doi:10.14311/ppt.2022.2.6
Plasma Physics and Technology **9**(2):6–11, 2022

ELECTRICAL AND NON ELECTRICAL CHARACTERISTICS FOR THE FAST DETECTION OF HIGH CURRENT FREE-BURNING ARCS

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Abstract. To guarantee save and reliable operation of low voltage grid devices and to protect all devices from disturbance or damage, it is absolutely necessary to separate normal operation from fault state. A typical fault state with an enormous hazard potential is the arc fault. Due to the high level of energy involved, it can lead to the total write-off of affected devices and hence interrupt the energy supply (service). To prevent extensive consequences, there is a high demand to detect these error conditions and to terminate the fault state in a period of a few milliseconds. The analysis of typical electrical and non-electrical signals with numerical algorithms enables fast detection of arc faults.

Keywords: high current arc faults, arc fault detection, numerical detection algorithm, low voltage circuit breakers, arc fault characteristics.

1. Introduction

An arc fault occurs when the isolation material that usually separates two electric conductors of different potentials losses its isolation capability. In most cases of low voltage systems, the isolation medium is gas. In fault case, the gas becomes conductive and offers an alternative duct. Such situation arise when an error state before already effected the isolation strength between current conductors, for example, when the isolation have been damaged. Other typical reasons that lead to arc faults are deterioration, forgotten tools after maintenance or the contamination of the switchgear [1].

2. Arc faults in low voltage grid

In electrical distribution systems, two main types of electrical arcs can be distinguished: switching arcs and arc faults. While switching arcs occur during the separation of electrical contacts in a switching device, arc faults ignite accidentally and unwanted in no certain position. Under rated conditions, it can be expected that switching devices have the capability to quench switching arcs. Hence, switching arcs show little potential to cause serious damages [2].

2.1. Characterisation of Arc faults

Arc faults can be further divided into two subtypes [3], such as series and parallel. The series arc fault is in series to the load. Therefore, the fault current is limited by the load and stays in the same range of the particular load current [2]. Despite the relatively low level of current, this arc faults can cause a high level of damage, because they can remain undetected by the circuit breaker for a long time [4].

If the arc fault ignites in a branch parallel to the load, one speaks of a parallel arc fault. The main difference to a series arc fault is that the load has no impact on the current maximum, which is limited only by the line impedance. In general, the fault current is higher than the rated current and reaches values up to the range of the short circuit current. As result, the parallel arc faults have a much higher potential to cause extensive damages of the surrounding devices. Due to the fact, that parallel arc faults burn between two phases or one phase and ground, the ignition is usually effected by external influencing factors. This leads to the fact that the voltage requirement is high and the arc itself damps the arc current.

The fact that the parallel arc itself can have a damping effect on the fault current is highlighted in [3]. For example, it is possible that the arc current is only 50 % of the prospective short circuit current [5]. Protective devices with a time-current characteristic trip caused by this after a higher time delay. But In this case, a fast and also reliable detection and fast arc fault suppression is necessary for avoiding hazardous fires.

2.2. Detection for different arc faults

For the arc fault detection, it is to differentiate between serial arc faults and parallel arc faults. Serial arc faults can be detected with the Arc Fault Detection Devise (AFDD) and have a less energy output. This allows not so fast detection times. For the detection of parallel arc faults it is necessary to take a fast detection within 2–3 ms which is not possible with the AFDD. Typical arc fault protection systems for parallel arc faults are based on optical detection methods.

New arc fault protection systems might also base on a detection by current and voltage measurement. [6]

2.3. State of the art of parallel arc fault detection

Obviously, arcs produce also a luminous emittance. On one hand, it is a dangerous effect that can burn the eyes and the skin. On the other hand, the optical radiation is interpreted for the detection in arc fault protection devices by several producers like e.g. ABB [7], Eaton [8], GE [9] or Dehn [10] to name just a few. In this paper, some detection principles will be presented and separated into non-electrical (chapter 5) and electrical properties (chapter 6), which they use.

