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Arc Fault Detection in Low Voltage DC System Using Wavelet Transform

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ABSTRACT: The main objective of this paper to detect an arc fault occurring in a low voltage dc system using wavelet transform. As we know arc faults plays a major role in an electrical power system, due to this fire, shocking hazard or system failure of the electrical system or equipment can be happen. It's very challenging to detect arc fault in a dc system because unlike a ac system a dc system cannot be based on zero crossing value rely on Fourier transform which is the pattern recognition of the signal either in time domain or frequency domain which cannot gives a accurate results. So for this deficiency a new technique called wavelet transform (WT) is used to detect fault in electrical system. Wavelet transform is based on multi resolution analogy in which signal can be tested in both time and frequency domain. This time-frequency domain wave shape determining method is very useful in ac as well as in dc, which gives approximate value of the fault occurring in the system. The process of detecting an arc fault involves signal analysis and then feature identification. The focus of this paper is on the former. Simulation models are synthesized to study the theoretical results of the proposed methodology and compare with the previous results analysis on arcing faults. A practical approach is also mentioned in it.

KEYWORDS: Arc fault analysis, dc distribution, dc micro-grid safety, signal processing, wavelet transform (WT).

I.INTRODUCTION

An arc fault is a high power electrical discharge between two or more conductors. This can damage the entire electrical system and cause fire to completely breakdown the electrical insulation of the conductors. 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 reigniting associated with the main frequency zero-crossing. However, there is no natural mechanism for periodic extinction and reigniting of the arc in dc systems, which makes detection difficult. In DC electricity distribution systems and dc micro-grids a large number of electrical connectors and long wire runs are expected. Combined with the high dc voltage, deterioration of the wire insulation due to aging or other circumstances such as rodent bites and abrasion due to chaffing with trees, building walls, or conduit during installation can cause electric arcs to occur. These dc arcs may result in shock hazard, fires, and system failure or fault in the micro-grid. As shown in Figure 1, 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 micro-grid system [1]. 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. Figure 2 illustrates possible sources of arc faults due to the way a utility-scale dc collection grid is installed. As long as this problem exists, dc distribution systems face significant concerns about liabilities 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 micro-grid systems Detecting arc flash is a difficult problem because unlike a bolted "hard short" fault in which high current flows through a metal-to-metal connection, arc flash involves short-term current flowing through ionized air or along an ion path and may not draw sufficiently high root-mean-square current, or have a high enough I2t energy to trip a thermal circuit breaker. This is particularly true in finite- energy systems, Such as many of the proposed dc micro-grids and systems energized by renewable energy sources. In these cases, an arc, like the one shown in Figure 3, can be sustained for hours or even days because the overcurrent protection devices never activate. Thus, the fire and safety hazard is left undetected and unmitigated [2]. Unlike an ac system in which power electronics are typically found only at the point-of-load, a dc system requires the use of Dc/dc converters throughout the distribution system which adds distributed capacitance throughout the system providing numerous coupling pathways for high-frequency signals. High-frequency noise from the dc/dc converter switching and other electromagnetic interference could obfuscate the arc signature, allowing an arc to establish and be sustained undetected.

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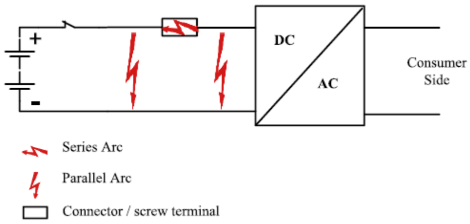

Figure 1: Example of locations where dc arcing may occur in a dc distribution System.

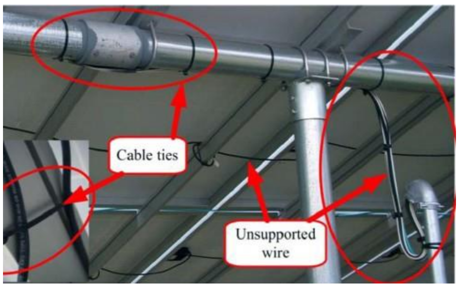

Figure 2: Example of dc wiring in a ground-mounted photovoltaic array. Cable ties can abrade wire insulation over time, causing a parallel arc fault to the grounded frame and rail. Unsupported wires put strain on connectors, causing conductor separation and series arcing.

