Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electrical Power Engineering

MASTER THESIS

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Methods of Detection of Serial Arc In the Presence of Household Electrical Loads

Supervisor:	doc. Dr. Ing. Jan Kyncl
Study program:	Electrical Engineering, Power Engineering and Management
Branch of study:	Electrical Power Engineering

Prague 2018

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Vetoshkin** Jméno: **Lavr** Osobní číslo: **420045**

Fakulta/ústav: **Fakulta elektrotechnická**

Zadávající katedra/ústav: **Katedra elektroenergetiky**

Studijní program: **Elektrotechnika, energetika a management**

Studijní obor: **Elektroenergetika**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Metody detekce sériového oblouku při zátěži běžnými domácími spotřebiči

Název diplomové práce anglicky:

Methods of Detection of Serial Arc In the Presence of Household Electrical Loads

Pokyny pro vypracování:

1. Make yourself familiar with the phenomena of serial electric arc and nowadays methods of its detection.
2. Using devices developed in the Department of Electrical Engineering CTU-FEL make a set of measurements using typical household electrical loads.
3. Compare the efficiency of the detection of the serial arc of several algorithms.

Seznam doporučené literatury:

[1] P. Muller, S. Tenbohlen, R. Maier and M. Anheuser, "Characteristics of Series and Parallel Low Current Arc Faults in the Time and Frequency Domain," 2010 Proceedings of the 56th IEEE Holm Conference on Electrical Contacts, Charleston, SC

[2] C. E. Restrepo, "Arc Fault Detection and Discrimination Methods," Electrical Con- tacts - 2007 Proceedings of the 53rd IEEE Holm Conference on Electrical Contacts, Pittsburgh, PA, 2007

[3] P. Muller, S. Tenbohlen, R. Maier and M. Anheuser, "In uence of Capacitive and Inductive Loads on the Detectability of Arc Faults," 2011 IEEE 57th Holm Confer- ence on Electrical Contacts (Holm), Minneapolis, MN, 2011

Jméno a pracoviště vedoucí(ho) diplomové práce:

doc. Dr. Ing. Jan Kyncl, katedra elektroenergetiky FEL

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) diplomové práce:

Datum zadání diplomové práce: **14.02.2018** Termín odevzdání diplomové práce: **25.05.2018**

Platnost zadání diplomové práce: **30.09.2019**

doc. Dr. Ing. Jan Kyncl podpis vedoucí(ho) práce	podpis vedoucí(ho) ústavu/katedry	prof. Ing. Pavel Ripka, CSc. podpis děkana(ky)

III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

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Datum převzetí zadání Podpis studenta

Acknowledgements

I would like to thank my supervisor, doc. Dr. Ing. Kyncl Jan, for his support and advice throughout my studies. Most importantly I want to thank my family for giving me opportunity and support in pursuing the engineering degree.

I hereby declare that I have completed this thesis with the topic "Methods of Detection of Serial Arc In the Presence of Household Electrical Loads" independently and that I have included a full list of used references. I have no objection to the usage of this work in compliance with the act §60 Zákon č.121/2000 Sb. (copyright law).

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Abstrakt:

Sérový oblouk je jednou z nejčastějších příčin požárů vyvolaných elektřinou. V současnosti se prevenci požárů, zlepšováním elektroinstalace a použitých přístrojů zabívá cela řada lídi. Táto práce zkoumá sériový oblouk v domácnostech. V této práce jsou představené různé přístupy k výzkumu charakteristik sériového oblouku. Analýza proudu pomocí směrodatné odchylky ukázala nadějné výsledky. Na základě těchto výsledků autor navrhuje prozkoumat metodu detekce, která používá rozdíly směrodatné odchylky vysokofrekvenční složky proudového signálu. Kromě toho v této práce jsou porovnaný metody detekce sériového oblouk. Přesto, že existuje spolehlivá metoda, autor usuzuje, že výzkum mel by pokračovat kvůli zmíněným možným problémům existujících metod.

Klíčová slova:

Seriový oblouk, Detekce Obloukové poruchy, přístroje pro detekci poruchového elektrického oblouku, AFDD, AFCI, Směrodatna odchylka, Fourierová Transformace

Abstract:

A series arc fault is a most frequent electrical cause of fires. Currently, many in fire safety field are concerned with deployment, developing and improvement of Arc Fault Circuit Interrupters. This thesis investigates series arc characteristics in the presence of household loads. The thesis presents different approaches to the investigation of a series arc's features. The standard deviation analysis of high frequency component of a current showed promising results, which may be a good indicator for the detection of a series arc. The author proposes a novel method based on the results, which utilises differences of a standard deviation of the high frequency component of a current signal. Moreover, several methods of arc fault detection are described and compared. Nevertheless, a reliable detection algorithm exists, the author concludes that the research should continue due to expressed concerns.

Keywords:

Series arc, Arc Fault Detection, AFDD, Arc Fault Circuit Interrupter, AFCI, Standard Deviation, Fourier Transform

Contents

1. Introduction

1.1 Motivation and thesis objectives

According to [1] arcing fault cause more than 30000 home fires a year in the USA and many times more worldwide. Peoples safety is always a major concern; thus the fire statistics triggered the research of arc fault circuit interrupters (AFCI) decades ago. However, due to nature of arc faults the existing devices are not 100 percent reliable. Hence, the investigation into series arc feature continues. The ultimate goal indeed is to find a reliable indicator for fault detection.

The thesis has multiple objectives. The first one is to make a set of measurements using setup made at CTU. The second goal is to describe well-known characteristics of a series arc and conduct an investigation into series arcs' features using obtained data. The third aim is to describe and compare several arc fault detection methods.

1.2 Thesis outline

The thesis consists of six chapters and a conclusion. The first one describes the thesis, its motivation and objectives. The second chapter briefly introduces Fourier series and explains the chosen approach to spectral analysis. The third chapter introduces a series arc. Moreover, it describes well-known characteristics of a series arc both in time-domain and frequency domain. The fourth chapter outlines author's investigation into series arc characteristics. The fifth chapter describes the setup made at the faculty of electrical engineering at CTU, its functionality as well as hardware. The sixth chapter describes several arc fault detection algorithms and compares them.

2. A brief introduction to the harmonic analysis

The author assumes that the reader is aware of the Fourier Series and Fourier transform. Nonetheless, not many engineers understand how Fourier transform algorithms work and what problems they have. Hence, this chapter explains to the reader, how the harmonic analysis was done and why particular approaches the author chose. Furthermore, the last section of this chapter provides information about the estimation of the fundamental frequency of a periodic signal.

2.1 Fourier series

Fourier series is broadly known as a possible representation of a periodic function via an infinite sum of sines and cosines. This form of a function helps to understand the behaviour and features of the signal source. The harmonic analysis is widely used across all fields of engineering like control of a dynamic system, signal processing and others. The most known form of the Fourier series is:

$$f(t) = \frac{\mathrm{a_0}}{2} + \sum_{n=1}^{\infty} \mathrm{a_n} \cos(n\omega t) + \sum_{n=1}^{\infty} \mathrm{b_n} \sin(n\omega t) \tag{2.1}$$

where: $\omega = 2\pi f = 2\pi/\mathrm{T}$, f is the fundamental ferquency (Hz) ans T is a period,
$n\omega$ is the nth harmonic,
a_n, b_n are the Fourier coeficients of nth harmonic,
$a_0/2$ is also known as DC component of signal.

The defenitions of the Fouurier coefficients are:

$$\mathrm{a_0} = \frac{2}{\mathrm{T}} \int_{-\mathrm{T}/2}^{\mathrm{T}/2} f(t)\mathrm{d}t \tag{2.2}$$

$$\mathrm{a_n} = \frac{2}{\mathrm{T}} \int_{-\mathrm{T}/2}^{\mathrm{T}/2} f(t)\cos(n\omega t)\mathrm{d}t \tag{2.3}$$

$$\mathrm{b_n} = \frac{2}{\mathrm{T}} \int_{-\mathrm{T}/2}^{\mathrm{T}/2} f(t)\sin(n\omega t)\mathrm{d}t \tag{2.4}$$

The from of the Fourier series shown above is rarely used in electrical power engineering field because, fundamental signals in the electric grid are sinusoidal or at least should be in normal opration. Therefore another representation of the

Fourier series form is more practical in that case. The cosine can be substituted by a sine with a phase shift, hence the Fourier series will be:

$$f(t) = \frac{\mathrm{a}_0}{2} + \sum_{n=1}^{\infty} \mathrm{c_n} \sin(n\omega t + \varphi) \tag{2.5}$$

where $c_n = \sqrt{a_n^2 + b_n^2}$ and $\varphi = \arctan a_n/b_n$

This form of the Fourier series shows which oscillations are dominant.

2.2 Fourier transform performance comparison

There are different algorithms for calculation of Fourier series coefficients. One of the most used is Fast Fourier Transform or FFT. This algorithm is commonly used in signal processing. Nevertheless, the author should be careful with FT algorithms because the precision of FFT might not give precision that some methods require. Therefore, the author compared his implementation of sine-cosine transformation and SciPy FFT algorithm in Python [2]. Let assume the measurement of the signal on the figure below with fundamental frequency 50 Hz, which has first, fifth, seventh, eleventh and fifteenth harmonic with amplitude {1, 0.2, 0.3, 0.5, 0.1} respectively. After that analysed signal should be represented by 15 harmonics. The signal will be measured with finite sample rate (sample

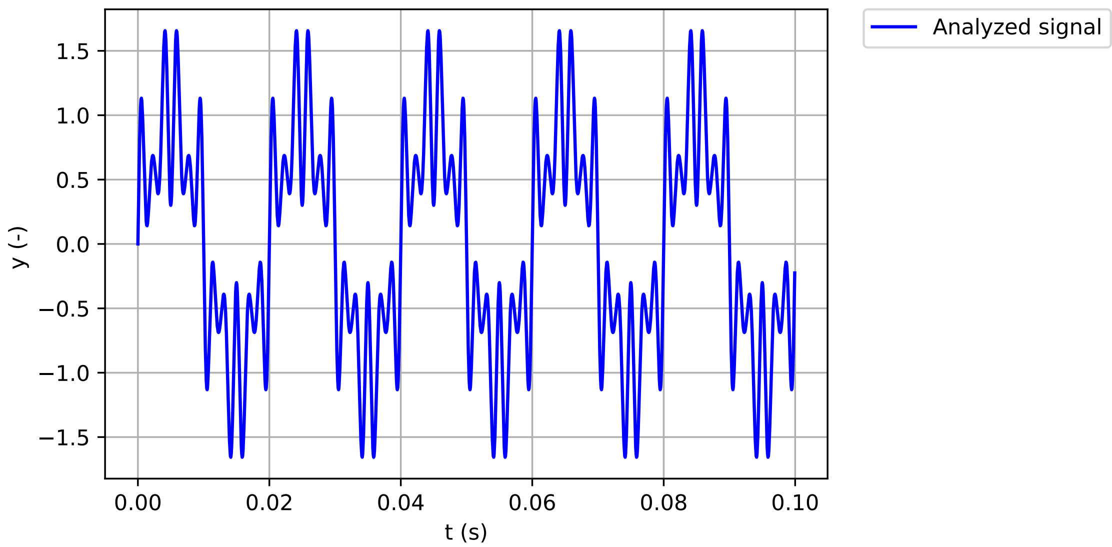
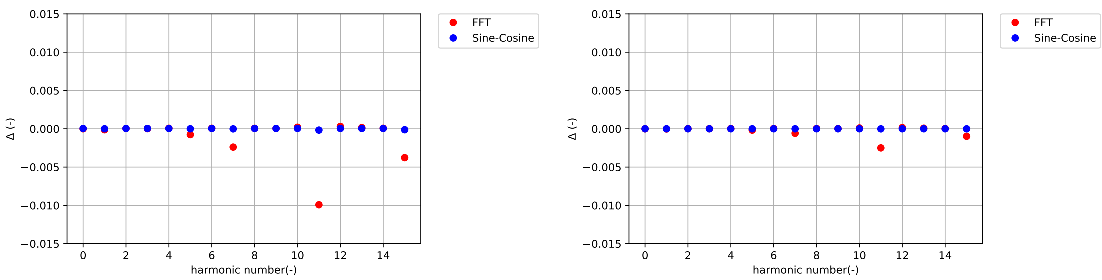


Figure 2.1: The signal for analysis

rate is the number of samples per period). Reasons for low sample rate will be given later, but the author is going to use relatively low sample rate probably 100 or 200 samples per period.



