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DC series arc faults in PV systems. Detection methods and experimental characterization.

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***Abstract* – This work is focused on the arc faults phenomenon in DC photovoltaic (PV) systems. The paper gives an overview of arc detection methods proposed in literature and presents a preliminary experimental characterization of the arcing current, focusing the attention on series arcs, whose detection is particularly challenging. Experimental tests are carried out, both in laboratory and on field, in order to investigate some relevant characteristics in the arcing current, which can be feasible for the arc detection purpose. Both arcing and non-arcing current signals are acquired and compared in both time and frequency domain. On-field measurements are carried out on a real photovoltaic system, in accordance with the tests requirements of UL 1699B Standard for protection devices against arc faults.**

I. INTRODUCTION

The arcing fault is defined as an unintentional arcing condition in an circuit; if such condition persists, it may lead to fire ignition. In photovoltaic (PV) systems, such events are not uncommon, due to various reasons, such as damaged wires and connectors, worn electrical insulation, components aging, overheat or stress [1].

As for AC applications in dwelling units, arc-fault circuit interrupters (AFCIs) have been introduced also for PV systems, in order to protect them against fire risk due to arcing occurrence, by timely detecting arcing conditions and de-energizing the PV circuit [2]. Since 2011, the U.S. National Electrical Code (NEC) requires that all PV systems with dc circuits operating at 80 V or greater on a building must be protected by AFCIs [3]. The Standard UL 1699B was then introduced in 2012 and further updated on 2018 [4]. It covers requirements for DC PV arc fault circuit protection devices with rated voltage of 1500 V or less. These requirements cover devices including PV AFCIs, arc fault detectors (AFDs), interrupting devices and inverter, converters and charge controllers with integrated arc fault circuit protection.

The detection of arc faults poses several issues, because of the intrinsic random nature of the arc fault phenomenon; furthermore, the presence of several factors, such as PV system topology, health and operating conditions, inverter noise and distortion, can modify the arc signal profile and characteristics, thus the arc signal can be filtered, masked or attenuated and the arcing condition may go undetected or a normal operating condition can be mistaken for an arcing one. In such situations the AFCI may not trip even if an arc fault is present (trip failure), or it may trip, even when an arc is not present (unwanted trip). In this viewpoint, UL 1699B introduces specific tests for the risk analysis related to unwanted tripping and failure to trip.

In PV systems arc faults can be essentially classified in parallel arcs and series arcs [5]. Parallel arcs occur between two conductors or between a conductor and ground; typically, they are characterized by high levels of current. Series arcs occur because of a failure of the intended continuity of a conductor, connection, module or other PV system components; in this case the current amount is limited by the load of the PV system components themselves. Thus series arcs detection is more challenging than parallel arcs detection.

Several methodologies and solutions have been studied and patented for AC arc fault detection [6], and the research on DC arc faults is ongoing too, concerning both DC arc fault modeling and detection methods [7]-[14]; however a unique and complete solution, able to correctly operate in all working condition is not yet available.

In this paper an overview is given of the DC arc detection methods, focusing the attention on series arcs. An experimental characterization of the series arcs is also presented, with both laboratory and on-field tests, reproducing some arcing conditions, in accordance with the UL 1699B Standard requirements. The aim of the study is to carry out a preliminary analysis of the arcing current in the low frequency range [6], in order to highlight some relevant characteristics for the arc detection purpose, which can be easily measured without the need of sophisticated measurement instrumentation.

II. DC ARC FAULTS IN PV SYSTEMS

A. DC arcs characteristics

It is known that a typical AC arcing current is characterized by some distinctive features, such as “shoulders” (i.e. nearly flat zero-current segments in each half cycle, as current extinguishes before and reignites after the normal zero-crossing), high rates of rise and peaks, high-frequency broadband noise (from tens of kilohertz to about 1 GHz), non stationarity. Such characteristics can be more or less distinguishable, depending on load conditions; for example, in the presence of masking loads, normal current can be very similar to that of an arcing condition, thus arc detection can be more difficult [6].