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 re-ignition associated with the main frequency zero-crossing. However, there is no natural mechanism for periodic extinction and re-ignition of the arc in dc systems, which makes detection difficult especially for series arc faults [3]. In this paper, the fundamental feasibility of applying wavelet theory to analyze arc fault and arc flash in dc micro-grid systems is examined first in simulation using synthetic waveforms generated in MATLAB/Simulink and then it's compared with the db9 and db15(mother wavelets) [1,4].

Figure 3: Arcing persists in the dc wiring even after a fire consumes a portion of the combiner box.

II. OTHER METHODOLOGY USED

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. AFCIs typically use current sensors and analog filters to acquire a filtered analog 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. Some research, however, has shown that neither branch/feeder AFCI nor combination AFCI would accurately detect all series arc faults. This could be in part due to

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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 Figure 4, 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 Figure 5. The detection method assumes that the arc signature lies predominantly in the frequency band between 40 and 100 kHz and uses a pre-filter to condition the analog signal Nevertheless, other non-arcing-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.

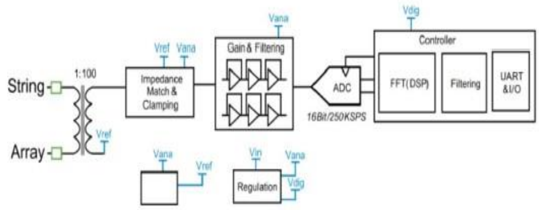

Figure 4: System diagram of a commercially available solution.

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. Further, only frequency information is given by traditional Fourier transform approaches; not enough time-domain information is provided to exactly verify the fault occurring time and location. 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. It is also worth pointing out that in order to minimization of the spectral leakage in the system, it is necessary to choose the window size to satisfy the coherent sampling requirement. However, the arc fault signature is distributed in a wide frequency band. 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.

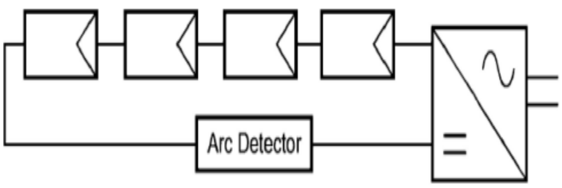

Figure 5: System application of SM73201 to detect series arc faults by sensing current.

III. DISCRETE WAVELET TRANSFORM

In this scheme, The WT is a linear transformation just like the Fourier transformation tool. But the only difference is, it can allow time localization with different frequency components of the signal which has taken for examine. Due to the

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wide variety of signals and problems encountered in power engineering, there are various applications of WT, such as fault detection, load prediction or forecast, and measurement purpose required in a power system [4]. The benefit is, relevant knowledge about the disturbances signals are mostly combination of features which can be well localized temporally or approximately such as the transients occurs in power system. For this, it's necessary to use the versatile multi-analysis methods by which it can handle all the signals with respect to their time- frequency localization, which is an excellent area to apply the special property of wavelets. The wavelet analysis method is based on a "mother wavelet," the wavelet prototype which can ease the signal can be examined by a time localization decomposition of the signals in a particular frequency range [5,6]. Wavelets can be a very effective tool in approximate detection of fault with respect to sharp changes in the signals like power transient in the power system. By the proper selection of the mother wavelet, it is a good tool for signal analysis of the system and fault feature extraction can easily done. The discrete wavelet transform (DWT) is defined as

$$C(j,k) = s(n)\, g j,k(n) \qquad n \in Z \quad j \in N, k \in Z \tag{1}$$

where C(j, k) is the corresponding wavelet coefficient, n is the number of samples in the signal, where s(n) is the signal to be examined, andthe discrete scaling function (also called as the father wavelet) is gj,k(n), which for dyadic-orthonormal WT is defined

$$g j,k(n) = 2 - j/2 g\_2 - jn\text{-}k \tag{2}$$

The auxiliary function to this is the mother wavelet.