(a) Sampe rate - 100

(b) Sample rate - 200

Figure 2.2: Comparison of FFT and sine-cosine approaches for calculation of Fourier's coefficients

There is no doubt that FFT is less precise than a numerical integration of interpolated data. Evidently, the sine-cosine transform shows more robustness with decreasing sample rate compared to FFT, which certainly faster but with low sample rate, is less precise.

2.3 Statistical method of frequency estimation

The previous section proves the superior precision of the author's method of calculation of coefficients, which uses interpolation and sine-cosine transform, to FFT. Although, this method does require information about fundamental frequency. Indeed, in real power system frequency is not exactly 50 Hz. Hence, for accurate computation of the Fourier's coefficients, the period of a signal should be known.

For frequency estimation, the author is going to use the statistical method, which was proven to handle well even a signal with low signal-to-noise ratio in [8] and [9] . The idea behind this method is quite simple. First of all, mean values for different lengths of a period, in other words for different numbers of samples per period, are calculated.

$$\bar{x}(n) = \frac{1}{n}\sum_{i=j}^{j+n} x_i, \qquad j = 1, 2, ..., k \tag{2.6}$$

where k is the size of the mean values set. Secondly, standard deviations of sets of acquired mean values are computed.

$$\sigma(n) = \sqrt{\frac{1}{k}\sum_{i=1}^{k}(\bar{x}_i(n) - \bar{\bar{x}}(n))^2} \tag{2.7}$$

Mention, that equation 2.10 is a definition of a function and $n \in \mathbb{Z}_{>0}$, where n is number of samples per period. The third step of this algorithm is a minimization of the function $\sigma(n)$. However, this function is not defined for non-integer numbers; therefore an approximation by parabola around minimum point is used. This approximation requires at least three points, hence from pairs of $(n, \sigma(n))$ three pairs are chosen, the smallest and one from each side of the smallest one. Then the equation of the parabola can be derived, by calculating its coefficients. This system of equations in matrix form is:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{bmatrix} = \begin{bmatrix} n_1^2 & n_1 & 1 \\ n_2^2 & n_2 & 1 \\ n_3^2 & n_3 & 1 \end{bmatrix} \times \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{2.8}$$

The fourth step is a calculation of parabola's vertex position, which is a commonly known formula:

$$x_{vertex} = -\frac{b}{2a} \tag{2.9}$$

Solving the system of equations:

$$n_{vertex} = \frac{n_3(\sigma_1^2 - \sigma_2^2) + n_1(\sigma_2^2 - \sigma_3^2) + n_2(\sigma_3^2 - \sigma_1^2)}{2(n_3(\sigma_1 - \sigma_2) + n_1(\sigma_2 - \sigma_3) + n_2(\sigma_3 - \sigma_1))} \tag{2.10}$$

Finally, using n_{vertex} calculated in the previous step, a period of a signal can be obtained:

$$T = \frac{n_{vertex}}{f_{sampling}} \tag{2.11}$$

3. Theoretical description of the Series Arc faults

This chapter introduces a series arc fault. Moreover, the chapter describes series arc's well-known characteristics and provides some explanations with examples.

3.1 A series arc fault

Series arc can be interpreted as an unintentional discharge on the suface of a conductor. Series arc fault occurs in the path of a circuit in series with a load. Mostly, an interruption of insulation or flawed mechanical contact causes this type of fault. Series arc fault represents an extra load, in a series with existing, in the circuit. Consequently, the current, flowing into the faulted branch, is close to standard operating current. Therefore, conventional protection devices cannot detect series arc faults.

3.2 Characteristics in time domain

The arc itself is a very complicated phenomenon. Therefore, for developing arc fault detection algorithm is better to understand how its presence affects current in the circuit. AC arc was studied a lot, and its features are well known. Major influential factors are voltage, gap distance, electrode surface and line impedance [3].
The voltage applied across electrodes controls arcing, so when AC voltage crosses zero, the arc extinguishes. After restoring a critical value of voltage, arc reignites. Figure 3.1 shows the arc voltage waveform. Between those two processes is a current gap, which duration depends mostly on the distance between electrodes and state of the plasma. Longer the distance gap, a higher voltage is needed to initiate arcing. Plasma between electrodes affects the insulating properties of the fluid between electrodes, and it leads to a smaller voltage that can cause a breakdown. Arc extinguishing and re-ignition cause a current edge. Current raise ration depends on applied voltage needed for a breakdown, on the load, and on the circuit parameters. Figure below 3.2 shows these edges, that are often called shoulders.

It is obvious that current gaps decrease RMS value of the signal. Also, time of arc re-ignition varies due to stochastic nature of the phenomenon.

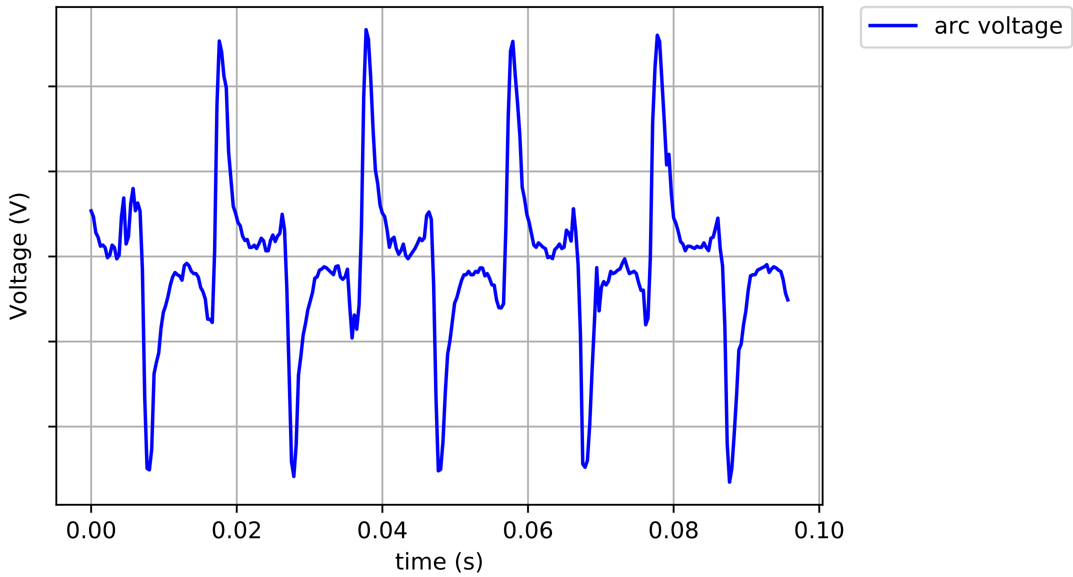


Figure 3.1: Arc voltage

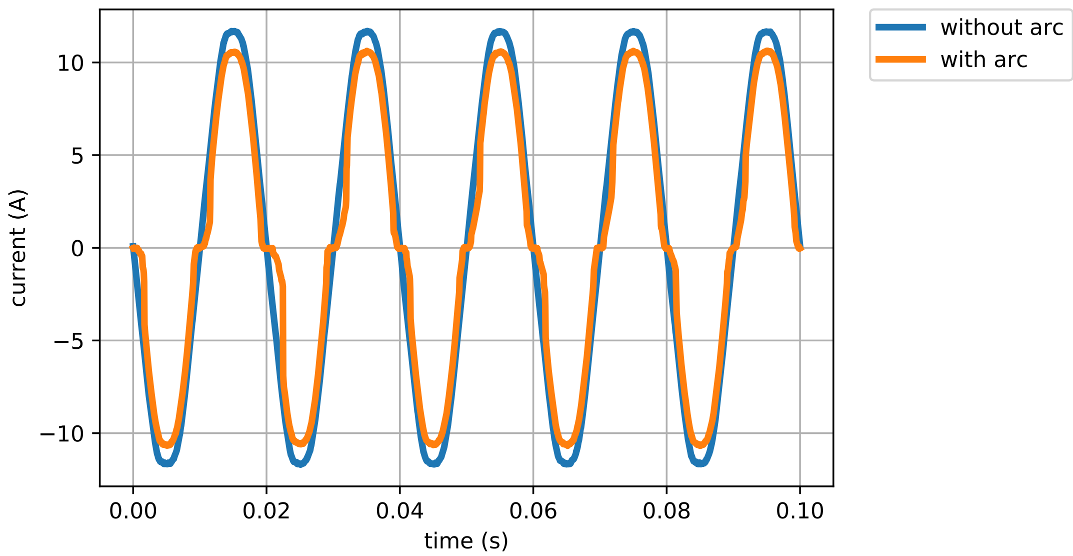


Figure 3.2: Current waveform without/with series arc

3.3 Characteristics in frequency domain

Several papers outline the importance of higher harmonics assessment in arc fault detection algorithm for reliable disclosure of failure [3,4]. Re-ignition of current, coming in hand with a current edge, generates high-frequency noise. As a result, signals spectrum significantly changes. There are different opinions which part of the spectrum suits better for detection algorithm. Carlos E. Restrepo in his paper suggests using RF component for AFDD [4]. Other researchers focus on frequencies in the range of 2 to 5 kHz [3]. Nevertheless, the idea behind those approaches is noise generated during arcing, which elevates higher harmonics.

The change in spectrum causes the decrease in amplitude of fundamental harmonic. Figure 3.3 shows current signals from figure 3.2 in frequency domain, obtained by using Fast Fourier Transform (FFT). High-frequency component is displayed on figure 3.4. The high-frequency component of the signal with arcing vastly distinguishes from the normal condition. Arc re-ignition, apparently, causes the peaks.
The characteristics outline features of arc presence in the circuit. The elevation of third harmonics (150 Hz) amplitude is noticeable, overall spectrum elevation up to 2.5 kHz is sharp and increase in higher frequency component is perceptible too. All that phenomena could be good and reliable indicators of an arc fault in the circuit. Unfortunately, harmonics of those frequencies are produced by different loads, for example, converters produce 3, 5 and 7 with high amplitude, there is the difference between them. First of all, the arc is a stochastic process, on the contrary power electronic devices are not. Therefore, it should be taken into account, during the development of AFDD. Otherwise, that kind of loads could cause undesired tripping of protection device.

