PV FAULTS: OVERVIEW, MODELING, PREVENTION AND DETECTION TECHNIQUES

Mohammed Khorshed Alam and Faisal H. Khan
Power Engineering and Automation Research Lab (PEARL)
Dept. of Electrical and Computer Engineering,
University of Utah, Salt Lake City, Utah, USA
Email: khorshed.alam@utah.edu

Jay Johnson and Jack Flicker
Sandia National Laboratories, Albuquerque, NM, USA

Abstract— **Recent PV faults and subsequent fire-hazards on April 5, 2009, in Bakersfield, California, and April 16, 2011, in Mount Holly, North Carolina provide evidence of a lack of knowledge among PV system manufacturers and installers about different PV faults. The conducted survey within the scope of this paper describes various faults in a PV plant, and explains the limitations of existing detection and suppression techniques. Different fault detection techniques proposed in literatures have been discussed and it was concluded that there is no universal fault detection technique that can detect and classify all faults in a PV system. Moreover, this digest proposes a transmission line model for PV panels that can be useful for interpreting faults in PV using different refelectomery methods.**

I. INTRODUCTION

A PV system converts the solar energy into electrical energy, and this energy is either stored in a battery bank in a standalone system or transmitted to the grid through grid interfacing power electronic converters. PV fault protection/detection and isolation devices of multiple kinds are installed in a PV station to isolate the PV converters/grid from the PV array during any fault in the PV system. Although, the rest of the power processing or storage units are isolated from the faulty PV array, the solar cells remain active and may produce significant current flow within the modules that may result in damages even catastrophic fire.

In some cases PV faults may remain undetected and result in more severe damages. Although the milestone of 100GW PV installation capacity throughout the world was achieved in 2012, any PV installation is susceptible to faults, and these faults may remain undetected. Most of the PV related published articles are based on improved cell level efficiency, electrical circuit modeling, maximum power point tracking (MPPT), panel architecture, circuit level optimization, and there have been comparatively few articles based on different faults in PV systems. This article will investigate different faults in PV systems including ground fault and other line-to-line faults, arc (open) faults, bypass diode failure, hot spot formation, and explore different prevention and detection techniques.

II. GROUND FAULTS

The exposed non-current carrying metals/conducting parts of PV systems are connected through a conducting wire to the ground (a reference – earth in most cases) as required

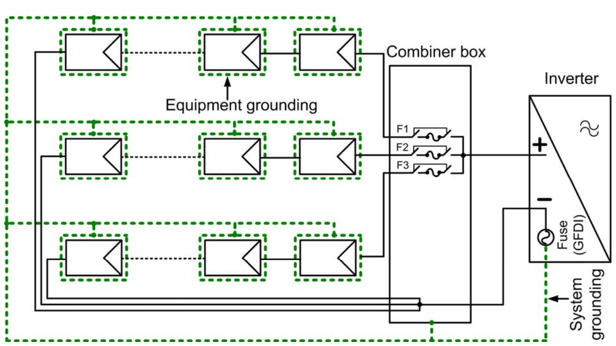

Figure 1. Schematic diagram of a typical PV system with both equipment and system groundings.

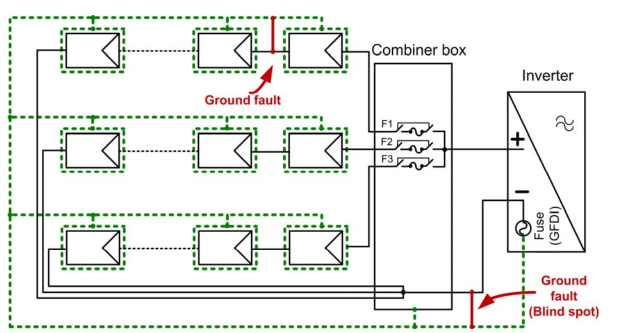

Figure 2. Example of PV ground faults. One of the ground faults represents a blind spot in traditional PV system ground fault detection systems (e.g., GFDI fuses).

978-1-4673-4916-1/13/$31.00 ©2013 IEEE

by the National Electrical Code 690.43, and this grounding is referred as equipment grounding. A PV system has system grounding if one of the current carrying conductors (CCCs) is functionally connected to ground. Depending on whether a PV panel has system grounding, there exist two types of PV systems: grounded and ungrounded. Schematic diagram of a typical grounded PV system is shown in Figure 1, and the schematic of an ungrounded PV system will be similar to the grounded PV system with the exception of containing the system grounding that is accomplished by the fuse (GFDI) [11]-[18].