Material Coefficient B	1.46
Corona Resistance Rc	2221 Ohm
Arc time constant for V	0.0001 s
Arc time constant for I	0.00001 s

Table 1: Parameters used in ideal arc model.

With this initial setting, the DWT can be easily implemented by multi-resolution analysis. As shown in Figure 6, at each level j, Aj (represented by linear combinations of father wavelets at the jth level) is the approximation signal and Dj (represented by linear combinations of mother wavelets at the jth level) represent the detail signal can be created.

$$S = A_J + \sum D_j \quad \text{for} J \geq j$$

Prove that s can be the sum of AJ and its approximation which can improved by details available in it.

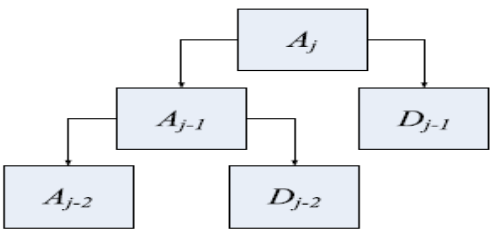

Figure 6: Dyadic wavelet decomposition tree.

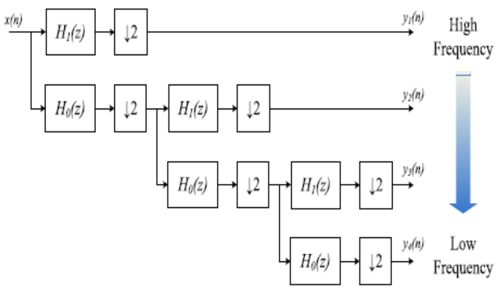

Figure 7: Dyadic wavelet filter bank.

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IV. WAVELET FAMILIES

In the present era we have some known families of orthogonal wavelets. An incomplete list includes Harr, Meyer family, Daubechies family, Coiflet family, and Symmlet family. But for this work Daubechies is showing more accuracy for detecting waveform discontinuities.

4.1. Daubechies Wavelets

- How they look like:
  - Translated copy
  - Dilation

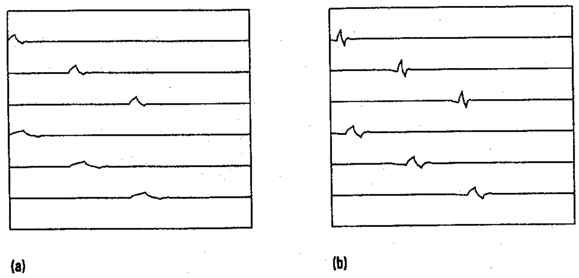

Figure 8: Db Signal analysis.

4.2. Coiflets

- It is designed for balancing an appropriate match between the trend value and the original signal.

$$a_m^1 \approx \sqrt{2}g(t_{2m}), \quad a_m^2 \approx 2g(t_{4m})$$

- Named after the inventor: R. R. Coifman

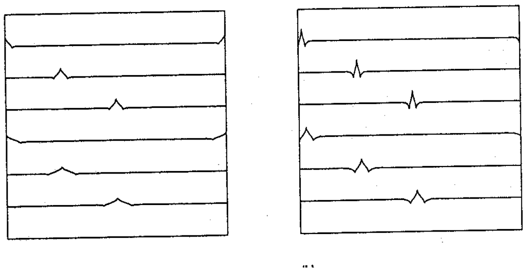

Figure 9: Coiflet Signal analysis.

