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Shunt active power filter-based approach for arc fault detection

Slavisa Jovanovic*, Abderrazak Chahid, Jinmi Lezama, Patrick Schweitzer

University of Lorraine, Institut Jean Lamour (IJL), UMR7198, Nancy F-54000, France

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ABSTRACT

In this paper, we present a novel method based on a single-phase active power filter (APF) for series arc faults detection in an AC electrical installation. The APF's reference current is used as the starting point for our method tested on a large variety of loads: resistors, vacuum cleaner, rotary drill, dimmer and AC-DC power supplies. Firstly, the proposed method is validated at the simulation level using the Matlab software and then experimentally using the Hardware-In-the-Loop (HIL) approach with an FPGA Altera Stratix III prototyping board. The results obtained in this work show that series arc faults can be successfully detected with an APF, only by updating its digital control with the arc fault detection functionality, instead of designing from the very beginning an arc-fault detection specific device.

1. Introduction

Home appliances present an important part of the overall market of electrical devices. They not only provide basic services to the customer but also have to be as secure as possible. Any dysfunction, especially the one caused by arc faults, can cause great damage to electrical equipments and even deadly accidents. That is the main reason why in the last ten years, different projects aiming to develop and design new technologies improving the detectability of the electrical arcing have been appearing and contribute to the safety of AC power supply systems. Several recent studies carried out by the U.S. Fire Administration (USFA) [1] reported about 46,500 fire accidents in the habitat due to the dysfunction of house holding appliances (the main causes are short-circuits and/or arc faults). The principal systems of protection that have been used in the habitat are circuit breakers whose functioning is based on the short-circuit or on over-voltage detection. In order to reduce the number of these accidents and increase the safety of home appliances, there have been adopted several safety standards: in 1999 the UL1699 standard in the USA [2] and in 2013 the IEC62606 standard in Europe [3]. The consequence of these aforementioned standards are systems called *Arc-Fault Circuit Interrupters (AFCI)* capable to detect and protect against arc faults, identified as a major cause of electrical fire accidents. These AFCI systems are generally composed of a magneto-thermal circuit breaker and an arc-fault detection system. The arc-fault detection system analyses line current and voltage and, if it detects some anomalies in these signals, it breaks the line circuit so as to eliminate the possibility to feed the generated arcs and cause a fire accident.

Different arc-fault detection approaches have been proposed in the literature [4–17]. They can be classified into two groups, depending on the type of electrical installation applied to: low- and high-voltage methods. Most of the proposed low-voltage methods are based on the frequency analysis of the line current and voltage. The main difference lies in the frequency range chosen to detect the presence of arc faults. The method presented in [4] is based on the analysis of harmonics, whose variations may provide some information about the presence of arc faults. The approach proposed in [5] relies on analyzing the variation of the amplitude of the 5th harmonic of the line current whereas the method proposed in [6] is based on the analysis of multiple frequency ranges: 1–3 kHz, 20 kHz, 33 kHz and 58 kHz. A similar approach that relies on observing the frequencies at 100 kHz and 900 kHz is proposed in [7]. Another family of low-voltage methods is based on the temporal analysis of line current and voltage. In [8], the variation of the RMS value of the line current is analyzed, whereas the crest factor of the line current is used as input in [9]. The methods proposed in [10,18] are based on the use of the correlation coefficient detecting the variations due to the presence of arc faults in the signal shape. In [17], an algebraic derivative method of the line current is used to detect the presence of arc faults in AC/DC electrical installations. The method can be easily implemented using an estimation FIR and a baseline extraction filter. Finally, a method using statistical moments applied to the line current is presented in [11]. Among arc-fault detection methods applied to high-voltage distribution networks, the major concern is not only to detect these high-impedance faults

* Corresponding author.
E-mail address: slavisa.jovanovic@univ-lorraine.fr (S. Jovanovic).

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but also to locate the place of their occurrence. The arc-fault detection methods are basically the same using either time, frequency or both analyses [12–16]. However, to locate the zone of arc-fault occurrence, either zone discrimination modules based on local bus measurements [13] or power line communication devices in multiconductor overhead distribution networks are used [15].

The problem with all the above mentioned arc-fault detection methods is that their integration in power line networks as arc-fault specific devices AFCI is costly and need additional investments. Indeed, the AFCIs use line current and voltage waveforms and have to be equipped with a processing unit and circuit breakers: the processing unit implements an arc-fault detection method; the current and voltage waveforms are usually supplied to the processing unit with current and voltage transformers respectively; and the circuit breakers switch off the power line circuit in the case of arc faults detection. However, the increasing use of *Active Power Filters (APF)* to improve power quality in power networks may come as a solution to reduce these additional investments needed to deploy AFCIs, introducing the APF's equipment (current and line probes, processing unit) that may also be used to provide arc-fault detection and protection. The main idea proposed here is to use an active power filter (which is assumed part of a power network) to detect arc faults by adding only an arc-fault detection functionality to its digital control without modifying its initial structure.