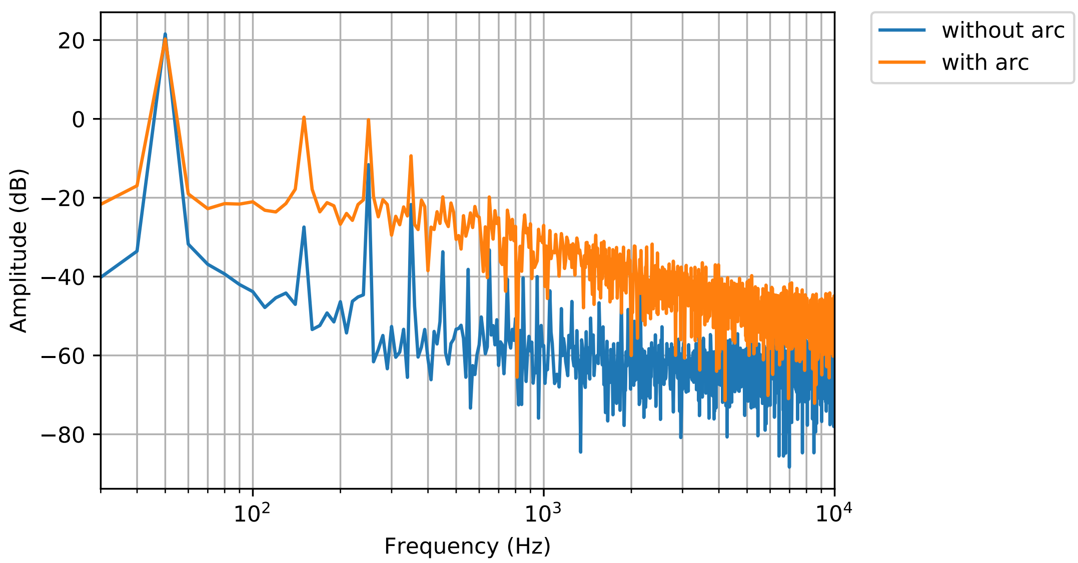


Figure 3.3: Spectra of current signals

3.4 Influence of capacitance and inductance

The signals that have been analyzed in the previous section were obtained from the circuit with a space heater, which is a resistive load. However, the majority of loads are not. The devices with a high inductance can significantly change the shape of a current. Hence, it could decrease a probability of detection

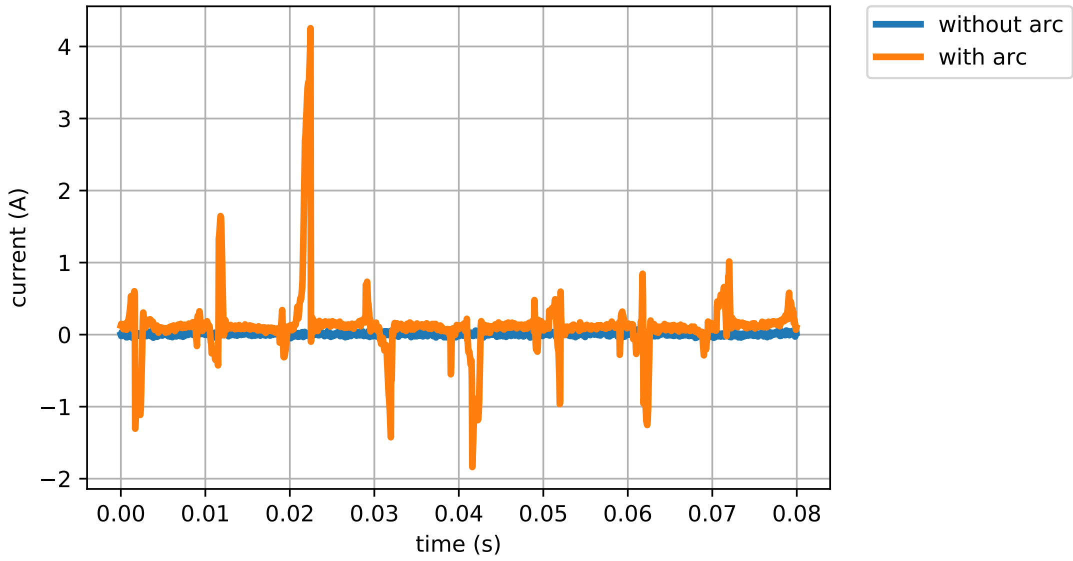


Figure 3.4: High-frequency components (higher than 50th harmonic) of currents

of an arc fault [5]. Loads with high inductance are frequently present in the residential sector, such as vacuum cleaners, basically all loads with electric drives and many others. Inductance in the circuit causes a phase shift in the current. As mentioned previously, arc in an AC circuit extinguishes due to current zero every half of a period. However, an inductance could cause a significant phase shift, so when current would cross zero voltage might be already high enough to prevent arc extinction. Apparently, it eliminates one of the main features of an arc - current shoulders. Moreover, inductance's impedance is much higher at high frequencies so that the circuit will behave like an analogue filter. The tests conducted in [5] showed an only minor influence of high capacitance loads on the current signal. Although a combination of inductance and capacitance could significantly change the spectrum of a current signal because RLC circuit behaves like a lowpass filter (capacitance is in parallel to the resistance and the inductance). The bode plot demonstrates that 3.5.

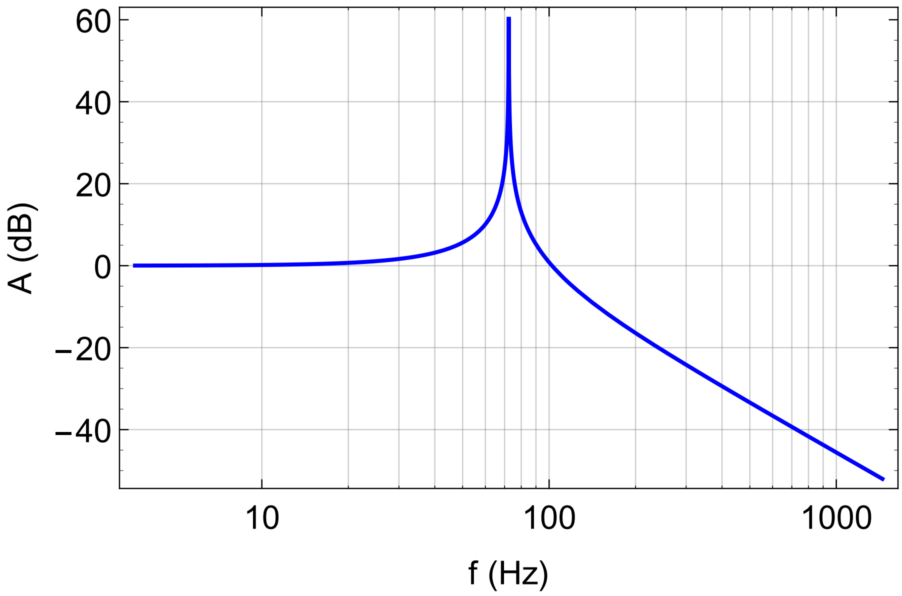


Figure 3.5: Bode plot of an RLC curcuit

4. An investigation into series arc characteristics

This chapter describes the author's investigation into series arc's characteristics. Firstly, the author focuses on a phase angle of a current signal with a series arc. Secondly, the high frequency component of a current signal is analysed with different approaches. Thirdly, the noise throughout the whole spectrum is investigated.

4.1 A shift of a phase angle of the current in the circuit with a series arc

4.1.1 How does appear a shift of a phase angle

The series arcing is a stochastic process during which many electrical parameters of an arc vary. That imply changes of an arc's resistance in the time domain. This variation hypothetically causes a change in a phase angle of a current signal in a circuit with arcing. For better understanding what happens, let first assume a simple circuit with a resistor and an inductance. This example does not approximate the behaviour of a circuit with a series arc, nevertheless gives an understanding how the resistance's value affects an RL circuit. Input voltage will be common European 230 Volt RMS with frequency 50Hz. Following equations describe such circuit:

$$V_{in} = \mathrm{L}\frac{\mathrm{d}i_{out}}{\mathrm{d}t} + V_{out} \tag{4.1}$$

where i_{out} is the current through the resistor

$$V_{in} = \mathrm{L}\frac{\mathrm{d}i_{out}}{\mathrm{d}t} + \mathrm{R}i_{out} \tag{4.2}$$

From this equation the transfer function of the circuit can be obtained:

$$\frac{i_{out}}{V_{in}} = \frac{1}{\mathrm{L}s + \mathrm{R}} \tag{4.3}$$

Now applying input signal on that system, we get i_{out} or the current through the resistor. For the circuit with inductance of 9 mH and resistance of 5 Ohm, output current wavefrom is shown in the Figure 4.1 This change in the phase angle can be visualized by drawing impedance in the complex plane4.2. The Current lag depends on R/L ration; we can see it by plotting output voltage of the same circuit

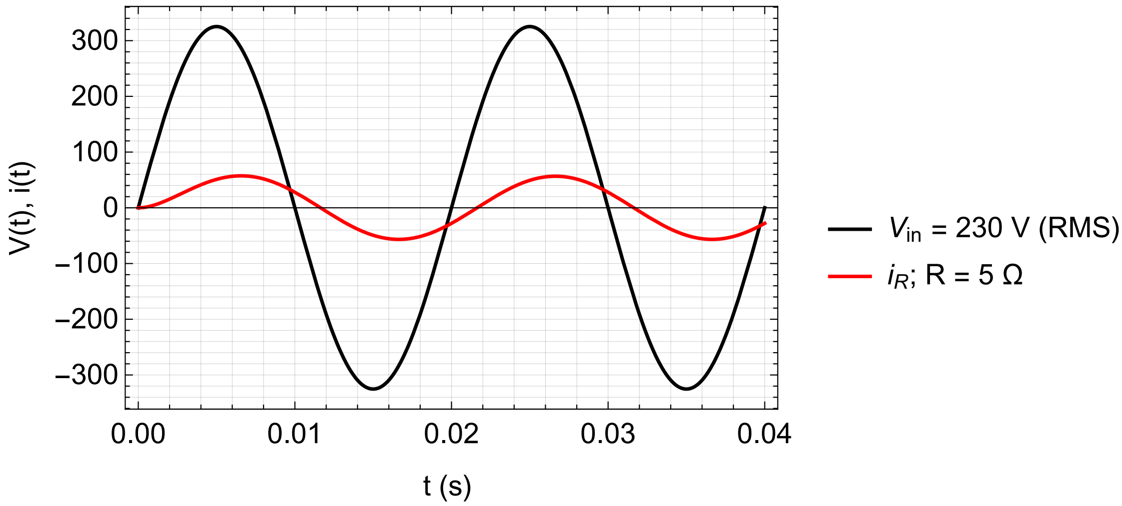


Figure 4.1: Demonstation of the current lag in an RL circuit

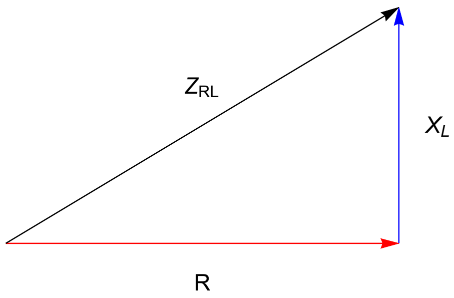


Figure 4.2: Impedance of RL circuit in the compex plane

with 10 Ohm resistor and compare it to the previous case. Hypothetically, in the circuit with a series arc resistance constantly changes, hence the phase angle as well. It is similar to constant switching between every possible phase angle. The following section will show that it may be the case. However, the R/L ration in a circuit can change during normal operating conditions for example change of the temperature of a load can cause variation in electrical parameters.

4.1.2 Experimental verification

By using Fourier transform described in chapter 2, from acquired data for the circuit with the power drill as a load phase angles were extracted. The figure 4.4 shows calculated phase angles for different cycles of the signals. It is clear that in case of arcing phase angle of the current had been changing from cycle to cycle. However, the phase angle in the case without the presence of a series arc had been changing too. As mentioned previously, it could have happened because of numerical errors or change in load's electrical parameters. From figure 4.5 we can derive similar conclusion as from the previous.

