Detection of DC Arcing Faults in Photovoltaic Systems

Robert Wilkins
Consultant, UK
boboverdee@gmail.com

Jean-Francois de Palma
Mersen, France
jean-francois.depalma@mersen.com

***Abstract*--The most difficult case for arc detection in PV systems is for a series arc. The most commonly-proposed solutions are based on the broadband noise generated, but it is difficult to ensure immunity from other sources such as local r.f. noise and the associated PV inverter. In this paper the possibility of arc detection by looking for evidence of chaos in the circuit current is reviewed.**

***Keywords*--PV systems. Arc detection. Chaos.**

I. Introduction

Fig.1 shows a simple photovoltaic system for power generation. PV modules are connected in series and parallel, generating DC power which is then fed into an AC power system by an inverter. In the past decade there has been increasing concern at the number of rooftop fires caused by DC arcing faults following the failure of system components such as cables and connectors [1].

One of the key issues in providing protection against the effects of arcing faults is their detection. In the case of a parallel fault such as P in Fig.1 detection is relatively easy, as the fault current is fairly high for a short time, due to the discharge of capacitors on the DC side of the inverter. However a series arcing fault such as S introduces additional resistance into the DC loop, and the arcing current is lower than the normal load current, making detection very difficult.

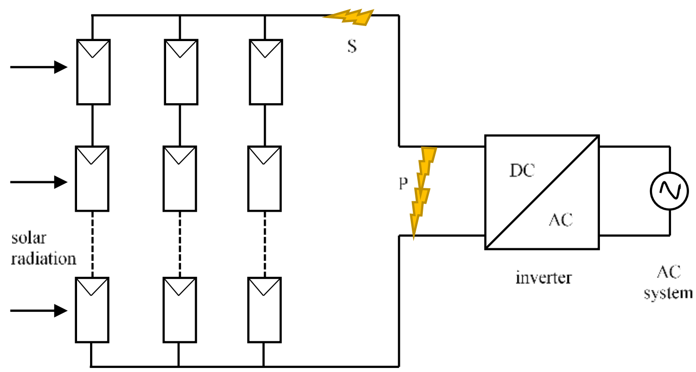

Fig.1 Typical PV system

Sustained DC arcs are possible in DC systems with voltages above about 15V (the sum of the anode- and cathode-fall voltages) and currents above about 2A. The voltage gradient in the arc column is of the order of 5 V/mm, and this falls slightly as current increases, for the range of values found in PV systems.

Fig.2 shows typical waveforms for arc current and arc voltage for a DC arc drawn between two electrodes in a PV system [2]. In this example, the gap between the electrodes is increasing, and as it does so, the arc voltage increases and the current falls. However, although this is nominally a DC system, there are considerable fluctuations in the circuit current and arc voltage. Note that the "noise" in the circuit current is greater during arcing than before the arc was drawn. The challenge for a DC arcing detector is to be able to recognize the difference between these two conditions.

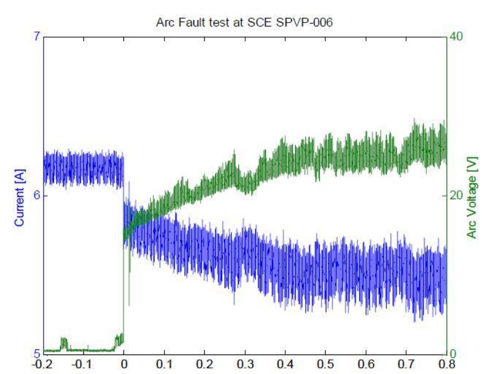

Fig.2 Arc voltage and current

II. Detection based on broadband noise

Fuses cannot deal with series arcing faults because of the low fault current. Most arc detection methods have been based on measurement of the broadband noise generated in the circuit current by waveforms such as shown in Fig.2. Dini *et al* [3] give a detailed account of how the UL standards for arc-fault circuit interrupters were developed. Testing of detectors is done using the UL "arc generator", which is used to produce a DC arc intended to be representative of a series arc in a PV installation. Two 6mm copper rods are used as electrodes, with an adjustable gap, enclosed in a clear plastic tube. Before switching on, some fine steel wool is placed in the gap. After switching on, the steel wool burns off quickly and triggers an arc across the gap.