This paper is organized as follows. In Section 2 an overview of most commonly used configurations for APFs and their theoretical background are given. In Section 3, the proposed arc fault detection method is presented and its validation at the simulation and implementation level. In Section 4, the performances of the proposed method tested in different loading conditions are detailed as well as a comparison with the most recent state-of-the-art methods. Finally, in Section 5 some conclusions and perspectives for future work are given.

2. Theoretical background

2.1. Introduction

Intensive use of non-linear loads in industry as well as in home power networks deteriorate the quality of the overall power system. As a result of these non-linearities, the power system voltage and current waveforms are distorted and rich in harmonics. This can drop the efficiency of the overall power system distribution network due to the greater power losses. Moreover, the low efficiency, low power factor, high total harmonic distortion (THD), and some detrimental disturbances to other devices can be caused by these non-linear loads. An example of line current and voltage for a non-linear load connected to a power single-phase system is presented Fig. 1. A variety of international standards such as IEC 61000-3-2 and 61000-3-12 settle threshold values for harmonic and reactive currents which should not be exceeded in terms of harmonic pollution generated by these non-linear loads. For instance, in France EDF (*Electricité de France*) imposes that this value should not exceed 5%.

There are two solutions to cope with these harmonic disturbances generated by non-linear loads: the use of passive and active filters. Passive filters are more rigid because they filter all currents no matter the type of load connected to the power network and may cause oscillation if combined with some type of loads. On the other hand, a more flexible solution to reduce the influence of non-linear loads on the quality of power distribution systems are active power filters. Depending on the type of harmonics that are targeted, they can be classified as either shunt or series active power filters, for current and voltage harmonics elimination respectively. The shunt active power filters (SAPF) allow also reactive power compensation and are mostly used due to their simplicity and high efficiency.

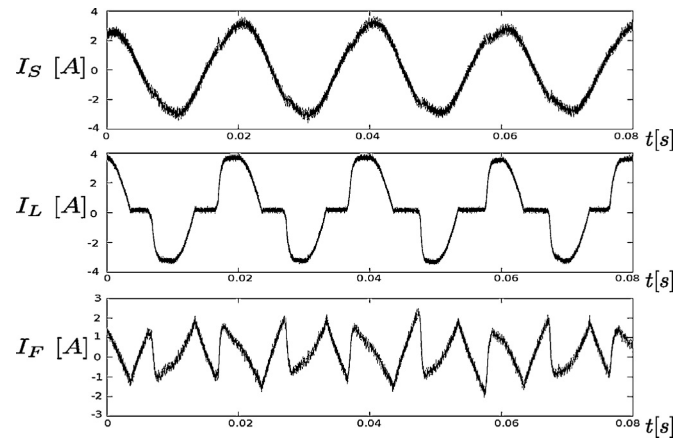

Fig. 1. Power system current and voltage waveforms for a single-phase system with a non-linear load connected to it; I_S, I_L and I_F stand respectively for source, load and filter current.

The single-phase SAPF is connected in parallel with non-linear loads and compensates all harmonic distortions introduced by these loads. It acts as a current source and injects into the power network the current needed to cancel non-linearities introduced by non-linear loads. Depending on the way how the reference currents are calculated, there are two types of shunt active power filters using: direct control methods [19,20], or indirect control methods [21,22]. The shunt active power filters using indirect control method are simpler to implement because they necessitate only one current sensor for the line current and provide faster transient response. In this work, a single-phase SAPF using indirect control is used.

2.2. Single-phase SAPF principle and control

A single-phase shunt active power filter is presented in Fig. 2. The equations describing its operation are the following:

$$v_F(t) = [s_1(t)s_4(t) - s_2(t)s_3(t)]v_c(t) \tag{1}$$

where s_i ($i \in [1, 4]$) is the switching function of the transistor *i*. For the usually used bipolar PWM scheme, the relationships between these switching functions are $s_1(t) = s_4(t)$, $s_2(t) = s_3(t)$, $s_1(t) + s_2(t) = 1$ and $s_3(t) + s_4(t) = 1$. Thus, Eq. (1) can be written as:

$$v_F(t) = [s_1(t) - s_2(t)]v_c(t) \tag{2}$$

or as:

$$v_F(t) = d(t)v_c(t) \tag{3}$$

where $d(t) = s_1(t) - s_2(t)$ is the switching function of the voltage-source inverter (VSI), which is supplied by the capacitor voltage $v_c(t)$. The relationship between the voltages $v_F(t)$, $v_s(t)$ and the current $i_F(t)$ is given by:

$$L_F \frac{di_F(t)}{dt} = v_s(t) - d(t)v_F(t) \tag{4}$$

The same analogy can be used to describe the current $i_F(t)$ of the active power filter:

$$i_F(t) = i_s(t) - i_L(t) \tag{5}$$

which is related to the capacitor's current $i_c(t)$ with the following equation:

$$i_c(t) = C\frac{dv_c(t)}{dt} = [s_1(t) - s_2(t)]i_F = d(t)i_F(t) \tag{6}$$

As the main objective of an active power filter is to correct the power factor and bring it as close as possible to its unity value,