However, a variation of a phase angle does not affirm that in the circuit is a

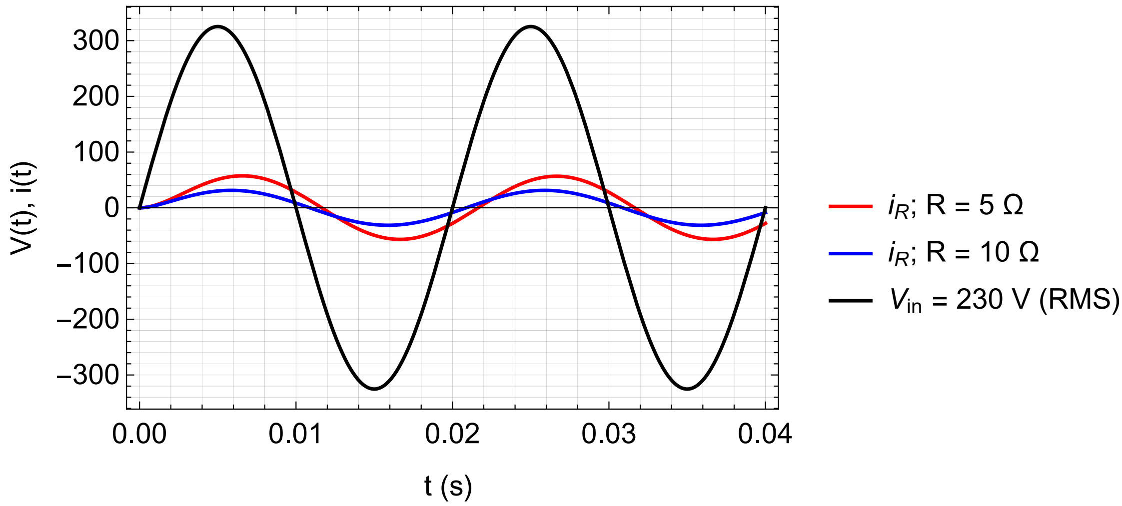


Figure 4.3: The current waveforms in an RL circuit for different resistance

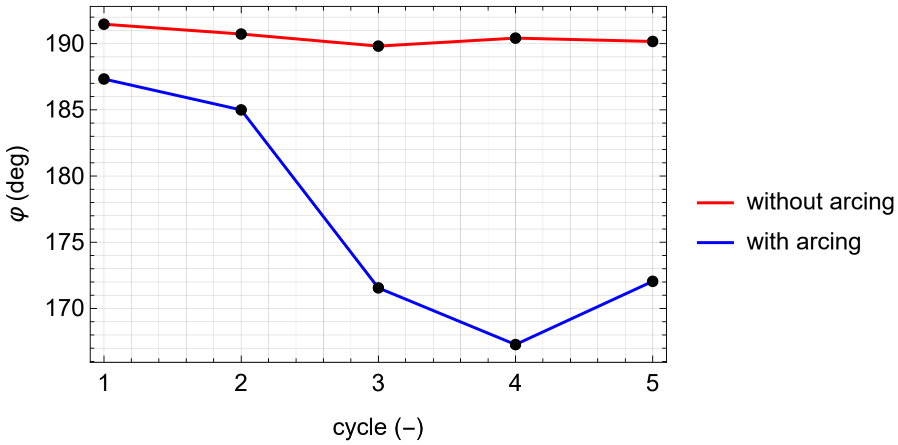


Figure 4.4: Phase angles of current of the circuit with power drill with/without arcing

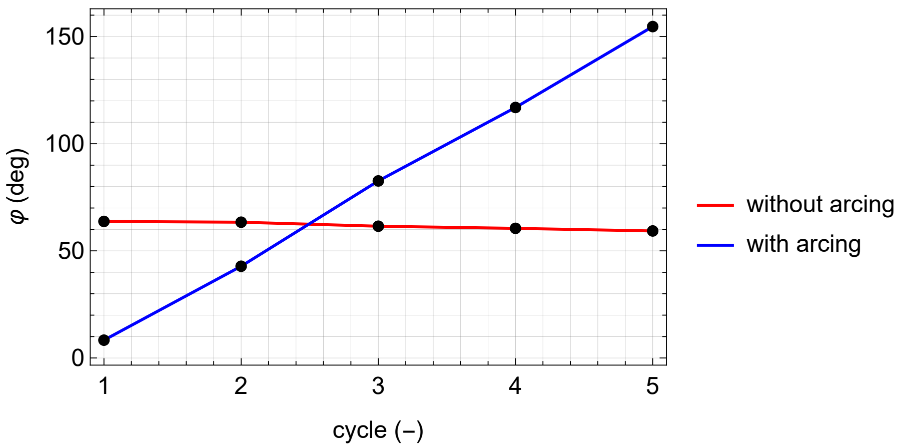


Figure 4.5: Phase angles of current with thyristor controlled load with/without arcing

series arc; it only says that there is a change in R/L ratio. Obviously, it does not specify the cause of the variation. Phase angles of the current obtained from the circuit with a power drill without arcing, are displayed on the figure 4.6. In the of this record, the power drill starts, and it causes variation in the phase angle. It proves that not only an arc can cause a shift of a phase angle.

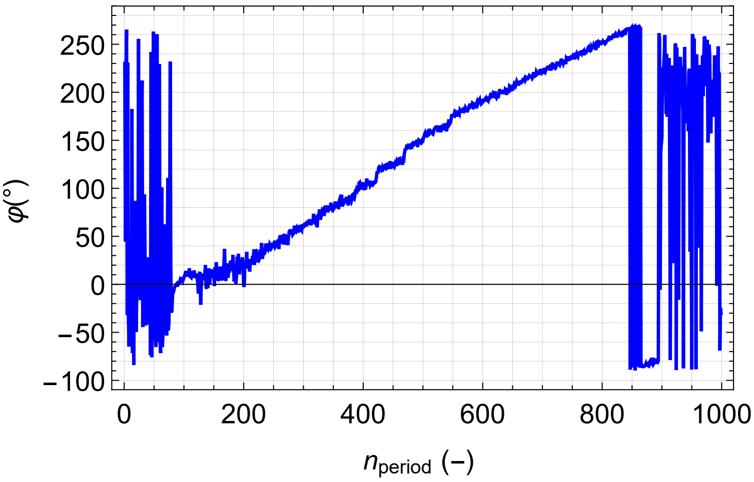


Figure 4.6: Phase angles of the current with a power drill without arcing

4.1.3 The Accuracy of a phase angle estimation

Essentially, the accuracy of such calculation depends on the precision of Fourier coefficients estimation. As was mentioned previously, the period for computation of that coefficients, i.e. fundamental frequency is crucial. Therefore the author tried to establish what imprecision of the fundamental frequency value can be tolerated. For the same data as in the previous section, the changes of the phase angle for different fundamental frequencies were calculated. The fundamental frequency was computed by using the statistical method described in chapter 2. Figures 4.7, 4.8, 4.9, 4.10 prove that calculation of a fundamental frequency is necessary for correct estimation of a phase angle. Also, they show that even a small deviation from true value causes a significant error.

4.2 High frequency component of arc current

4.2.1 Variability of the high frequency component of an arc current

The high frequency or hereafter i_{HF} components is a very known feature of a series arc. In this section, the author investigates the features of that components. First of all, fundamental frequencies of the analysed signal should be taken into account. One of the significant characteristics of data is a standard deviation. It shows how far data lays from the mean, in other words, variability in the

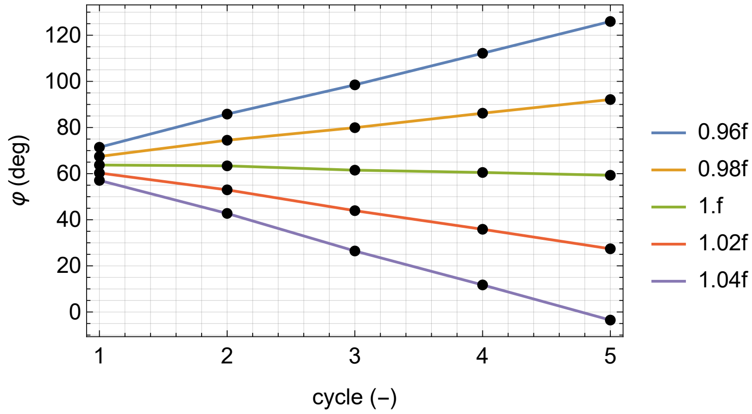


Figure 4.7: Phase angles of current with thyristor controlled load without arcing calculated for differen frequencies

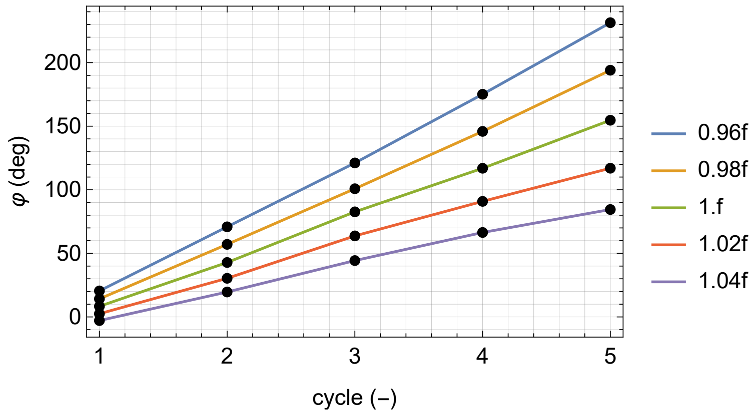


Figure 4.8: Phase angles of current with thyristor controlled load with arcing calculated for differen frequencies

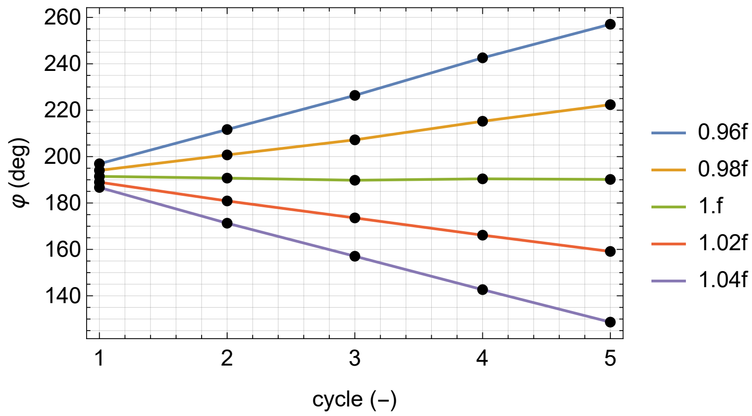


Figure 4.9: Phase angles of power drill's current without arcing

examined sample. Apparently, for a pure sinusoidal signal, it will be RMS value. For comparison of Standard deviation values of different signals is helpful to do normalisation, so they can be compared in the same framework without losing information. The author and the supervisor agreed that normalisation by RMS value division is a viable approach. Moreover, in that case, normalised sigma or

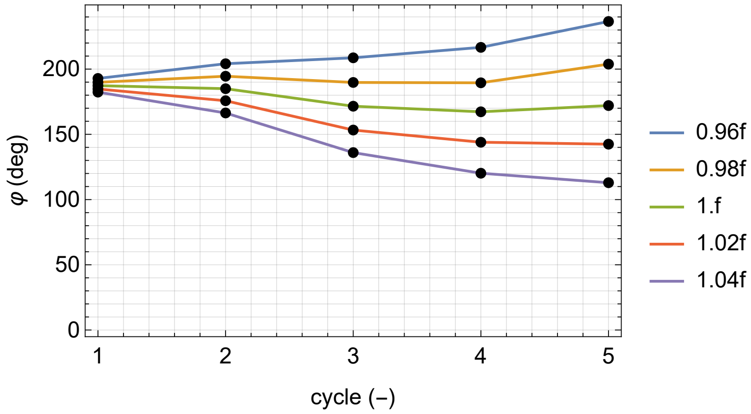
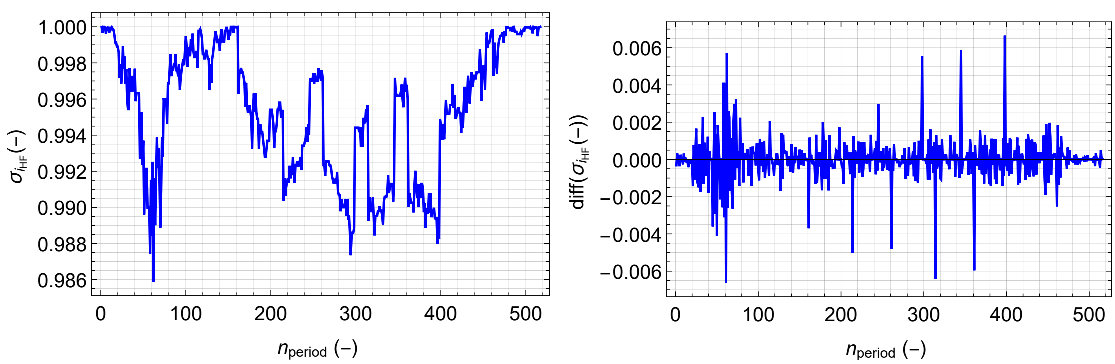


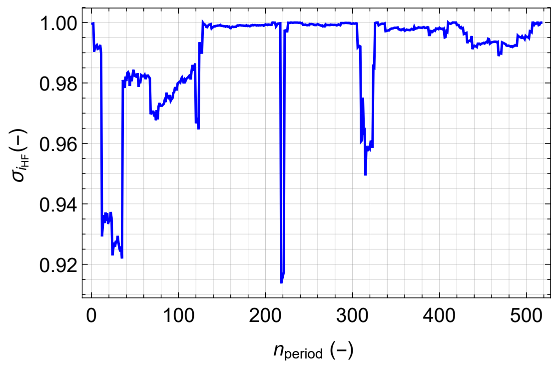
Figure 4.10: Phase angles of power drill's current with arcing

Standard deviation will be a dimensionless quantity.
For the signals analysed in the previous section were also acquired high frequency components of the current signals. The fundamental frequencies were estimated, and standard deviations were calculated for the closest integer number of samples of the real value of the signals periods. Figures 4.11 and 4.13 show characteristics of the signals without arcing. It is obvious that in those data is some variability and naturally differences of standard deviation show changes in that variability. Apparently, the main concern, in this case, is a source of the variability. Comparing these figures with figures of the signals with arcing 4.12, 4.14, it becomes obvious that in case of the presence of a series arc the rate of change in variability is larger. Furthermore, it seems to be more random. For instance, in the figure 4.11b peaks can be referred to switching of thyristors. Also, the change shown in the figure 4.13b can be explained by the presence of noise. Consequently, from that observation, the hypothesis can be derived that unfrequent changes in the variability of examined samples probably is an indicator of the presence of a series arc.