Fig.3 shows frequency spectra measured by Dini *et al* using the UL arc generator, for frequencies up to 20kHz. The signal amplitudes decrease by almost exactly one decade for each decade in frequency, confirming that the arcing has the characteristic of "pink" noise, for which the amplitude falls as (1/*f*).

The UL documents specify the required performance for an Arc Fault Circuit Interrupter, and the National Electrical Code contains a requirement that PV systems with a DC voltage of 80V or higher, on or penetrating a building, must have a listed Arc-Fault Circuit Interrupter (or components to give equivalent arc-fault protection). However it is not clear whether any product is yet available which fully meets these standards.

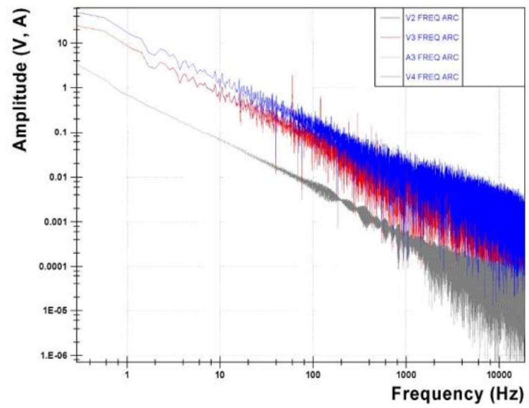

Fig.3 Spectra published by Dini *et al*

Most of the published work on the detection of low-current DC arcs is based on the higher level of broadband noise which is found in the circuit current when an arc is present. The system used most commonly is to convert the current signal to digital form using an A/D converter, then to use an FFT algorithm to give the frequency response, which is then filtered and processed digitally in some way. Some systems use analog filtering before digital processing. Usually a bandpass filter is used to select the range of frequencies to be processed. Fig.3 shows that for frequencies higher than 10kHz there is a very wide spread in amplitude, which makes it difficult to distinguish between the arcing state and the normal state. Furthermore the signal amplitudes are very low, which adds to the difficulty. Johnson [4] gave a summary of the key issues and highlighted two key challenges for the detection of DC arcing in PV systems.

(a) Missed or delayed detection due to filtering in PV components (e.g., modules, connectors, bypass diodes)

(b) Nuisance tripping due to noise from electromagnetic coupling (crosstalk), inverter switching, and radio frequency (RF) effects

An early system was described by Boksiner and Silverman [5] in 1994, who were concerned with detecting DC arcing in telecommunication systems. They proposed to measure the noise in the frequency band between 4Hz and 5kHz. If this was higher than a certain threshold (set above the background noise level), then an arc was assumed to be the cause.

Boico and Obenhauser [6] used a frequency band of 40kHz to 100kHz in order to be free of interference from the inverter. This (long-wave) frequency band is used by certain services (such as maritime navigation) and a physically large PV array is a very effective antenna to pick up these unwanted signals. It was also noted that harmonics of the inverter switching frequency are still found in the 40-100kHz range.