4.3. Haar Wavelets

- The elements in the synthesis and analysis matrices are

$$\alpha_1 = \alpha_2 = \frac{1}{\sqrt{2}}$$

$$\beta_1 = \frac{1}{\sqrt{2}}, \beta_2 = \frac{-1}{\sqrt{2}}$$

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$$P^2\begin{bmatrix}\alpha_1 & \\ \alpha_2 & \\ & \beta_1 \\ & \beta_2\end{bmatrix}, Q^2=\begin{bmatrix}\alpha_1 & \\ \alpha_2 & \\ & \beta_1 \\ & \beta_2\end{bmatrix}$$

$$\begin{bmatrix}\alpha_1 & & & \\ \alpha_2 & & & \\ & \alpha_1 & & \\ & \alpha_2 & & \\ & & \alpha_1 & \\ & & \alpha_2 & \\ & & & \alpha_1 \\ & & & \alpha_2\end{bmatrix}=\begin{bmatrix}1 & & & & & & & \\ & 1 & & & & & & \\ & & 1 & & & & & \\ & & & 1 & & & & \\ & & & & 1 & & & \\ & & & & & 1 & & \\ & & & & & & 1 & \\ & & & & & & & 1\end{bmatrix}\begin{pmatrix}\alpha_1 & & & \\ \alpha_2 & & & \\ & \alpha_1 & & \\ & \alpha_2 & & \\ & & \alpha_1 & \\ & & \alpha_2 & \\ & & & \alpha_1 \\ & & & \alpha_2\end{pmatrix}$$

Figure 10: Synthesis Filter P^3.

$$\begin{bmatrix}\beta_1 & & & \\ \beta_2 & & & \\ & \beta_1 & & \\ & \beta_2 & & \\ & & \beta_1 & \\ & & \beta_2 & \\ & & & \beta_1 \\ & & & \beta_2\end{bmatrix}=\begin{bmatrix}1 & & & & & & & \\ & 1 & & & & & & \\ & & 1 & & & & & \\ & & & 1 & & & & \\ & & & & 1 & & & \\ & & & & & 1 & & \\ & & & & & & 1 & \\ & & & & & & & 1\end{bmatrix}\begin{pmatrix}\beta_1 & & & \\ \beta_2 & & & \\ & \beta_1 & & \\ & \beta_2 & & \\ & & \beta_1 & \\ & & \beta_2 & \\ & & & \beta_1 \\ & & & \beta_2\end{pmatrix}$$

Figure 11: Synthesis Filter Q^3.

DC Voltage	110V
AC ripples voltage	200V
Phase delay	0
Frequency	50

Table 2: Parameters used in the input source.

4.4. Wavelet and Filter Banks

Multi-resolution signal analysis using DWT can be implemented by filter banks where a wavelet and a scaling function are associated with a high-pass and a low-pass filter, respectively [4]. As shown in Figure 7, on each level of De-composition, the input signal is split into a lower frequency component and a higher frequency component [8]. With dyadic wavelet filters (WT), only the low-frequency part is further decomposed. In comparison, binary-tree wavelet filters (wavelet packets), which split both low- and high-frequency components on each level, lead to decomposed signals with an equal bandwidth. In this paper, only dyadic wavelet filter implementation is discussed [9,10].

4.5. Selection of Mother Wavelet

The criteria for selecting the mother wavelet adopted in this work are summarized in and are as follows [4].

1) The wavelet function should have a sufficient number of vanishing moments which can easily represented.

2) The wavelet should provide sharp cut off frequencies to reduce the amount of leakage energy into the adjacent resolution levels.

3) The wavelet should require tobe orthonormal to detecting the signals.

4) In application where the information needed to be last for a very short instant, wavelets with fewer numbers of coefficients are better option; and other things are, for a signal signature which is spread over a long period of time, wavelets with larger numbers of coefficients tend to show smoother results. There are several families of orthogonal wavelets which is available. Out of that some families are described as, Harr, Meyer family, Daubechies family, Coiflet family, and Symmlet family. Daubechies wavelets are taken under consideration for this work due to their very well and have an ability to detect discontinuities in the waveform.

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The frequency responses of filter banks of Daubechies 9 (db9) and Daubechies 15 (db15) are shown in Figure 12 and Figure 13. It can be seen that the frequency response of db15 filters has a significantly sharper cutoff frequency in comparison with that of db9 filters. Considering the extra computational load brought on by wavelets with more coefficients, db15 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. The original time domain waveform and the spectrum of this signal are plotted in Figure 12 and Figure 13. Wavelet analysis using db9, and db15 is performed on this signal. The fourth-level detail component was designed to span the frequency band .04 to 1 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 regions are available to decrease the information leaking into other decomposition levels and a more accurate signal approximation is present. While the db15 filter banks are better choices than the db9 filter bank. Thus, we can tradeoff the accuracy by the use of real time filter bank with wavelet decomposition can be implemented in a microcontroller (MCU) or DSP.

