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A Method for Determining Arc Breakdown in Low-Voltage Electrical Networks

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Abstract: In low voltage distribution networks, there is a high risk of fires caused by wiring faults that lead to short circuits. Arcing protection devices (ARCs) already exist, but experiments show that they also often do not disable such faults. The operation of most existing arc fault detection devices is based on the detection of high frequency current components and their comparison with load profiles. For the fast arc fault recognition low-frequency oscillations can be assessed, which serve as a marker of the arc fault presence in a LV distribution network. This method of arc fault recognition in LV networks is easier to implement practically. Using the windowed Fourier transform or Wavelet analysis, it is possible to determine the change in time of the harmonic components of the current, which will be a characteristic sign of the presence of an arc fault along with other signs.

Keywords: Arc faults harmonic analysis, Simulation Matlab/Simulink protection of low-voltage networks, Current and voltage harmonics, Arcing, Nonlinear loads.

1 Introduction

When designing and operating low voltage (LV) networks, correct determination of the possible short-circuit current values may present a significant challenge. Even for a metal short circuit, calculations may become problematic despite of the fact that most of substation circuits and equipment are typical, and therefore respective characteristics are well known. However, equipment impedance values are usually provided by manufacturers for ideal operating conditions. Therefore, over time the value of these impedances may change, especially contact resistance. The calculations of arc short-circuit currents feature even lower accuracy, because of the difficulties with the determination of the short-circuit circuit resistance. The main obstacle in solving this issue is the lack of correct data on the arc resistance value. Especially in case of remote arc short circuit featuring low current values protection devices such as

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circuit breakers may not trigger the circuit despite of the fire hazard and, hence, the urgent need for immediate disconnection.

Another typical failure in LV networks corresponds to a series arc fault.

In order to minimize the consequences of an arc fault special devices can be used (Arc fault circuit interrupter or Arc fault detecting device) as the common protective devices like circuit breakers, fuses or leakage current interrupter are not able to detect this malfunction. The operating principle of these devices is based on detecting several parameters, e.g. current harmonic spectrum, calculated derivatives, existing high frequency oscillations. However, implementation of such methods is complex and requires high sampling rate of measuring device, as well as a set of reference patterns for each load type. Nevertheless, for each arc detection approach certain load types can be defined that cause false triggering or, non-triggering during the arc fault. For the fast arc fault recognition that can be further implemented in protection devices, low-frequency oscillations can be assessed, which serve as a marker of the arc fault presence in a LV distribution network. This method of arc fault recognition in LV networks is easier to implement practically.

2 Problem Description

The research in this field mainly focuses on development of approaches for arc characteristics determination resulting in significant amount of papers and patents studying with devices and methods for arc detection. However, sufficiently comprehensive and validated solution has not been proposed yet. Hence the main aim of the present study that is to find a suitable technique for correct arc fault detection in the presence of load masking effect.

Current research on arc fault detection is limited to practical design of respective devices that utilize the waveshapes of voltage and arc current, as they generally show most clear phenomena when an arc breakdown occurs [1, 11, 12]. Many of the existing approaches for arc fault detection study current waveform and its first and second derivatives in order to identify peaks, zero “pads”, or fast front rise after the zero “pad” [1, 3, 10]. Another way to distinguish an arc occurrence is to analyse broadband high frequency (HF) noise, in the range of kHz to MHz. For example, in [2] HF component is analysed by constructing slices of a 3D surface based on a bispectrum. Other references consider signal non-periodicity as an arc detection criterion [3]. In order to improve detection reliability multiple criteria can be used [3, 8, 13]. In this case, measured parameters of current waveshape are compared with predefined threshold values corresponding to the presence of arc currents. For HF detection methods adopted digital signal processing techniques bring about the need for precise measurement of HF components and hence high sampling frequency [4, 14, 15].

Methods for investigation and detection of the arc fault are mainly based on spectral analysis of the current waveshape with special focus on harmonic variation over time [3, 13]. In [4] continuous wavelet transform is adopted for study of the frequency bands of the current time variation during series arc fault. The use of continuous wavelet transform requires significant amount of measurement data, that can be reduced by introducing discretization techniques, utilizing selected parts of the entire set of coefficients for continuous transformation [6]. Time-domain analysis of the differences in the signal frequency bands allows to identify series arc faults and distinguish them from the regular current waveshapes. Signal processing of the current by means of the digital signal processor allows to extract high-frequency part of the signal, indicating the presence of an arc-over.

The discrete wavelet transform processes the signal by separating high-frequency signals (detailed representation) with low-frequency signals (approximate representation). Then compares the normal state and in case of a series arc breakdown, the appearance of a malfunction. The fault current will be converted into the form of a wavelet so that it gives certain coefficients, then the coefficients will be converted into certain variables that can be used for detecting interference. The presence of this interference causes the turn OFF of a circuit breaker with a message to the user that there is an arc.

