.

A better representation of the effect of capacitance could probably have been done if the parallel resistance circuit had been omitted and only a parallel capacitance had been used in the circuit. It seems that the additional current from the parallel branch has the biggest impact on the HF noise. But this also indicates that the influence of this extra current has an impact on the detectability of arcing.

7.5.4 AFDD performance

The comparison showed that two of the manufacturers were affected by the capacitance, while the other two were not. No correlation was observed between the change in capacitance and the change in disconnection times, but one of the devices performed worse with respect to arc detection when capacitance was included in the circuit. The device of this manufacturer was changed with another identical device to see if the results were similar. When the new device was tested, it performed similarly to the previous one, indicating that the performance of devices from this manufacturer is negatively influenced by the capacitance in the circuit.

Chapter 8

Disturbing load, switch mode power supply

8.1 Background

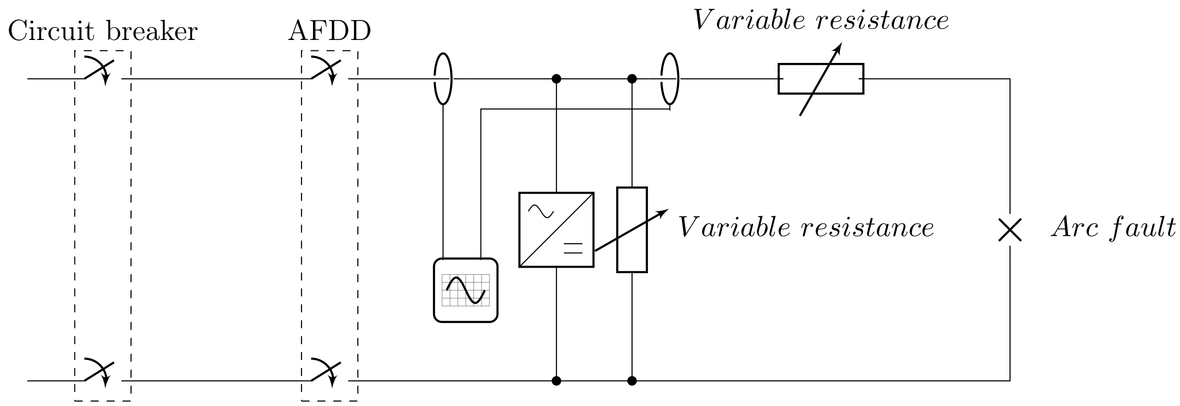
Electronic loads, such as power supplies, can cause distortion of the input current as a result of the electronic components they are made up of. This current distortion causes changes to the total waveform seen by the AFDD, and it is of interest to investigate whether these distortions cause any issues for the AFDD in detection of series arcs. This test will be conducted to see how these devices manage to detect series arcs while a power supply is connected as a parallel load in the circuit.

8.2 Test setup

The experimental setup consists of the enclosure containing the different AFDD's, a resistive parallel load, and the arcing cable sample series connected with a resistive load. The switch mode power supply was connected as a separate parallel load. The circuit parameters are shown in Table 8.1. The test was conducted with several arc current to parallel current ratios to see if a higher percentage of arc current had any influence on the detection rate and disconnection times. The ratios used are similar to the *Small arc fault current to parallel current ratio* and allowed the results to be compared with subsection 5.4.4. An oscilloscope was used to record the total current as seen by the AFDD and the arcing current. The time to disconnect was also obtained from the recordings. The circuit diagram is shown in Circuit no.5.

Table 8.1: Parameters of the test circuit

Arc load to parallel load ratio	**Parallel current**	**Arcing current**	**Power-supply current**
0.25	10.0 A	2.5 A	2.2 A
0.5	5.0 A	2.5 A	2.2 A
1.0	5.0 A	5.0 A	2.2 A
No parallel load	0 A	2.5 A	2.2 A



Circuit no.5: Test circuit for power electronic converter as load

8.3 Measuring procedure

To test whether the power supply influences the AFDD's ability to detect series arcs, the circuit was tested with several different load configurations. The configurations consisted of different parallel load current to arc current ratios, together with the parallel connected SMPS. The different configurations are shown in Table 8.1 and each device was tested 10 times for each circuit configuration. The test was conducted as the other tests with five attempts on each device before moving to the next, then testing every device five more times.

The use of preconditioned cable samples as an arc source dictates, according to IEC 62606 that the devices should disconnect within 0.5s at an arc current of 5.0A and within 1.0s for an arc current of 2.5A. To catch delayed disconnections, but avoid excessive wear on the cable sample, the arc was maintained for up to 4.0s.

8.4 Results

8.4.1 Waveform comparison

The current drawn from the switch-mode power supply will distort the total current, as illustrated in Figure 8.1 which shows the current waveform captured when the circuit only consisted of the arc branch and the SMPS. Before arcing, the total current and the power supply current can be seen in the figure on the left. The distortion of the total current is evident and is similar to what is observed during arcing. The figure on the right displays the total current while arcing and the arcing current with the SMPS connected as parallel load. The most obvious alteration is the reduction in current amplitude that takes place during arcing.

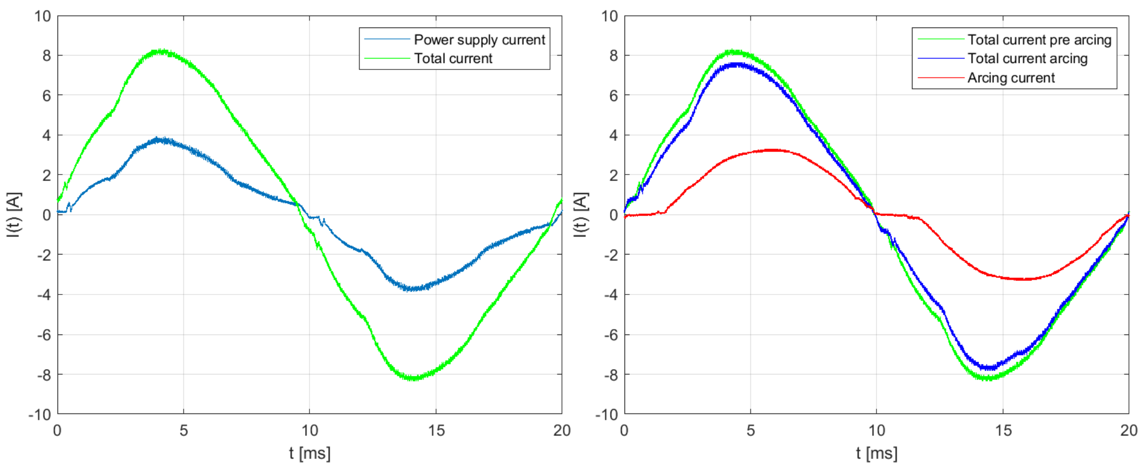


Figure 8.1:
Left side: Plot of total current and power supply current.
Right side: Plot of total current and arcing current with only the SMPS connected as parallel load

Figure 8.2 illustrate the total current and the arcing current with a parallel connected power supply and two different current ratios. The figure on the left shows the arcing current to parallel load current ratio of 0.25, and the figure on the right shows an arcing current to load current ratio of 1.0. In both figures, it is difficult to observe any clear signs of arcing in the total current, most notably the decrease in the total current amplitude when arcing occurs. The typical shoulder or quick increase seen in the total current in previous chapters caused by the current zero crossing of the arc current is hard to detect.

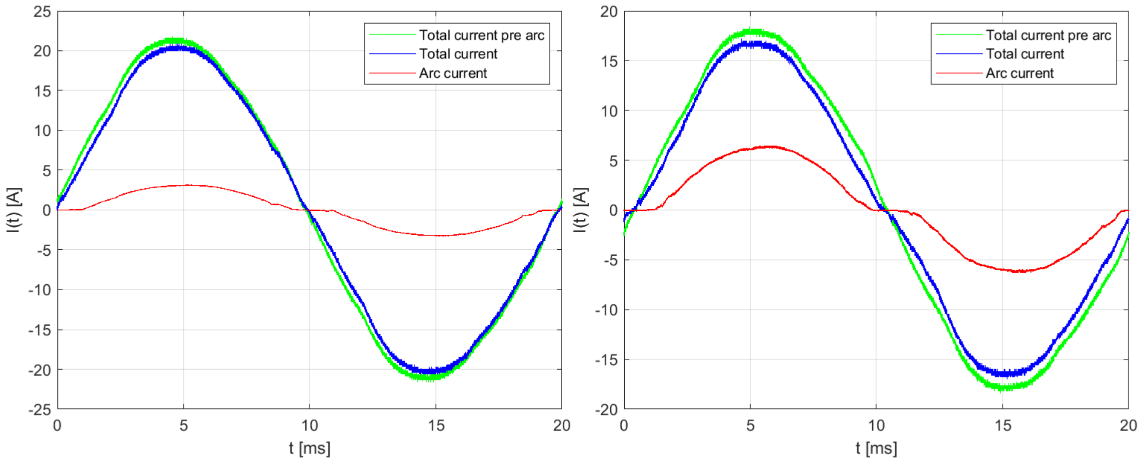


Figure 8.2:
Left side: Plot of the captured current waveforms with a arc current to parallel branch current ratio of 0.25, with the power supply connected.
Right side: Plot of the captured current waveforms with a arc current to parallel branch current ratio of 1.0, with the power supply connected

Figure 8.3 illustrates the total current before and after arcing, as well as the total current after arcing with the power supply connected in parallel for a current ratio of 0.25 on the left side and 1.0 on the right side. The current without power supply was adjusted with an increased parallel load current to compensate for the power supply current. For the current ratio 0.25, it is difficult to detect any clear differences in the waveform. However, for the current ratio 1.0, it is evident that the total current with the power supply connected exhibits fewer signs of the current zero crossing. This is visible at the start of the first half period when the amplitude is increasing, and the peak amplitude is also reached earlier.