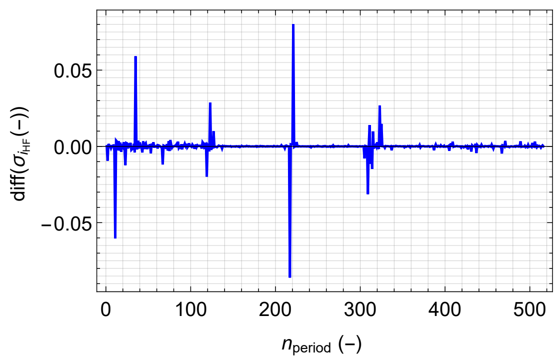


(a) Standard deviation (b) Differences of standard deviation

Figure 4.11: i_{HF} of a thyristor controlled load without arcing

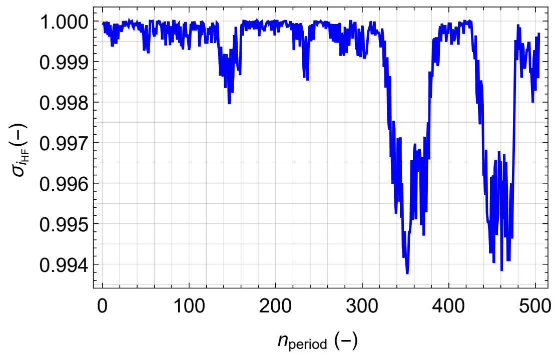


(a) Standard deviation

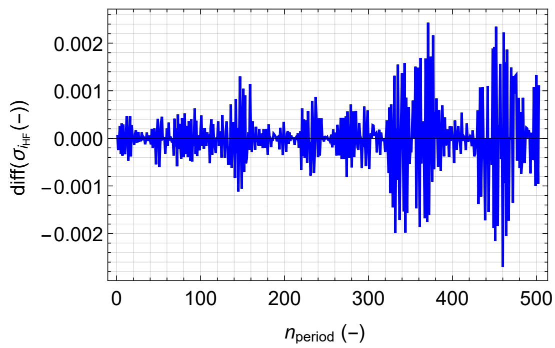


(b) Differences of standard deviation

Figure 4.12: i_{HF} of a thyristor controlled load with arcing

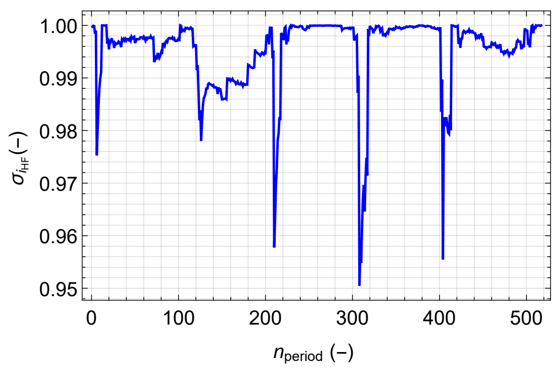


(a) Standard deviation

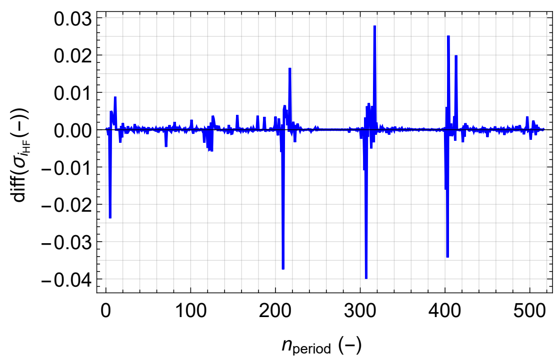


(b) Differences of standard deviation

Figure 4.13: i_{HF} of the power drill without arcing



(a) Standard deviation



(b) Differences of standard deviation

Figure 4.14: i_{HF} of the power drill with arcing

4.2.2 Integration of high frequency component

As mentioned previously, arcing is a stochastic phenomenon thus the energy consumed by a circuit with a series arc indeed is volatile. However, energy analysis requires more instruments rather than current measurement. Consequently, the measurement of energy should be substituted by current assessment in a way that it will convey the information about energy. Furthermore, power is a product of impedance times current squared, and energy is an integral of power. Apparently, the assessment of energy is reasonably replaceable by analysis of the integrated squared current signal. However, in that case, a piece of information about energy will be lost. Although that seems to matter in fact is irrelevant. Apparently, significant variation in impedance will affect current hence current signal assessment regarding changes does not require impedance value. The author assumed that at normal operation an integral of the current squared would be smooth and probably almost linear. Here is why. Let assume a periodic function - $f(t)$ that represents a current signal. For such function is true:

$$f(t) = f(t + \mathrm{T}) \tag{4.4}$$

then $f^2(t)$ is also a periodic function

$$(f(t))^2 = (f(t + \mathrm{T}))^2 \tag{4.5}$$

any periodic function can be approximated by Fourier series

$$\mathcal{F}(f^2(t)) = \frac{\mathrm{a}_0}{2} + \sum_{k=1}^{\infty} \mathrm{a}_k \sin(kx) + i\mathrm{b}_k \cos(kx) \tag{4.6}$$

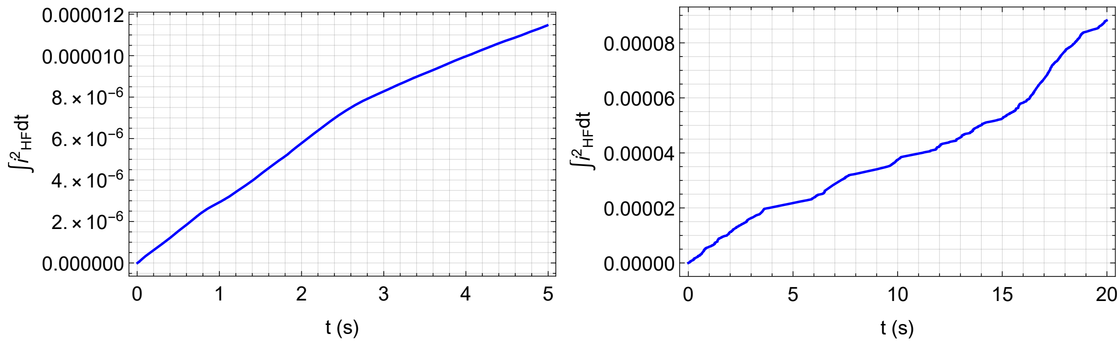
coeficient a_0 is positive because $(-n)^2 = n^2$. Integral of $f^2(t)$ is:

$$\int f^2(t)\mathrm{d}t = \int \mathcal{F}(f^2(t))\mathrm{d}t \tag{4.7}$$

$$\int \mathcal{F}(f^2(t))\mathrm{d}t = \frac{\mathrm{a}_0}{2}t + \sum_{k=1}^{\infty} -\frac{\mathrm{a}_k}{k}\cos(kt) + \frac{i\mathrm{b}_k}{k}\sin(kt) \tag{4.8}$$

From the equation, 4.8 is consequent that the function probably looks close to a straight line. However, it is more convenient to assess a periodic signal using standard deviation; thus a DC component of the squared current signal should be subtracted and in the result will be a periodic function if there is no arcing in an analysed circuit. To that point, this approach of analysis was aimed at the current signal; however, the author is going to assess high frequency component, because everything above is valid for that. Furthermore, a change in a current signal is sharper in the high frequency component when an arcing occurred.

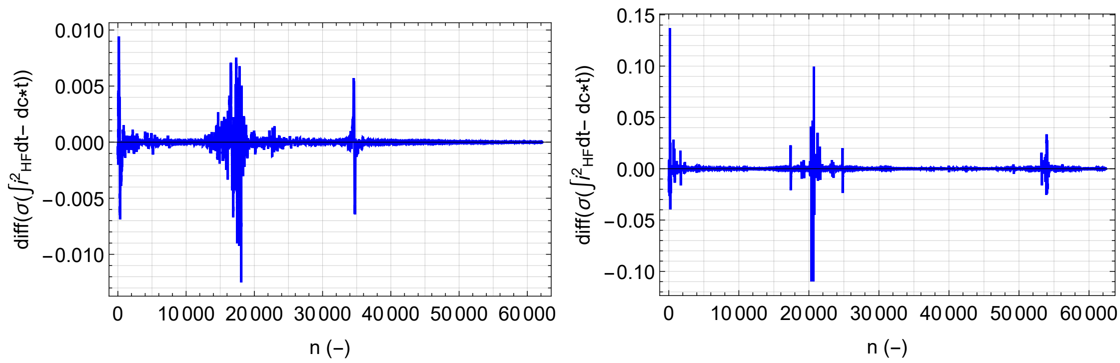
Figures 4.16, 4.15 show results of analysis using the approach described above. Indeed, smoothness of integral in the case without arcing is confirmed comparing to signal with arcing, as the author assumed. Nonetheless, from standard deviation is hard to understand whether a series arc was in the circuit during record. To conclude, this approach does not convey more information about arcing in a circuit than standard deviation analysis described in the previous section.



(a) Curret signal without arcing

(b) Curret signal with arcing

Figure 4.15: $\int i_{HF}\mathrm{d}t$ of the bulb's current



(a) Differences of standard deviation of the current without arcing

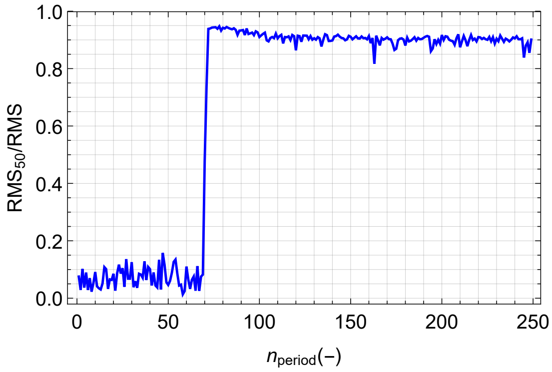
(b) Differences of standard deviation of the current with arcing

Figure 4.16: SD differences of $\int i_{HF}\mathrm{d}t$ of the bulb's current

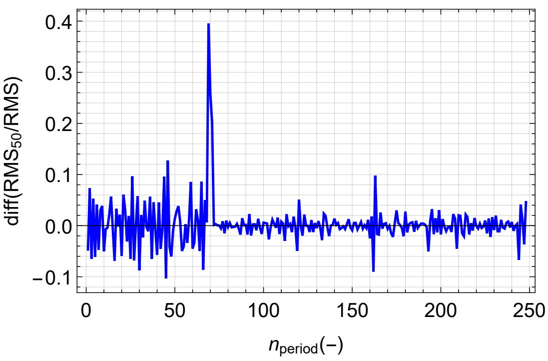
4.3 Fundamental harmonic and noise

The feature of a series arc to produce a broadband noise was investigated a lot. However, many approaches have time-consuming operations. On the contrary, faster algorithms, for instance, FFT, are not precise as was discussed in chapter 2. Hence, the author examined slightly different approach, which can give precision and does not require many calculations. The concept is similar to THD (Total Harmonic Distortion). Although, the author modified that to attempt to eliminate excessive operations without losing information about the signal. The steps are simple. Firstly, using method described in chapter 2 estimate fundamental frequency. Secondly, calculate Fourier coefficients of the fundamental harmonic. Thirdly, compute RMS of the examined current signal. Finally, calculate a ratio of RMS of the fundamental harmonic to the RMS of the raw signal. Let us examine that with real data.