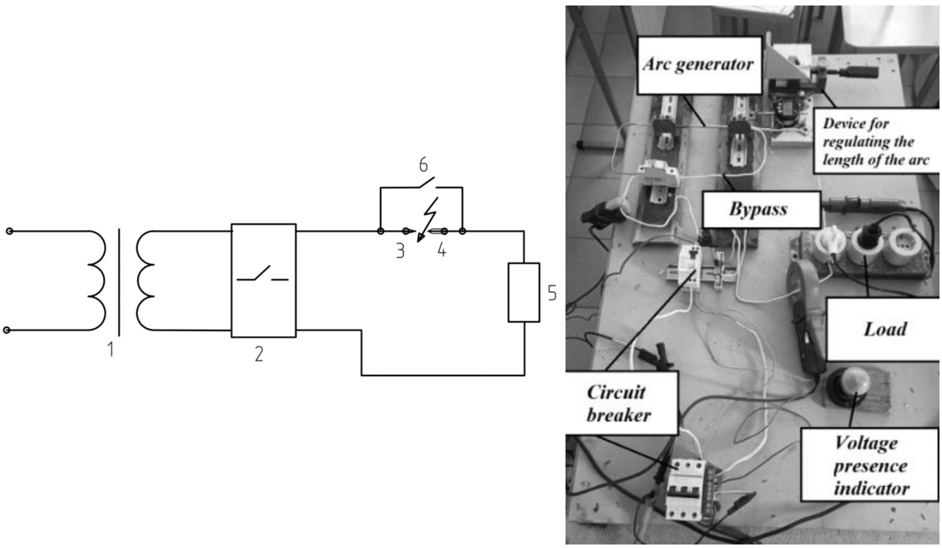
Additionally, low-frequency (LF) current harmonics can be analysed for arc-over detection. For residential buildings [5] suggests the fifth harmonic level as an arc fault indicator. [7] presents a method for detecting series arc fault in electrical circuits, using a high-resolution low-frequency harmonic analysis of the current signal based on the modified version of the discrete Fourier transform and the corresponding set of indicators. In [8] the distinction of the regular household current waveshapes from those corresponding to the arc-over is produced based on the ratio of the RMS current rate of change versus duration of the zero current. To study the shape of the current curve, it is necessary to suppress random noise when extracting useful information, as well as normal mode data for different loads for comparison when determining the appearance of an arc. The ratio of the current rate of change to the RMS value, that is, the difference between two adjacent sampling points divided by the sampling interval, is used to obtain the rate of change. The sampling interval is a fixed value, but unfortunately a specific calculation is not given in this article. It is also unclear for which harmonics the RMS current is calculated. When monitoring the state of the circuit, it is possible to distinguish by current changes not only the appearance of an arc breakdown, but also its localization, since the load affects current changes when an arc appears.

Altogether using time variation of LF components of the current spectrum for an arc fault detection shows itself as a promising approach that is sufficiently effective and easy to implement and thus will be further considered in the current paper.

3 Figures

Multiple experiments were produced in order to determine characteristics of the arc fault in real network conditions corresponding to various load types.

It follows form the study that an arc fault may appear if conductor is “burnt”, that presents certain difficulties for experimental creation of an arc in laboratory conditions. If uninsulated conductors are used for the experiment, their separation or bringing together may not feature arc-over in the gap between the contacts. Hence, in order to assure the arc occurrence, a copper and carbon contacts were used in the experimental set-up [15]. Additionally, experiments using copper and aluminium electrodes with preliminary carbonized isolation were conducted as well [22]. This corresponds to the real conditions of an arc over within isolated conductors utilized in low voltage grids. For simulations of length-wise arc-over in consumer networks the distances between the electrodes were assumed to be equal to tenths of a millimetre, which corresponds to possible real-life cases: e.g. of a poor contact or a conductor fracture. A simplified scheme of the arc testing set-up is shown in Fig. 1.



(a) (b)

Fig. 1 – (a) *Arc fault testing set-up: 1 - Transformer; 2, 6 – Circuit breakers; 3 – Copper electrode; 4 – Graphite or carbonized isolated metal electrode; 5 – load;* (b) *General view of the installation for the study of arc breakdown.*

4 Experimental Results, Data Processing

Experimentally obtained waveshapes including current and voltage at the input and directly at the arc-over point; were transformed into harmonic spectra and analysed. The voltage curve was slightly distorted at the input circuit breaker, unlike the current curve, featuring rich and wide band harmonic spectrum [15]. Sufficient non-periodicity of the waveshapes corresponding to the arc fault and, hence, significant variations of harmonic spectra were the reason why application of traditional Fast Fourier transform was considered ineffective. Hence time-frequency decomposition methods (Short-Term Fourier Transform (STFT) and Wavelet Packet Transform (WPT)) were applied to the arc waveshapes allowing to derive correct representation of harmonic variation over time.