In comparison with AC phenomenon, a DC arc do not have zero crossing segments, thus it can be more persistent. Broadband noise remains a prominent characteristic of a DC arc (up to about 1 MHz). Typically, due to the inductive behavior of cables, the noise level decreases as frequency increases. As already mentioned, DC arc characteristics can be affected by noisy conditions and disturbances due to the normal operation of the electric system [7]. Generally speaking, arc noise and variation depend on a lot of factors, such as electric circuit materials and topologies, voltage and current level, load and supply characteristics. Cables length can act as an antenna, introducing noise in the frequency band of hundreds of kilohertz. Crosstalk effects and power electronic components can introduce harmonics and high frequency noise. Current steps and variations due to load shifting, inverter power adjustment or environmental phenomena (fast moving clouds, wind vibrations, etc.) can determine current waveforms similar to arc faults.

The arc phenomenon is typically represented by the quasi-static V-I characteristics, whose plots are qualitatively represented in Fig. 1.

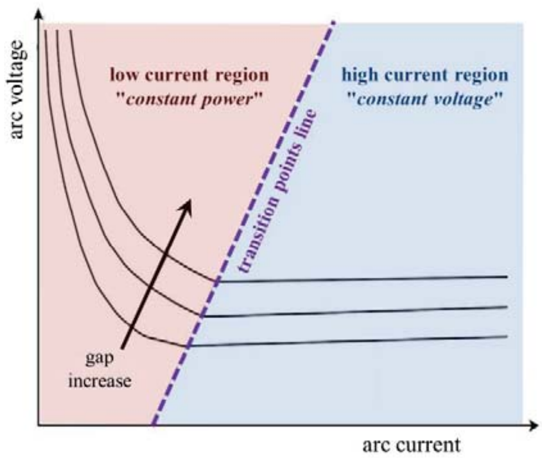

Fig. 1. Arc V-I characteristic

In Fig. 1 two regions are highlighted. In the low current one voltage and current are almost inversely proportional and the arc power is almost constant; on the other hand, in the high current region voltage tends to be almost constant. The transition points line represents the transition current values which delimit the two regions. The voltage needed to maintain an arc depends on current magnitude and gap width between electrodes; for a given arc current, the higher the gap width, the higher the voltage.

Some studies can be found in literature concerning the definition of realistic arc fault models, which have been introduced to develop and verify in simulation the arc fault detection methodologies [8]. They can be classified in physics-based models (based on physical principles), V-I empirical models (obtained from experimental measurements) and heuristic models (which include additional parameters in the model to better correlate simulation and experimental data). Some of them can be usefully applied for applications on PV arc faults. Even if such models can be useful for preliminary arc fault detection studies, they have some limitations due to implementation difficulties, validity ranges (in terms of arc type, current level or arc length), as well as for characterization of data acquisition and signal processing techniques, where real measurement issues should be taken into account (such as sampling requirements or computational burden, as well as accuracy features). Thus experimental studies are needed, in order to reproduce real arcing conditions, as well as to test real measurement and protection equipment (as required in [4]).

B. Detection methods

The need for arc fault protection in PV systems and the introduction of UL1699B have fostered the research on DC arc faults detection methods; some of them have been specifically developed for PV systems; other solutions have been proposed for different applications, such as DC microgrids or electric vehicles, but they can be adapted also for PV arcs recognition [9]-[14]. Generally speaking, most methods are based on current (and, less frequently, voltage) signal analysis; few other methods are based on the recognition of arcs physical properties, instead.

As regards current (or voltage) signal analysis in the frequency domain, one of the most addressed signal characteristic is the broadband noise and its analysis in specified frequency bands, typically from tens of kilohertz up to 100 kHz. Some proposed methods are based on Fast Fourier Transform (FFT). They allow evaluating amplitude and power of signal spectrum in the considered frequency bands and measured values are compared with given thresholds to discriminate between arcing or normal conditions. When thresholds are predetermined, some limitations arise with respect to method applicability in different operating conditions. To improve detection accuracy, some solutions have been developed based on adaptive thresholds, statistically determined from the analysis in subsequent observation windows. Such approaches can have problems when signal changes occur due to the normal operation of the system (for example start-up or power changes). Furthermore, some issues arise concerning sampling parameters choice, observation window, frequency resolution and reasonable computational burden and complexity. In fact, for the implementation of the aforesaid methods, required sampling frequencies and number of acquired samples are relatively high, if compared with the typical sampling and memory features of commercial platforms typically used for power systems measurements applications.