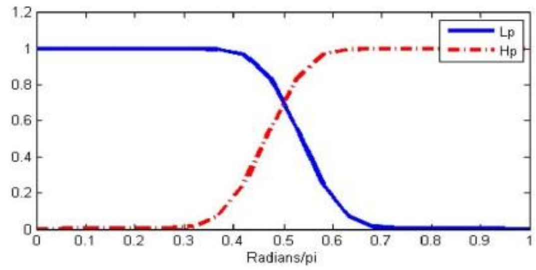

Figure 12: Frequency response of db9.

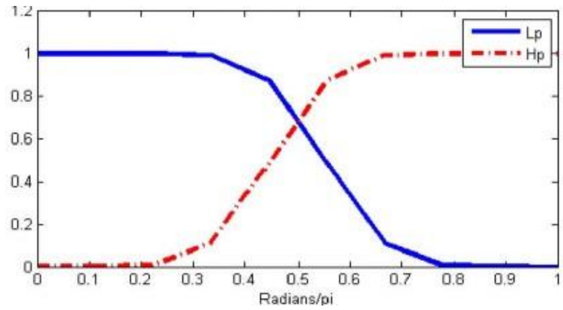

Figure 13: Frequency response of db15.

V. ARC FAULT DETECTION- PRACTICAL APPROACH

Detecting primary In order to simulate the arcing condition, black box modelling is commonly used to describe the arc interaction with the electrical network. The black box models use voltage and current traces from a circuit breaker test, together with a select differential equation, to produce a mathematical model for the desired arc under study. Till now only black box model with a Cassie and Mayr models [1] is studies and developed. But in this case we have taken a physical arc generator model in which arc can be generate and can c be compare with the original signal from the source. In this we have taken a mosquito zapper bat which can produce an arc whenever a path is created between the low voltage and high voltage net. The mosquito zapper bat (Shown in Figure 14) works on the principle of voltage differences, in this two nets are having two different voltage (one is having high and other is low). Whenever a mosquito comes in between the two nets, it's creates an arc to be developed in it.

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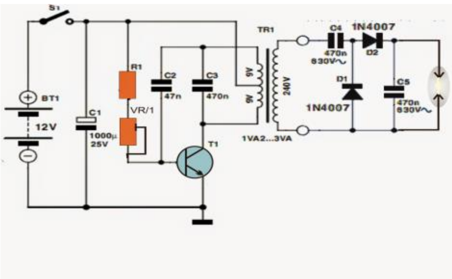

Figure 14: Mosquito zapper bat circuit.

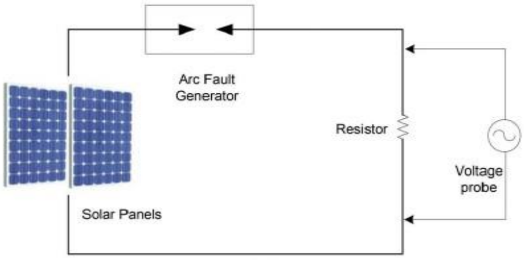

Figure 15: Circuit diagram of a propose system.

VI. SIMULATION MODELS AND RESULTS

Transmitter detection: The system bus voltage source is comprised of a dominant 110V dc component with small-amplitude ac components at 100 to 200 Hz, which represent single-phase double frequency power ripple and power electronic switching noise, respectively. The sustained series arc starts at 0.5 s. The simulink model is described as, the physical source signal is connected with ideal arc block set, which creates the arc in the input signal thrugh PS S converter, converts signal into a voltage or curent signal proportional to input signal. Now the arc is generated and it is given to DWT blockset with order 15 and level 4 in a daubechies family is taken. A reshape block is also used to change the frame signal to scalar signal in 2-D array with 16 delay block sets. This signal is now given to the assymetric DWT block set which decomposes the signal into sub-bands level of 4. Now the signal is given to the unbuffer block set to change the signal into scalar based signal and the result output is taken in the scope.