A ground fault establishes an unintentional low impedance path between one of the CCCs and the ground. Ground faults in a PV system may occur in several ways, and two possible ground-faults are depicted in Figure 2. Most of the grounded PV systems are system-grounded using a ground-fault detection and interruption (GFDI) device to detect ground faults and interrupt the fault current. GFDI is a fuse with less than 5A rating (according to UL 1741) or a residual current circuit breaker (RCCB), and these GFDI devices either melt or open the current path whenever the fault current amplitude is higher than a threshold limit and sustains longer than a predefined minimum time duration.

A. Blind spot:

GFDI devices in general trip based on the magnitude of fault current. Therefore, if there is a fault in a PV system with fault current below the trip threshold, it becomes undetectable. This gap in traditional, fuse-based ground fault protection is known as the blind spot [11]-[15]. An example of blind spot is shown in Figure 2. A blind spot ground fault is dangerous since it establishes a bypass current path for the GFDI devices, and any further ground fault will remain undetected for indefinite period unless otherwise interrupted. It should be noted that blind spot does not exist in an ungrounded PV system.

B. Double ground fault:

A double ground fault occurs if there is another ground fault established followed by a blind spot or there are two consecutive ground faults as depicted in *Figure 2.* Recent PV fires on April 5, 2009, in Bakersfield, California, and April 16, 2011, in Mount Holly, North Carolina are claimed to be caused due to double-ground fault. Therefore, it is extremely important to detect the blind spots before a second ground fault occurs. Moreover, two ground faults may occur within a short period of time at low irradiance and stay undetected. This double ground fault may remain undetected during the daytime as well and may damage or burn the entire system.

C. Effect of maximum Power Point Tracking (MPPT):

The effect of MPPT on fault current has been discussed in detail in [10] [16] [48]. The MPP tracker reduces the amplitude of the fault current if undetected by GFDI, and this reduction in fault current poses a challenge to the GFDI devices to detect and isolate the PV array. Sometimes, a ground fault occurs at low irradiance, and the fault current is below the threshold current level of GFDI device. Therefore, there is a need for smarter GFDI devices that can detect and/or locate the ground faults irrespective of the fault current amplitude.

D. General PV ground fault detection techniques and limitations:

Most of the ground fault prevention devices are based on passive fuses, periodic isolation resistance measurements, or differential current measurement methods and these GFDI devices suffer from the following limitations:

1) A ground-fault may occur in the absence of the solar irradiation (i.e., during night) and remain undetected.

2) Ground-fault current may be smaller than the GFDI threshold current limit and remain undetected.

3) If more than one ground fault occurs during the absence of sunlight, both of the faults will remain undetected by the GFDI device. Moreover, the GFDI device will not be able to de-energize the fault in presence of a double ground fault.

4) Differential current measurements (DCM) may suffer from external noise and may result in nuisance shutdown of the system. Nuisance tripping of fuses may occur with large leakage currents as well.

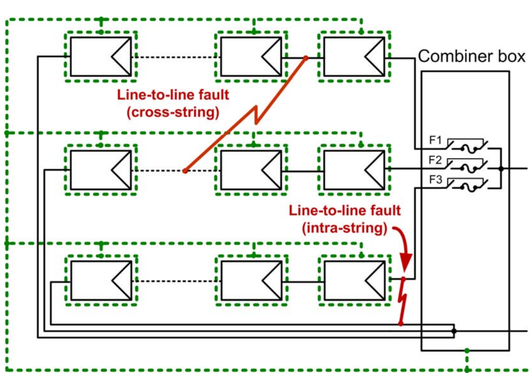

Figure 3. Example of PV line-to-line faults.