Some methods based on time domain and statistical analysis have been also proposed, which allows lower sampling frequencies and computational costs. In such methods features like magnitude, RMS or peak values of the current or voltage signal can be used for arc detection purpose. Signal rate of change or difference of maximum and minimum value are monitored and compared with given thresholds, in order to determine high and random variations, which are typical of the arcing conditions. Statistical analysis and proper estimators are used to evaluate the variance of the signal; outlier analysis has been also proposed to determine anomalies with respect to V-I characteristics which can be related to an arc fault occurrence. Main limitations of such approaches are related to threshold values used for distinguishing arcing from normal operating conditions; furthermore they can be strongly affected by noise and disturbances introduced be PV system equipment.

To increase the arc detection accuracy, some "multi-criteria" methods have been proposed, based on the simultaneous monitoring of both time and frequency domain characteristics (for example time domain fluctuations and specific frequency components spikes). Some solutions make use of Short Time Fourier Transform (STFT) analysis, where the trend is analyzed of the considered frequency components over time and increasing values and monitored to detect the fault. To decompose the signal into considered frequency bands with suitable resolution, some approaches have been based on Discrete Wavelet Transform (DWT) or Wavalet Packet Decomposition (WPD). Methods based on Artificial intelligence (AI) techniques have been also proposed, such as artificial neural network (ANN), support vector machine (SVM) or other machine learning techniques; they exploit large amount of data of the considered time and/or frequency domain features to train the system and identify the threshold value for discriminating arcing from normal conditions. For such methods, main problems are due to high computational burden, complexity and reliability.

Only few methods make use of signal analysis in low frequency range (up to few kilohertz or lower). This is mainly due to environmental or PV power electronics noises, which may be similar to low frequency components arc signals, thus affecting detection methods based on such signatures. However, the possibility of exploiting low frequency analysis can allow solving the aforementioned problems related to the choice of sampling frequency and number of acquired samples, thus enabling the use of commercial acquisition and signal processing systems. In this viewpoint, the experimental study herein presented, has been aimed at investigating the suitability of using low frequency harmonic current analysis for arc detection purposes [6], even considering real case noisy situations. As for the AC case, another critical aspect can be the need of sophisticated relatively expensive signal processing systems and high processing speed requirements; this is particularly true for multi-criteria solutions, where the analysis of more than one arcing characteristics should be performed in reasonable short time. In this framework, the choice of sampling frequency and number of acquired samples is crucial to obtain a good tradeoff between spectral resolution and the observation window. In fact, typical processing algorithms for frequency-domain analysis (such as FFT) are known to require the signal stationarity in the observation window. On the other hand, arc signal, in both AC and DC systems, is typically non stationary, thus the observation window should be as small as possible, in order to maintain valid the condition of stationary signal. This can cause a poor spectral resolution. Thus, the algorithm used for the frequency analysis should be able to ensure a good spectral resolution even with very short observation windows. Furthermore, when dealing with the measurement chain, attention should be paid to the measurement transducers, whose behavior can be critical when high frequency components must be acquired and processed. The possibility to use low frequency analysis can allow to better face all the aforesaid problems.

III. EXPERIMENTAL TESTS AND RESULTS

Experimental tests were carried out both in laboratory and on-field on a real PV power plant. The test bench for the on-field tests is schematized in Fig. 2. The arc generator (see Fig. 3) was build according to [4] and it was connected between the PV field and the inverter. During the tests the arc generator was inserted or short-circuited, in order to reproduce both arcing and normal conditions. The same bench was used for preliminary laboratory tests, which were carried out by using a DC power supply and resistive loads.

The measurement set-up was similar to that of [6]. Voltage and current were sensed by means of a hall-effect transducer Tektronix P5200 and a current shunt Fluke A40B, respectively. Signals were acquired by means of a data acquisition board NI USB 9239 (4 analog input channels, simultaneous sampling mode, maximum sampling frequency f_{s_max} = 50 kS/s, ADC Delta-Sigma with analog prefiltering, alias-free bandwidth 0.453 f_s, 24 bits resolution, input range ± 10 V). For the experimental tests herein presented, the sampling frequency value was f_s = 10 kS/s. The processing stage was implemented on a personal computer (PC) in LabVIEW environment. A virtual instrument was programmed in order to perform both time-domain and frequency domain analyses of the acquired current and voltage waveforms.