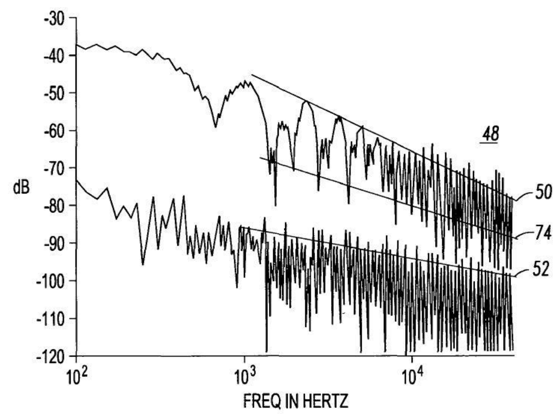

Fig.4 Current spectra, with and without arcing

The patent by Hastings *et al* [7] gives the examples of current spectra shown in Fig.4. The upper spectrum was obtained with arcing present, and the lower spectrum without an arc. The gap between the two decreases as the frequency increases, and they begin to overlap at the right hand side of the plot. The concept used to detect arcing without nuisance tripping is as follows. Three frequencies, such as 1kHz, 4kHz and 10kHz are selected, and the amplitudes of the current in a narrow band around each of these frequencies is calculated. If all three amplitudes exceed a threshold for a certain time (typically 30ms), an arc is assumed, and a trip signal generated. The patent also mentions the possibility of selecting the three frequencies for a specific inverter so that they coincide with valleys in the inverter input current spectrum. Solar inverter switching frequencies range from 8kHz (large inverter) to 20kHz (small inverter), and these frequencies and their odd harmonics will be present in the input current.

III. DC Arc Fault Detection Methods (Chaos Based)

Mathematical chaos can be produced in a physical system which is non-linear or turbulent. The electric arc meets these criteria. The arc roots at the cathode and anode move around, and electrode material is injected into the arc column in various forms. The arc column moves due to thermal convection, and in a real PV system an arc will probably move more than it does in the confined space of the UL arc generator. All these effects give rise to fluctuations in the arc voltage, which are then reflected in the circuit current. These fluctuations are not "noise", they are the **real behaviour of the system**.

Systems which behave chaotically can display fractals, geometric shapes that are self-similar, with portions which are endless repetitions. Parker [8] dealing with the problem of DC arc detection in aircraft systems pointed out that variations in current during arcing are not random, like Gaussian noise, they are chaotic. He stated that the frequency spectrum of the current of a DC arc exhibits fractal properties, logarithmically distributed across the spectrum, indicating the presence of chaos. He also states that the fractal subsets in the spectrum of a DC arc occupy less than one decade in frequency, so that sampling over this reduced frequency range is representative of the whole. Although Parker did not publish actual spectra to support this, self-similar fractal shapes can be clearly seen in the spectrum Fig.4, and the pattern repeats in less than one decade of frequency. Close examination of Fig.3 reveals similar behaviour. For the practical implementation, Parker used the concept of chaos only to choose a limited frequency band which includes one fractal subset, rather than broadband. His preferred range was very low, 3Hz to 3KHz. He claimed that the advantage of using a low frequency is that signal is much higher at these low frequencies, and therefore can be more reliably detected

Schimpf and Norum [9] developed a DC arc detector for PV systems, based on the detection of chaos, following Parker's work. A bandpass filter with a range from 1kHz to 7.5kHz was used, which should include a fractal subset, according to Parker. They then simply calculated the *variance* of the data, on the basis that the variance increases significantly when arcing in present and an arc was indicated if a certain threshold was exceeded. This system worked well in laboratory tests but some difficulties were reported with tests on a PV array.

However there are other (and better) ways of detecting chaos in experimental data. For example the "0-1" method was described in 2004 by Gottwald and Melbourne [10]. This algorithm accepts data as a time series and outputs 0 if the system is non-chaotic and 1 if it is chaotic. The "0-1" algorithm has been proved to be very successful. For the DC arcing fault the input data could be the time interval between successive events like pulses in the current.

IV. Conclusions

Whether broadband noise, chaos, or any other method is used the first decision to be made is the range of frequencies to be examined, after analog or digital filtering. Almost all of the spectral power during arcing is contained below 10kHz. At 10kHz the signal amplitude is roughly 0.01% of the DC value. For higher frequencies the signal is very small and highly attenuated, so that the distance at which arcs can be detected is reduced. Schimpf and Norum state that " *...the arc-detector has to be tuned to rather low frequencies. It does not make sense to try to detect an arc in the HF-range*".