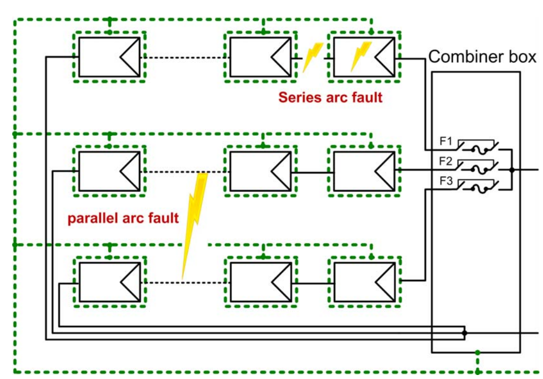

Figure 4. Example of series and parallel arc-fault in a PV array

III. LINE-TO-LINE FAULTS

A line-to-line fault in a PV system is defined as an unintentional connection between two points in a PV panel through a low resistance path [10]. However, if one of the points is on the Equipment Grounding Conductor (EGC), the line-to-line fault is considered as a ground fault as discussed earlier. A line-to-line fault may occur between two points on the same string or between two adjacent strings as shown in Figure 3, and the magnitude of the line-to-line fault current depends on the potential difference between the points before the fault occurs. The higher the potential difference the higher the back feed current results, and the chance of tripping the over current protection devices (OCPDs) increases [2][10].

If the current flow through one of the CCCs due to the line-to-line fault is less than the rated current of the OCPDs which is no less than 1.56 times of the short circuit current of the array according to the US NEC requirement, the line-to-line fault may remain undetected and poses significant loss of the efficiency in the system [48] [50].

IV. ARC (OPEN) FAULTS

Arc fault establishes a current path in the air, and this current path might be established due to any discontinuity in the current carrying conductors or insulation breakdown in adjacent current carrying conductors. Any type of arc fault is harmful for the PV system, and may introduce fire that may result in insulation burn-out and fire hazards in presence of any flammable substances in the vicinity of the PV plant [2]-[7]. National Electrical Code® (NEC)-2011 requires a series arc-fault protection device in a PV system if the DC operating voltage is equal to or higher than 80V. These devices are called as arc-fault circuit interrupters (AFCIs) [8] [9]. In general, both GFDI and AFCI devices are installed inside the inverter of the PV system, and there is a display in the front panel of the inverter to read out the type of fault occurred.

Any arc generated due to any discontinuity in CCCs mostly resulting from solder disjoint, cell damage, corrosion of connectors, rodent damage, abrasion from different sources, etc. is called a series arc-fault, and any arc fault between two adjacent conductors at different potentials is termed as parallel arc fault. Both the series and parallel arc-faults are illustrated in Figure 4. Most of the AFCI devices are designed to interrupt the operation of the PV system whenever there is a series arc fault, and these AFCIs may not be able to respond properly in presence of parallel arc fault.

Both series and parallel arc-faults introduce high frequency noise in the DC current of the PV string, and a parallel arc fault results in additional sudden voltage/current drop inside the PV array. Therefore, series and parallel arc faults can be distinguished from each other by observing the sudden voltage/current drop associated with increased noise in the DC current. All series arc faults can be extinguished by disconnecting the PV array from the inverter by opening one of the terminals of each PV strings. However, some parallel arc faults require module-level disconnects or short circuiting the PV string or module terminals after disconnecting from the inverter to de-energize the arc.

V. OTHER FAULTS

A significant number of bypass diode failures have been reported in past, and thereby, bypass diodes are considered to be one of the main concerns for the safe operation of PV modules [43] [44]. Long-term power dissipation in the bypass diode due to any mismatch or partial shading increases the operating temperature of the bypass diode, junction box and the PV cells adjacent to the junction box, and these phenomena could lead to failure of the bypass diode, hotspot formation, insulation damage of the cables/junction box, damaged encapsulation of the module and burn-out of solar cells [45].

Localized heating or a hot-spot may be formed in a photovoltaic module due to cell failure, solder disjoint or interconnection failure, partial shading, and mismatch in parallel connected strings [46]. Hot-spot may appear in the cells or in high resistive solder bonds (RSB) that interconnect cells and contact ribbons, and the impact of the hot-spot in PV modules is significant since it may reduce the output power generated by the group of cells under the same bypass diode to zero [47]. Therefore, PV modules need to be inspected frequently, and modules with significant number of hot-spots should be replaced in order to ensure longer lifetime and efficient operation of the system.

Besides the previously discussed faults, PV plants suffer from other different types of minor faults: ice/sand/soil formation, broken glass, partial shading, and corrosion of wire, terminals, and cell metal, etc. [40].