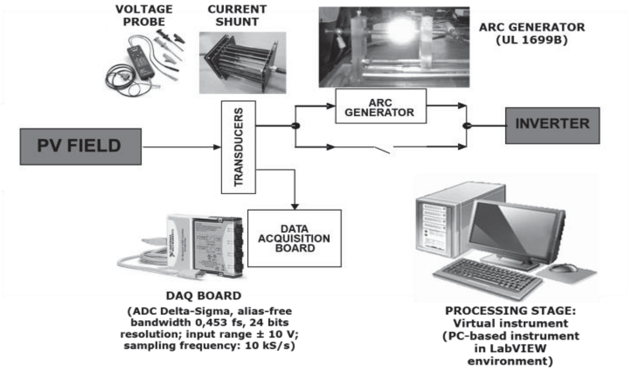

Fig. 2. Scheme of the test bench

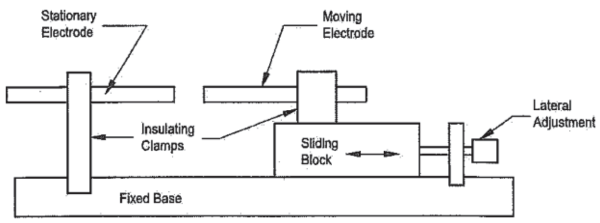

Fig. 3. Arc generator [4]

As an example, Fig. 4 reports the current waveform for one of the laboratory tests (test with 500 W load). Fig. 5-6 and 7-8 report two current waveform portions and their frequency spectra, in the absence and in the presence of arc, respectively. Similarly, Fig. 9, 10-11 and 12-13 show the current waveform acquired during one of the on-field tests on the PV plant, and the two current waveform portions and their frequency spectra, in arcing and non-arcing conditions, respectively. In both cases, by comparing arcing and normal portions of current and related spectra, typical arc characteristics are clearly distinguishable. In both tests arcing current is very non-stationary and noisy; peaks and high rates of change are clearly visible, current amount decreases. Frequency components show higher amplitudes in arcing conditions than in normal ones. In comparison with the laboratory tests, the on-field results show harmonics overlapped to the DC current, due to PV system operation; for example, non-arcing current shows a ripple at 100 Hz, i.e. twice the fundamental power line frequency of 50 Hz (because of the inverter switching). In all cases, the obtained results show that low frequency analysis can be suitable for detecting arc faults.

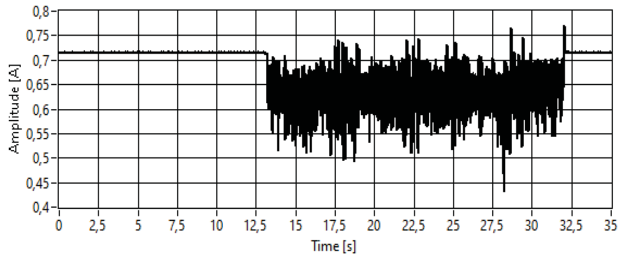

Fig. 4. Laboratory test. Current waveform.