2.4. Hazard potential of parallel arc faults

The main effect caused by a parallel arc fault is the high amount of thermal energy created by the high current. The arc consists of plasma that can heat up from 10,000 K to 20,000 K. This energy is spread into the environment by convection and radiation and surrounding parts can be damaged or set on fire. Because of the high rms value of the current the heating process of the plasma is initiated very fast. These sets free a pressure wave with a steepness of up to 1 bar/ms. Therefore, especially for the protection of enclosed devices, a superior effort has to be carried out for extreme fast detection and suppression of the arc fault. Other effects are the noise created by the pressure wave and the magnetic field created by the current. [2]

As shown, arc faults have to be taken into account when to design switchboards with high short circuit currents. And that arc faults are not a rarity shows a look at the statistics. In the grid, arcs ignite mainly in switching devices. Therefore, all on-load switches have to be able to quench fault arcs. Due to the rising number of switching operations in the grid, this point gains more and more in importance. But also, the above described parallel arcs occur in a significant number. Up to 90 % of all short circuits show arc faults. Around 50 % of these take place in switch gears and distribution systems, which are in general high current systems. In these applications the probability for the occurrence of damaging arc faults is increased and an expired protection of the system is advisable [5].

3. Reference time

As shown before, a parallel arc fault has to be detected and quenched as fast as possible. To compare the detection time of different detection systems, a reference point for the arc's ignition is needed.

The ignition process starts with a voltage step physically explicable by the anode-cathode-voltage drop that refers to the electrodes material. Afterwards, the arc's voltage increases about the arc column until the arc plasma is completely ionized. This, in turn, is shown by a followed decrease of the voltage, because now the ionization is completed and the resistance of the arc column breaks down. The voltage curve for different ignition processes is presented in figure 1. The ignition is initiated by a copper wire with different diameters. It shows that the time until the wire is burned up, and the arc is fully ignited increases with bigger diameter. In figure 2 for certain sample points of the voltage and current curve during the ignition process, a picture of the arc is presented. The pictures confirm the result that the peak in the voltage curve is similar with the moment when the arc is fully ignited. Therefore, this is defined as the reference point for the arc fault ignition. It is independent of the ignition mechanism and forms an objective measure for the burning time of the arc. This point in time is called t_{rz}.

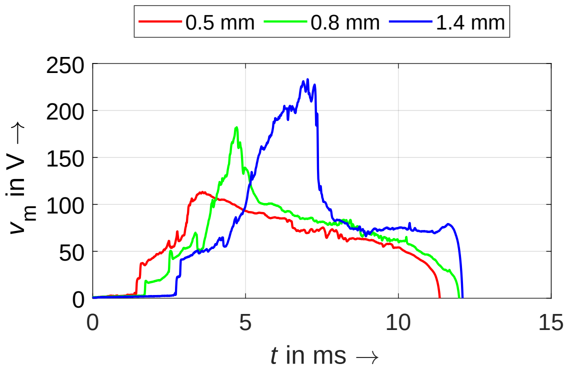

Figure 1. The arc fault voltage measured for different diameters (0.5 mm, 0.8 mm and 1.4 mm) of the ignition wire, in reference to the beginning of current flow

4. Experimental setting

To investigate the electrical and non-electrical properties of an arc fault, an arrangement with three copper bars is used. On this setup, arc faults are ignited via a thin wire between two phases or all three phases.

Figure 3 shows an example of an ignition process on a two phase arc fault. Above the diagram, pictures from a high-speed camera are displayed. The first picture show the busbars before ignition. In the following pictures, the busbars were visualized via white rectangles.

The arc fault is ignited via a thin wire, which heats up until t_{rz} and evaporated. Now the plasma is relatively cold and will heat up to more than 10.000 K. Until then, the resistance of the plasma is high and the current will sharply decrease for a short time.

Caused by the Lorentz force, the arc is pushed to the end of the busbar. At the End of the busbar the arc will expand and the voltage requirement rises. The pictures show that the arc starts its journey at t_{rz} + 2.2 ms and reaches the end of the busbar at t_{rz}+4.4 ms. With the distance of 0.5 m a speed around 230 m/s is reached.