From figures 4.17 and 4.18 a conclusion can be derived that a change in RMS_{50} to RMS ratio could mean a change in load conditions or an arcing in a circuit. The small values of the ratio corresponding to the no-load operation.

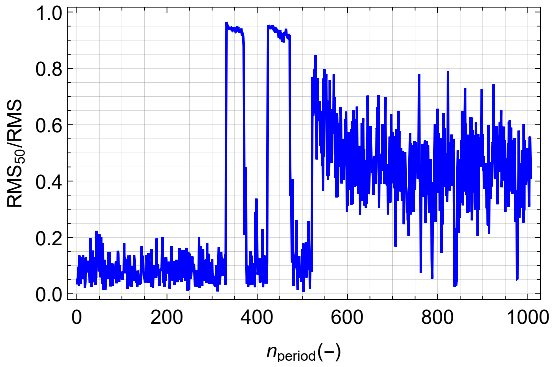


(a) RMS_{50} to RMS ratio

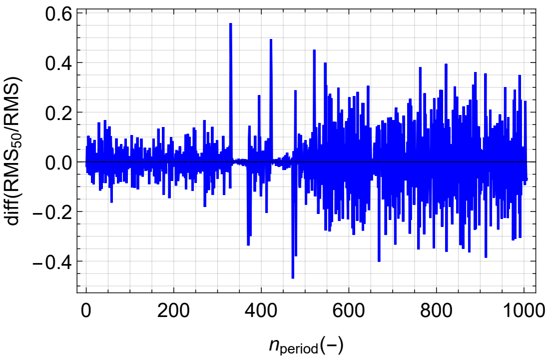


(b) Differences of RMS_{50} to RMS ratio

Figure 4.17: Drill's current without arcing



(a) RMS_{50} to RMS ratio

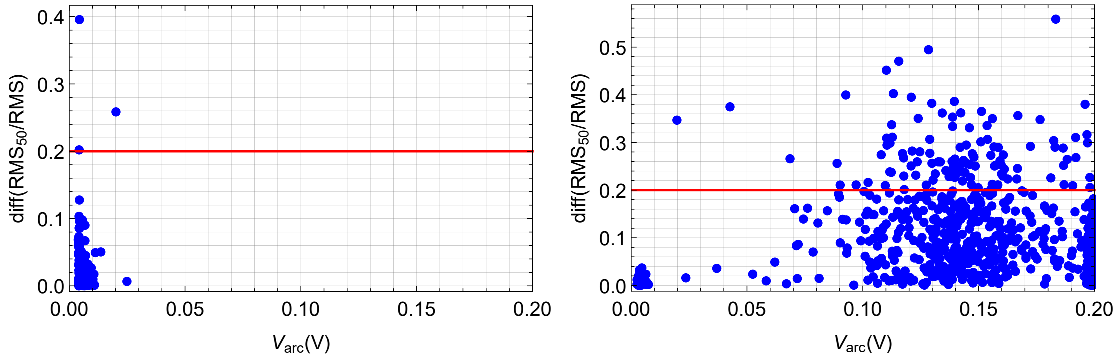


(b) Differences of RMS_{50} to RMS ratio

Figure 4.18: Drill's current with arcing

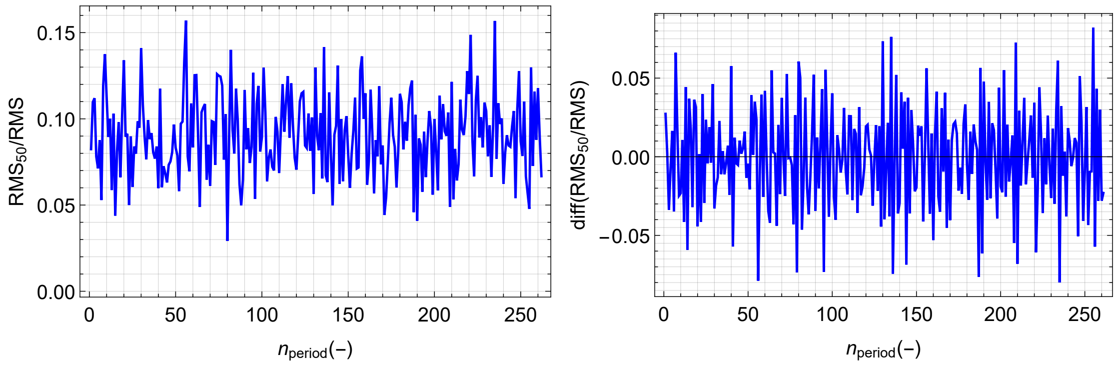
Furthermore, a change in the ratio higher than 0.4 seems to be an indicator of switching. However, these observations should be proven on a much high data set. The author observed on acquired data that RMS_{50} to RMS ratio higher than 0.2 and lower than 0.6 most likely correlate with an arcing condition. Figure 4.19 supports author's conclusions. The arc voltage lower than 0.02 is a short-circuited arc and arc voltage 0.2 is open circuit. There are certain outliers; however, the pattern is clear.

Figures 4.20, 4.21 and 4.22 show the result obained for current signal of a LED in the same fashion as for drills' current signals above.



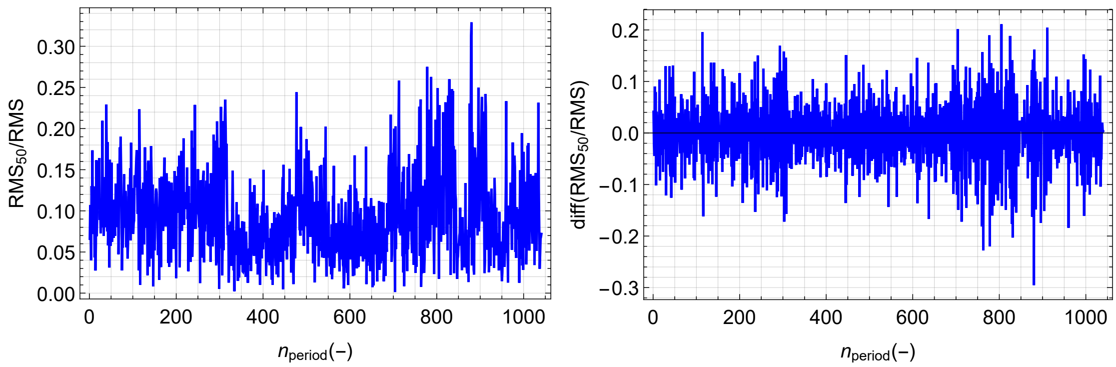
(a) Current without arcing (b) Current with arcing

Figure 4.19: RMS_{50} to RMS ratio with coresponding RMS of arc voltage



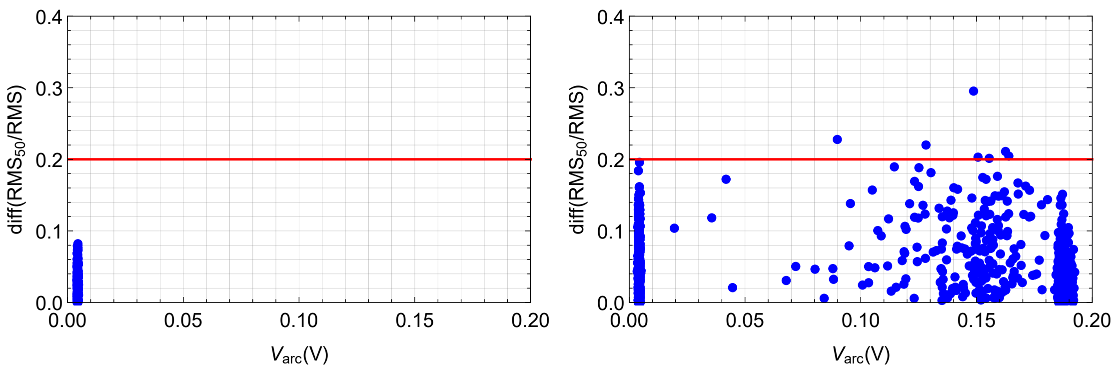
(a) RMS_{50} to RMS ratio (b) Differences of RMS_{50} to RMS ratio

Figure 4.20: LED's current without arcing



(a) RMS_{50} to RMS ratio (b) Differences of RMS_{50} to RMS ratio

Figure 4.21: LED's current with arcing



(a) LED's current without arcing

(b) LED's current with arcing

Figure 4.22: RMS_{50} to RMS ratio with coresponding RMS of arc voltage

5. Measurement setup for series arc faults

This chapter describes the setup made at the Faculty of Electrical engineering at CTU. Furthermore, the electrical scheme of the setup is provided and used filters are brifly described.

5.1 The description of the setup's functionality

The setup made at the faculty of electrical engineering at CTU for arc faults measurements uses arc generator. It is one of the two options how to create arcing in a circuit according to IEC standard [7]. The block scheme of the setup is shown in the figure 5.1. It explains from a high-level perspective what the setup can provide. The first block from the left is a transformer which converts the current signal into the voltage signal, which is gained after that and goes to the oscilloscope. That is a raw current signal. This signal additionally goes through two analogue filters. The first one is a second order lowpass filter, which's output is gained and connected to the oscilloscope. The second is a second order highpass filter, which's output is also gained, after that goes through an envelope detector and eventually to the oscilloscope input. This signal shows the envelope of the high frequency component of the current in the circuit. Furthermore, the arc's voltage is measured. The output of a transformer gained and connected to the input of the oscilloscope.

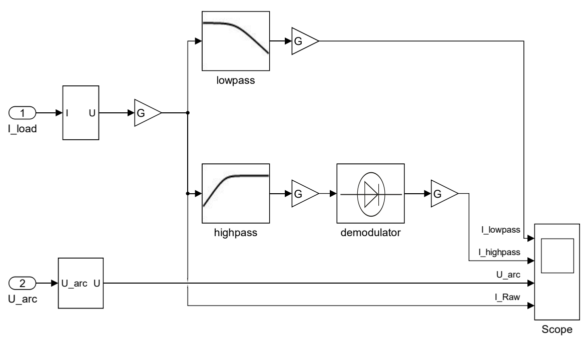


Figure 5.1: The block scheme of the setup

5.2 Detailed description of the setup

Figure 5.2 shows the setup scheme. The subscribed arrows are oscilloscope chanels. Transistor amplifiers are used to gain the signals. Two arrows mean an arc generator, which can be short circuit with the switch connected in parallel.

Figure 5.3 demonstrates the highpass filter part of the setup with transistor amplifiers resistances taken into consideration. This filter consists of two stages in series, which are essentially first order highpass filters. Apparently, the order of such filter is defined by a number of cascaded RC stages. The only difference between used highpass and lowpass filters are the places of resistors (R_1, R_2) and capacitance (C_1, C_2); they are switched in places.For the better understanding of the filter's behaviour, let us examine the filter, using real values of capacitors and resistors. The Bode plot 5.4 shows the gain of the filter for different frequencies. In the similar manner the lowpass filter behaviour can be described 5.5.

