Arc Fault Detection & Localization by Electromagnetic-Acoustic Remote Sensing

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Abstract. Electrical arc faults that occur in photovoltaic systems represent a danger due to their economic impact on production and distribution. In this paper we propose a complete system, with focus on the methodology, that enables the detection and localization of the arc fault, by the use of an electromagnetic-acoustic sensing system. By exploiting the multiple emissions of the arc fault, in conjunction with a real-time detection signal processing method, we ensure accurate detection and localization. In its final form, this present work will present in greater detail the complete system, the methods employed, results and performance, alongside further works that will be carried on.

1. Introduction
This current work intends to propose a case-study of an electrical arc fault detection and localization system, with emphasis on the detection and localization principles, and also on statistical performance evaluation. The physical principle behind this system is the simultaneous generation of the arc fault of electromagnetic waves, as well as sound (and low ultrasound) pressure waves. By exploiting this bidimensionality of the arc phenomena, the system (and the signal processing methods that it uses) manages to correctly assess the presence of the arc fault, as well as the distance at which it occurred.

In the first section, a brief description of previous and current embodiments of the system will be presented. Following, in section 2, we will describe the necessary signal processing in order to ensure robust detection of the arc fault. And in section 3, results and performances for one type of measurement will be presented, followed by our conclusions. The full paper version of the article will focus on the statistical evaluation of methods, in a wider range of configurations.

2. Experimental Configuration
The study of electrical arc fault has been widely treated in the scientific community [1]-[3], especially DC arc faults, that occur in photovoltaic power systems. This is the main focus of this work, as the type of arc faults that have been reproduced for this study are of the same nature.
Previous work on this issue has been carried out by the authors, with regards to the arc fault feature of generating electromagnetic and acoustic waves. This bidimensionality of the arc fault has been previously exploited in [4]-[6] with the use of a previous embodiment of a system composed from electromagnetic sensors in conjunction with an array of acoustic sensors. The electromagnetic sensor acts as an instantaneous detector and triggers the acoustic sensor data acquisition, which is then used for DTOA (Difference in Time of Arrival) estimation. The experimental system, with its remote sensing elements, is presented in figure 1.

An example of the setup is depicted in figure 2, with the arc fault source is located at a certain distance from the sensing system.

In the following section, we will present the signal processing methods used for DTOA estimation.

3.DTOA Estimation: Signal Processing

To better understand the nature of the localization problem, a first look at the three acoustic signals and the electromagnetic one is depicted in figure 3.

We see how the first sharp peak in the electromagnetic (blue) signal triggers the data acquisition, and how the delayed acoustic pressure wave reaches each of the sensors. The objective is to robustly detect those peaks and their moment of occurrence (Time of Arrival), in order to exploit the DTOAs for proper localization. The Short Time Fourier Transform is then used to analyze the frequency content of the acoustic signals, as we can see in figure 4, for one of the channels.

We see, how the frequency bandwidth of interest is approximately between 20-70kHz. The three proposed methods are:
- Peak of the envelope of the signal;
- RMS moving window;
- Statistical indicator moving window.
The choice for these methods is based on their simplicity, in order to prove the robustness of the physical detection principle: the electromagnetic-acoustic behavior of the arc fault facilitates the TOA estimation with different methods.

For a given signal, \( s(t) \), its envelope, \( R(t) \), is such that:

\[
s(t) = R(t)\cos(\omega t + \phi(t))
\]

(1)

The RMS is such that, for a given sample \( k \), of the discrete signal \( s[n] \), the RMS moving window has the value at the time instant \( k \):

\[
RMS[k] = \frac{1}{L} \sqrt{\sum_{i=k-L+1}^{k} s_i^2}
\]

(2)

, where \( L \) is the sample-width of the sliding window.