There is striking evidence of the existence of fractal self-similarity in published frequency spectra. Chaos based detectors are rooted in the physical nature of arcing, rather than just regarding the arc as a source of noise. This is a promising concept but the amount of work done on this is very small compared with that put into broadband noise detectors. Whether a chaos based detector would work reliably in the presence of inverter noise remains to be seen. A chaos based detector may have to have a method incorporated for dealing with inverter noise, in the same way as is done for broadband noise systems.

For further work, it is recommended that:

- For the best chance of reliable arc detection, sampling of the circuit current should be restricted by a bandpass filter to the low frequency range from a few Hz up to 10kHz (or even lower). An upper frequency which is below the inverter switching frequency is an attractive idea.
- For detection of chaos in the system the 0-1 method and other methods should be investigated.
- Whatever detection algorithm is used methods for suppressing or otherwise dealing with inverter noise will need to be addressed.
- Measured transient waveforms need to be made public so that researchers can investigate the efficiency of different algorithms.
- Details of experimental conditions, such as instrumentation and measurement techniques, time window and sampling rates should be given when reporting results.

V. References

The following key publications are referred to in the text of this article

[1] W. Vaassen, J. Zornikau, "Failure Mechanisms of Contact Faults in the DC Circuit of the PV Arrays", *presentation at Int. Workshop "Arcing in Photovoltaic DC-Arrays - Potential Dangers and Possible Solutions"*, Burgdorf, Switzerland, Oct. 2007. Available at: *http://labs.hti.bfh.ch/index.php?id=2161*

[2] C. Luebke *et al* (Eaton Corporation and Southern California Edison). "Field test results of dc arc fault detection on residential and utility scale PV arrays", *37th IEEE Photovoltaic Specialists Conference, Seattle, June 19-24, 2011* (with poster)

[3] D. A. Dini *et al*, (Underwriters Laboratories Inc), "Development of arc-fault circuit-interrupter requirements for photovoltaic systems", *37th IEEE Photovoltaic Specialists Conference, Seattle, June 19-24, 2011* (with poster).

[4] J. Johnson, "Overview of Arc-Faults and Detection Challenges", *PowerPoint presentation, Sandia Labs, Feb 8, 2011*.

[5] J. Boksiner and E. J. Silverman, "Electrical Cable Arcing Fault Detection by Monitoring Power Spectrum in Distribution Line". US Patent 5,359,293. 1994.

[6] F. Boico and C. Obenhauser, SolarMagic SM73201 DC Arc Detection Evaluation Board. National Semiconductor Application Note 2154, June 6, 2011.

[7] J. K. Hastings *et al* (Eaton Corp), " Direct Current Arc Fault Circuit Interrupter", World Patent WO 2011/073772 A2, 23 June, 2011

[8] M.T. Parker *et al* , "Electric Arc Monitoring Systems", U.S. Patent 6,772,077 B1, Aug. 16, 2004.

[9] F. Schimpf and L.E. Norum (Norwegian University of Science and Technology, Trondheim). "Recognition of Electric Arcing in the DC-wiring of Photovoltaic Systems", *Telecommunications Energy Conference, 2009. INTELEC 2009.*

[10] G. Gottwald and I. Melbourne, "A New Test for Chaos in Deterministic Systems". *Proc. R. Soc. Lond. A*, 8, February 2004 vol. 460 no. 2042 pp 603-611.

The following publications are not referred to in the main text but are relevant, and listed here for further study

[11] P. Kremer, "Arcing Potential in Fuses: Missing Standards for Adequate Testing of Fuses in PV Applications", presentation at *Int. Workshop "Arcing in Photovoltaic DC-Arrays - Potential Dangers and Possible Solutions"*, Burgdorf, Switzerland, Oct. 2007. Available at: *http://labs.hti.bfh.ch/index.php?id=2161*

[12] Liang Ji, (Underwriters Laboratories Inc), "PV Fire: Experience and Studies", *International Photovoltaic Reliability Workshop II*, July 31, 2009

[13] M. Dargatz, "DC Arc Faults and PV System Safety". *www.renewableenergyworld.com/article/2009/12*

[14] J. K. Hastings *et al*. "A study of ignition time for materials exposed to dc arcing in PV systems", *37th IEEE Photovoltaic Specialists Conference*, Seattle, June 19-24, 2011

[15] T. Zgonena, "PV Arc Fault Protection", PowerPoint PPT presentation, Underwriters Laboratories Inc, February 8, 2011.

