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Arc Fault and Flash Signal Analysis In Dc Distribution Systems Using Wavelet Transformation: A review

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Abstract : Arc faults are significant with respect to reliability and safety concern for electrical systems which can cause stoppage in intermittent operation and electrical shock hazards which can even result in fire. Arc fault in such vast systems are random and challenging which makes the study of arc fault detection using arc signature difficult. The high-frequency content of the arc requires fast sampling, which are having long memory, which requires proper data storage for fast processing and analyzing the arc. As signal to noise ratio is low and arc signal are not periodic in nature, commercialized existing techniques like Fourier Transform do not work well since they depend on recognizing pattern with time domain or frequency domain. In contrast, wavelet Transform (WT), recently developed method for analyzing, provides a time and frequency approach to analyze target signals with several resolutions. This review paper proposal proposes a method based on Wavelet Packet analysis which has the localization characteristics to detect low-voltage DC arc fault. The mother wavelet selection is studied as well by using various orders of Daubechies wavelet. Efforts have been made in this study to incorporate and review approximately all important techniques and philosophies of arc fault detection. This comprehensive and exhaustive survey will reduce the difficulty of new researchers to evaluate different WT based techniques with a set of references of all concerned contributions.

Keywords: Arc fault analysis, arc flash, dc distribution, dc microgrid safety, signal processing, wavelet transform (WT)

I. INTRODUCTION

The growing need for highly reliable power supply for critical applications like in hospitals, data centers, telecommunication systems, and semiconductors industry, there is increase in use of power electronic converter (PEC). PECs have been extensively incorporated in the power system i.e. in renewable energy sources like wind and solar and energy storage systems.[1] For this power distribution system should be designed by considering factors like system architecture, energy flow control, and protection and power quality.

Fig. 1: Damage to a PV system attributed to an arc

In the dc distribution systems, recent developments are done in renewable energy technology system which should be flexible and able to utilize all the energy sources and also flexible for future expansion. In residential applications, a

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dc micro-grid structure is used for dc buildings which are having higher voltage in dc systems. The reasons like combination of high dc voltage lines, deterioration of wire insulation due to rodent bites and abrasion due to chaffing with trees, building walls, or conduit during installation can cause electric arcs to occur. Arc faults can occur in small-scale load in residential systems as well as large-scale distribution systems and can also cause harmful threats to the human safety. Arc fault has a major problem in electrical installation.[2] This dc arc may result in shock hazard, fires, and system failure or fault in the micro-grid. If dc arc faults are not detected and extinguished on time, the arc fault could spread to adjacent circuits and endangered the power sources, control systems, or even cause explosions in a confined space due to the growing arc pressure. While the arc creates high temperature plasma that can ignite surrounding materials, such as in the example shown in Fig. 1, the impedance of the arc may not draw sufficiently high current to activate overcurrent protection devices. Thus the arc can be sustained undetected for hours or longer as in the example shown in fig. 2. Arc faults in PV systems not only threaten property loss but can also pose significant threats to human safety [3-6]. With arc fault, it is also important to detect arc flash, which is the pre fault event of sparking and dielectric breakdown. As long as this problem exists, dc distribution systems face significant disabilities which threaten their extensive use. Thus, arc fault detection is extremely important for reliable and safe system operation and is a prerequisite for widespread adoption of dc microgrid systems.

Fig. 2. Arcing persists in the DC wiring even after a fire consumes a portion of the combiner box.

AC arc faults have been well studied. The detection of ac arc faults has been well developed [8], [14]–[18] with commercial products designed and under writers laboratories listed [19] for safety [20] – [22]. Comparatively, a much smaller body of work pertaining to arcs in dc electrical systems and commercialization of sensing and protection devices has only recently begun [23]. A significant complication to their detection is that arcs in dc systems are not periodic, and thus may not have easily recognizable amplitude or frequency signatures for pattern recognition-based detection techniques. Spectral analysis using Fourier techniques to decompose the frequencies of a sustained arc or bolted fault requires a linear system and a stationary signal, and therefore Fourier techniques are not capable of reliably detecting arc flash.

In ac systems, signal decomposition using wavelet transform (WT) and wavelet packet have been proposed and worked well to detect the impulse-like effect of the discontinuous arc due to periodic extinguishing and reignition associated with the main frequency zero-crossing [7], [8], [14]–[16], [24]. However, there is no natural mechanism for periodic extinction and reignition of the arc in dc systems, which makes detection difficult especially for series arc faults [25].