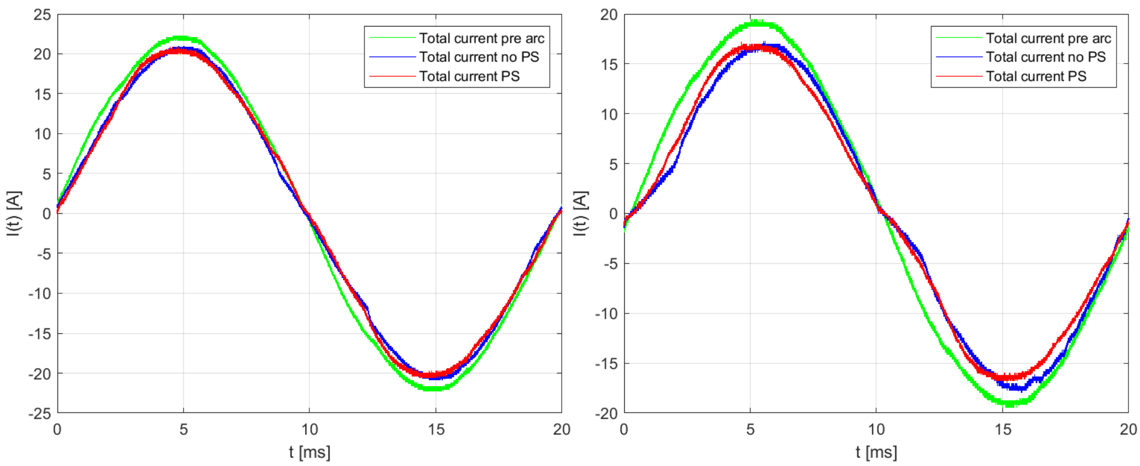


Figure 8.3:
Left side: Plot of the captured current waveforms with a arc current to parallel branch current ratio of 0.25, with and without a power supply connected.
Right side: Plot of the captured current waveforms with a arc current to parallel branch current ratio of 1.0, with and without a power supply connected

8.4.2 Frequency spectrum comparison

The distortion made by the SMPS to the current waveform should be visible as increased amplitudes at different frequencies compared to a circuit without an SMPS. Figure 8.4 show a comparison of the test circuit with and without an SMPS. Both recordings were of the total current in the circuit and were taken before arcing occurred. The blue plot represents a current of 5.5A without the SMPS, and the red plot represents a total current of 7.7A with the SMPS having a current of 2.2A. It can be observed that the circuit influenced by the power supply has a higher frequencie amplitude in the frequency band between 2kHz and 70kHz. The third harmonic frequency is also seen to be elevated by approximately 20dB, which corresponds to a 10 time increase in amplitude. The rest of the odd harmonic frequencies were also elevated in comparison. There was no noticeable difference in the higher frequency band between 80kHz and 20MHz.

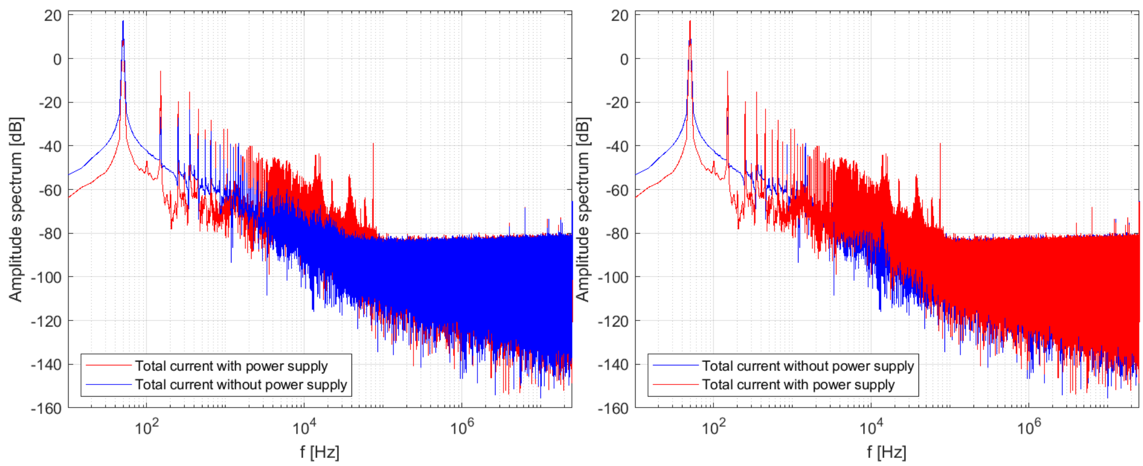


Figure 8.4: *Left side:* Frequency domain comparison of the circuit before arcing occurs but with and without a power supply.
Right side: Same as left side with opposite order

To check if any difference was noticeable when a series arc occurred in the circuit, the same circuit was tested with the addition of an arcing branch. Figure 8.5 shows the amplitude distribution in the frequency spectrum before and during arcing when the total current was 9.7A, with the SMPS drawing 2.2A. First, when comparing Figure 8.4 and Figure 8.5 it is noticeable that the elevated amplitudes seen between 2kHz and 70kHz have been reduced. A further comparison of the arcing and non-arcing cases in Figure 8.5 shows little difference in the distribution of amplitude in different frequencies. In the recording with series arcing, the amplitudes in the frequency band from 100Hz to 1kHz were generally higher, but the odd harmonics seem to have had the same power before and after arcing. In the frequency range above 1MHz no difference is noticeable.

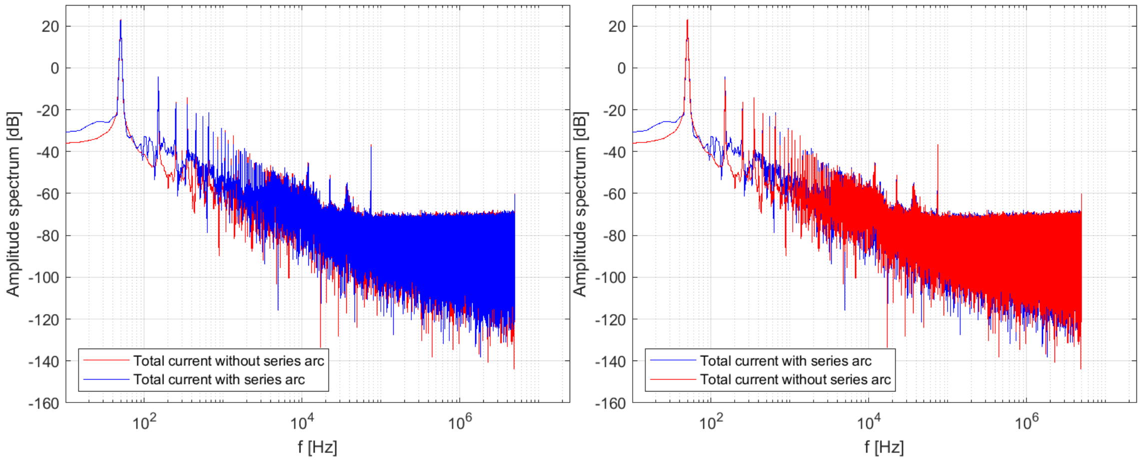


Figure 8.5: *Left side:* Frequency domain comparison of the circuit with power supply. but with and without arcing
Right side: Same as left side with opposite order

Figure 8.6 shows how the frequency amplitude spectrum changes with different current ratios during arcing with the power supply connected in parallel. From the figure it is apparent that the amplitude spectrum's are similar for both current ratios. There were no big differences in the amplitudes of the different frequency components. A peak in frequencies around 15kHz can be observed in the amplitude spectrum at 1.0 current ratio, which was missing in the amplitude spectrum of the 0.25 current ratio. In the frequencies above 1MHz the 0.25 current ratio had slightly higher amplitudes and an increase can be observed near the edge of the plotted are of 25MHz.

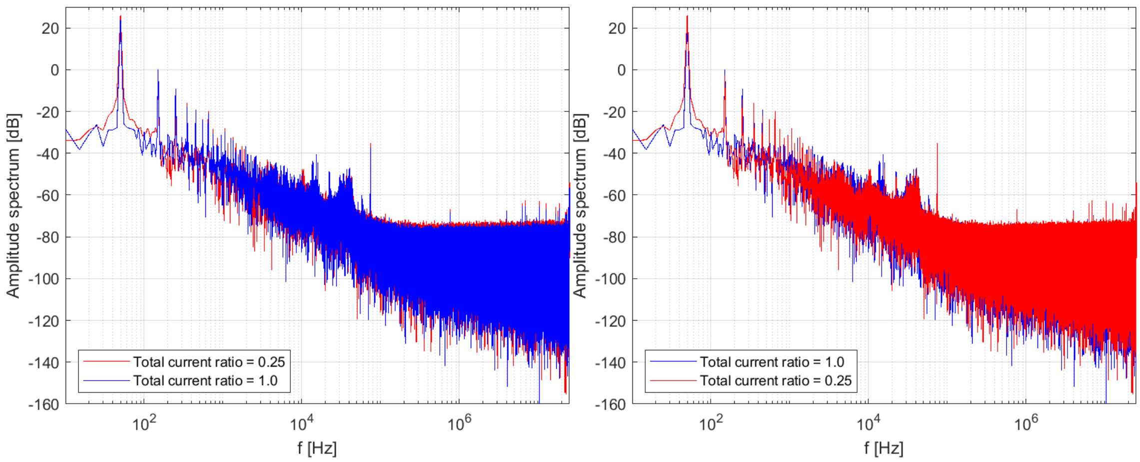


Figure 8.6: *Left side:* Frequency domain comparison of the circuit during arcing with power supply. 0.25 and 1.0 arcing current to parallel load current ratio.
Right side: Same as left side with opposite order

8.4.3 Spectrogram

The spectrograms in Figure 8.7 illustrate the frequency power of the arc current and total current with a parallel connected SMPS at two different current ratios. On the left side, a 0.25 arc current to parallel load current ratio is shown, where the zero crossings are clearly visible in the arc current measurement, but not in the total current. On the right side, a 1.0 arc current to parallel load current ratio is represented, where the zero crossings are also visible, but the arc current exhibits a higher noise power level between the zero crossings compared to the 0.25 ratio. In the total current representation at the bottom, the zero crossing can be slightly observed, but the difference in noise power between zero crossing and arcing is small.