Fig. 2 shows the current and voltage waveshapes for the case of resistive 800 W load corresponding to the contacts being separated. As the arc appears, current magnitude decreases by appr. 8%, and after that varies slightly from period to period.

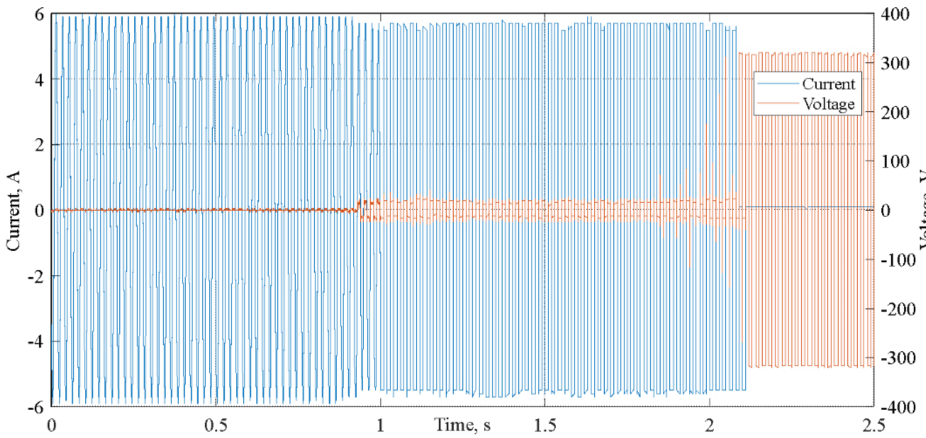


Fig. 2 – *Current and voltage waveshapes at the point of arc-over for the case of resistive load.*

Using the STFT for decomposition of the current waveform, shows significant variation of all harmonic magnitudes during arc fault and almost constant harmonic levels while in the normal operating mode. Additionally, significant variation during the arc-over occurs for the total harmonic distortion (Fig. 4) and harmonic phase angles (Fig. 3)

The levels of considered current harmonics varied in the range of (2−7) A while arc current harmonic spectra using graphite or carbonized isolated metal electrodes were almost similar. Also, it should be noted that an arc fault with aluminium conductors emerged under lower current values, starting from 2.5 A and featuring higher levels and more rapid increase of even harmonics.

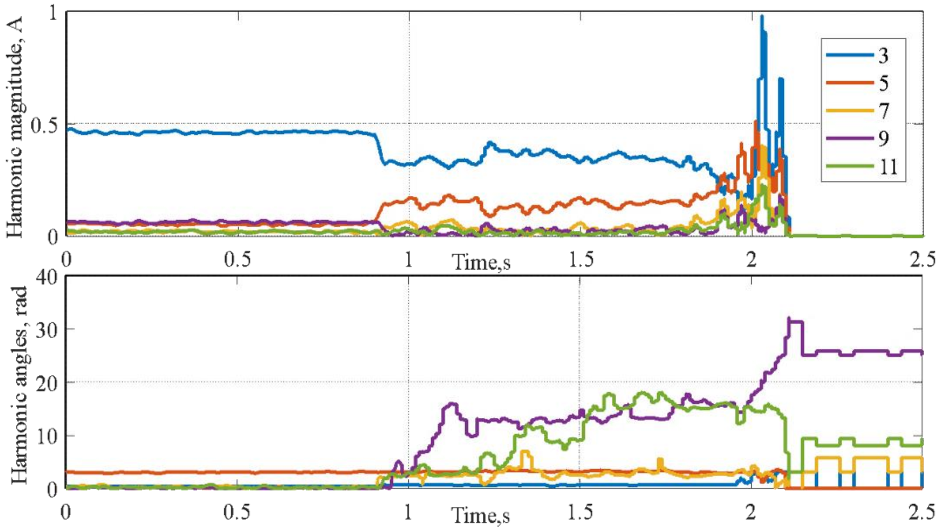


Fig. 3 – *Time variation of current harmonics produced by STFT during arc-over for the case of resistive load.*

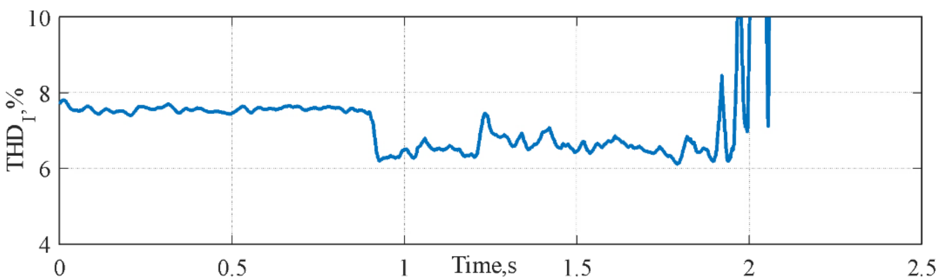


Fig. 4 – *Time variation of total harmonic distortion of the current during arc-over for the case of resistive load.*

Application of the WPT to the measured waveforms results in similar time dependencies of harmonics, Fig. 5. Compared to STFT results of the WPT feature spikes at the beginning of considered intervals originating from inherent properties of the WPT. Both techniques, STFT and WPT, produce a significant harmonic spike before the arc goes out.