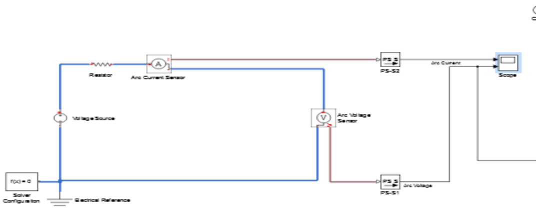

Figure 16: System DC voltage without Arcing block.

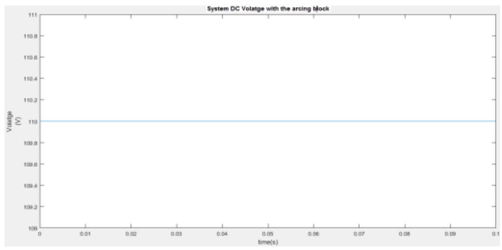

Figure 17: 110DC voltage without Arcing.

In this the physical model is disconnected with the ideal arc model and the output from the system is taken in a workspace.

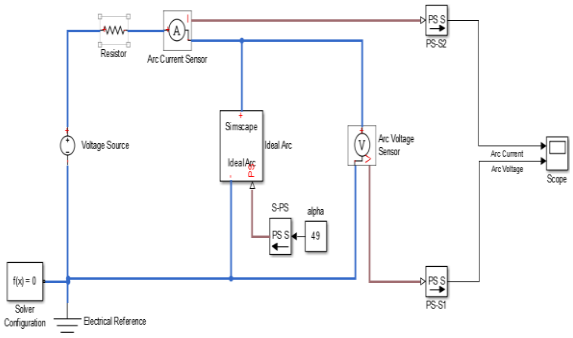

Figure 18: System with Arc block set.

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In this, the physical system is connected with an ideal arc model, and from that we can easily see that arc is developed and the current and voltage signal are affected by it. Here we have taken the input source with or without AC ripples (i.e., 200V ac with 50 Hz frequency) and result is taken on the workspace. Although the decomposed result is same for both.

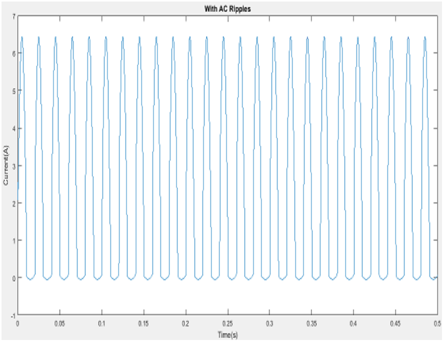
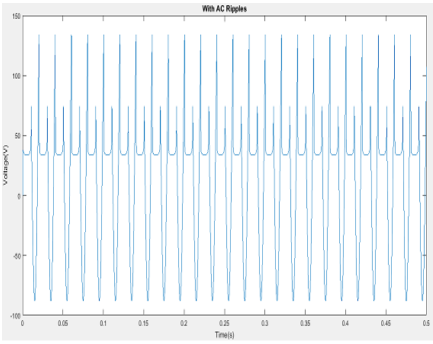


Figure 19: Output of a current arc signal.