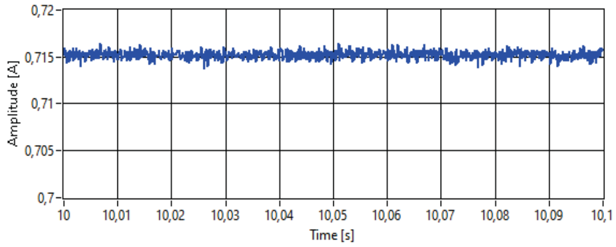

Fig. 5. Laboratory test. Non-arcing current portion

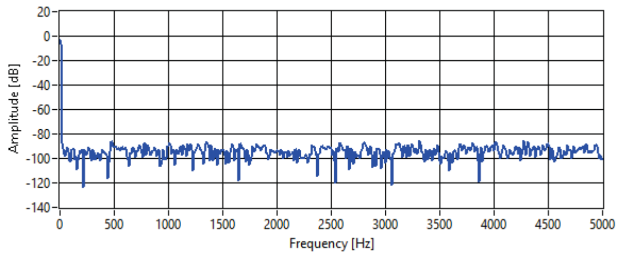

Fig. 6. Laboratory test. Frequency spectrum of non-arcing current portion

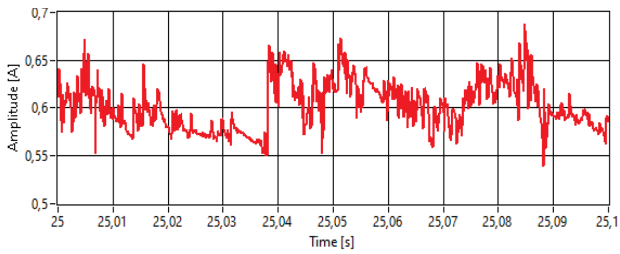

Fig. 7. Laboratory test. Arcing current portion

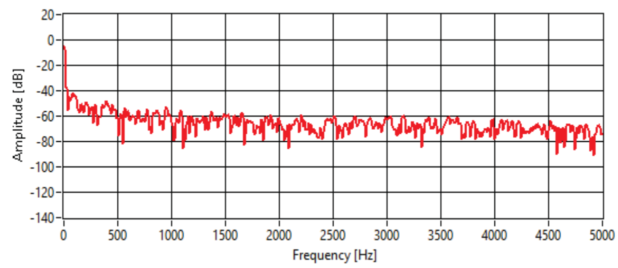

Fig. 8. Laboratory test. Frequency spectrum of arcing current portion

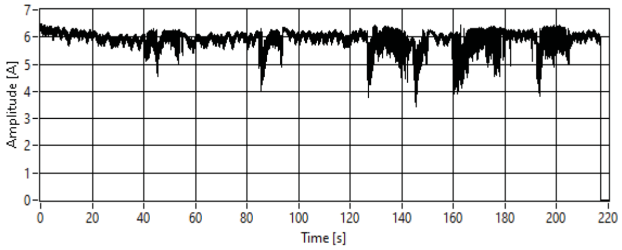

Fig. 9. On-field test on PV plant. Current waveform.

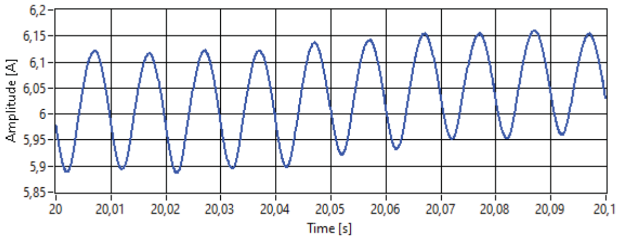

Fig. 10. On-field test on PV plant. Non-arcing current portion

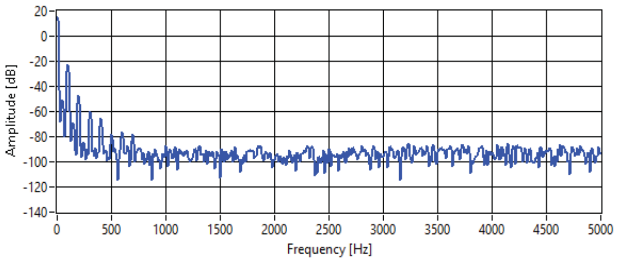

Fig. 11. On-field test on PV plant. Frequency spectrum of non-arcing current portion