As shown in Fig.3, arc faults can be series or parallel. Series arc faults often occur due to loose electrical connections while parallel faults can be caused by abrasion of conductors from thermal cycling or vibration, puncture of the insulation by rodents, or other failures within the microgrid system [9], [10]. Arc faults can occur in small-scale point-of-load residential systems as well as large-scale distribution systems and can pose significant threats to human safety. Fig. 4 illustrates possible sources of arc faults due to the way a utility-scale dc collection grid is installed.

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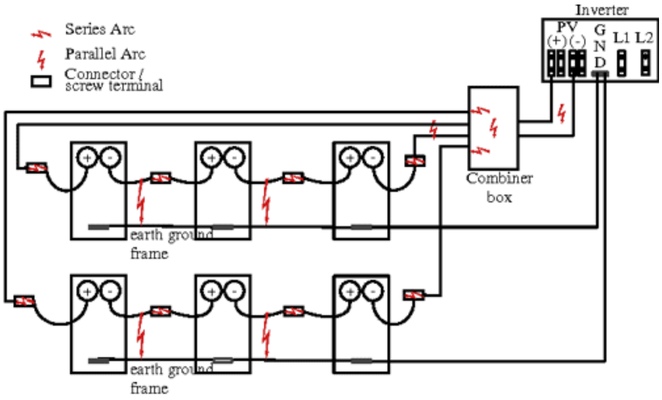

Fig. 3. Example of locations where dc arcing may occur in a dc distribution system.

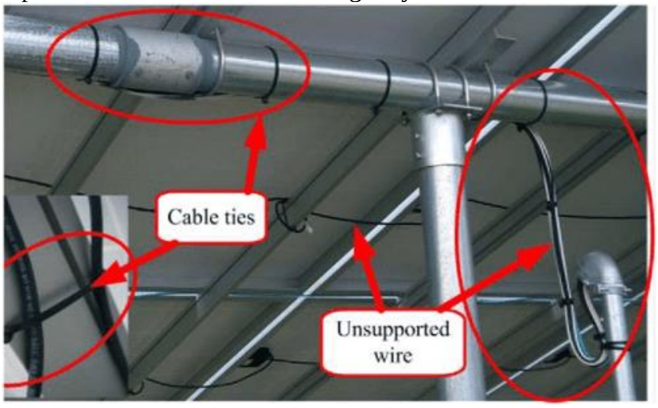

Fig. 4. Example of dc wiring in a ground-mounted photovoltaic array. Cable ties can abrade wire insulation over time, causing a parallel arc fault to the grounded frame and rail. Unsupported wires put strain on connectors, causing conductor separation and series arcing.

II. CONVENTIONAL METHODS FOR ARC DETERMINING

There are currently commercial products available and even required in some applications for ac arc detection in residential ac systems. Known as combination arc fault circuit interrupters (AFCIs), these products are required to detect both series and parallel arc faults [19]. AFCIs typically use current sensors and analogue filters to acquire a filtered analogue current signal in a specific frequency band, where the arc fault signal is assumed to be the most detectable. The filtered time domain current signal is then processed, usually by proprietary detection algorithms and a carefully tuned threshold setting in a digital signal processor (DSP) or microprocessor [20], [22]. Some research, however, has shown that neither branch/feeder AFCI nor combination AFCI would accurately detect all series arc faults [26]. This could be in part due to how the threshold detection algorithm was tuned and the assumptions made in the filter as to the frequencies in which the arc signature signal appears.

To give an example, a commercially available solution is designed to detect arc fault in a PV dc system using FFT as the detection method. The complete process, as shown in Fig. 5, uses a wide bandwidth coupled inductor circuit. An isolation transformer is used to isolate the high dc voltage and current from the arc monitoring circuit. The system application in a PV string array is shown in Fig. 6. The detection method assumes that the arc signature lies predominantly in the frequency band between 40 and 100 kHz and uses a prefilter to condition the analogue signal [27].