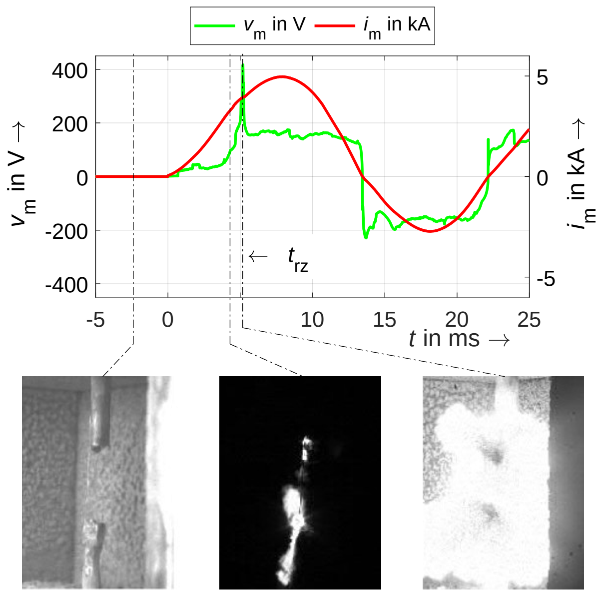

Figure 2. The curves of arc fault voltage and current measurend during the ignition process with the reference time point of ignition (t_{rz}) and images of the electrode arrangement with the ignition wire, the arc fault during the ignition process and the fully ignited arc fault.

5. Non-electrical characteristics of arc faults

Next to the electrical properties such as voltage or current, there are non-electrical properties like radiation or sound. Many of them can also be used to detect an arc fault. Due to high temperature gradient, fluctuations in pressure are created and these results in emitted low frequency pressure waves, sound and ultrasonic. As shown in section 2.4 furthermore, the arc plasma reaches a very high temperature [11]. At this high temperature, a wide range of radiation is emitted: from infrared light up to ultraviolet, where ultraviolet has the highest intensity.

To investigate this physical properties, a measuring system with different sensors was designed. For sound measurement, a standard microphone is used. The ultrasonic is detected with a piezoelectric sensor. Furthermore, the low frequency pressure wave should be detected by a pressure sensor. Because of the high temperature of the arc plasma, a PT100 temperature sensor was used. The infrared radiation is detected via a phototransistor. The visible light is measured via a light dependent resistor (LDR). For ultraviolet light, the photoelectric current of a UV-LED is amplified and measured.

A representative arc fault test with his main physical properties is visualized in figure 5. Sound has a relatively slow velocity, so the distance between the arc and the sensor has a significant impact on the timeshift. In case of figure 5 the delay is approximately 5 ms. All measured signals are normalized to the maximum. The DC bias is subtracted from the signal.

The experiments show a steep ascent in sound, ultrasonic and in the full spectrum of electromagnetic radiation. This steep ascent can be used to detect the arc fault via these sensors. In comparison to the microphone, the ultrasonic sensor showed less interference. For example, the cut-off from the circuit breaker results also in a spike on the microphone.

The ultraviolet sensor has the lowest amount of disturbing influences compared to the light or the infrared sensor. The light sensor is triggered by the daylight or other light sources also, whereas infrared radiation is also emitted by the busbars or other hot components in the switchgear.

Furthermore, it turned out that the pressure sensor was not sensitive enough in the open structure to detect any spikes in pressure. In addition, the temperature sensor was not sensitive enough to react to short arc faults less than 300 ms. Only for longer arc faults, a slow ascent in temperature can be seen. Therefore, both sensors are not usable for fast arc fault detection.

In this section, it turned out that radiation sensors are the most suitable signals for detection arc faults. The algorithm behind is a simple threshold comparison (TC). The height of the threshold is a trade-off between reliability and speed.

6. Electrical characteristics of arc faults

Figure 3 show the voltage and the current of a two phase arc fault. The steep ascent in the voltage is typical for the arc ignition and is called the ignition spike.

With both electrical signals, it is possible to detected arc faults in the frequency domain as well as in the time domain. In the frequency domain exist different algorithms for the calculation of specific frequencies. The most popular algorithm is the Fourier transformation. But with the Fourier transformation, it is not possible to get a direct frequency time allocation. Further, the detection in the frequency domain is not fast enough. For this reason, the detection should be basing on the time domain.

A Parallel Arc Fault Electrical Detection Device (PAFEDD) measures the current and voltage at the boundary of an arc fault protection zone. The protection zone includes the entire electrical system connected to the central measuring device. For the calculation procedure of the detection algorithm, the electrical system within the protection zone is combined as one line impedance. The equivalent electrical network of the protection zone (figure 4) also contains a voltage source to represent the behaviour of the arc.