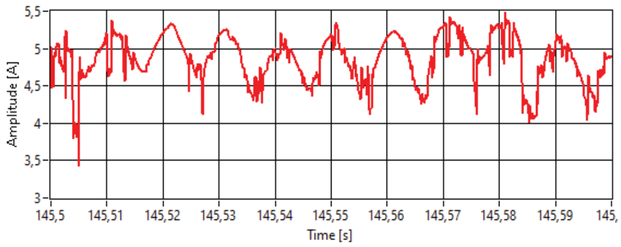

Fig. 12. On-field test on PV plant. Arcing current portion

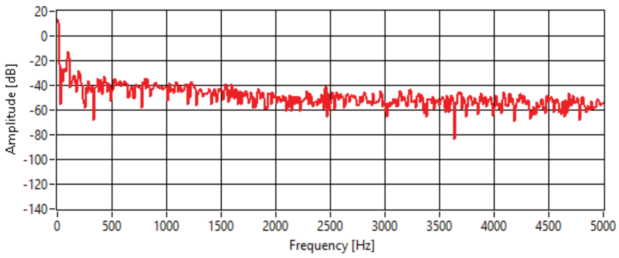

Fig. 13. On-field test on PV plant. Frequency spectrum of arcing current portion

IV. CONCLUSIONS

In this paper an analysis has been made on series arcs characterization and detection in DC PV systems. A survey on arc characteristics and detection methods has been presented, putting in evidence advantages and drawbacks of solutions proposed in literature. An experimental characterization of series DC arcs is also presented, reproducing arcing conditions, in accordance with the UL 1699B Standard requirements. Some laboratory tests and on-field measurements on a real PV plant are presented. The preliminary experimental results show that it is possible to suitably detect DC arc faults, by using low frequency harmonic current analysis. Relevant parameters can be measured by means of a low frequency spectral analysis, with proper resolution, reaching a good tradeoff between sampling parameters and computational burden. This can make feasible the use of low cost commercial platforms for power system measurements, with low sampling frequencies and limited computational and memory capabilities.

V. ACKNOWLEDGEMENTS

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REFERENCES

[1] K. Klement, “DC arc flash studied for solar photovoltaic systems: challenges and recommendations”, IEEE Transactions on Industry Applications, Vol. 51, pp. 4239–4244, 2015.

[2] K.M. Armijo, J. Johnson, R.K. Harrison, K.E. Thomas, M. Hibbs, A. Fresquez, “Quantifying photovoltaic fire danger reduction with arc-fault circuit interrupters”, Progress in Photovoltaics: Research and Applications, Vol. 24 No. 4, pp. 507-516, 2016.

[3] National Electrical Code, NFPA70, National Fire Protection Association, Quincy, MA.

[4] UL 1699B, Photovoltaic (PV) DC Arc-Fault Circuit Protection, Underwriters Laboratories Inc., 2018.

[5] J. Yuventi, “DC electric arc-flash hazard-risk evaluations for photovoltaic systems”, IEEE Transactions on Power Delivery, Vol. 29, pp. 161-167, 2014.

[6] G. Artale, A. Cataliotti, V. Cosentino, D. Di Cara, S. Nuccio, G. Tinè, “Arc Fault Detection Method Based on CZT Low-Frequency Harmonic Current Analysis”, IEEE Transactions on Instrumentation and Measurement, Vol. 66, No. 5, pp. 888-896, May 2017.

[7] R.F. Ammerman, T. Gammon, P.K. Sen, J.P. Nelson, “DC-Arc Models and Incident-Energy Calculations”, IEEE Transactions on Industry

Applications, Vol. 46, No. 5, pp. 1810-1819, 2010.
[8] S. Lu, B.T. Phung, D. Zhang, "A comprehensive review on DC arc faults and their diagnosis methods in photovoltaic systems", Renewable and Sustainable Energy Reviews, Vol. 89, pp. 88-98, 2018.
[9] M. Ahmadi, H. Samet, T.Ghanbari, "Series Arc Fault Detection in Photovoltaic Systems Based on Signal-to-Noise Ratio Characteristics Using Cross-Correlation Function", IEEE Transactions on Industrial Informatics, Vol. 16 No. 5, pp. 3198-3209, 2020.
[10] W. Fenz, S. Thumfart, R. Yatchak, H. Roitner, B. Hofer, "Detection of Arc Faults in PV Systems Using Compressed Sensing", IEEE Journal of Photovoltaics, Vol. 10 No. 2, pp. 676-684. 2020
[11] W. Miao, X. Liu, K.H. Lam, P.W.T. Pong, "Arc-Faults Detection in PV Systems by Measuring Pink Noise with Magnetic Sensors", IEEE Transactions on Magnetics, Vol. 55, No. 7, art. no. 8693915, 2019.
[12] S. Liu, L. Dong, X. Liao, X. Cao, X. Wang, B. Wang, "Application of the Variational Mode Decomposition-Based Time and Time-Frequency Domain Analysis on Series DC Arc Fault Detection of Photovoltaic Arrays", IEEE Access, Vol 7, pp. 126177-126190, 2019
[13] S. Lu, T. Sirojan, B.T. Phung, D. Zhang, E. Ambikairajah, "DA-DCGAN: An Effective Methodology for DC Series Arc Fault Diagnosis in Photovoltaic Systems", IEEE Access, Vol. 7, art. no. 6287639, pp. 45831-45840, 2019.
[14] Z. Wang, R.S. Balog, "Arc Fault and Flash Signal Analysis in DC Distribution Systems Using Wavelet Transformation", IEEE Transactions on Smart Grid, Vol. 6 No. 4, pp. 1955-1963, 2015.