VI. DIFFERENT FAULT DETECTION TECHNIQUES FOR PV SYSTEMS

Different methods have been proposed in literature to find and locate different types of faults in PV systems, and most of the techniques utilize different on-site measurement data such as: operating voltage and current, MPP, temperature, irradiance, power loss, fill factor, etc. [19]-[23]. An artificial neural network (ANN) based algorithm has been proposed that uses the temperature, MPP voltage and current of the PV modules as inputs to determine one of the four conditions of the PV panel: normal, degraded, short-circuit fault, and shaded [19]. A decision tree-based algorithm has been reported in [21] to find different faults in a PV module, and this method requires sufficient previous data under normal and faulty condition in order to train the algorithm. However, the algorithm provided a very high accuracy to find different fault depending on the size of the tree and number of leaves used in the algorithm.

In [22], a method based on mutually comparing the currents of each string to locate an abnormally operated string has been proposed, and this method can decide an abnormality based on the ratio of different string currents. Infrared (IR) thermograph based solar cell's health monitoring was presented in [23] and it was shown that IR thermograph can locate hot spots. More advance approaches were presented in [27]-[28], where Light Beam Induced Current/Voltage (LBIC/LBIV), Photoluminescence (PL) and Electroluminescence (EL) based instruments and InSb thermal camera have been used for monitoring the quality of solar cells.

The effect of MPPT on different line-to-line faults has been investigated in [20][24][48], and it was shown that any fault occurred at low irradiance is more challenging to detect because there is less photo-induced current and therefore the electrical measurements are less informative and less accurate (e.g., closer to the noise floor of the instrumentation). A fault detection analysis based on comparing I-V curves of an operating PV array with the expected I-V curve has been described in [26]. PV fault detection was considered as a clustering problem, and a minimum covariance determinant (MCD) estimator based method was described in [25]. This method calculates both the probability of detection and probability of false alarm to determine the presence of faults, and successfully tested for PV series arc fault and ground fault using a 10 Ω resistor across a single module.

Several PV fault detection techniques based on the transmission line reflectometry theory have been presented in literature, and these methods can be used for detecting and locating faults in PV systems even in the absence of sunlight. A critical comparison among different reflectometry

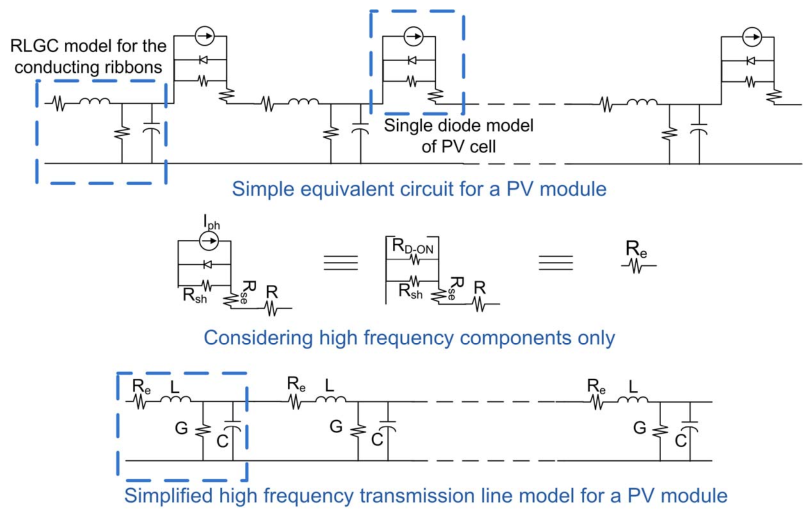

Figure 5. A simplified high frequency transmission line model for a PV module.

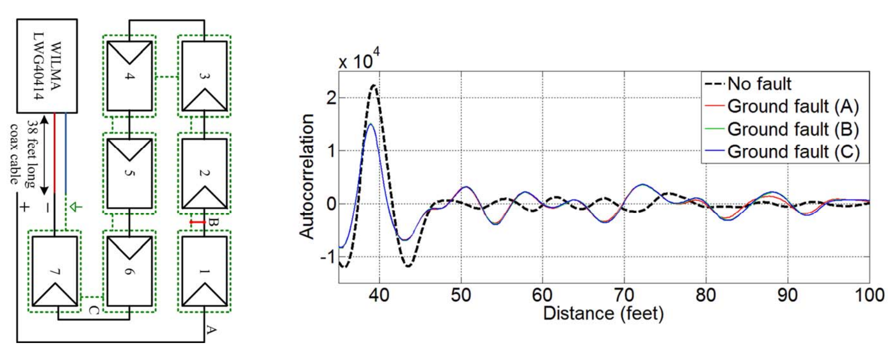

Figure 6. Experimental results showing the auto-correlated output of the WILMA LWG40414 SSTDR board generated incident signal and reflected signal from the PV module. A schematic of the test setup has been shown as well [42].