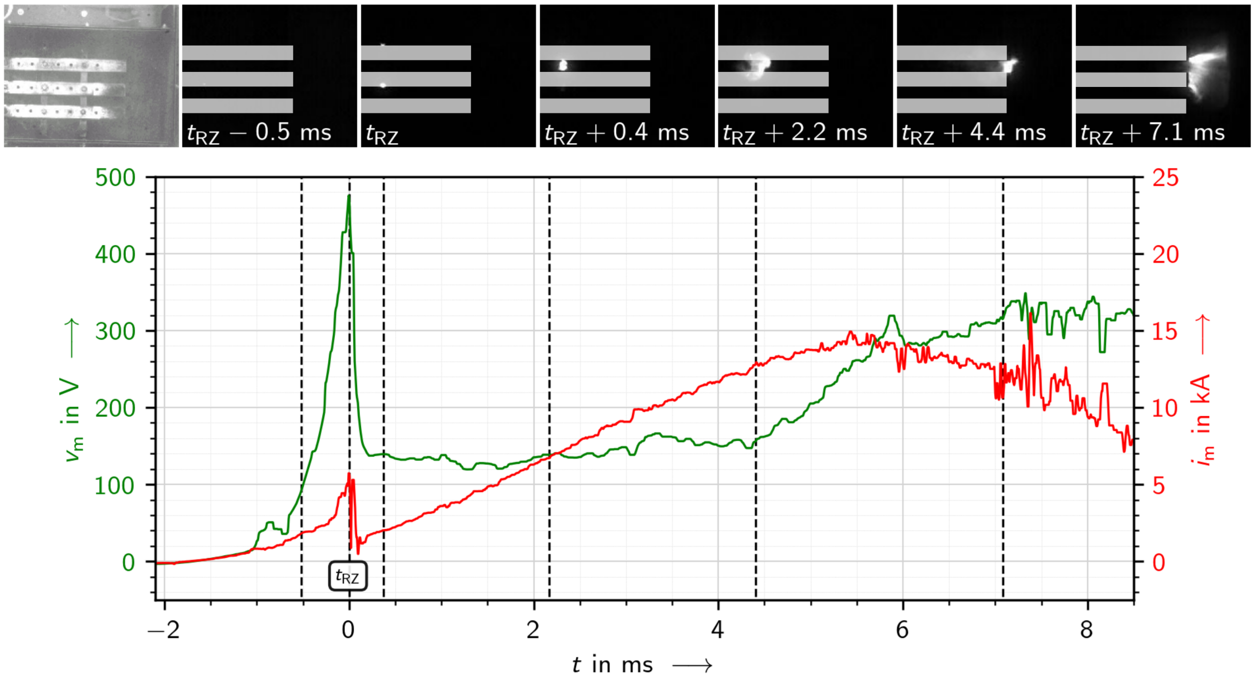

Figure 3. The curves of voltage and current while an arc is ignited and moved because of the Lorentz force.

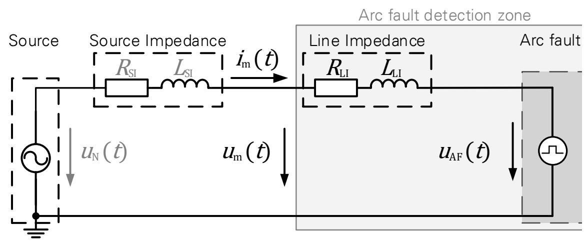

Figure 4. Equivalent circuit diagram of an arc fault detection zone

There are two ways to detect an arc fault with voltage and current measurements: the waveformalgorithm (WFA) and the extended distance algorithm (EDA). [6]

6.1. Waveformalgorithm

The WFA uses the time curve of the measured voltage. It shows significant properties when an arc fault occurs. The extraction of significant properties is possible by the use of wavelet algorithms. Depending on the signal property that has to be extracted, different wavelet algorithms are suitable. Typically, for the extraction of significant ascent of the measured voltage the Haar wavelet with the definition according to (1) is used.

$$\Psi\left(\frac{x-n}{m}\right) = \begin{cases} -1 & \text{for} \quad n-m \le x < n - \frac{m}{2} \\ 1 & \text{for} \quad n - \frac{m}{2} \le x < n \\ 0 & \text{for} \quad \text{other} \end{cases} \tag{1}$$

With the wavelet transformation, the proportions of the Haar wavelet in the signal can be determined. They are named as detail coefficients. By the further procedure in [6] and a threshold comparison, it is possible to detect an arc fault in its beginning.