The level of odd harmonics can be quite high even under normal conditions for various nonlinear loads. Therefore, the occurrence of even harmonics may be considered as clearer sign of an arc fault, despite of significantly lower harmonic magnitudes, Fig. 6.

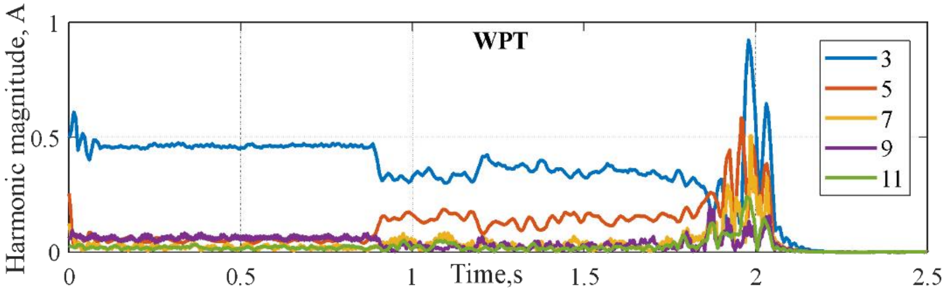


Fig. 5 – *Time variation of current harmonics produced by WPT during arc-over for the case of resistive load.*

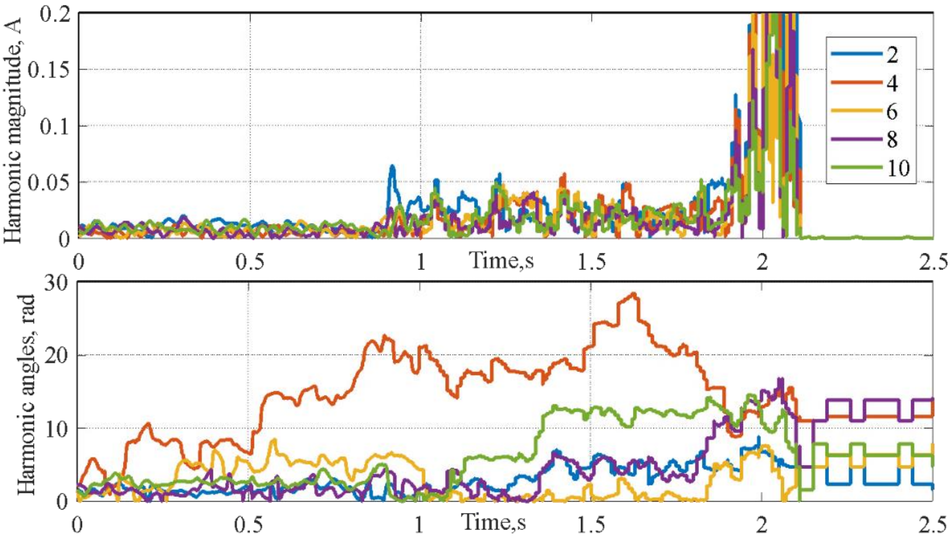


Fig. 6 – *Time variation of even current harmonics during the arc-over for the case of resistive load.*

When considering the time variation of current total harmonic distortion, the occurring arc fault tends to increase both level variation and value of the THD_I (Fig. 7). Additionally, significant deviations of harmonic phase angles for even harmonics are observed. The wavelet analysis produces similar outcome, with addition of fake “bursts” originating from transformation properties, that can lead to false conclusions about the presence of an arc fault.

Repeating experiments with closing and opening of contacts, provides a fairly stable reproducible result. It should be noted that deviation of harmonic phase angles varies, but in general, the occurrence of an arc fault demonstrates itself in significant increase of harmonic phase angle variation, especially noticeable for the 9^{th} and 11^{th} harmonics.