methods for locating different wire faults is presented in [49]. In time domain reflectometry (TDR), a step voltage signal is transmitted along the length of the two CCCs or one CCC and the ground wire, and the reflected signal is captured to determine if there is any open or ground fault present in the PV string [29]-[32]. The spread spectrum time domain reflectometry (SSTDR) based ground fault detection technique has been presented in [42] where a PN modulated high frequency sine wave (48 MHz) is transmitted through the negative CCC and the ground wire. The reflected and incident signals are auto-correlated to determine the presence of ground fault and some key experimental results are shown in Figure 6.

The presence of long direct-current (DC) cabling, inverter generated common-mode (CM) voltages, use of line frequency transformers and different level of grounding affect the radio-frequency (RF) behavior of the PV system in the frequency range starting from 150 kHz to 30 MHz [34]-[38]. Moreover, a PV module itself can be modeled as a transmission line, and several approaches have been taken to model the DC-side of the PV system or the PV module as a transmission line [1] [39]. A simple high frequency transmission line model derivation for the DC side of the PV system is depicted in Figure 5 where a PV cell is modeled using the high frequency electric circuit model of PV cell described in [33].

If the length of the transmission line (L) is comparable to the wavelength (λ) of the transmitted signal ($L > \lambda/10$), there exist reflections of the signal at any impedance discontinuity along the length of propagation.

Table I summarizes all the faults in PV systems discussed in this paper along with the detection techniques.

Table I. SUMMARY OF DIFFERENT PV FAULTS, AND DETECTION TECHNIQUES

Fault type	Detection methods	Fault locating tools
Ground fault	Fault current measurement	GFDI, DCM
	Reflectometry	SSTDR [42]
	Current and voltage measurement	MCD estimator [25]
Line-to-line fault	Analysis based on measured ambient conditions, current, voltage, etc.	ANN [19], *I-V* curve [20], Decision tree based [21]
	I-V curve simulation and comparison	PV simulator [26]
	Reflectometry	TDR [29]-[31]
Open fault	Analysis based on measured ambient conditions, current, voltage, etc.	Decision tree based [21]
	Reflectometry	TDR [29]-[31]
Series arc-fault	Current and voltage measurement	MCD estimator [25]
	Frequency domain analysis of PV array current	AFCI [2]-[4]
Parallel arc-fault	Frequency domain analysis of current along with detecting sudden drop in voltage/current magnitude of the PV array	AFCI and voltage/current measuring/sensing equipments [4]
Bypass diode failure	Temperature sensing and diode testing	Infra-red, multi-meter [43][44]
String fault	String Current measurement	Current sensor [22]
Hot spot formation	Thermograph	Infra-red [23] [47]
Dust or soil formation	Thermograph, visual inspection	Infra-red [23]
Cell level degradation (quality control)	Different imaging techniques	PL, EL, LBIV, IR, X-ray tomography,etc. [27] [28]

V. CONCLUSIONS

Installation of PV power plants has been expedited on a large scale for the last decade, and most of the countries with large economy are now constructing large scale (>30 MW) PV plants in order to meet the growing energy demand and to reduce carbon emission in the environment. However, PV industry is still working on the safe operation of these PV plants and developing products to prevent or suppress various PV faults. There have been several accidents including fire hazards reported in recent years, and most of these incidents occurred due to the lack of knowledge of different types of faults in PV system. This paper has discussed different kind of PV faults including ground faults, line-to-line faults, arc faults, bypass diode failure, hotspot, and other minor faults that might be present in a PV plant, and limitations of existing detection devices has been described as well. A summary of different fault detection techniques proposed in literature has been presented in detail.

ACKNOWLEDGEMENTS

The authors express their appreciation to the US Department of Energy Office of Energy Efficiency and Renewable Energy and Sandia National Laboratory for supporting this work.

REFERENCES

[1] Clément Miquel, "Frequencies Studies Applied to Photovoltaic Modules" Degree project in Electrical Engineering Master of Science, KTH, Stockholm, Sweden 2011.

[2] Jay Johnson, Scott Kuszmaul, Ward Bower, and David Schoenwald, "Using PV module and line frequency response data to create robust arc fault", 26th EU PVSEC, Hamburg, Germany, 2011.