6.2. Extended distance protection algorithm

The distance protection algorithm can calculate the impedance between the measurement point and the fault location. First, a bolted fault is assumed, which means that no additional impedance is introduced into the fault-affected network. In this case, the following approach describing the voltage drops occurring in the network can be used to calculate the impedance of the network:

$$u_m(t) = R_{LI}\, i_m(t) + L_{LI}\frac{\mathrm{d}i_m(t)}{\mathrm{d}t}. \tag{2}$$

The equation (2) has two unknown variables, R_{LI} and L_{LI} respectively. In order to determine these two variables, it is possible to solve the equation at two different points in time ($\nu = t_1, t_2$).

Second, if an arc fault occurs within the detection zone (corresponding to figure 4), the approach from (2) can be extended as follows:

$$u_m(t) = R_{LI}\, i_m(t) + L_{LI}\frac{\mathrm{d}i_m(t)}{\mathrm{d}t} + u_{AF}(t). \tag{3}$$

Here, the arc fault voltage can be assumed as a constant amplitude U_{AF} with the same sign as the arc fault current $i_{AF}(t)$:

$$u_{AF}(t) = U_{AF}\,\mathrm{sgn}(i_{AF}(t))\,. \tag{4}$$

By replacing $u_{AF}(t)$ in equation (3) with (4) and assuming that $\mathrm{sgn}(i_{AF}(t)) = \mathrm{sgn}(i_m(t))$, the modified