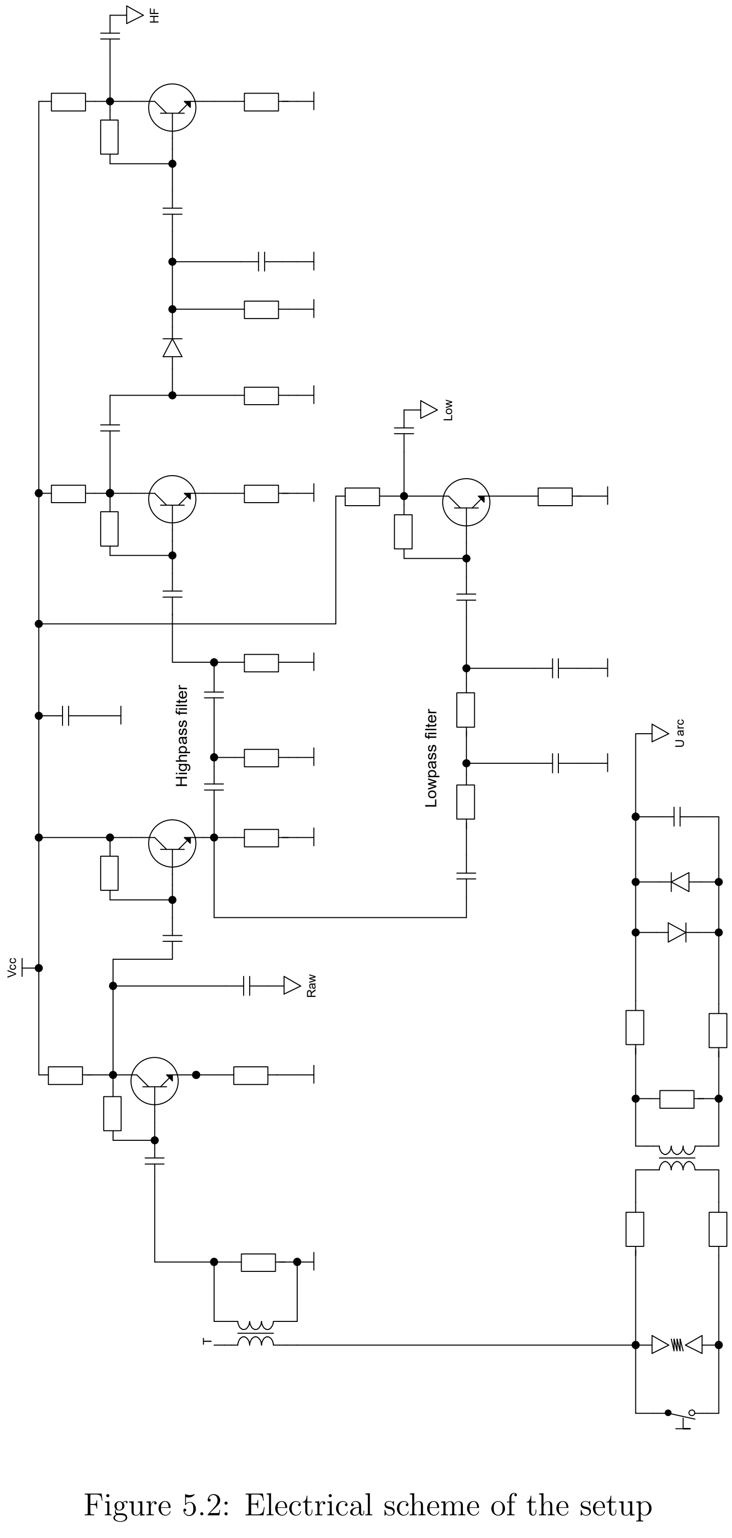


Figure 5.2: Electrical scheme of the setup

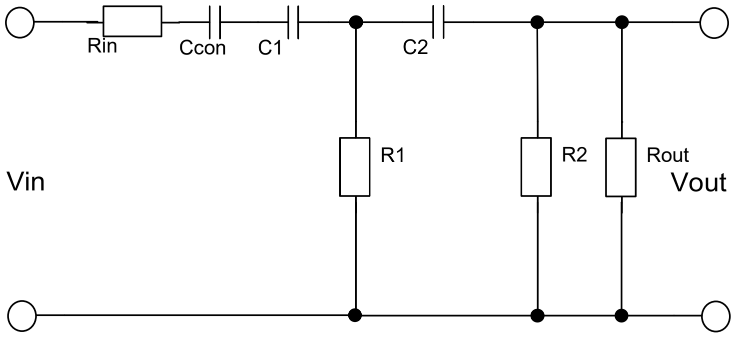


Figure 5.3: Highpass filter

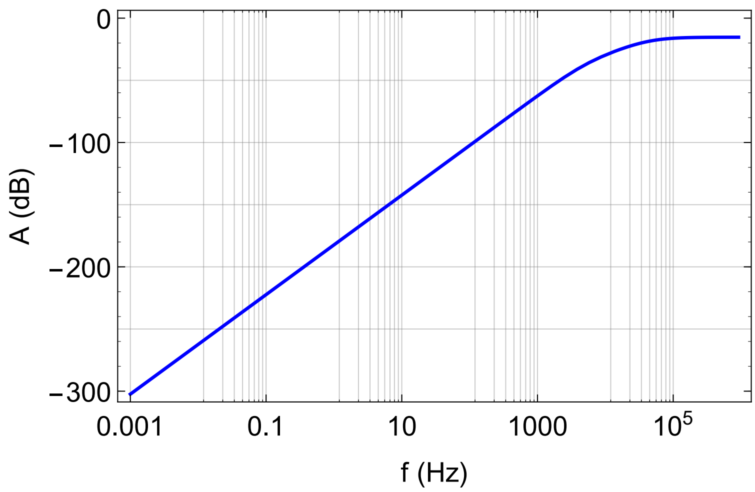


Figure 5.4: Bode plot of the highpass filter

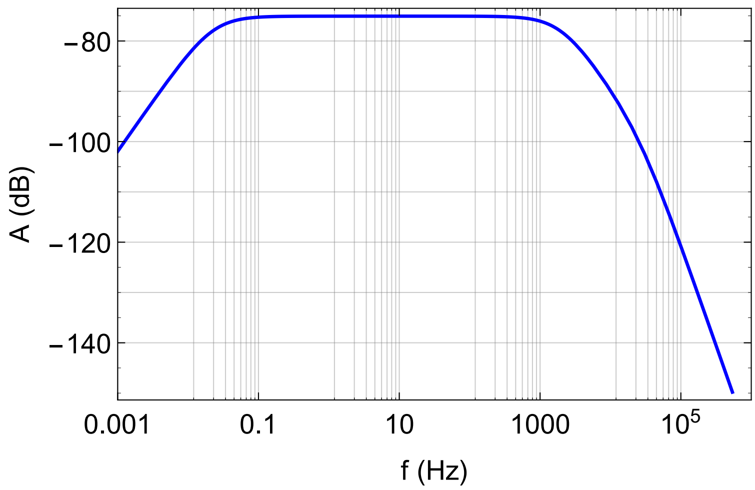


Figure 5.5: Bode plot of the lowpass filter

6. Nowadays methods of arc fault detection and its comparison

In this chapter, several methods of arc fault detection are described. Besides, the author proposes a novel approach to detection of a series arc. Moreover, the chapter presents a comparison of those algorithms.

6.1 AFDD by OEZ

The figure 6.1 shows the block diagram of AFDD made by OEZ company [15]. The device consists of two current sensors, an analogue circuit, a control unit and a switching mechanism, which able to disconnect both wires phase and neutral. The signals are measured on the phase conductor using two sensors. The first one is a detector of the fundamental frequency signal. The second one measures high-frequency component within 22-24 MHz band. Those two signals go through the analogue circuit which preprocesses signals which are assessed by the control unit. In the analogue circuit, the first signal is rectified and gained. The second one is an indicator of the power of high frequency component (RSSI). The series arc fault detection algorithm is based on an assessment of those two signals. The whole process is visualized in the figure 6.2. The derivative of RSSI signal is used to calculate the reference signal. The system indicates a presence of an arc in case of fulfilment of the conditions: the fundamental signal is crosing zero, the reference signal is larger than limit value G4 and value of RSSI is at least equal to G2. In case, there is nontypical RSSI signal for a series arc i.e. RSSI changes during high values of current signal, the fault integrator will be reseted.

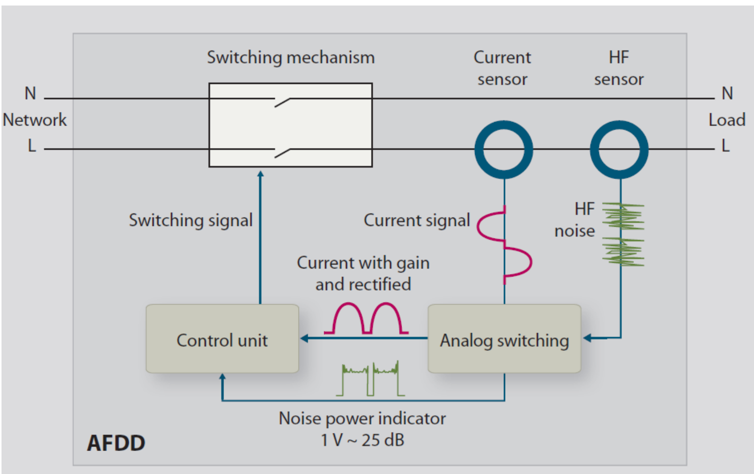


Figure 6.1: Block diagram [15]

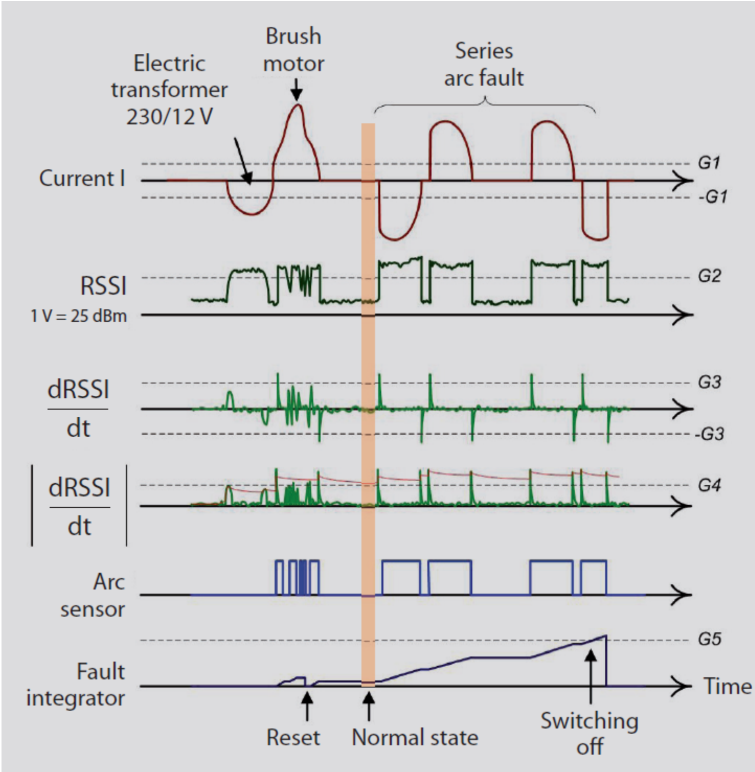


Figure 6.2: Detection algorithm visualized [15]

6.2 Arc fault detection method using low frequency harmonic current analysis

This chapter briefly describes a series arc detection method based on low frequency harmonic assessment and presents the description of required hardware. [16] This method analyses low frequency spectrum of a current signal. Furthermore, the time domain analysis of a current signal is utilised in that method. Spectrum analysis and time domain signal assessment are used to determine whether an arcing occurred. The method uses one of the high-resolution algorithms for spectral analysis; the Chirp-Z transform is a preferable choice.
The hardware is trivial; the figure 6.3 shows the block diagram of required hardware. This method needs a current transducer, which measures the current signal of a protected AC circuit. The signal from the transducer goes to the signal conditioning unit. It consists of two stages an anti-aliasing filter and a signal amplifier. The output of the conditioning unit is connected to the sample and hold unit, which is connected to an analogue-digital converter. The inventors claim that 10-12 kHz sampling frequency will give the desired precision. The converted signal is analysed in a processing unit, which decides whether it should send a command to the tripping circuit.