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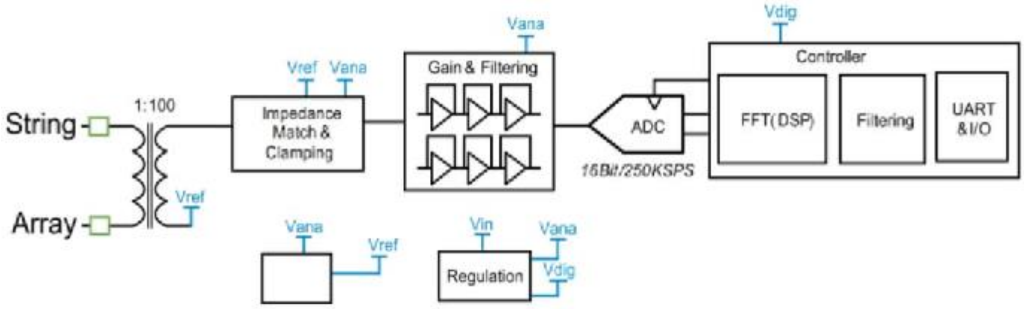

Fig. 5. System diagram of a commercially available solution.

Nevertheless, other nonarcing-related signals, such as switching harmonics from inverters and dc/dc optimizers may also generate signals in this frequency band which can lead to false detection or non detection by masking the arc signature. Non detection is obviously detrimental since the hazard is undetected. False detection is also undesirable because the response may unnecessarily shut down the system, causing loss of revenue or even the potential for grid instability when the PV generation trips offline both needlessly and unexpectedly.

Although the conventional Fourier transform is deeply researched and widely used, the fact that it works best for periodic signals is a significant limitation. The nature of arc faults in power systems is not periodic [7]. Further, only frequency information is given by traditional Fourier transform approaches; not enough time-domain information is provided to find out exactly when the event occurs. Such temporal localization could help correlate the electrical arc characteristics with other accompanied events such as lighting or fast transients that couple from other devices in the system.

The short-time Fourier transform (STFT) is a Fourier-related transform used to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time. This transform still has a fundamental drawback in that the length of the window used in the STFT is the same for all frequencies which leads to a fixed resolution. The window length selection then becomes a trade off between good frequency resolution and good time resolution. A large number of samples are required to obtain high-frequency resolution, which in turn causes low-time localization. A shorter window provides better time localization but inferior frequency resolution [28], [29].

It is also worth pointing out that in order to minimize the spectral leakage, window size usually has to be chosen carefully to meet the coherent sampling requirement. However, the arc fault signature is distributed in a wide frequency band [27], [30]. In practice, it is impossible to choose a perfect window to accurately extract all the relevant information using Fourier transform-based methods.

In the conclusion, discrete STFT might be suitable for time frequency domain analysis of harmonic-related disturbances, but it is not ideal for capturing abrupt disturbances or short transient signals.

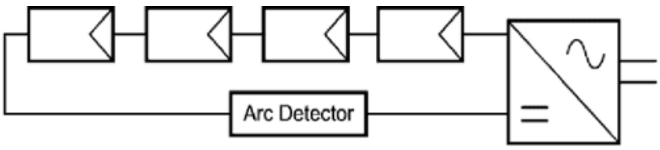

Fig. 6. System application of SM73201 to detect series arc faults by sensing current.

III. THE ULTIMATE SOLUTION: THE WAVELET TRANSFORM

A. Discrete wavelet transform

The WT is a linear transformation like the Fourier transform. But unlike FFT, it allows time localization of different frequency components of a given signal [31]. Due to the wide variety of signals and problems encountered in power engineering, there are various applications of WT, such as fault detection, load forecasting, and power system measurement. In addition, relevant information about power disturbance signals is often a combination of features that are well localized temporally or spatially such as power system transients. This requires the use of versatile analysis methods in order to handle signals in terms of their time-frequency localization, which is an excellent area to apply the special property of wavelets [32].

The wavelet analysis procedure is based on a wavelet prototype function called a “mother wavelet,” which provides a localized signal processing method to decompose the differential signal into a series of wavelet components, each of

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which is a time-domain signal that covers a specific frequency band [33], [34]. Wavelets are particularly effective in approximating functions with discontinuous or sharp changes like power system fault signals [35]. With proper choice of the mother wavelet, wavelet transformation is a good tool for signal analysis and fault feature extraction.