[16] Subject 1699B - Outline of investigation For Photovoltaic (PV) DC arc-fault circuit protection, Issue number 1, (with covering letter), Underwriters Laboratories Inc, April 29, 2011

[17] Eaton Corporation "Code Breaker, 2011 NEC - Photovoltaic DC AFCI", Publication PA0832-4008E, Sept 2010.

[18] J. Brooks and G Scott, "Arc-fault Circuit Interrupters for Aerospace Applications", SAE 1999. (400Hz AC only)

[19] R. Pappas (Federal Aviation Administration) and C. Singer (Naval Air Systems Command), "Arc Fault Circuit Breaker Development and Implementation " project report, 25 October, 2001.

[20] J. Luis, "Detection of Electric Arcs in 42V Automotive Systems", Masters Thesis, Massachussetts Institute of Technology, 2003.

[21] M. D. Mishrikey, "Detection of Arcs in Automotive Electrics Systems", Masters Thesis, Massachussetts Institute of Technology, 2005.

[22] S.Y. Guo, J.L. Jones and A.S. Dooley, "DC Arc Detection and Prevention Circuit and Method", U.S. Patent 6,683,766 B1, Jan. 27, 2004.

[23] J.C. Zuercher *et al*. (Eaton Corp), "Detection of arcing in DC electrical systems" US Patent 027749 A1, Feb 12, 2004.

[24] M. Naidu *et al*. "Arc Fault Detection Schemes for an Automotive 42V Wire Harness". *SAE World Congress*, April 11-14, 2005

[25] Dortmund Hochschule, "Method and device for detecting a broad-band noise source in a distribution network", World Patent WO 2005/060063 A1, 2005

[26] H. Haberlin and M. Real, "Arc Detector for Remote Detection of Dangerous Arcs on the DC Side of PV Plants", *presented at the 22nd European Photovoltaic Solar Energy Conference*, Milano, Italy, Sept 2007. (presentation with the same title at *Int. Workshop "Arcing in Photovoltaic DC-Arrays - Potential Dangers and Possible Solutions*", Burgdorf, Switzerland, Oct. 2007).

[27] M. Dargatz *et al*. "Method and Apparatus for Detection and Control of DC Arc Faults", U.S. Patent 2011/0019444, Jan 27, 2011.

[28] C. Strobl and P Meckler, "Arc Faults in Photovoltaic Systems." *Proc 56th IEEE Holm Conference on Electric Contacts*. Charleston, SC, 2010.

[29] C. Goeltner and M. Sclocchi, "SolarMagic: Distributed Electronics and Safety Solutions for PV Systems". National Semiconductor Corporation, PowerPoint presentation, April 13, 2011

[30] National Semiconductor (UK) Ltd. "Chipset detects hazardous DC arc faults in PV systems", 10 June 2011.

[31] M.T. Parker (Hendry Telephone Products), "Arc Detection, Arc Fault Interruption", presentation, April 12, 2000.

[32] H.A. Koroji *et al* (Honeywell). "Method and Apparatus for Generalized Arc Fault Detection". U.S. Patent 7391218 B2, June 24, 2008.

[33] F. Schimpf and L.E. Norum (Norwegian University of Science and Technology, Trondheim). " Possibilities for Prevention of Electrical Arcing in PV-Systems ", *24th European Photovoltaic Solar Energy Conference*, 21-25 September 2009, Hamburg, Germany.