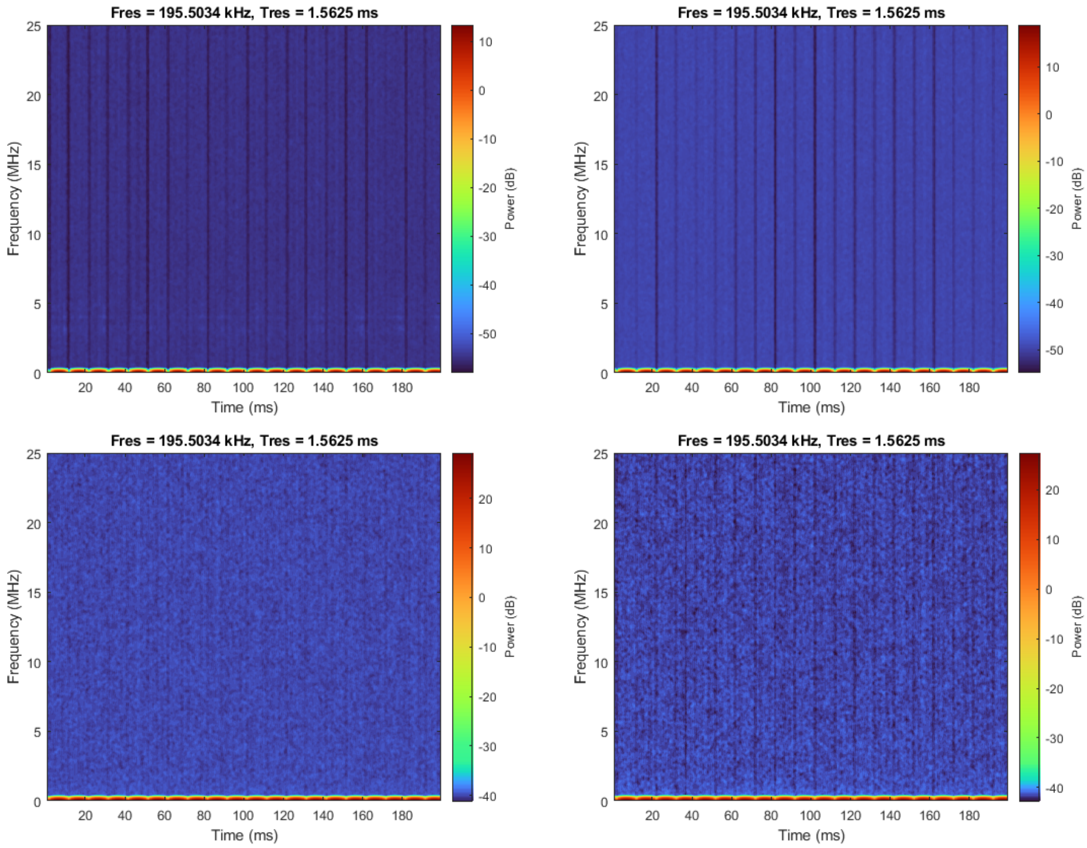


Figure 8.7:
Left side: Spectrogram of frequency power, arc current and total current measurements from current ratio 0.25 and a parallel connected SMPS, arcing from cable sample.
Right side: Same type of spectrogram but with a current ratio of 1.0

8.4.4 AFDD performance

The results of the tests where a switch-mode power supply(SMPS) was used to hide the signs of a series arc fault are presented in Table 8.2 and Table 8.3. Table 8.2 shows the average tripping times calculated from the successful detection of arcing. Table 8.3 shows how many times the devices failed to detect arcing from the 10 tests performed on each current ratio.

Device 1 had problems consistently detecting arc faults when the power supply was connected to the circuit. On every configuration except the arcing current to load current ratio of 1.0 there were several arcs that went undetected. In the configuration with only the power supply and the arc branch, the device only detected arcing one time, and that was with a new cable sample. On the next attempt with the same sample, arcing was not detected. The average disconnection time for this configuration with this device was calculated from a single attempt. The next configuration, with a parallel load current og 10A and a arcing current og 2.5A the device had 5 successful detections, but the average time was the highest from all tests. When the parallel load current was reduced to 5A the device had six successful detections and a lower average disconnection time of 0.17s. In the last configuration with a 5A parallel load current and a 5A arc current, the device detected and disconnected every arc in expected time.

Device 2 was successful in detecting all arcs in the configuration without a parallel load, but encountered problems when a parallel load was added. With an arcing current to parallel load current ratio of 0.25 the device only detected arcing three times and had a longer average disconnection time. When the parallel load current was reduced to 5.0A the device only detected the arc once. With an arcing current of 5.0A and a parallel load current of 5.0A, the devices performed better and detected every arc.

Devices 3 and 4 were mostly unaffected by the power supply and detected all arcs in all circuit configurations. The only difference was the average disconnection times, which had some variation.

Table 8.2: Table of average disconnection times when power-supply was connected to the circuit

Current ratio	Device 1	Device 2	Device 3	Device 4
No parallel load	0.63 s	0.19 s	0.37 s	0.16 s
0.25 (2.5A/10A)	1.54 s	0.73 s	0.16s	0.08 s
0.5 (2.5A/5.0A)	0.17 s	0.11 s	0.22 s	0.11 s
1.0 (5.0A/5.0A)	0.14 s	0.11 s	0.17 s	0.08 s

Table 8.3: Table of number of times the devices detected arcs during 10 tests when power-supply was connected to the circuit

Current ratio	Device 1	Device 2	Device 3	Device 4
No parallel load	1/10	10/10	10/10	10/10
0.25 (2.5A/10A)	5/10	3/10	10/10	10/10
0.5 (2.5A/5.0A)	6/10	1/10	10/10	10/10
1.0 (5.0A/5.0A)	10/10	10/10	10/10	10/10

8.5 Discussion

In a similar fashion as the previous chapter, switch-mode power supply's are speculated to be able to influence the current such that the detection of high-frequency noise is inhibited. The electronics in the power supply can produce highly distorted currents when it is loaded. The distorted current often has similarities with the current signatures produced by series arcing, and SMPS's are also equipped with filters that can remove the HF noise produced in the arc. AFDD's have to be able to distinguish between currents produced by SMPS's and current signatures produced by arcing but also reliably detect arcing when a SMPS is connected to circuits.

The problem has been raised in earlier theses and papers, as in M. Fagerås[8], G. Alqabbani[10] and J. Budzisz & M. Czosnyka[31] where the influence of electronic devices has been tested and discussed in different ways. The test performed in this thesis was designed to mimic the influence of the power supply together with other parallel loads to better imitate a real electrical installation. Several different load configurations were used, referred to as current ratios or *arc fault to parallel load current ratios.* The same ratios have been used in other tests, making the results comparable.

8.5.1 Waveform comparison

The waveform of different current ratios, together with the power supply, was analyzed in the results section. Comparisons of different current ratios showed that the signs of arcing are not very visible when the total current is measured. The only real sign in the current waveform is the decrease in amplitude when the arcing is occurring. The characteristic zero crossing shoulder was not observable, and the rapid increase in current that follows the ignition of the arc was neither. With a larger series arc current than parallel load current, this would most likely change, but as a worst case, the characteristics of small arc fault currents are harder to detect in the waveform of the current. As seen in Figure 8.3, no large change is noticebale in total current when the SMPS was added. The quick increase in current caused by arc reignition may be a little more noticeable without the power supply, but that was only visible in the 1.0 current ratio. It appears that the largest obscuring of arcing signs in the waveform is caused by the parallel connected load.

8.5.2 Frequency spectrum comparison

Fourier transform was used on some of the recorded waveforms from the total current to make amplitude spectrum comparisons. The amplitude spectrum showed a clear influence from the SMPS in the frequency band from 2kHz to 70kHz. The frequency band of interest for arc detection is higher and, as explained in section 2.3 the frequency range of 20-25 MHz is presented as the most reliable range for the detection of arcing, due to a lower level of background noise. From the comparisons made in the result section, it is not possible to distinguish arcing from background noise in the frequency spectrum. The SMPS did produce increased amplitudes at distinctive frequencies in the range of 2kHz to 70kHz, which was clearly observable in the frequency amplitude plots with and without arcs occurring. The comparison between current ratios showed that the lowest current ratio 0.25 had slightly higher amplitudes in the HF range that is used for arc detection, but it is not clear whether this has any impact on the detection of arcs.

8.5.3 Spectrogram

The spectrograms shown in Figure 8.7 showed clear signs of a change in the HF noise at current zero crossings when the arc current was measured. When the total current was measured, these signs were harder to observe. At a current ratio of 0.25, no signs could be confidently identified. However, when the ratio was increased to 1.0, the noise change was slightly visible. This current ratio consisted of an arcing current of 5A, a parallel load current of 5A, and a power supply current of 2.2A. The lower parallel load current likely explains why the change was visible in this ratio, and an increase in the ratio between the arc fault current and the parallel load current would likely make the signs even more apparent.