[3] Luebke, C.; Pier, T.; Pahl, B.; Breig, D.; Zuercher, J., "Field test results of DC arc fault detection on residential and utility scale PV arrays," Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE , vol., no., pp.001832,001836, 19-24 June 2011.

[4] J. Johnson, M. Montoya, S. McCalmont, G. Katzir, F. Fuks, J. Earle, A. Fresquez, S. Gonzalez, and J. Granata, "Differentiating

series and parallel photovoltaic arc-faults,"38th IEEE PVSC, Austin, TX, 4 June, 2012.
[5] J. Johnson, W. Bower, and M.A. Quintana, "Electrical and thermal finite element modeling of arc faults in photovoltaic bypass diodes," World Renewable Energy Forum, Denver, CO, 16 May, 2012.
[6] J. Strauch, M.A. Quintana, J. Granata, W. Bower, S. Kuszmaul, "Solar module arc fault modeling at Sandia National Laboratories," 2011 NREL Module Reliability Workshop.
[7] J. Johnson, D. Schoenwald, S. Kuszmaul, J. Strauch, W. Bower, "Creating dynamic equivalent PV circuit models with impedance spectroscopy for arc fault modeling," 37th IEEE PVSC, Seattle, WA, 19-24 June 2011
[8] Schimpf, F.; Norum, L.E., "Recognition of electric arcing in the DC-wiring of photovoltaic systems," Telecommunications Energy Conference, 2009. INTELEC 2009. 31st International , vol., no., pp.1,6, 18-22 Oct. 2009
[9] Edward D Spooner, Nigel Wilmot, "SAFETY ISSUES, ARCING AND FUSING IN PV ARRAYS" Australian solar council, 23 November, 2011.
[10] Zhao, Y.; de Palma, J.; Mosesian, J.; Lyons, R.; Lehman, B., "Line-Line Fault Analysis and Protection Challenges in Solar Photovoltaic Arrays," Industrial Electronics, IEEE Transactions on , vol.PP, no.99, pp.1,1, 0.
[11] Bower, W.; Wiles, J., "Investigation of ground-fault protection devices for photovoltaic power system applications," *Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE* , vol., no., pp.1378,1383, 2000
[12] Bill Brooks, "The Ground-Fault Protection BLIND SPOT: A Safety Concern for Larger Photovoltaic Systems in the United States" A Solar ABCs White Paper, Jan 2012.
[13] John Wiles, "PV Systems—Should They Be Grounded?", IAEI news, sep-oct 2004.
[14] John Wiles, "Questions from the AHJ To Fuse or Not to Fuse?", IAEI NEWS May-June 2008.
[15] John Wiles, "Ground-fault protection for PV systems", IAEI NEWS Jan-Feb 2008.
[16] Ye Zhao, Robert Lyons Jr., "Ground-Fault Analysis and Protection in PV Arrays", photovoltaic protection, note 1, issue 1, 2011.
[17] Hernandez, J.C.; Vidal, P.G., "Guidelines for Protection Against Electric Shock in PV Generators," Energy Conversion, IEEE Transactions on , vol.24, no.1, pp.274,282, March 2009.
[18] Bower, W.I.; Wiles, J.C., "Analysis of grounded and ungrounded photovoltaic systems," Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference - 1994, 1994 IEEE First World Conference on , vol.1, no., pp.809,812 vol.1, 5-9 Dec 1994.
[19] Zhihua Li, Yuanzhang Wang, Diqing Zhou, and Chunhua Wu, "An Intelligent Method for Fault Diagnosis in Photovoltaic Array", ICSC 2012, Part II, CCIS 327, pp. 10–16, 2012.
[20] Ye Zhao; Lehman, B.; De Palma, J.-F.; Mosesian, J.; Lyons, R., "Fault analysis in solar PV arrays under: Low irradiance conditions and reverse connections," Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE , vol., no., pp.002000,002005, 19-24 June 2011.
[21] Ye Zhao; Ling Yang; Lehman, B.; De Palma, J.-F.; Mosesian, J.; Lyons, R., "Decision tree-based fault detection and classification in solar photovoltaic arrays," Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE , vol., no., pp.93,99, 5-9 Feb. 2012.
[22] N. Takehara and K. Fukae, "Abnormality detection method, abnormality detection apparatus, and solar cell power generating system using the same," 5669987, 1997.
