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An embedded system for AC series arc detection by inter-period correlations of current

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ABSTRACT

This paper presents a method for detecting series arcs for a 230 V AC–50 Hz residential installation, its implementation in an embedded circuit and its performance under real conditions. First, we evaluated the inter-period autocorrelation coefficient *r* of the line current. The algebraic estimation of the derivative of the signal *r* was then used to obtain an indicator of arc detection. *r* was calculated on the current at a sampling rate frequency of 5 kHz and the 50 Hz component was attenuated by an high pass (HP) filter. Tests carried out with domestic appliances with different power loads (resistive load, lamp, vacuum cleaner, dimmer etc) show a value for *r* which is very stable and close to 1 under normal conditions. The coefficient *r* weakens in the presence of an arc (initiated by a carbon path) and is no longer constant. The complete algorithm was implemented in real time on a 32-bit ARM Cortex-M3 microcontroller with a 12-bit ADC. The measuring current, which ranges from 0 to more than 20 A, was provided by a passive toroidal inductive probe. Four typical household loads were tested. The results obtained show that detection is operative and very fast (10 ms) with currents which exceed 400 mA.

Contents

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1. Introduction

Developing reliable arc fault detectors is a major issue in protecting AC domestic installations. Indeed, in the United States and Europe, several studies have shown that a significant proportion of domestic fires are caused by arcing faults [1,2]. Unlike the United States, where these circuits are imposed in homes, this is not the case in the Europe (EEC). However, new European Regulations (IEC 62606) [3] will make them compulsory in the coming years. Currently, some devices are available which are suitable for detection in 230 V/50 Hz AC power installations.

The main methods for detecting arc faults, as presented in current literature, are based on an analysis of the line current. Several detection methods are based on current spectral composition. The analysis is performed in a variety of bands ranging from low frequencies up to 20 kHz [4–7] and at even higher frequencies [8,9]. Other methods focus specifically on analyzing the odd harmonics [10], more specifically third and fifth harmonics [4,5,11]. In general the frequency range is selected to avoid interference caused by the load. Other solutions operate with a time domain feature approach—rapid changes in arcing currents (di/dt) [12], autocorrelation [13], crest factor or inter-harmonic distortion [14,15]. Some methods are based on the implementation of time-frequency analysis or wavelet packet transform [16], which require long and empirical settings which negatively affect their uses on a large scale.

Siemens, for example, proposes a detection device for the European market for use with low and average AC voltage (AFD Siemens unit [17]) which is suitable for currents between 3 and 16 amps.

Very few studies show detection results in the presence of nonlinear or switching (dimmer) loads where the power signature is closed to an arc signature [18]. Finally, it is difficult to find studies giving the lower current limit above which the detection method is reliable.

In a previous paper [19], we presented a detection method based on the algebraic derivation of the line current. This method, which can be used in AC or DC regimes, is very robust with respect to measurement noise, but remains limited to installations which do not use switching electrical devices. It is therefore not possible to apply the algebraic derivation directly on the current in domestic electrical installations where many domestic loads include dimmers.

To overcome this limitation, we looked for an arc indicator which is far less sensitive to the nature of the load than the current itself. Numerous studies [20–22] have demonstrated the non-stationary nature of the statistical characteristics of the current in the presence of a series arc. The random behavior of the arc introduces temporary differences between successive periods which can be demonstrated by measuring the correlation coefficient from one period to another. The detection strategy presented here is based on the monitoring of real-time fluctuations of this coefficient by algebraic derivation.

In the first part of this paper, we give the assumptions made in our study and present the theoretical background based on the calculation of the inter-period autocorrelation coefficient r from the current line and its derivative by an algebraic estimator. Off-line, the calculation of r is performed on real currents in the presence or absence of a series arc. The results of the calculations are summarized in the second part. The third and final parts are devoted to the implementation of the detection method on an embedded operating system produced around an ARM Cortex-M3 microcontroller.

2. Method

2.1. Theoretical background

The principle that we propose derives from the double hypothesis that first, the statistical characteristics of the line current in the absence of arc are constant throughout a period T_0 (the load can be linear or not), and that second, the arc phenomenon results from a non-stationary random process [20–23].

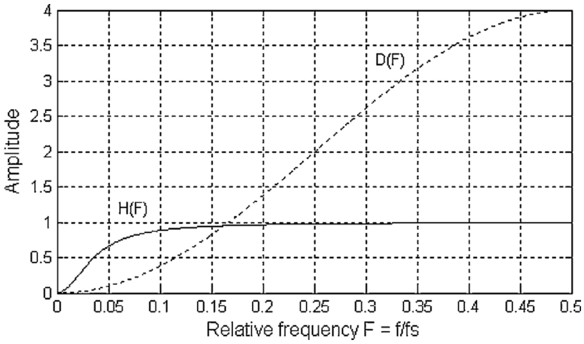

Fig. 1. Time frequency responses of the notch filter and second order differentiator.

In order to produce an arc discharge between two electrodes, after the zero-crossing of the voltage and current, the increase in voltage will cause ionization of the isolator, which must be broken when the voltage reaches the restrike value. This value may vary greatly from one cycle to the other, and depends on numerous factors: gap width, the surface condition of the electrodes and the temperature and presence of ionized air [22]. Therefore the restrike of arc voltage behaves randomly.

In practice, we observe an inter-period correlation coefficient r:

- Stable and close to 1 in normal operation.
- Lower and variable with the arc presence.

However, in order to highlight the fall of r, it is necessary to attenuate the deterministic components of the current, especially the fundamental frequency. The DC component (offset of the measuring probe and bias circuit) must be totally eliminated.

To meet these constraints, the current I is filtered by a notch filter centered on zero frequency. Its transfer function is given by:

$$H(z) = (1-e)\frac{1-2z^{-1}+z^{-2}}{1-2(1-e)z^{-1}+(1-e)^2z^{-2}} \tag{1}$$

This filter acts as a high pass (HP) filter with a low cutoff frequency and a very narrow rejected band. e is a positive real value well below 1 and the −3 dB cutoff frequency (f_{cutoff}) is obtained according to the following equation:

$$f_{\text{cutoff}} \approx \frac{e}{4} f_s \tag{2}$$

with f the signal frequency and f_s the sampling frequency.

Nevertheless, the fundamental component (50 Hz) should not be completely eliminated in order to allow the correct calculation of r for little deformed current. This is the case for linear loads without the presence of an arc in the line.

The numerator of $H(z)$ is identical to a second order differentiator function. The notch filter is adapted to highlight discontinuities generated by the arc current, while being less sensitive to high frequency noise.

The frequency responses of the notch filter (where $e = 0.2$) and the second order differentiator are compared in Fig. 1.

The autocorrelation coefficient $r_k(n)$ can be estimated at each sampling time using the Pearson formula [24]:

$$r_k(n) = \frac{\sum_{j=1}^{M}\left[\left(x_{k-j}-\bar{x}_k\right)\left(x_{k-n-j}-\bar{x}_{k-n}\right)\right]}{\sqrt{\left[\sum_{j=1}^{M}\left(x_{k-j}-\bar{x}_k\right)^2\right]\left[\sum_{k=1}^{M}\left(x_{k-n-j}-\bar{x}_{k-n}\right)^2\right]}} \tag{3}$$

where x_k is sampled and filtered current signal.