8.5.4 AFDD performance

Results from the test show that some devices seem to be influenced by the SMPS. The effected devices being devices 1 and 2, where a failure to detect the arc occurred several times at different current ratios. This was apparent for both devices when the arc current was lower than the parallel load current. The results from this test compared with the results from *Small arc fault current to parallel current ratio* found in subsection 5.4.5 show that the performance of Device 1 and Device 2 became noticeably worse when the SMPS was used as a parallel load. This can be seen in the 0.5 current ratio and in the 0.25 current ratio, where both devices had fewer detections with the SMPS than without it. As seen in the comparison of waveforms the signs of arcing become increasingly harder to notice as the current without fault is increasing. Device 1 also had issues detecting arcing when only the SMPS was connected to the circuit, where it might seem like the distorted current from the SMPS distorts the total current enough to hide the signs of arcing. The other two devices performed well and detected arcing within the expected time for each test.

Chapter 9

Discussion

In this chapter a general discussion about interesting and relative aspects found during the master's thesis work is presented.

9.1 Comparison of the test methods

9.1.1 Arc generator

Generating arcs with the arc generator is one of the two suggested ways to produce arcs according to the test standard IEC 62606. The arc generator allows for repeated testing and is in that regard practical to use for testing of several AFDD's, but this method did present some problems. When attempting to produce consistent arcing for longer periods, the occurrence of arcs that reignited very quickly was normal. These arcs did not display the expected zero crossing shoulder, and thus can be harder to detect. This phenomenon is referred to as sparks in this thesis. From the detection device perspective, it was a clear distinction between arcing with a characteristic zero crossing and sparking with the shorter zero crossing. Devices 2, 3 and 4 did not recognize sparking as a fault that would cause disconnection.

The origin of sparking is assumed by the author to be caused by short distances and the use of the carbon graphite electrode that has thermionic properties. This is assumed to create adequate conduction in the air gap between the electrodes, causing the electric breakdown strength of the air gap to be reduced. The reduced zero crossing time caused by this could potentially have an effect on arc detection, as seen in section 4.4. Another possible explanation is the potential similarity between sparking and the current from equipment that the device is programmed to discriminate. The arc resembling currents are often seen from electric drills with brush motors, electronic dimmers and vacuum cleaners.

9.1.2 Contact arc generator

Contact arcing is one form of arcing that is not tested for according to IEC 62606. As seen in subsection 2.1.7 it can be assumed that the energy dissipated from a contact arc in air is less than that from a series arc occurring in a cable and thus less severe. Contact arcing could also be a source of unwanted disconnection caused by switches and relays.

As shown in section 6.4 the detection of arcs made by the contact arc generator when only the arcing branch was connected was initially bad across all the AFDD's. The lower arc stability caused by the contact arc generator was too low for persistent detection. This changed when a parallel load was connected, and the detection rate increased a lot. It was also found that an arcing half-period should occur approximately every eight period for the device to disconnect. This is probably a good solution to avoid wrong detection, but it can also hinder the ability of the devices to detect arcing in loose connections.

9.1.3 Cable samples

Arcing produced in a preconditioned cable sample is the last arcing method tested in this thesis and is also one of the two methods proposed in IEC 62606. This method resembles the most severe kind of series arcing with respect to fire hazard because the energy dissipated from arcing in a cable is much higher, as seen in the example presented in subsection 2.1.7.

The test standard IEC 62606 requires that cable samples be changed after every arcing test. This was not practiced in this thesis because some variability of the arc was desired, but can have had influence on the result. The use of one cable sample numerous times resulted in a less recognizable waveform of the arcing current. The longer current zero crossing shown when the arc extinguishes and reignites becomes less visible. Arcing was still observable in the cable sample, but the fact that the current zero crossing became shorter implies that the breakdown of the charred gap occurred at a lower voltage. The effect on each device's capacity to detect arcs was different, since it was evident that Device 3 and Device 4 did not have any issues, but Device 1 and Device 2 did. This could be one of the reasons why devices 1 and 2 performed worse than expected.

It is possible that using the cable sample multiple times eventually creates an unrealistic arc current and therefore is a poor representation of real arcs occurring in electrical installations. Evaluation of the realism of the arc current was not considered before testing, and without knowing the specifics of how each AFDD works, it is impossible to know if the arcs that are produced by the worn cable samples are considered as arc resembling loads or simply not recognized as arcs by the AFDD's that failed to trip. The implementation of arc detection seems to be different between the different manufacturers, and since some manufacturers detected these arcs and others did not, it should give some reassurance to the validity of the tests. What is more problematic is whether the circuit configuration or the arc generation method is the reason for the failure to detect arcing occurrences. Due to the uncertainty with respect to the arcs, it is hard to know to which degree the circuit configuration is disturbing the detection.

Since the tests performed in this thesis do not directly comply to the test standard, and the goal was to expose the AFDD's to other conditions than what the standard does, it is a possibility that the arc created simply is not recognized as arcs. This raises the question of whether the series arcs that were made were a bad representation, or if some of the devices are tuned at a too high degree for detection of series arcs as they are tested against in IEC 62606.

9.2 Testing method

The procedure used to test the AFDD's involved testing each device 5 times sequentially, followed by 5 additional tests on each device. When the arc generator was used, this test method gave a good balance between time consumption and degradation of the carbon electrode. Ensuring that the carbon electrode was leveled before the 5 tests on each device was performed gave comparable results for each device. When switching to testing with cable samples, the same care was not taken with the samples. The cable samples were used until they no longer could arc, either because a high resistance path would be created or because the charring would erode and make a gap large enough to prevent arcing. The decision caused more variance in the series arcs and made them not as defined as in the test standard. This could again better resemble some of the variance of real situations. With this approach, some of the control of the testing did get lost, and other possible analyses could have been done with another approach. For example, if an approach similar to that of the arc generator was used, an estimate of how many arcs could be made from one cable sample before a specific device could no longer detect it could have been made. It would also give a little more structure to the testing and make the performance of each device even more comparable.

Because of the way the cable samples were used, it could have been a good idea to also perform tests with one of the other arc generation methods. This would have shown if the test results were caused only by the cable sample or if the circuit parameters also had a greater influence. At this point it is tough to know if the devices that failed to trip failed because of the arc generation method or because of the circuit elements that were added.

Other test methods that could have been used include testing each device one time after another. This would have increased the testing time, but it could possibly better have distributed the wear on the cable sample in a different way. Unfortunately, it could also have introduced bias in the results if some devices always had longer tripping times or if one device always was tested first with a new sample.

The test procedure used necessitates a large enough number of measurements. In this thesis, the number of measurements per test was ten for each device. Ten attempts may be too few to get an accurate representation of the performance, but at the same time, these devices are sold as a finished product that should work consistently to protect the circuits they are installed in.

9.3 Verification method

The used of time domain recordings and the amplitude frequency spectrum did not give the expected results. It was expected to see noticeable differences in both the amplitude spectrum and the time-domain recording when the circuit parameters were changed. The amplitude spectrum was expected to show differences in amplitude at HF ranges when the devices had problems with detecting arcs and this was supposed to be used as a way to verify that the influence from the circuit was affecting the detection.

After the data had been processed it was apparent that the use of FFT to compute a frequency domain representation of the time domain recording did not give a good estimation of the HF content of the arc current. There can be multiple reasons that caused this, but first and foremost the high-frequency content is many times smaller in amplitude and energy than the fundamental frequencies, and easily influenced by background noise and measuring inaccuracies. Although care was taken to use a sufficient sampling rate and take a sufficient number of samples to display the HF range through an FFT, the results were not satisfying. Another reason could have been the lack of low-pass filtering at frequencies above the Nyquist frequency limit. This could have caused aliasing in the recordings if the current contained even higher frequencies.

The spectrograms that were made gave a clear indication of the zero crossings in the arc branch recordings. The change in HF power was apparent in all the recordings of arcing, and in recordings of the same branch without this the change could not be observed. When spectrograms were made from the recordings of the total current, the obscuring of the zero crossings and change in HF power was apparent. This indicates that the circuit has influence on the detectability of series arcs, but not to what extent. Since a parallel load was used in most tests, it is hard to decide which parameter influences the most.

It is possible that if the accuracy of the measuring equipment was higher, the change in HF noise power would be more evident in the total current recordings. There are also several settings that can be used in the Matlab function *pspectrum*. In this thesis, no other parameters were chosen, but the use of other window parameters and other overlap values could make the identification of change in HF noise more visible. This could be further explored in future work.

9.4 Influence from parameters

Parameters such as parallel load, parallel capacitance, and loads such as switch mode power supplies has been mentioned as being able to influence the detectability of series arcs. The parallel load case of equal arc current to load current, 1.0 ratio, was used as the reference case for the other two cases. This ratio was chosen because it was the only case where all devices detected 10 out of 10 arcing incidents. During the parallel load test, the results showed that Device 2 had problems with detecting arcing for the other load ratios. It indicates that the ratio between arc current and load current has an influence on the detectability of arcing, but only one of the devices was very affected.

When testing with different values of parallel capacitance, similar results were obtained. The current ratio used in this test was 1.0, 5A arcing current, and 5A parallel load current, which all devices had performed well with. When capacitance was added, the same device, Device 2, had the worst performance with only 6 out of 10 arcs detected. The device was changed to a similar device from the same manufacturer, but it also had worse performance than expected. This also indicates that the parallel capacitor had influence on the detection of arcing, but only one manufacturer was affected by it.

