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Series arcing detection by algebraic derivative of the current

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ABSTRACT

We present in this paper an algebraic derivative method of the line current in order to detect the presence of series arcs in an AC or DC electrical installation. The first derivative is computed from a limited Taylor-McLaurin series transposed in Laplace space. The temporal estimation is achieved by integration over a sliding window of the product of a particular polynomial with the instantaneous current. The discrete version can be synthesized by a simple FIR filter.

The tests, with and without series arc, are conducted on experimental currents (3–12 A) measured on domestic loads (resistors, vacuum drill, dimmer). The sampling frequency is set to 1 MHz.

Short integration times (50 μs in AC and 200 μs in DC) are sufficient to observe, with high contrast, the derivative peaks due to the arc ignition. The detection is then performed by comparing the derivation filter output to its instantaneous noise level. The response time is equal to the integration duration.

This method, simple to set up and easy to implement, is ideally suited for installations that do not use load switching current.

1. Context and objectives

Arc-fault detection, especially series arcing, is a key factor for increasing the safety of DC and AC power supply systems [1,2].

A series arc occurs in a galvanic interruption of the supply circuit. Involuntary separation of a contact point (breaking or disconnection) or insulation breakdown by carbon path, are the main causes of series arcs [3]. Less frequently, the arc can be initiated by a power overvoltage.

Physically it is reflected in a current flow across the discontinuity. This results strong local temperature increase which causes the ionization of the air in the form of plasma. Since the current intensity is limited by the load, the average level takes no abnormal value which makes the series arcs detection very difficult and gives them a high hazard potential.

In the presence of a series arc, the temporal shape of the current reveals:

- disruptions in the average level in DC mode. The resistance of the arc being often low, the current slightly decreases.
- discontinuities in the sinusoidal shape in AC mode.

Spectrum analysis is the most often used detection method [4–6]. The frequency range is selected to avoid interferences caused by the load.

Statistical analysis has proven advantages in some situations [7]. In the DC mode, the rupture detection can be achieved through the Page-Hinkley procedure which requires the selection of detection thresholds based on the noise level [8]. In the case of chaotic signals, multiple false detections can appear.

The time-frequency or time-scale decomposition can provide the frequency characteristics of the arc during its evolution [9–12].

Some authors propose detection based on the estimation of the impedance of the arc [13]. This method is more sensitive than the simple spectrum analysis, but requires knowledge about the arc voltage which is not actually possible in practical situations.

Other methods rely on identifying a real-time model of the load [14–17]. An arc can be considered a non-linear and chaotic variable dipole; its apparition leads to a strong prediction error in the model.

The proposed solutions are often restricted to special cases (single power system, known load, range of spectrum analysis tailored to the situation, unique ignition mode).

We propose in this work a detection technique based primarily on the time derivative of the line current. We searched for a derivative estimator which has high robustness to noise present in the signal [18–20]. Indeed, in real situations, especially in dwellings or in an industrial environment, the current can be polluted by a

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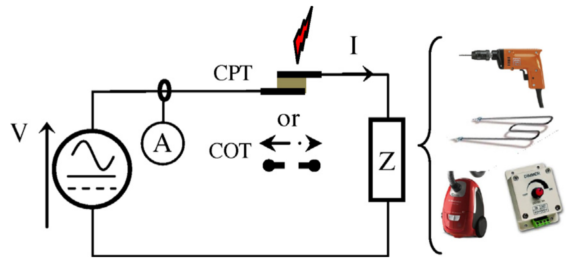

Fig. 1. Diagram of the experimental setup.

multitude of internal and external sources (LF induction, Power Line Communications, EMI,...). Also for practical reasons the current measurement is generally carried out using Hall effect probes whose accuracy and noise immunity are far from excellent.

This detection method, which is suitable for situations that involve different types of load, is usable in DC or AC system. It is compatible with arcs ignited by contact opening or by carbon path.

The method is suitable for low or high values of current. As the series arc detection is generally more difficult for low currents, all tests of this paper are made with domestic loads whose power is less than 2000 W.