The discrete wavelet transform (DWT) is defined as

$$C(j,k) = \sum_{n\in Z} s(n) g_{j,k}(n) \qquad (1)$$

$$j \in N, k \in Z$$

Where C(j, k) is the corresponding wavelet coefficient, n is the sample number, s(n) is the signal to be analysed and $g_{j,k}(n)$ is the discrete scaling function (also called the father wavelet), which for dyadic-orthonormal wavelet transform is defined by

$$g_{j,k}(n) = 2^{-j/2} g(2^{-j}n - k). \qquad (2)$$

The auxiliary function to this is the mother wavelet.

TABLE I
PARAMETERS USED WITH THE CASSIE ARC MODEL

Tau	1.2e-6 s
Uc	100 V
g(0)	1e4 S
Contact separation starts	0.5 s

With this initial setting, there exists an elegant algorithm, the multi-resolution signal decomposition (MSD) technique, which can decompose a signal into levels with different time and frequency resolution. At each level j, approximation and detail signals Aj (represented by linear combinations of father wavelets at jth level) and Dj (represented by linear combinations of mother wavelets at jth level) can be created. The words "approximation" and "detail" are due to the fact that Aj-1 is an approximation of Aj taking into account the “low frequency" of Aj, whereas the detail Dj-1 corresponds to the "high frequency" correction.

As shown in Fig. 6, for a reference level J, there are two categories of details: 1) those details associated with indices $j \geq J$ correspond to the scales $2^{-j/2} \leq 2^{-J/2}$, which are the fine details; and 2) the other details correspond to $j < J$ and are the coarse details, which define an approximation of the signals

$$s = A_J + \sum_{j\geq J} Dj$$

which signify that s is the sum of its approximation AJ improved by the fine details [36].

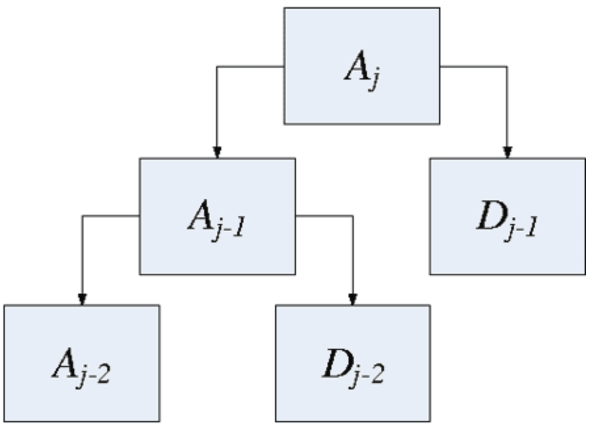

Fig. 6: Wavelet decomposition tree.

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B. Wavelet and filter banks

Multi-resolution signal analysis using discrete wavelet transform (DWT) can be implemented by filter bank theory, where a wavelet and a scaling function is associated with a high pass and a lowpass filter respectively. As shown in Fig. 7, on each level of decomposition, the input signal is split into a low-frequency component and a high-frequency component. With dyadic wavelet filters (wavelet transform), only the low frequency part is further decomposed. In comparison, binary tree wavelet filters (wavelet packets), which splits both low- and high-frequency component on each level, leads to decomposed signals with an equal bandwidth [23]. In this paper, only dyadic wavelet filter implementation is discussed.

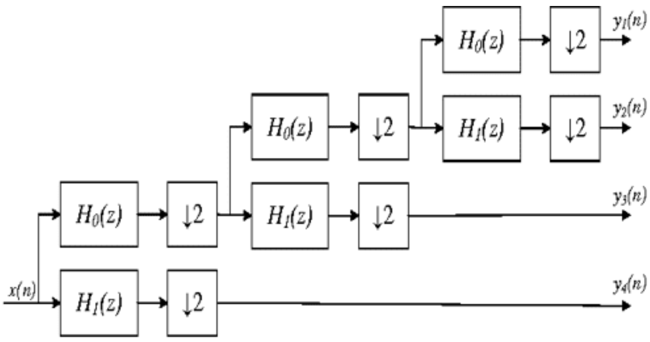

Fig. 7: Dyadic tree wavelet analysis bank.

C. Cassie Arc Model

Circuit-breaker's performance in power system is analysed by representing the circuit-breaker characteristics by a operate of electrical parameters like current/voltage, and mixing with, although difficult, facility circuit. For such functions, supposed "Black-box modelling" is applied, in which, despite of actual circuit-breaker hard-ware like contact form, pressure, range of snapping point, etc., a function of electrical parameters is introduced. Within the chapter, as being popularly used equations, Mayr arc model and cassie arc model are concerned. In Cassie arc modelling, the assumptions are:

-Heat loss depends on the arc flow (convection loss).