The test with the switch mode power supply was performed together with different arc current to parallel load current ratios. All devices showed comparable results at the current ratio 1.0 but with decreasing ratio Device 1 and Device 2 showed decreasing performance. The results indicate that the addition of a power supply does influence the detection of arcing, but only two of the devices were affected. In this case, it must also be seen together with the current ratio, as the load current becomes larger than the arcing current, the power supply load has a larger influence. The comparison was made between *Small arc fault current to parallel current ratio* test found in subsection 5.4.5 and the results from the *Disturbing load, switch mode power supply* tests found in subsection 8.4.4. There was a noticeable decrease in the detection performance of Device 1 and Device 2 in the latter tests when comparing the current ratios.

9.5 Overview and impressions of the detection performance

It is clear from the results that two of the devices performed a lot better than the other two devices. Device 3 and device 4 were not influenced to any extent by how cable samples were used or the circuit parameters that were changed. The also displayed tripping times within the expected range for all tests that were performed. Device 1 and 2 showed several problems with arc detection for different circuit parameters. Whether this was caused by how the cable samples were used or by the circuit parameters is difficult to determine. Testing with another arc generation method such as the arc generator, could have been performed on the same circuits so that these results could be compared.

It is concerning that two of the devices worked nearly perfectly, while two others did not. Even if the cable sample is the common reason for insufficient arc detection in Device 1 and Device 2 the arcing in the cable sample was clearly visible and Device 3 and Device 4 had no problem with detecting the arcs. All devices are approved for sale, and design and detection algorithms are tested according to IEC62606. This result could be an indication of too strict tuning towards detection of arcs, as they are determined by the test standard. There is of course a fine line between discriminating the right amount and detecting the right amount, but clear arcing with ignition of the cable sample, as was observed with the cable sample used several times, should not be discriminated.

The lowest arcing current that caused disconnection was found to vary between manufacturers, Device 1 disconnected at arcing currents of 1.0A and Device 2 did not disconnect before the arcing current was 2.5A. The test standard IEC 62606 has decided on a 2.5A limit, but proposals to lower this limit due to the potential for ignition at lower currents [9]. All devices performed within the limit of IEC 62606, but not within the proposed lower limit of 1A [9].

The verification of function test presented in section 4.4 showed a lot of failed attempts from generally all devices. The author believes that these failures were caused by the sparking phenomenon discussed earlier. Inconsistencies this severe across all devices were not encountered in any of the subsequent tests. Although this test was carried out in a way similar to what is proposed in the test standard IEC 62606, it was apparent that the way the arc generator was adjusted had an impact on the results.

In general, it should be noted that the detection performance displayed by Device 1 and Device 2 falls short of expectations. If their performance in this thesis was representative of the overall protection AFDD's provide, it would not be advisable to recommend their use. The performance of the other two devices was in comparison good and suggests that their implementation would enhance fire protection. This difference in performance raises questions about the tests demanded from IEC 62606. When devices with such different performance all meet the qualifications, it causes doubt about requirements of the test standard.

9.6 Future work

This thesis has examined aspects regarding series arc detection and the functionality of AFDD's. Future work on this topic should include:

- Further testing in real installations should be done. An example of such a test could be testing in an actual installation in a house with the use of the arc generator and a resistive load. This would better take into account local conditions such as the extent of cabling, attenuation of the cables, and a variety of different parallel loads.
- Further testing the ability of spectrograms in disclosing how circuit parameters affect obscuring of HF noise and exploring the use of spectrogram analysis made from sampled recordings with Matlab to a greater extent.
- Gather long-term data from installations where AFDD's are installed. In order to make reliable conclusions about the efficacy of AFDD's in fire prevention, long-term data is essential.
- It is necessary to further investigate how parallel capacitance in the circuit affects the detection of series arcs by testing different capacitance levels. Additionally, it is important to understand why capacitance caused issues for only one of the devices.
- Due to the different detection method used by these devices, they can potentially have the ability to enhance the detection of short circuits in electrical installations with weak short circuit performance. Thus testing of the capability of AFDD's to detect arcs and short circuit in such installations should be done.

Chapter 10

Conclusions

In this master thesis, the ability to detect series arc faults during different circuit configurations has been tested. Devices from four different manufacturers were used to detect series arc, together with measurements, and analysis of the current was used to determine how severely the series arc fault was obscured. The tests that were performed have led to the following conclusions:

- The use of a frequency amplitude spectrum produced with a discrete Fourier transform was shown to not give a good indication of the change in HF noise.
- Detection of change in HF noise has been shown to be feasible by representing a time series recording as a spectrogram using a short-time Fourier transform.
- The ratio between arcing current and parallel load currents in a circuit is shown through the analysis of HF noise with spectrography and the testing of devices to have an influence on the detectability of series arc faults.
- The inclusion of parallel capacitance in the circuit was shown through testing to have an effect on the arc detection performance of one of the devices, but the underlying reason for this influence could not be determined with certainty through the methods used in this thesis.
- When a power supply was used as a parallel load in the circuit, two of the devices showed worse detection performance, but the underlying reason for this influence could not be determined with certainty through the methods used in this thesis.
- The detection rates of the four devices varied significantly. Two of them showed good performance, while the other two were affected by the presence of obscuring loads. This difference in detection capabilities leads to the question of whether the requirements in IEC 62606 are too low or if some manufacturers have tailored their devices to detect the arcs as they are suggested by the test standard.
- The lower detection threshold for the detection of arcing currents varied between manufacturers. The lowest registered threshold was 1.0A, the highest threshold was 2.5A.
- Detection of glowing contacts was not tested, but the results from the contact arc testing lead to the conclusion that contact arcing as a precursor to glowing contacts can be detected.

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Appendices

A - Results from tests with arc generator

A1 - Small arc fault current to parallel current ratio test

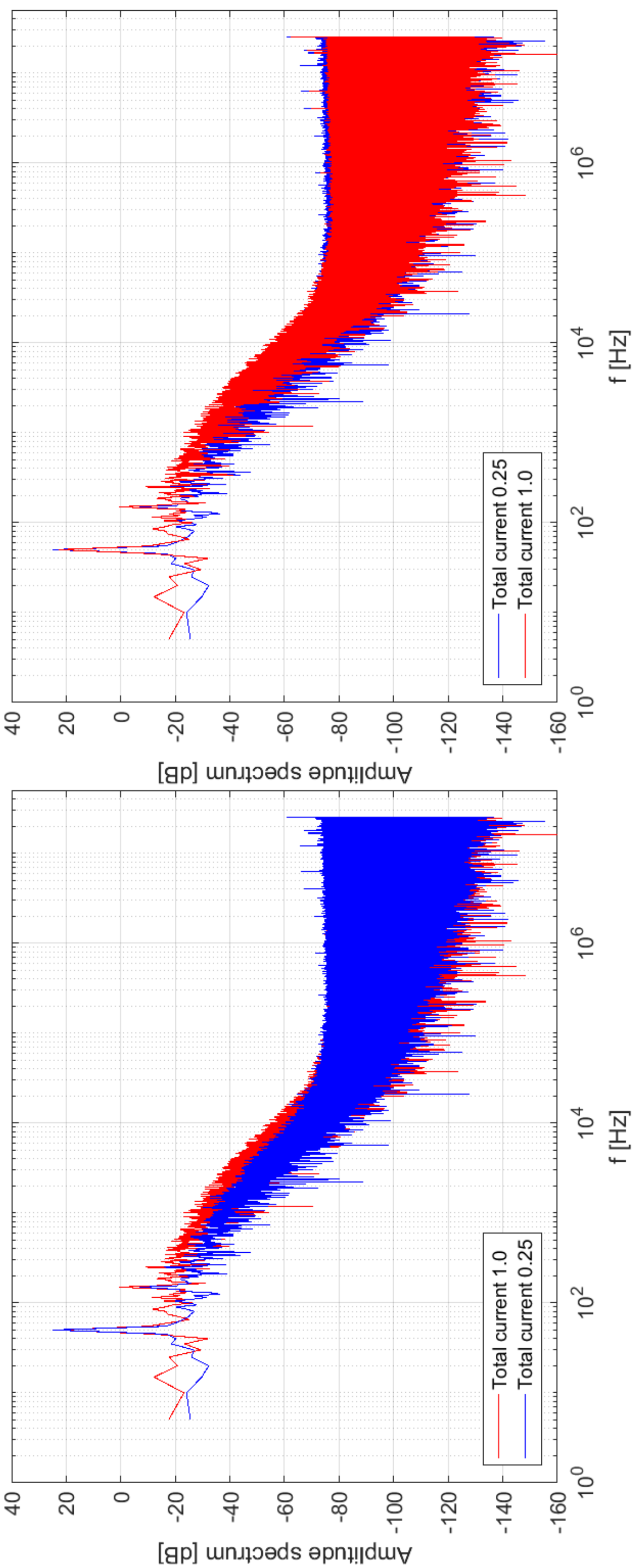

Figure A1.1:
Top: Plot of frequency amplitude spectrum, measured total current with arcing from arc generator with current ratio 0.25 and 1.0.
Bottom: Same as left side with reverse order of plots