The detection algorithm uses several indicators to evaluate a current signal.

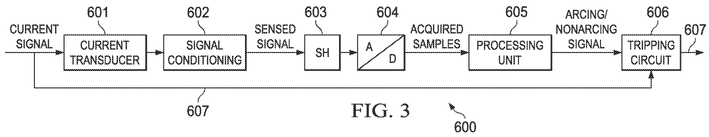


Figure 6.3: Block diagram of the hardware

The flow chart of the method is shown in the figure 6.4. After obtaining the number of samples that corresponds to the analysed window, indicators are calculated. The computed values are compared to the thresholds. In case differences between actual values and thresholds are within predefined limits. A conclusion would be that in a circuit is no arcing and algorithm proceeds with updating thresholds. If one of the indicators is outside of the limits, it means that there is a possibility of arcing in the circuit or there is a change in the load. In that case, the second group of indicators is compared to the threshold values. If the result of this step is positive, the second group of indicators is within limits; a conclusion is that there is no arc, and thresholds will be updated. Otherwise, the arc condition is presumed, and threshold values are maintained.

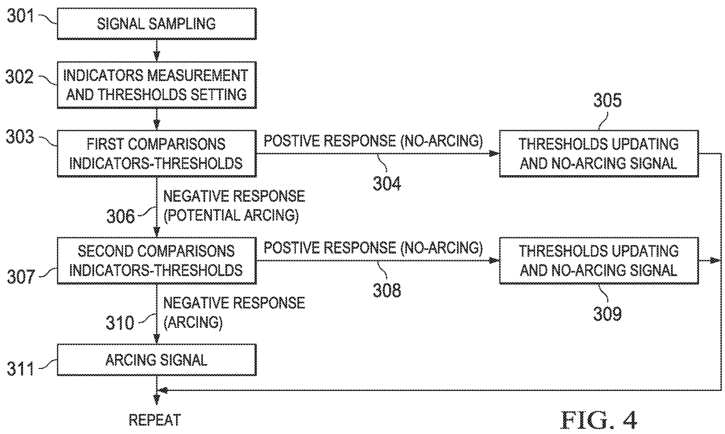


Figure 6.4: Flowchart of the algorithm

The indicators used in the algorithm were derived from analysis of low frequency spectrum [16]. According to the inventors of [16], the first group of the indicators could be switched with the second group. The main difference between those two groups is one uses time-domain analysis, and another uses frequency domain analysis. One of the indicators is a difference between RMS values of observation windows. The second is differences between samples of two subsequent short-time windows and can be calculated using formula 6.1.

$$DCW = \frac{1}{N}\sum_{i=1}^{N} I_{1\_i} - I_{2\_i} \tag{6.1}$$

The third indicator DFS 6.4 assesses a change in low frequency spectra of two following observation windows.

$$DFS = \frac{1}{N}\sum_{i=1}^{N} F_{i\_1} - F_{i\_2} \tag{6.2}$$

where F_{i_1} is an amplitude of ith harmonic of the previous observation window.

The forth indicator DHFS evaluates the difference between the maximum values of the low frequency spectrum of consecutive observation widows [16]; it is defined as follows.

$$DHFS = HFS_1 - HFS_{i2} \tag{6.3}$$

where HFS is a maximum amplitude of the low frequncy harmonic, which is an integer multiple of the fundamental.

On the contrary, the fifth indcator asesses interharmonic oscilations (noninteger multiles of the fundamental frequency); The NFS can be calculated using folowing equation:

$$NFS = \frac{FS}{N} \tag{6.4}$$

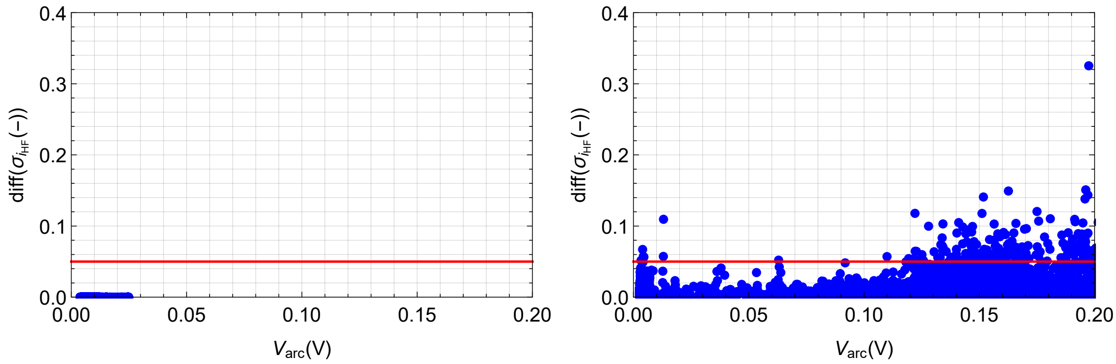
where FS sum of the low frequency interharmonic amplitudes and N is a the number of those frequecies.

6.3 A novel approach (Future work)

This section introduces a novel approach for arc fault detection. Nevertheless, an invention of a new method of AFD is out of the scope of the thesis; the author decided to propose an approach, which is based on arc's features discussed in chapter 4. There is a need to disclaim that everything below is just a discussion of a possible detection method. Moreover, this section should be interpreted as a proposition of future work at the department of electrical power engineering at CTU.

The author observed that some of the features of a current signal with arcing, which were investigated in chapter 4 might be useful in the detection of a series arc. As discussed previously, the differences of a standard deviation of a high frequency component of a current signal might be a good indicator of arcing in a circuit. Therefore, the author examined that hypothesis, whether high differences of sigma correlate with arcing. The figure 6.5 shows that a dependance between differences of SD and RMS of arc's voltage. Arc's voltage around zero volts corresponds to a short-circuited arc and around 0.2 volts to an open-circuit.

That is clear that in case of arcing the values of $diff(\sigma_{i_{HF}})$ are higher. There is definitely a pattern, which, however, should be proven on a much bigger data set. Furthermore, there are exceptions that contradict author's hypothesis, some of high values of $diff(\sigma_{i_{HF}})$ could occur with a short-circuited arc 6.5b. These outliers are probably caused by switching. Therefore, another indicator should be utilised to eliminate false tripping of an AFDD; the RMS_{50} to RMS value may be a good solution.



(a) Current without arcing

(b) Current with arcing

Figure 6.5: Differences of standard deviation of high frquency component of a drill's current

However, the author does not go beyond proposition of a new method, since it is a not a goal of the thesis. Hopefully, the proposed approach will be investigated further at the department of electrical power engineering at CTU. A lot of engineering work should be done to prove the feasibility of that approach. First of all, the thresholds should be established with the respect of possible load conditions. The thresholds could be dynamically updated or static. Also, the method should be examined with very different loads. However, the author on purpose experimented with drill's current because it is one of the hardest loads for arc fault detection, due to drill's behaviour during acceleration. The obtained result looks promising. Although, it does not prove this approach is viable.

6.4 Comparison of AFD methodes

Unfortunately, it is impossible to compare these three methods of arc fault detection directly using real data or connecting to the setup. Therefore, the author will examine hereafter the differences in the detection approaches. Furthermore, the author will attempt to establish, under which conditions the methods could possible not detect or falsely detect a series arc.

The detection approach used by OEZ company seems to be an industry standard. Moreover, it is the only one of compared methods, which is on the market.

However, the author sees one major flaw of that algorithm; it depends on noise in 22-24 MHz band. In case there will be anything that produces such frequencies it might mask a series arc fault.

On the contrary, the algorithm described in 6.2 uses low frequency spectrum for detection of the fault. Moreover, there is other difference this method utilises Fourier transform. Furthermore, this approach uses time-domain analysis as well as frequency domain.

The proposed method 6.3, on the other hand, uses the whole spectrum for detection. The first indicator (differences of a standard deviation of a current high frequency component) uses only high frequency component. The second utilises the whole spectrum, by comparing fundamental harmonic to the RMS of the signal. This approach in some sense closer to the method described in 6.2 because it uses both time-domain and frequency-domain analysis. However, not explicitly but rather indirectly by comparing RMS_{50} to RMS of a signal. Nonetheless, it distinguishes this approach from the one used by OEZ, because it still requires computation of Fourier coefficients.

Let us compare more systematically. In the table 6.1 Method 1 is the approach used by OEZ, method 2 is the approach described in 6.2, and method 3 is the proposed one.

	Method 1	Method 2	Method 3
On the market?	Yes	No	No
Uses HF component?	Yes	No	Yes
Uses LF component?	No	Yes	Yes
Uses specific frequeny band?	Yes	No	No
Uses Fourier Transform?	No	Yes	Yes
Time-domain Analisys	Yes	Yes	Yes
Frequency-domain analysis	No	Yes	Yes

Table 6.1: Differences in appproaches

From table 6.1 is clear that the Method 1 is the only that essentially uses only one indicator for detection, comparing to the other two. Furthermore, it does not utilise frequency-domain analysis. From that a conclusion can be derived, that even it is a reliable method, it does not have redundancy, which may be not the best for detecting such a problematic fault as the series arc. However, it has to be mentioned that in virtually infinite possible combinations of household loads might exist a combination that could mask a series arc in the way that any arc fault detection algorithm will not be able to detect the fault.

7. Conclusion

The thesis aimed to investigate the problematics of series arc faults detection in households. The first part, i.e. chapters 2 and 3 of the thesis focuses on the theoretical background of the topic. The mathematical tools necessary for the understanding of this work are explained. Moreover, the author outlines well-known characteristics of a series arc fault.

The other goal of the thesis was to conduct experiments using setup mad at CTU. The chapter 5 describes the setup functionality and hardware. The obtained data was later utilised to conduct an investigation, which is described in the chapter 4. The chosen approaches were not used so far or at least not widely known and not present in the popular literature on that topic.

The third objective of the thesis was a description of several algorithms of AFD and its comparison. Chapter 6 briefly outlines several AFD methods and compares them. A conclusion of the chapter 6 is, besides the effort to find a reliable approach was tremendous, the goal is still not achieved. Also, the author proposes future direction of the research of AFD methods at the department of electrical power engineering at CTU.

The author concludes that even though the AFD method used by OEZ company is reliable 6.1 there is room for improvement. The research should continue, finding new indicators of series arc fault may enhance AFD. The main concern stays yet that there is a possibility of masking of a series arc fault by loads in the household. The author assumes, having a redundant algorithm may be a better solution. The meaning of the redundant algorithm is, in this case, it has to utilise not only one indicator and to use the whole frequency spectrum.

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List of Abbreviations

A	Ampere
AC	Alternating current
AFCI	Arc Fault Circuit Interrupter
AFD	Arc Fault Detection
AFDD	Arc Fault Detection Device
CTU	Czech Technical University
DC	Direct Current
Diff	Differences
FT	Fourier Transform
FFT	Fast Fourier Transform
HF	High Frequency
Hz	Hertz
LED	Light-Emitting Diode
LF	Low Frequency
RF	Radio Frequency
RMS	Root Mean Square
SD	Standard Deviation
THD	Total Harmonic Distortion
V	Volt

List of Figures

List of Attachments

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- HFComponent.nb ...... SD analysis of HF component
- phase_shift.nb .... Calculation of phase angles of a current signal
- RMS50toRMS.nb .... Rms_{50} to RMS
- Data .... Some of the obtained data
  - scope_0.csv
  - scope_1.csv
  - scope_2.csv
  - scope_3.csv
  - scope_4.csv
  - scope_5.csv
  - scope_6.csv
  - scope_9.csv
- Methods of Detection of Serial Arc In the Presence of Household Electrical Loads.pdf Thesis