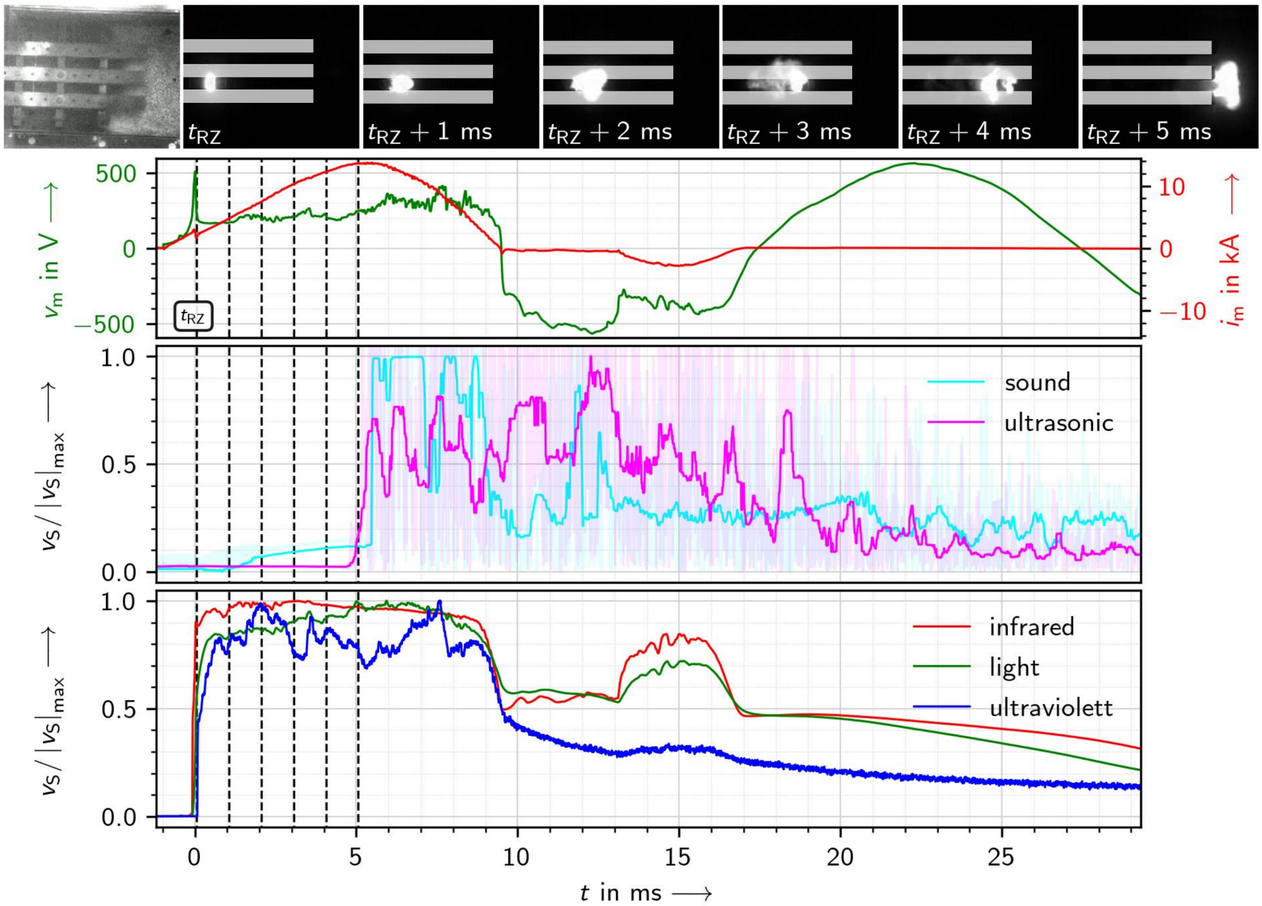

Figure 5. Measured curve of radiation, sound and ultrasonic while an arc fault.

Table 1. Evaluation of the physical properties by some parameters

Physical property	**Algorithm**	**Detection time (ms)**
Sound	TC	2,18
Ultrasonic	TC	2,19
Infrared	TC	0,19
Light	TC	0,14
Ultraviolett	TC	0,06
Voltage	WFA	-0,20
Voltage, Current	EDA	1,10

approach can be obtained:

$$u_{\mathrm{m}}(t) = R_{\mathrm{LI}}\, i_{\mathrm{m}}(t) + L_{\mathrm{LI}} \frac{\mathrm{d}i_{\mathrm{m}}(t)}{\mathrm{d}t} + U_{\mathrm{AF}}\, \mathrm{sgn}(i_{\mathrm{m}}(t))\,. \quad (5)$$

With (5) the value of the arc fault voltage can be determined. A threshold comparison decides whether an arc fault is ignited or not.

Now, the WFA and EDA can be compared to the non-electrical signals.

7. Evaluation of the signals

To quantify the suitability of the sensors, different properties were defined and determined in order to evaluate the before mentioned algorithms. The detection time was defined as the time difference between the reference ignition time t_{RZ} and the time when 20 % of the maximum signal amplitude is reached. This detection algorithm is named as threshold comparison (TC).

Table 1 shows the results of this analysis, where are only these sensors are considered which gives reasonable results. The detection time of the sound and ultrasonic sensor is high, depending on the distance between the arc fault and the sensor. Because of the relatively slow speed of sound, the sensor needs every 34.3 cm one millisecond more time to detect the arc fault. The radiation sensor is significantly faster and not dependent on the distance to the fault. It require about hundred microseconds only. The impact of the environment radiation is shown in the basic level. With the open experimental set up the light sensor is affected by the highest disturbances. In closed facilities, the infrared sensor might have the highest disturbances because of the hot environment inside. Thereby, the ultraviolet sensor showed the lowest disturbances in open and closed environment of the tested sensor principles for detecting.

The magnetic flux is not suitable for the detection because it is not possible to differentiate between the magnetic flux of the busbars and the arc fault. The body sound doesn't show any arc fault specific behavior and is also not suitable. Sound is too slow if the distance between the arc fault and the sensor exceeds a few centimeters. The radiation sensors are fast and reliable. Ultraviolet shows the lowest influences from other sources. But all radiation sensors tend to don't detect reliable arc faults because of pollution.

8. Conclusions

In electrical energy systems, a distinction is made between useful switching arcs and hazardeous arc faults. Due to the high hazard potential, parallel arc faults must be detected and cleared within a few milliseconds. Nowadays, mainly optical detection systems are used for the detection of high-current arc faults. Besides this, a number of electrical and non-electrical properties can be used for the detection. Non-electrical properties are the radiation and pressure or sound waves. Electrical properties are the specific voltage and current behavior. Our presented investigation shows, that the intensive ultraviolet emissions are very specific for an arc fault and allow a reliable and fast detection. The main disadvantage are the high installation and maintenance effort and that the sensor can get dirty over time. The pressure and sound sensors are slower dependent on the distance between the arc fault and the sensor, because of the relatively slow speed of sound. By the help of the WFA and the EDA specific characteristics of the arc voltage and current can be extracted which enables the detection of arc faults. Therefore, a centralized measurement is necessary. With the WFA based on stationary wavelet transformation, the detection time is in the same range as sensors that evaluate the ultraviolet emissions.

Abbreviations list

AFDD	Arc Fault Detection Device
EDA	Extended Distance Protection Algorithm
PAFEDD	Parallel Arc Fault Electrical Detection Device
TC	Threshold Comparison
WFA	Wave Form Algorithm

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