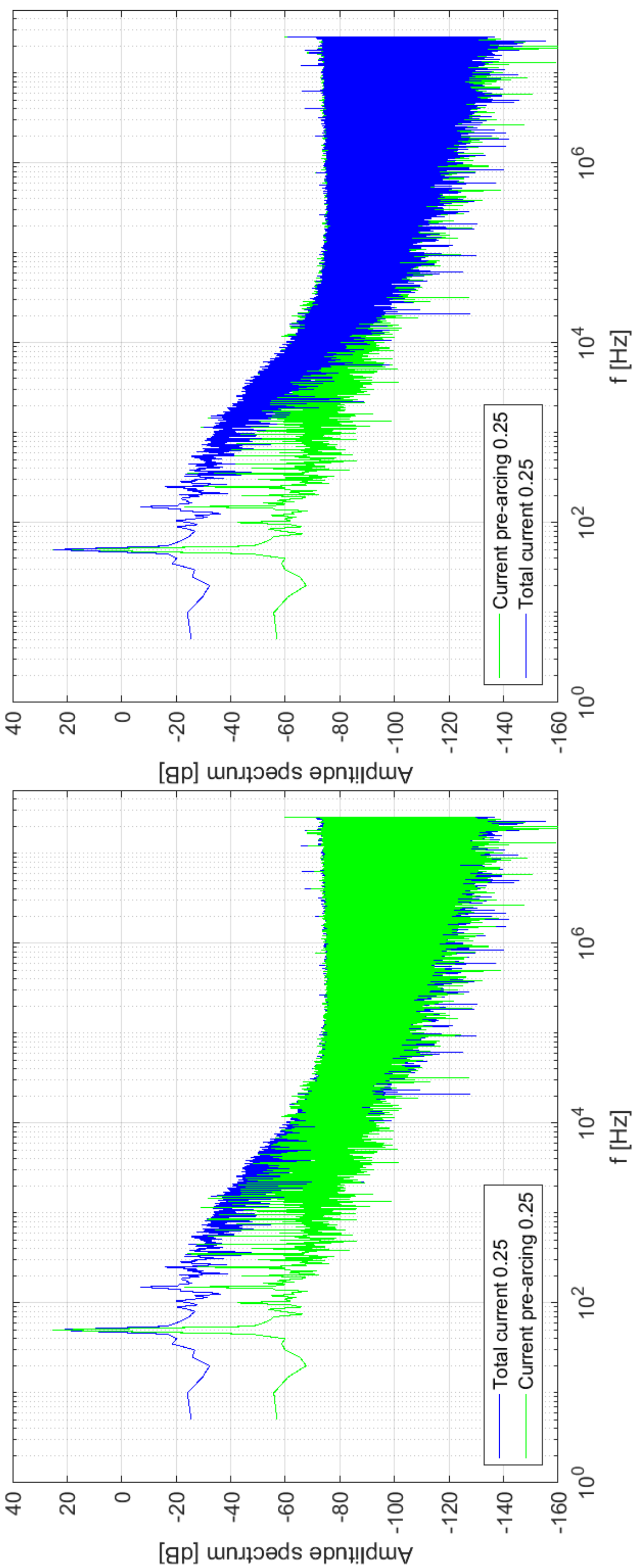

Figure A1.2:
Top: Plot of freq amplitude spectrum, current before arcing and measured total current with arcing from cable sample with current ratio 0.25.
Bottom: Same as left side with reverse order of plots

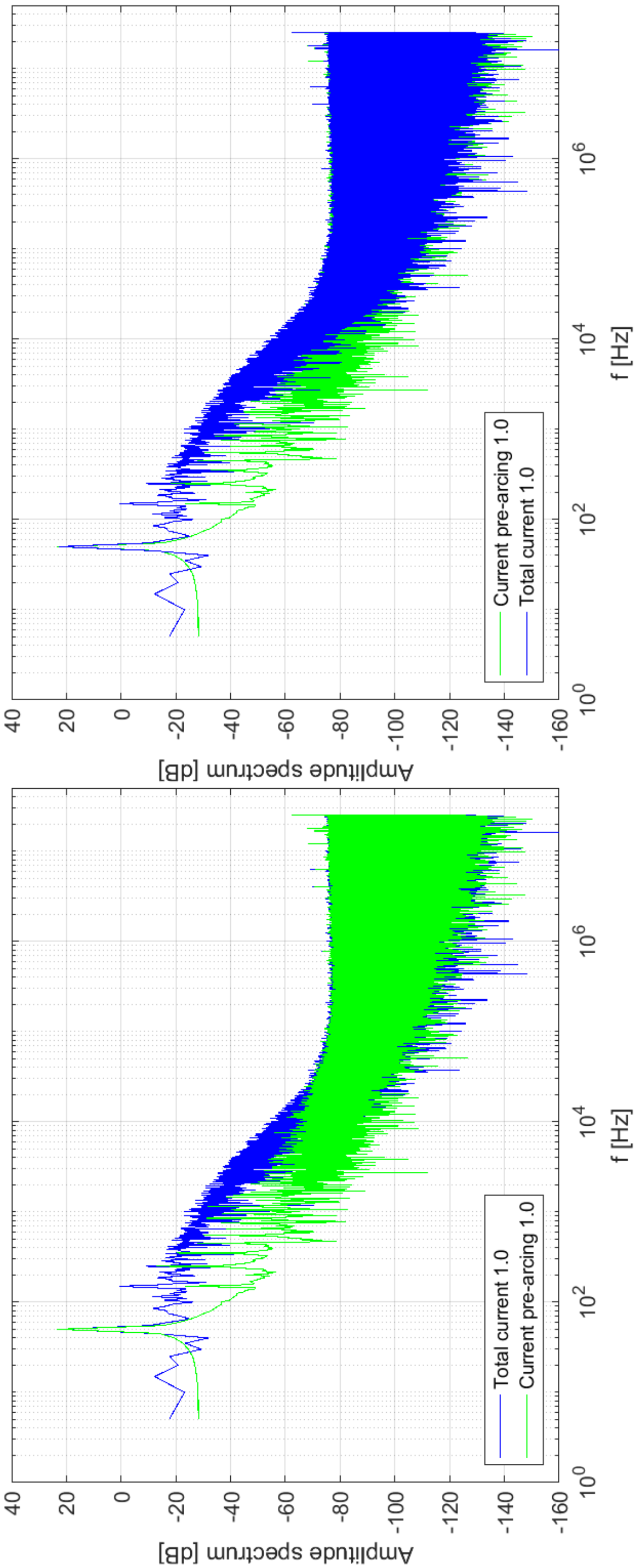

Figure A1.3:
Top: Plot of freq amplitude spectrum, current before arcing and measured total current with arcing from cable sample with current ratio 1.0.
Bottom: Same as left side with reverse order of plots

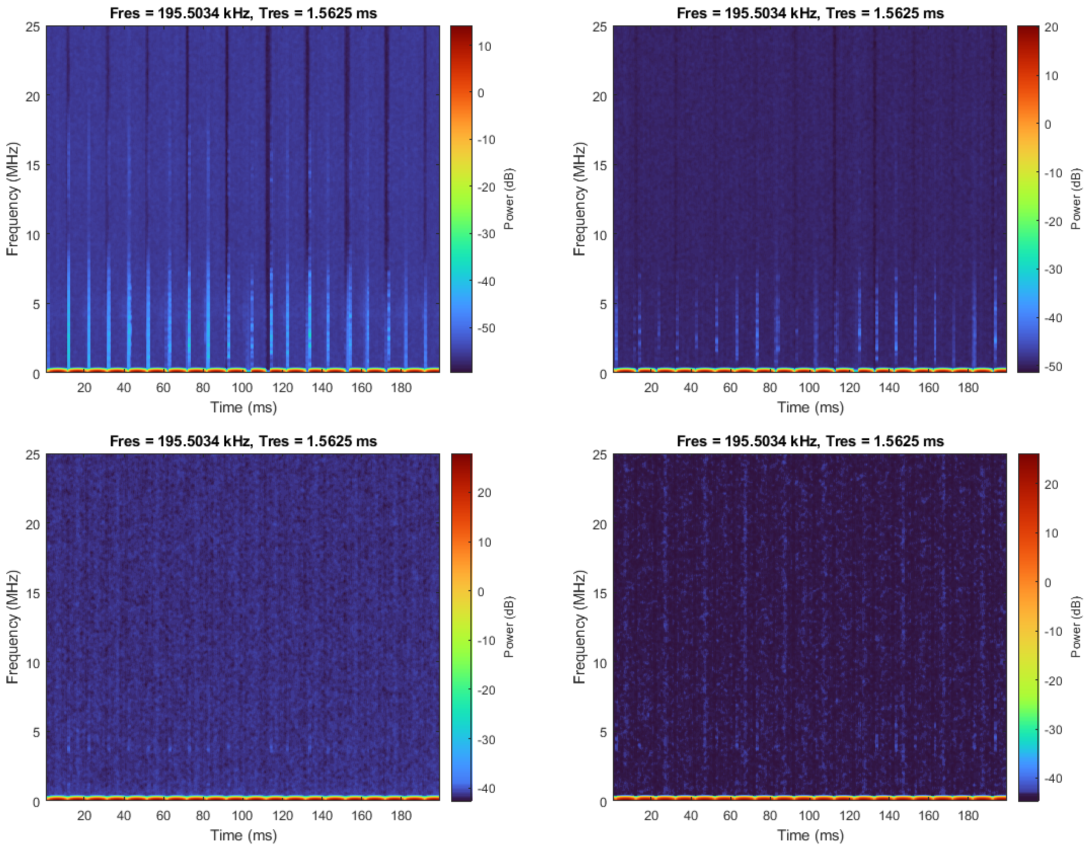

Figure A1.4:
Left side: Spectrogram plot of frequency power, arc current measurements from current ratio 0.25 with arcing from a arc generator.
Right side: Same type of spectrogram but with current ratio 1.0