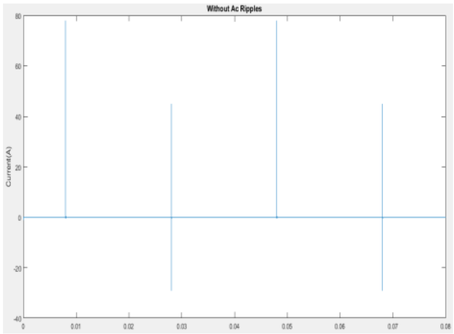
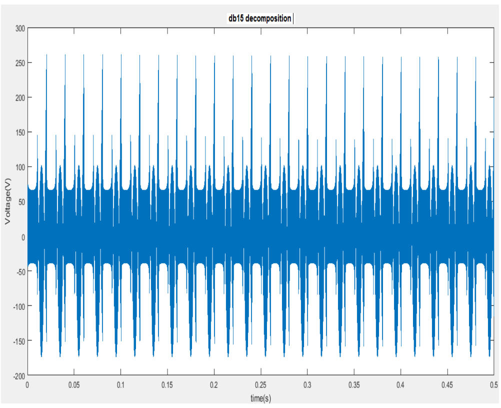


Figure 20: Output of a Voltage arc signal.

Figure 21: Output of a Voltage arc signal with a pulse source.

In the above results, the input signal is either connected with pulse block set or not connected. In the first figure, the input is not connected with pulse block set and only source is connected with ac ripples. But in the second figure the source is connected with pulse block with zero ac ripples and frequency, such we can see the arc is happening at every .02 sec interval of time.

Result of the entire System with Comparison with db15 and db9.



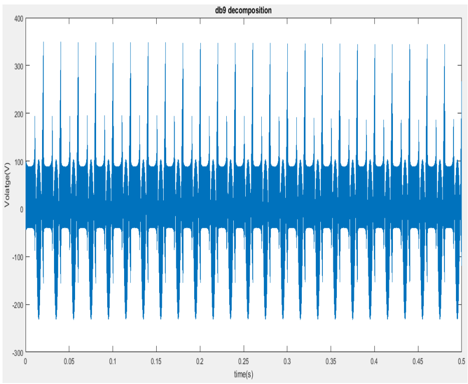


Figure 22: db9 decomposed Signals/Sub-bands.

Figure 23: db15 decomposed Signals/Sub-bands.

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In both of the results (shown in Figure 22 and Figure 23), the cut frequency is can be noted out. In the first figure the db9 has a amplitude between 300 to 400 but in case of db15 it has signal ranges between 200 to 250. So it's easily observe that db15 has a greater sharp cut-off frequency than db9. And the boundary limits also decreased, so we can calculate the time at arcing is happening at most probable value with respect to original signal.

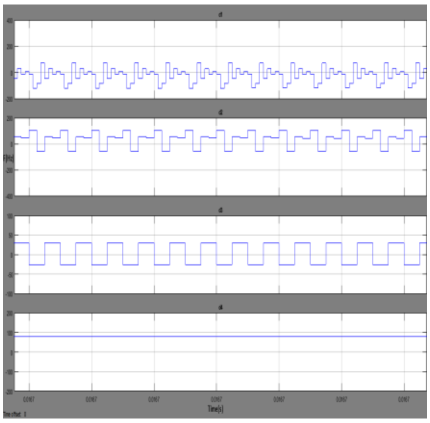

Figure 24: Decomposed signal or sub-bands.

The Sub-bands signal (Figure 24) can be compared with the original signal without arc and it approximate arcing time can be figure out through this. The Novelty itself is arc fault is detected in a low voltage dc system with a physical arc model and it is compared with the db9 wavelet and db15 wavelet. After all this db15 signal decomposed and the level of both the arc signal as well as non-arc signal are compared such that result can be taken. And it is found that db15 has better results than db9, such that it has a high sharp cut-off frequency.

VII. CONCLUSIONS

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 analyzing arc fault in dc systems but that it also provides a more readily detectable signal and better performance than the FFT method. From the previous studies, it can be seen that it is possible to detect arc faults using FFT, but it is not as effective as using WT, especially when it comes to the practical problem of threshold setting for arc fault determination. Setting the detection threshold involves consideration of the signal-to-noise ratio, which may change from application to application. However, when using wavelet transformation, the arc signature is significantly distinguished from the non-arcing signal and is easy to be detected when the detection method is embedded in a MCU for real-time arc fault detection. Furthermore, since the WT preserves the time-domain localization information, the precise time of the arc is available for cross-correlation with other system events to improve the confidence of arc fault detection rather than some other benign electrical event.

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