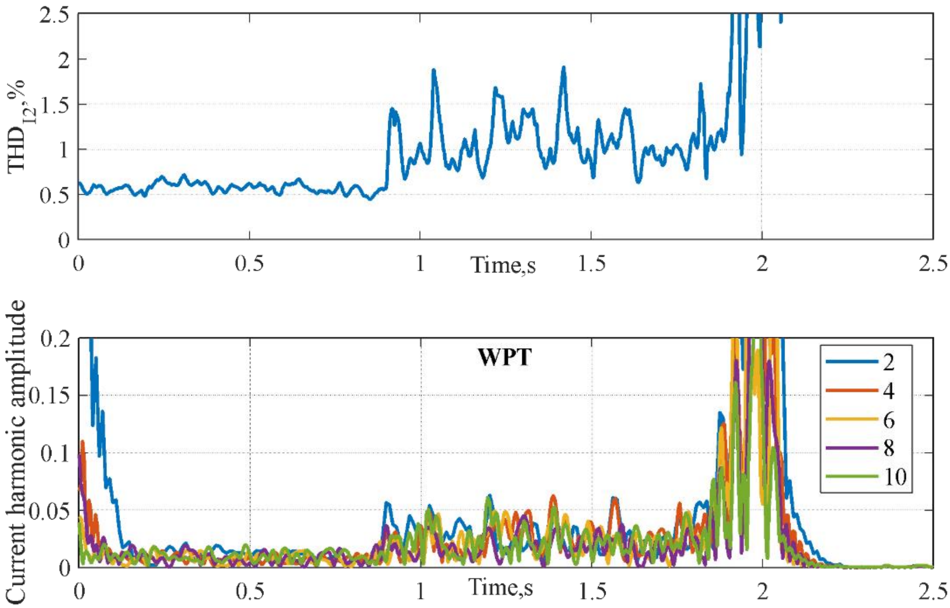


Fig. 7 – *Time variation of current harmonics produced by WPT during arc-over for the case of resistive load.*

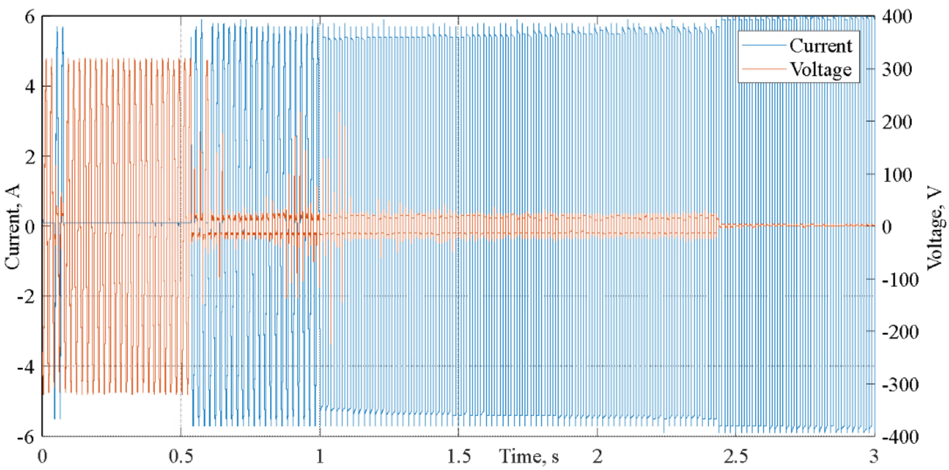


Fig. 8 – *Current and voltage waveshapes at the point of arc-over for the case of nonlinear load for the closing of contacts.*

During sparking caused by unstable arc burning (time interval from 0 to 0.6) harmonic “spikes” are clearly seen, especially for even harmonics. However, using sparking as an arc identification sign may be misleading in case of connected universal or DC motors with the sparking of brushes inherent to their operating mode. That said, the use of the STFT looks more promising, since the acquired results feature less noise.

Similar results were obtained from the measurements of an arc fault for the case of nonlinear load – a vacuum cleaner with a universal motor, (Fig. 12). Despite of the less prominent increase of harmonic spikes during the arc fault (), it is nevertheless possible to accurately determine the time instant when the arc dies out (after 2.4 s).

In Fig. 13 a time interval of (4.2–4.5) s can be clearly seen, that corresponds to normal operation with no arc fault and, hence, features no current harmonic spikes.

Considering the volt-ampere characteristic at the terminals of the circuit with an arc fault, one can notice its typical distortions, i.e., points corresponding to the zero current interval near the zero crossings of the voltage waveform. This phenomenon is clearly visible in the volt-ampere characteristic measured at the input circuit breaker (Fig. 14).

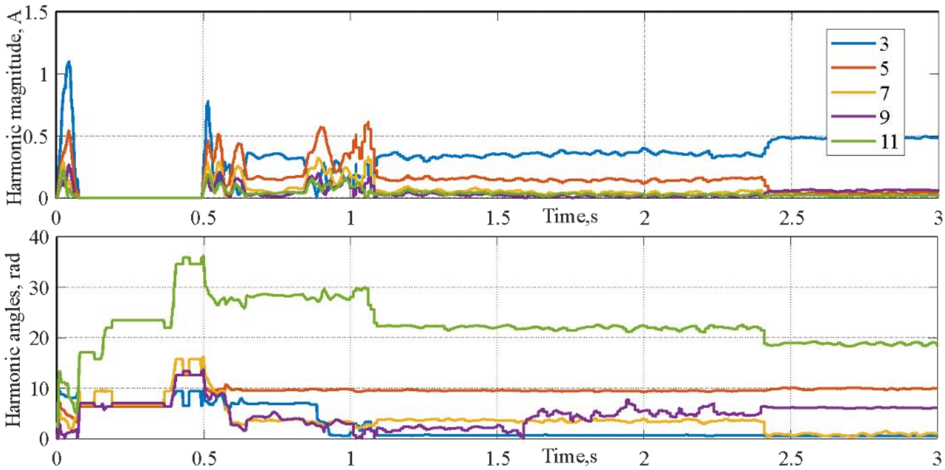


Fig. 9 – *Time variation of odd current harmonics produced by STFT during arc-over for the case of nonlinear load.*