A2 - Disturbing load - parallel capacitance

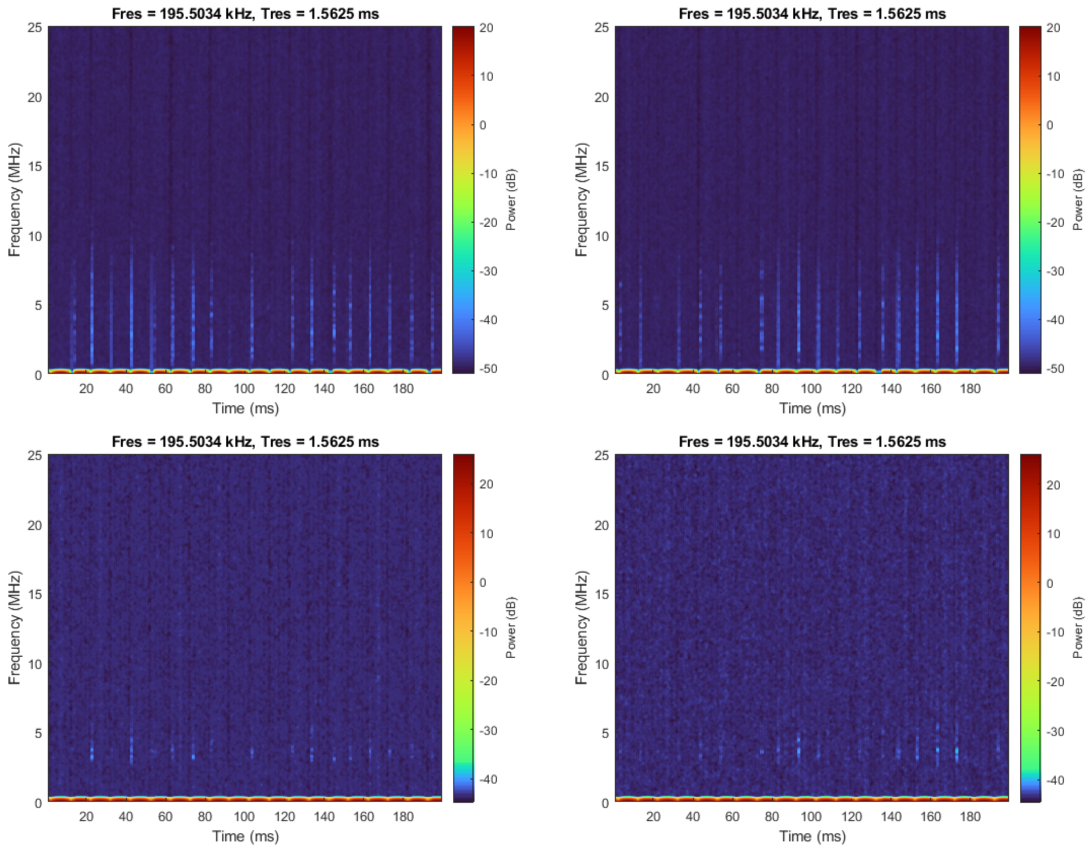

Figure A2.1:
Left side: Spectrogram of frequency power, arc current and total current measurements from current ratio 1.0 and 80nF capacitor in parallel with arcing from arc generator.
Right side: Same type of spectrogram but with a 8μF capacitor in parallel

A3 - Disturbing load - parallel power supply

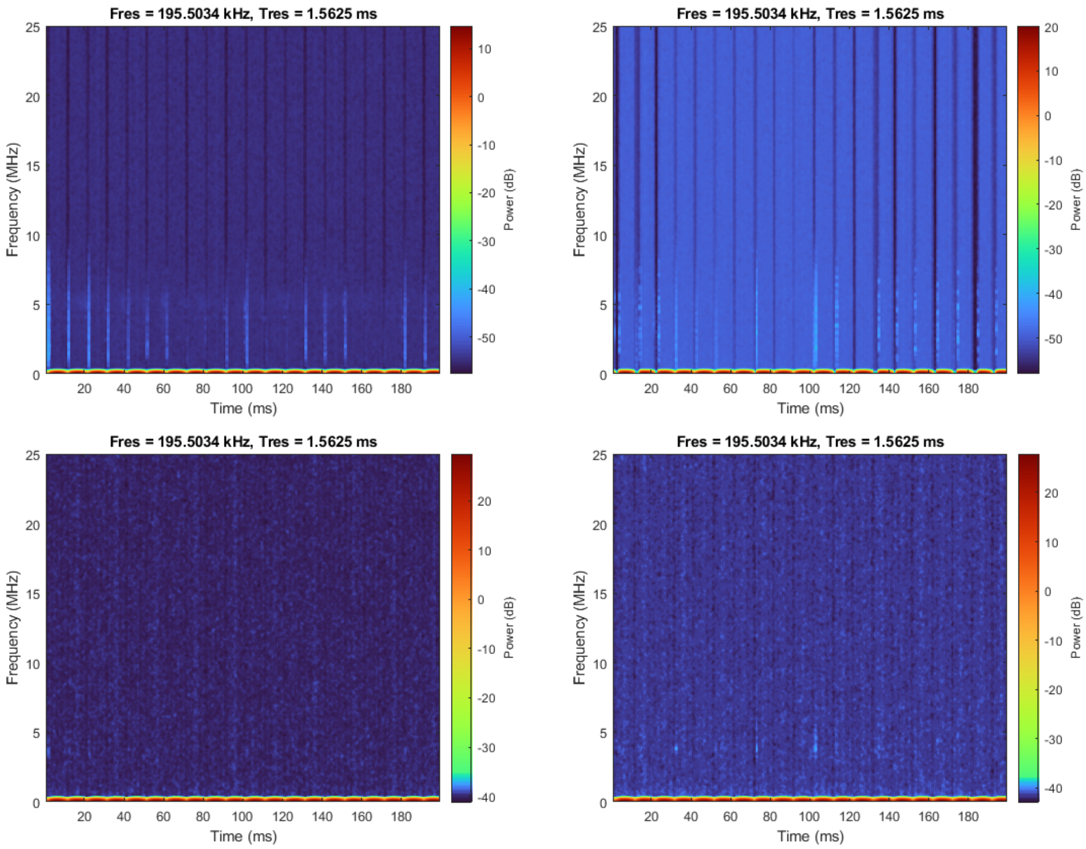

Figure A3.1:
Left side: Spectrogram of frequency power, arc current and total current measurements from current ratio 0.25 and a parallel connected SMPS, arcing from arc generator.
Right side: Same type of spectrogram but with a current ratio of 1.0

B - Equipment used in laboratory tests

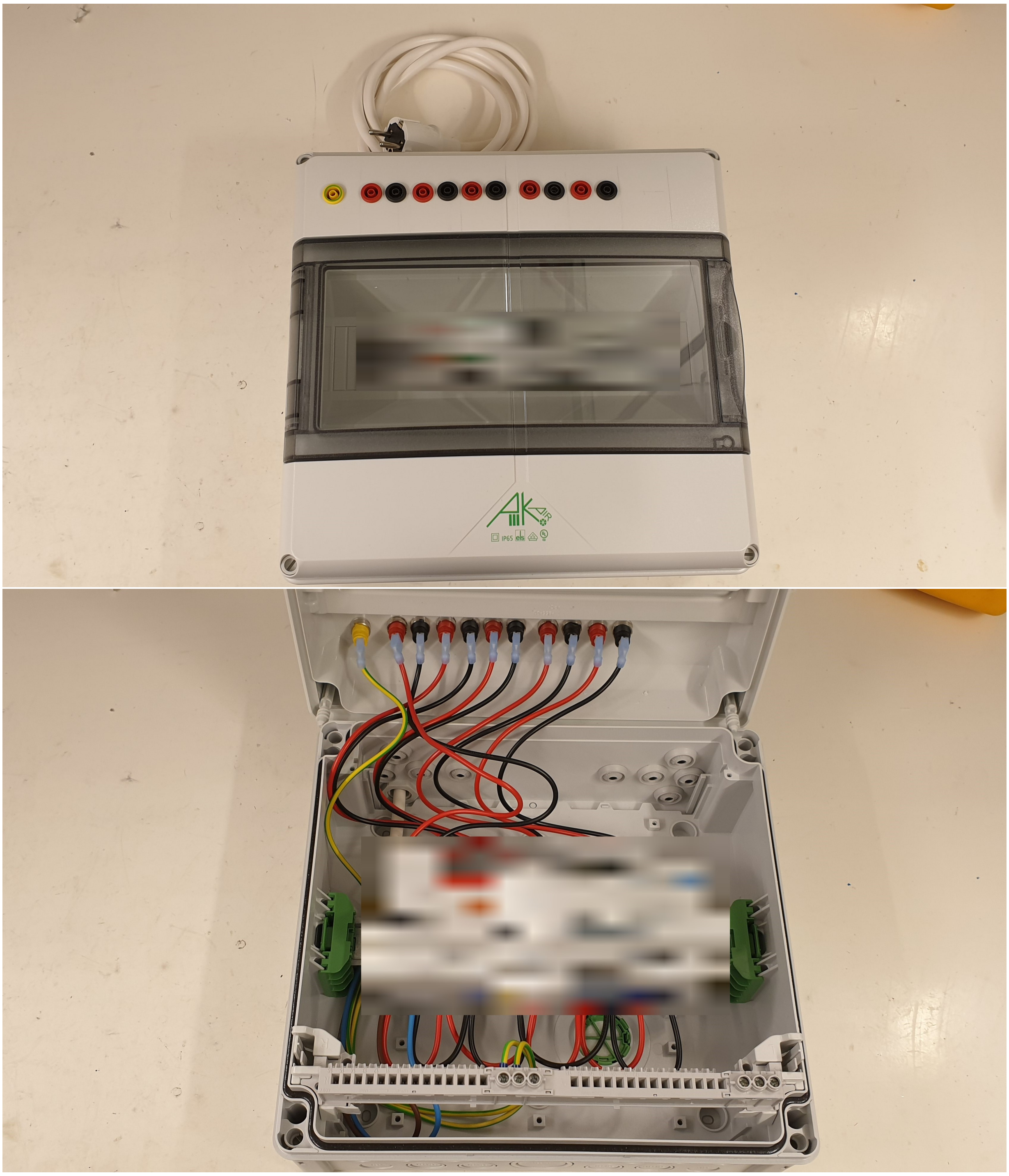

Figure B.1: Picture of the enclosure made for the AFDD's

Figure B.2:
Left side: Current probes Tektronix TCP0150 and FLUKE i200s.
Right side: Voltage differential probe Tektronix THDP0200