-Heat loss, hold on heat, and electrical conductance phenomenon area unit proportional to the cross section space. Then, because the result, the subsequent is obtained.

$$\frac{1}{g}\frac{dg}{dt} = \frac{d\ln g}{dt} = \frac{1}{\tau}\left(\frac{u^2}{U_C^2} - 1\right)$$

Where

g conductance of the arc;

u voltage across the arc;

i current through the arc;

Uc constant arc voltage;

τ arc time constant.

The above assumptions correspond to relatively high current of arc, such as higher than several hundred A, so Cassie arc model is applicable to higher current of arc.

D. Selection of Mother Wavelet

The criteria for selecting the mother wavelet adopted in this paper are summarized in [37] and [38] are as follows. 1) The wavelet function should have a sufficient number of vanishing moments to represent the salient features of the disturbances. 2) The wavelet should provide sharp cut off frequencies to reduce the amount of leakage energy into the adjacent resolution levels. 3) The wavelet basis should be orthonormal. 4) For applications where the information lasts for a very short instant, wavelets with fewer numbers of coefficients are better choices; on the other hand, for signal signature spread over a longer period of time, wavelets with larger numbers of coefficients tend to show smoother results. There are several well-known families of orthogonal wavelets. An incomplete list includes Harr, Meyer family, Daubechies family, Coiflet family, and Symmlet family [39]. Daubechies wavelets are chosen in this paper due to their outstanding performance in detecting waveform discontinuities [37], [40]. The frequency responses of filter banks of Daubechies 3 (db3), Daubechies 9 (db9), and Daubechies 19 (db19). It can be seen that the frequency response of db9 filters has a significantly sharper cut off frequency in comparison with that of db3 filters. But db19 does not provide

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equally significant improvement over db9. Considering the extra computational load brought on by wavelets with more coefficients, db9 presents a good compromise. By the way of example, consider a dc system in which there is a switching noise introduced by the power electronic converters in the system. Wavelet analysis using db3, db9, and db19 is performed on this signal. The fourth-level detail component was designed to span the frequency band 31.3–62.5 kHz. Since the goal of wavelet analysis is to separate the arc fault signal from electronic converter noise (which resides in specific frequency bands) and other electrical disturbances (which usually vary slowly), a narrower transition frequency region leads to less information leaking into other decomposition levels and a more accurate signal approximation. While the db9 and the db19 filter banks are better choices than the db3 filter bank, from a hardware implementation standpoint, db9 filters require less mathematical operations than db19 wavelet. Thus, we can trade off the accuracy of the wavelet decomposition with the processing overhead of the real-time wavelet filter banks implemented in a microcontroller (MCU) or DSP.

IV. CONCLUSION

This paper has proposed a new approach for arc analysis in dc microgrid systems based on WT. The fundamental feasibility of applying WT has been presented. A comparison between the Fourier transform method and the proposed WT method has been studied with both simulation analysis and experimental results.

The presence of switching harmonics and ambient electrical noise can mask the arc signal, making detection of an arc difficult. Fourier analysis is usually not able to discover transient signals and abrupt changes like sudden arc faults and arc flashes. If the duration of the arc flash lasts for a very short period of time in comparison with the sampling window of FFT, it is likely that the arc flashes will not be observable. However, WT is extraordinarily effective with detecting the exact instant the signal changes. The results suggest that the WT approach is not just capable of analysing arc fault in dc systems but that it also provides a more readily detectable signal and better performance than the FFT method. In subsequent work, we have further studied arc fault signals in the presence of inverter noise by using waveforms synthesized from real-world PV system voltages and currents. These waveforms are comprised of superimposed arcing and inverter electrical noise at a user-specified arc-signal-to-noise ratio [41]. The test results using the synthesized test signals coincide with foregoing theoretical analysis [42]. Future research efforts will be devoted to:

1) the identification of the most numerically efficient mother wavelet still capable of detection of arc faults and flashes;
2) implementation of real-time “on-line” arc fault detection by integrating the detection algorithm into a DSP controller;
3) distinguishing arc fault from other harmless disturbances that might occur in the system by applying pattern recognition and expert system theory.

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