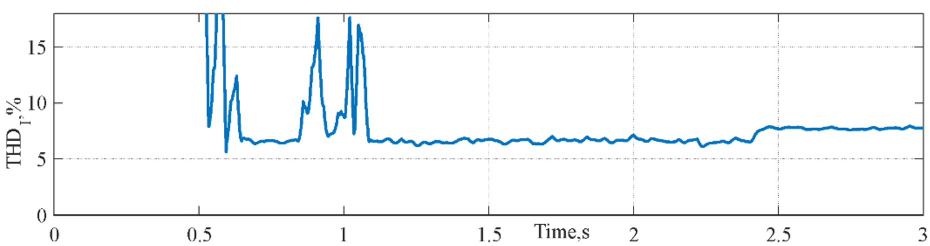


Fig. 10 – *Time variation of total harmonic distortion of the current during arc-over for the case of nonlinear load.*

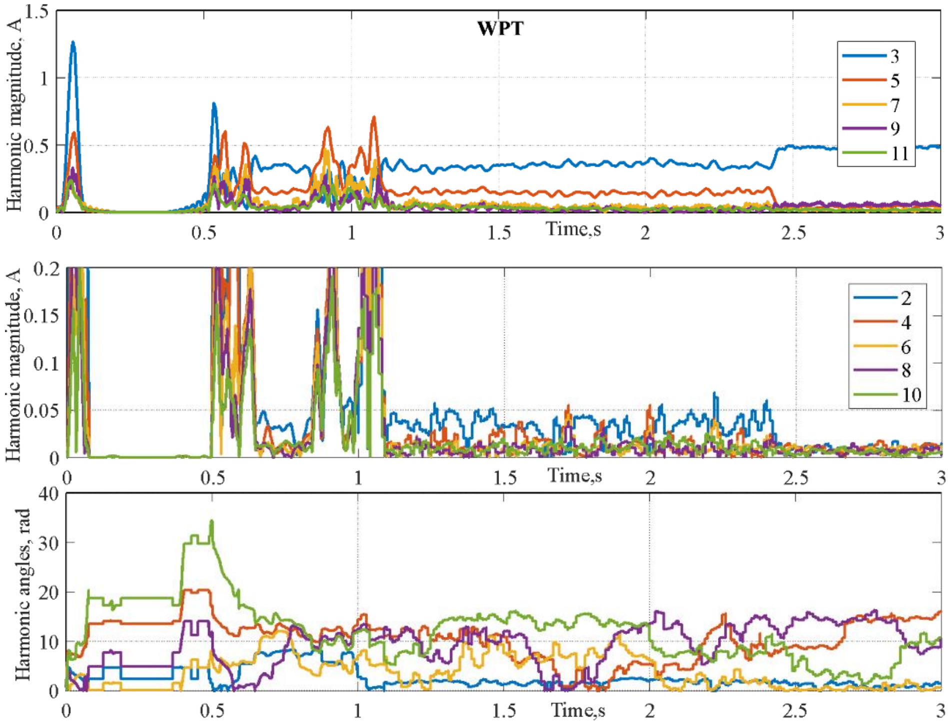


Fig. 11 – *Time variation of even current harmonics produced by WPT during arc-over for the case of nonlinear load.*

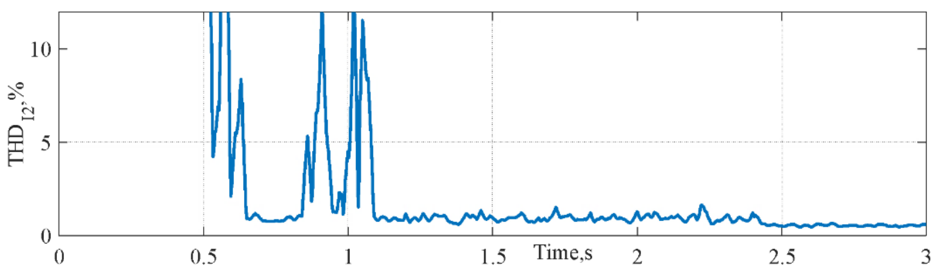


Fig. 12 – *Time variation of total harmonic distortion of the current during arc-over for the case of nonlinear load.*

A volt-ampere characteristic of a linear circuit can be approximated by an inclined line, while the presence of a vertical line in the zero current region may be considered as one of the signs of an arc fault in the circuit.