Table B.1: Measuring probe specifications

Model	**Bandwidth**	**Current range**	**Measuring principle**
Tektronix TCP0150	DC - 20 MHz	$150A_{rms}$	Hybrid AC/DC(Hall-effect)
FLUKE i200s	40 Hz - 40 kHz	$240A_{rms}$	Current transformer
Tektronix THDP0200	DC - 200MHz	$1500V_{peak}$	Differential voltage

Figure B.3: Picture of the Tektronix MDO34 mixed domain oscilloscope used in the tests. The maximum sampling rate of this oscilloscope was 2.5 GS /s, with a bandwidth of 200MHz and a maximum record length of 10 million samples

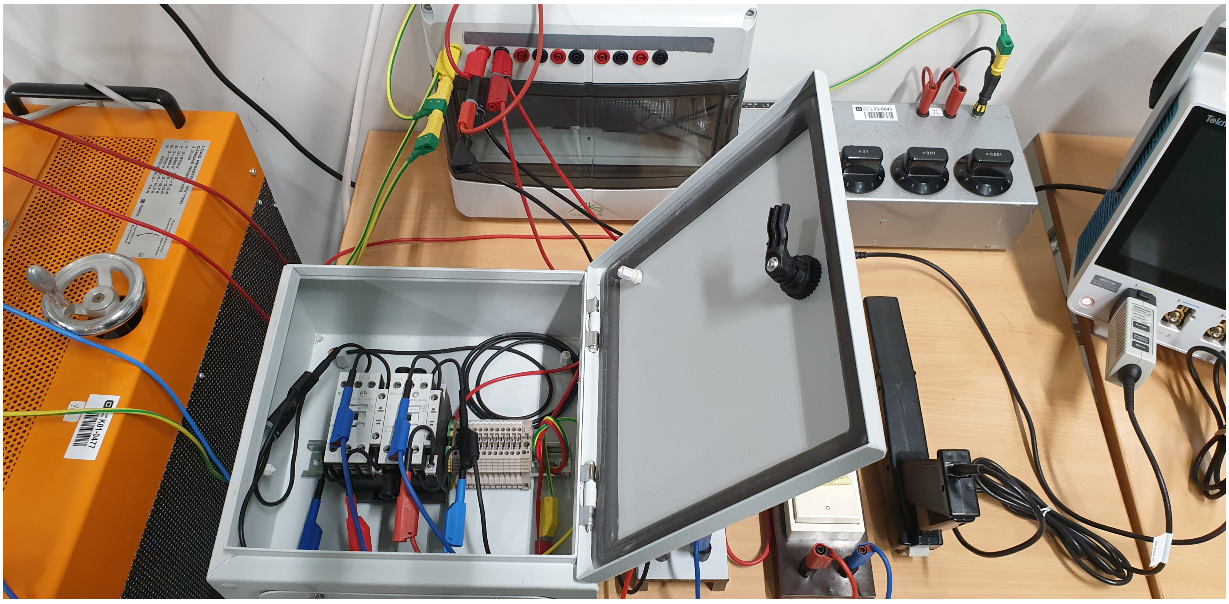

Figure B.4: Picture of the control circuit used to initiate arcing when the cable sample was used. The circuit made it possible to simulation an arc fault spontaneously appearing in the circuit

Figure B.5: Picture of the three phase load that was used as arc branch load. An adjustable load was used so the arcing current could be adjusted from <1.0A to 15A. Each phase of the load had a resistance that could be adjusted from 100Ω to 14Ω with the possibility of parallel or series connecting as needed

Figure B.6: Picture of the single phase resistance that was used as parallel branch load during testing. The resistance of the load could be adjusted from 5Ω to 25Ω

Figure B.7: Picture of the adjustable capacitance that was used as parallel capacitance during testing. The capacitance was adjustable in the range of 1 nF to $11.11 \mu F$

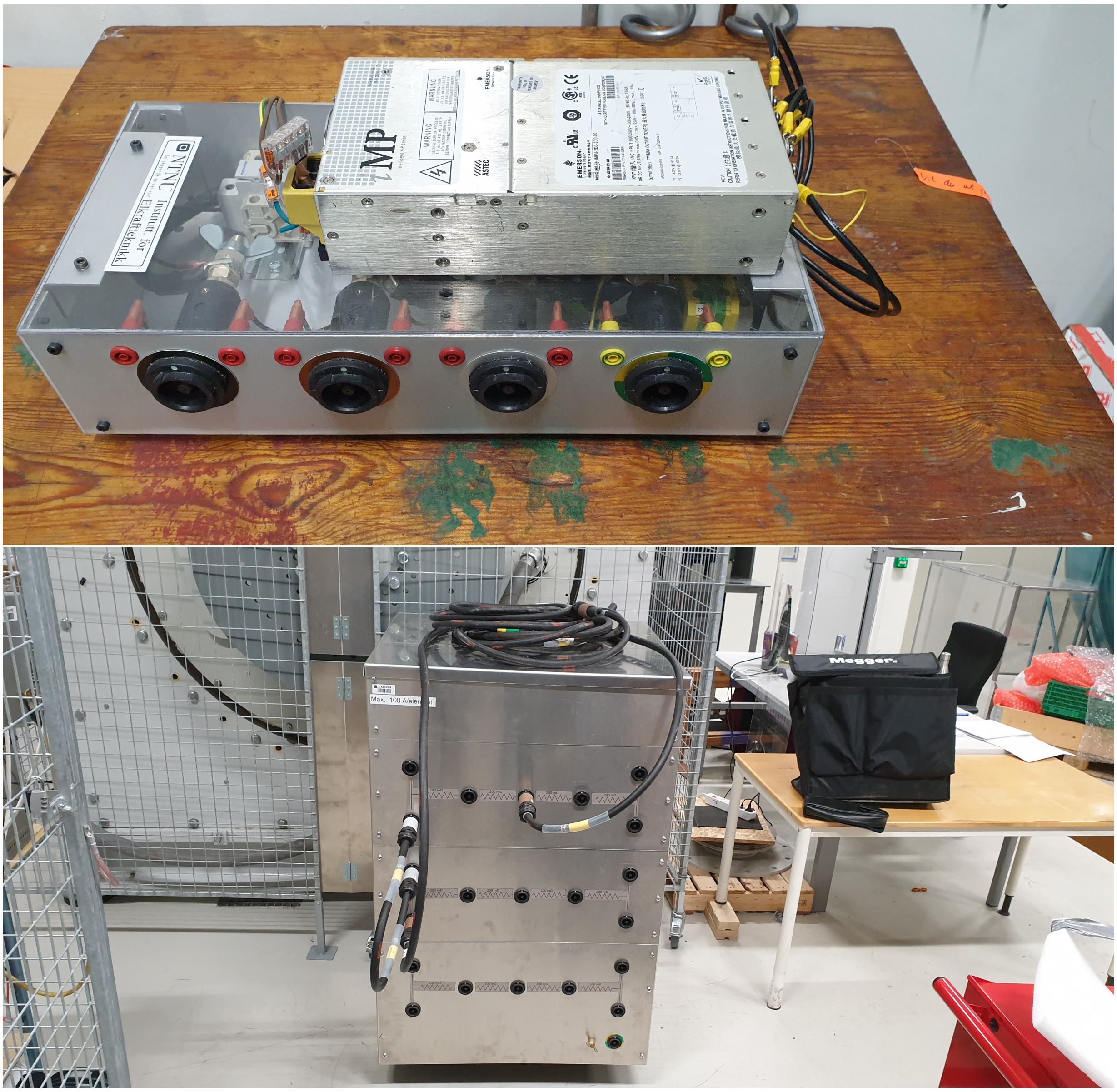

Figure B.8: Pictures of the switch mode power supply and high current load used in the test setup

C - Matlab code for frequency amplitude spectrum

```matlab
T = 1e-07;          % Sampling period
Fs = 1/T;           % Sampling frequency
L = 10000000;       % Length of signal
t = (0:L-1)*T;      % Time vector

% Reading file from table made from .csv file
X_current = Data_table(1:end,3);
X_current = X_current{:,:}';

% Performe Fast fouirer transform using the FFTW package
Y_current = fft(X_current);

% Making the two-sided spectrum by gathering the absolute
% values of the Fourier transformed values normalised for
% amount of samples
P2_current = abs(Y_current/L);

% Making the single-sided spectrum including the DC value
% douling of the amplitudes to take acount for the other half
% of the spectrum
P1_current = P2_current(1:L/2+1);
P1_current(2:end-1) = 2*P1_current(2:end-1);

% Converting values to dB
P1_dB_current = 20*log10(P1_current);

% Make adapted vector of frequency values that fit with the
% length of the signal
f = Fs*(0:(L/2))/L;

%Plot results with logarithmic frequency values
semilogx(f, P1_dB_current)
ylabel('Amplitude spectrum [dB]')
xlabel('Frequency [Hz]')
legend({'Current'},'Location', 'southwest')
grid
xlim([1 2.5e7])
ylim([-160 40])
```

NTNU

Norwegian University of
Science and Technology