2. Equipment and method

2.1. Test-bench

The test bench developed specifically for this study is shown schematically in Fig. 1 [21]. It has a mixed 4 kW power supply (270 V DC and 220 V AC, 50 Hz) which supplies different charges *Z*. In our tests we used resistive loads, appliances with universal motors and current switching systems (dimmer).

An arc triggering device (CPT/COT) is inserted in series with the load. The current *I* is measured by a Hall effect probe. It is sampled at frequency f_s of 1 MHz and recorded using a Lecroy WavePro 950 digital storage oscilloscope.

All calculations are done using Matlab. All algorithms are implemented in Simulink.

2.2. Arc ignition methods

Several kinds of arc tests are available [22,23]. We use the carbonized path (CPT) and the contact opening test (COT) according to the UL1699 standard [24].

2.2.1. Carbonized path test (CPT)

The carbonized path test is based on two electric wires that have an insulation fault (Fig. 2). We damage the insulation with a knife (cut about 0.5 cm long). The carbonization process involves complex chemical reactions. It starts with the heat rise; sparks and fire can appear.

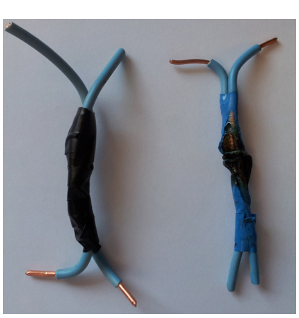

Fig. 2. Carbonized path.

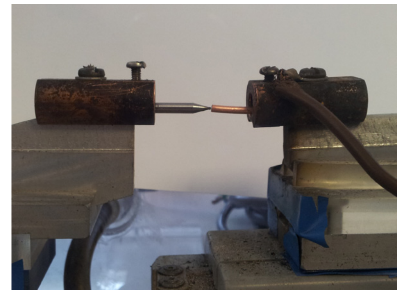

Fig. 3. Robotic cylinder.

2.2.2. Contact opening test (COT)

The usual interpretation of the arcing during contact opening involves two main phases. Upon detachment of the contact, the reduction in the conducting area introduces a localized resistive point which heats quickly. The thermal effect in turn leads to a molten metal bridge. When the conducting bridge breaks, it gives rise to plasma consisting of ions from the metal and the surrounding medium (initially an insulator). The conduction in this ionized medium takes the form of an electric arc.

In our setup, one tungsten electrode and one cooper electrode are in touch while a nominal current goes through the circuit. A robotic cylinder (Fig. 3) makes a separation between the electrodes (0.03 mm resolution).

This test reproduces what can happen in a relay, in a breaker or during an unexpected unplugging.

In order to choose a gap value we conducted preliminary tests for different values of the gap. With a value of 0.1 mm, the holding voltage of the arc is around 10 V and the current drop is very low. Most often one can observe an intermediate glow phenomenon between the molten bridge and the true arc. For values greater than 1.1 mm, the arc is obtained in most cases and its voltage exceeds 30 V. The COT presented here was obtained with a reference gap of 1.1 mm and an opening speed of 10 mm/s.

2.3. Experimental conditions

Experimental conditions and the specifications of the loads used are summarized in Table 1.

For the DC mode we used the COT to properly control the time of occurrence of the arc, the only reliable indicator of the presence of a DC arc.

For the AC case we realize only the CPT that is the only ones recommended by the IEC62606 European standard.

2.4. Typical currents

The waveforms of currents recorded during these tests are shown in Figs. 4–9. With the range used here, the measurement resolution (noise of the Hall effect probe and the quantization) is about 0.25 A. The noise level is almost doubled in the test involving the universal motor. Indeed this generates micro arcs between the collector and the brushes during the rotation of the motor.

Table 1
Experimental conditions.

	V	Arc ignition	Load	I_{RMS}
Test 1	DC	COT	$R = 34\,\Omega$	8 A
Test 2	AC	CPT	$R = 48\,\Omega$	4.8 A
Test 3	AC	CPT	Motor	5.5 A
Test 4	AC	CPT	Several	Variable

For all tests: Pressure = 1 atm, Temperature = 22 °C, sampling frequency: 1 MHz.