The statistical indicator \( A[k] \) is the aggregate (arithmetic mean) of the L-sample-width window standard deviation and its sample kurtosis (similar to the RMS sliding window, of length \( L \)):

\[
A[k] = \frac{\sigma_{k+Kurt_k}}{2}
\]

(3)

The TOA’s are given by:

\[
TOA = \arg \max_n (\text{Method}[n]), \text{Method} := R[n], RMS[n], A[n]
\]

(4)

In order to properly localize the arc fault, we proceed to solve the geometric problem [4]-[6]:

\[
\begin{align*}
\Delta TOA_{i+1} &= \Delta TOA_{i} = TOA_{i+1} - TOA_{i} \\
&= \Delta TOA_{i+1} - TOA_{i} \quad \text{is the difference of time of arrival (DTOA), } TOA_{i} \text{ is the time of arrival at each acoustic sensor } S_{i}, \quad i = 1, 4, \quad S_{i}(x_{S_{i}}, y_{S_{i}}, z_{S_{i}}), \quad v \text{ is the speed of sound.}
\end{align*}
\]

(5)

4. Results and Performances

We conducted tests in the following configurations (with the following arc fault source position):

I. \( X_{ARC} = 150 \text{cm}, Y_{ARC} = 180 \text{ cm}, Z_{ARC} = 0 \text{cm}; \)
II. \( X_{ARC} = 180 \text{ cm}, Y_{ARC} = 180 \text{ cm}, Z_{ARC} = 0 \text{cm}; \)
III. \( X_{ARC} = 510 \text{cm}, Y_{ARC} = 0 \text{cm}, Z_{ARC} = 0 \text{cm}. \)

The following results were obtained and averaged over 5 measurements per configuration, for each of the three methods of TOA estimation (the errors are underlined):

| Table 1. Envelope Peak Results |
|-------------------------------|
| Conf. | X_{ARC} | Err. (%) | Y_{ARC} | Err. (%) |
| 1     | 154.3   | 2.9     | 187.9   | 4.4     |
| 2     | 183.7   | 2.1     | 186.1   | 3.4     |
| 3     | 510.6   | 3.8     | 188.4   | 4.8     |

| Table 2. RMS Sliding Window Results |
|----------------------------|
| Conf. | X_{ARC} | Err. (%) | Y_{ARC} | Err. (%) |
| 1     | 151.2   | 2.1     | 184.4   | 2.4     |
| 2     | 183.5   | 1.5     | 182.9   | 1.6     |
| 3     | 512.7   | 3.2     | 196.8   | 4.4     |

| Table 3. Statistical Indicator Results |
|---------------------------------------|
| Conf. | X_{ARC} | Err. (%) | Y_{ARC} | Err. (%) |
| 1     | 161.3   | 2.4     | 196.5   | 9.1     |
| 2     | 187.2   | 4.4     | 196.8   | 9.2     |
| 3     | 523.6   | 4.4     | 196.5   | 9.1     |

From the results tables 1-3, it is noticeable how the Statistical Indicator is more sensitive to noise and more importantly, to window length (more valid estimates are obtained when the window length \( L \rightarrow \infty \)), therefore we obtained the less precise localization results for the Statistical Indicator sliding window. The best results were obtained for the Envelope Peak method, as it does not require the use of a moving window,
and, in consequence, can indicate the exact instant (e.g. time sample, TOA) the arc fault occurs.

Seeing as the envelope peak method was the most precise, we conducted a Monte Carlo simulation analysis based on the measurements (using the 5-measurement-per-configuration mean and sample standard deviation), in order to ensure the degree of separation between the probability distribution function of the maximum value of the arc fault acoustic signal (its ignition) and the amplitude of the noise. The survival function visualization (figure 5) shows us how the probability of the noise amplitude rapidly goes to zero, while that of the arc fault remains at 1, thus the risk of false alarms is 0% and probability of detection is 100%. As expected, the distance of the arc fault source with regards to the sensing system influences the performances, in the sense that there is less and less margin between the range of amplitudes which ensure 0% probability of false alarm and 100% probability of detection, as the arc fault source is farther away from the sensing system.

Figure 5. (Left to right) Configuration 1-3 noise (red) & arc fault (blue) probability vs. Amplitude threshold (survival function).

5. Conclusions
In this paper we have presented an updated version of an arc fault detection and localization system, which is based on the simultaneous emission of electromagnetic and acoustic waves from the arc fault. Experimental measurements have been carried out and different Time of Arrival estimation methods have been proposed, as well as the associated performances, which confirm the success of this approach. For the most promising of the methods, the envelope peak approach, we have constructed estimations of the statistical performances.

For future development, a more classical detection scheme will be investigated, such as the energy detector, with the corresponding enunciation of the detection problem in the shape of a binary hypothesis classification (arc fault vs. non-arc fault).

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