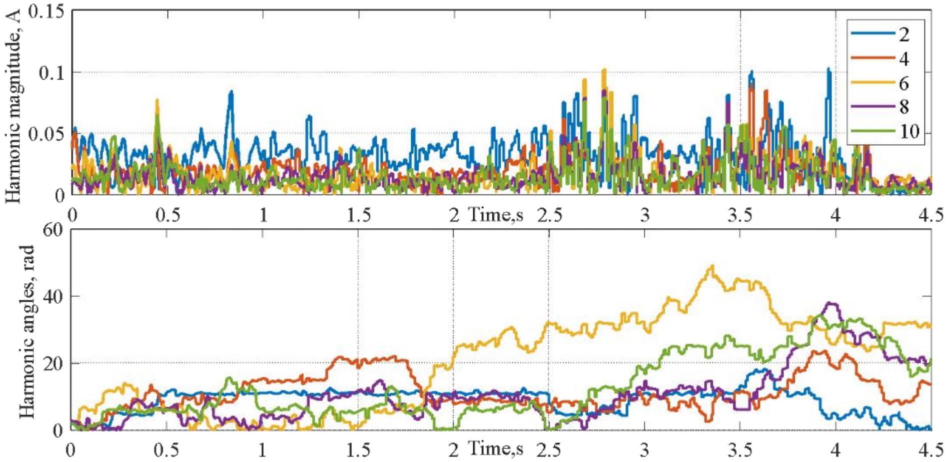
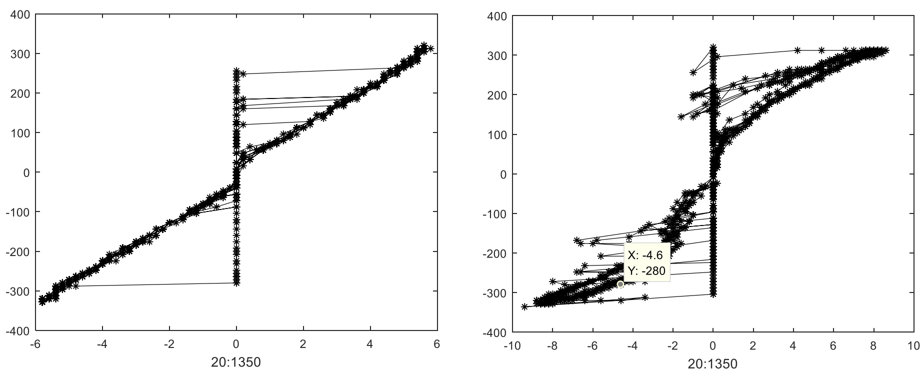


Fig. 13 – *Time variation of current harmonics produced by STFT during arc-over for the case of nonlinear load.*



(a) (b)

Fig. 14 – *Volt-ampere characteristics measured at the input circuit breaker for the cases of linear* (a) *and nonlinear* (b) *loads during an arc fault.*

5 Mathematical Modelling of a Series Arc-Over Process

Due to the presence of the masking effect produced by supplied loads, another challenge in arc identification consists in evaluation of the impact of the load's input current on the arc current waveshape and determination of approaches for correct arc detection in these cases. Usually, computer modelling techniques are adopted in order to solve such problems. A dynamic mathematical model of a low-voltage AC series arc-over in a resistive-inductive circuit can be described by the following equation [15]:

$$U_m \sin \omega t = i_a R + L\frac{\mathrm{d}i_a}{\mathrm{d}t} + a + \frac{b}{i_a + c}. \tag{1}$$

Based on the work [16], a corresponding model of an arc fault was built in Matlab/Simulink (Fig. 15):

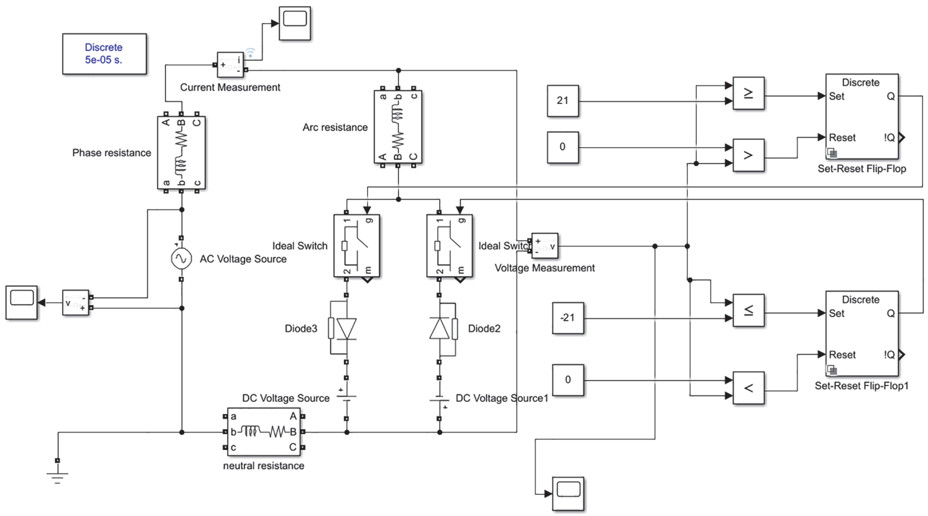
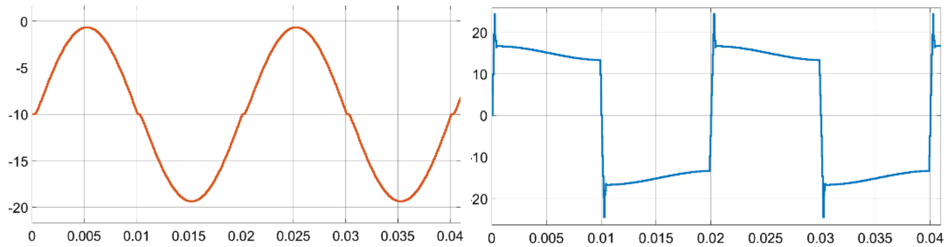


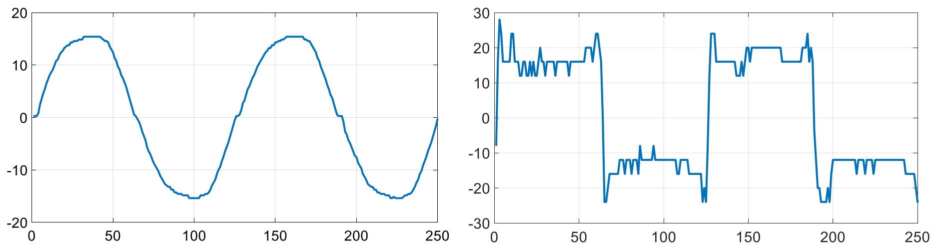
Fig. 15 – *A Simulink-based model of an arc fault for a resistive-inductive circuit.*

The modelled circuit consists of a single-phase 220 V AC voltage source, resistive 2800 W load and an arc model implemented by respective block. Arc introduces additional impedance to the circuit, its values may be varied in accordance to the arc power: exemplarily for the considered case the active resistance of an arc is selected to be 1 Ω, while the inductance is set to 300 mH [17]. Modelling of zero-current regions during the zero crossings of the voltage curve is carried out by a control circuit based on a constant comparison of the voltage parameter at the terminals with the arc ignition voltage in positive and negative half-periods. The voltage meter unit continuously measures the value of the input voltage of the arc. As long as the voltage is higher than the ignition voltage, one of the ideal switches is turned ON. Until the voltage drops to zero, this switch will not turn OFF and the arc current flows in the positive half-cycle. As soon as the instant voltage becomes negative, there will be no current until the voltage reaches the ignition value in the negative half-period. Then the arc current flows again until the voltage drops to zero and so on through the cycle. To avoid the flow of reverse currents during the turning ON of ideal switches, diodes are added to respective branches of the circuit [18, 19]. The voltage constant for each half cycle is set by respective DC voltage source.



(a) (b)

Fig. 16 – *Simulated current* (a) *and voltage* (b) *waveshapes of the arc with connected resistive load.*



(a) (b)

Fig. 17 – *Measured current* (a) *and voltage* (b) *waveshapes of the arc with connected resistive load.*

When comparing measured and simulated results, it should be taken into account that for the computer simulation a pure sinusoidal voltage source is adopted in the circuit, while for experimental measurements a real grid distorted voltage source is used.

The fast Fourier transform gives the following values of the coefficients of the higher harmonics of the current from 2 to 40: for the model K_{imodel} = 1,7%, according to the experiment K_{iexp}= 4,9%.

6 Summary and Conclusions

Design of modern LV networks presents an important challenge of providing their safe and reliable operation, that is usually addressed by development of adequate circuit protections [21]. In order to avoid fire hazards, both series and parallel arc breakdowns should be effectively prevented, which is difficult or even impossible to perform without use of special protection devices. These devices should monitor not only the level of the current, but its characteristics, e.g. harmonic spectrum and its time variation. Following phenomena in the LV circuit can be considered as the signs of an arc breakdown:

Variation of both odd and even low order current harmonics (from the 2nd to the 11th) at the input. Perhaps the emphasis should be placed on even harmonics, since their appearance is less typical for various types of nonlinear load;

Appearing straight vertical region in the volt-ampere characteristic that results from the delay of the current transition across zero

The absence of a current spike and even a slight decrease of current value by 8-10% during a series arc breakdown.

Both STFT and WPT are suitable for studying the occurrence of arc in the circuit, since these methods allow consideration of time varying current harmonic levels. But the result of the wavelet analysis features higher noise levels.

7 Acknowledgment

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