[23] Ancuta, F.; Cepisca, C., "Fault analysis possibilities for PV panels," Energetics (IYCE), Proceedings of the 2011 3rd International Youth Conference on , vol., no., pp.1,5, 7-9 July 2011
[24] Ye Zhao; Lehman, B.; DePalma, J.-F.; Mosesian, J.; Lyons, R., "Fault evolution in photovoltaic array during night-to-day transition," Control and Modeling for Power Electronics (COMPEL), 2010 IEEE 12th Workshop on , vol., no., pp.1,6, 28-30 June 2010
[25] Braun, H.; Buddha, S. T.; Krishnan, V.; Spanias, A.; Tepedelenlioglu, C.; Yeider, T.; Takehara, T., "Signal processing for fault detection in photovoltaic arrays," Acoustics, Speech and Signal Processing (ICASSP), 2012 IEEE International Conference on , vol., no., pp.1681,1684, 25-30 March 2012
[26] Stellbogen, D., "Use of PV circuit simulation for fault detection in PV array fields," Photovoltaic Specialists Conference, 1993., Conference Record of the Twenty Third IEEE , vol., no., pp.1302,1307, 10-14 May 1993
[27] Jim Colvin, "Comparative Failure Analysis of Photovoltaic Devices" ISTFA™ 2009, Conference Proceedings from the 35th International Symposium for Testing and Failure Analysis November 15–19, 2009, San Jose, California, USA, p 149-156
[28] Glenn B. Alers, "Photovoltaic Failure Analysis: Techniques for Microelectronics and Solar", Department of Physics, University of California, Santa Cruz
[29] Takumi Takashima, Junji Yamaguchi, Kenji Otani, Takashi Oozeki, Kazuhiko Kato, MasayoshiIshida, "Experimental studies of fault location in PV module strings", Solar Energy Materials & Solar Cells (2009),1079–1082.
[30] Takashima, T.; Yamaguchi, Junji; Ishida, Masayoshi, "Fault detection by signal response in PV module strings," Photovoltaic Specialists Conference, 2008. PVSC '08. 33rd IEEE , vol., no., pp.1,5, 11-16 May 2008.
[31] Takashima, T.; Yamaguchi, Junji; Otani, K.; Kato, K.; Ishida, M., "Experimental Studies of Failure Detection Methods in PV Module Strings," Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on , vol.2, no., pp.2227,2230, 7-12 May 2006.
[32] Schirone, L.; Califano, F. P.; Moschella, U.; Rocca, U., "Fault finding in a 1 MW photovoltaic plant by reflectometry," Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference - 1994, 1994 IEEE First World Conference on , vol.1, no., pp.846,849 vol.1, 5-9 Dec 1994.
[33] Johnson, J.; Schoenwald, D.; Kuszmaul, S.; Strauch, J.; Bower, W., "Creating dynamic equivalent PV circuit models with impedance spectroscopy for arc fault modeling," Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE , vol., no., pp.002328,002333, 19-24 June 2011
[34] Stathopoulos, N.A.; Palilis, Leonidas C.; Savaidis, S.P.; Yesayan, S.R.; Vasilopoulou, Maria; Papadimitropoulos, Giorgos; Davazoglou, Dimitris; Argitis, Panagiotis, "Optical Modeling of Hybrid Polymer Solar Cells Using a Transmission-Line Model and Comparison With Experimental Results," Selected Topics in Quantum Electronics, IEEE Journal of , vol.16, no.6, pp.1784,1791, Nov.-Dec. 2010.
[35] H Haeberlin, "New DC-LISN for EMC-Measurements on the DC side of PV Systems: Realisation and first Measurements at Inverters", 17th European Photovoltaic Solar Energy Conference, Munich, Germany, Oct 2001.
[36] Christian Bendel, Thomas Degner, Norbert Henze, J¨org Kirchhof, Gerald Klein, Holger Lange, Celine Trousseau, Dr. Wolfgang Enders, Christian Halter, Peter Scheibenreiter, Peter Wurm, Peter Claus, Carsten Metzger, Armin Sch¨ulbe, Hans Daub, Katharina Stanley, "EMC and Safety Design for Photovoltaic Systems", Publishable Final Report, Version 28. March 2002.
[37] Araneo, R.; Lammens, S.; Grossi, M.; Bertone, S., "EMC Issues in High-Power Grid-Connected Photovoltaic Plants," Electromagnetic Compatibility, IEEE Transactions on , vol.51, no.3, pp.639,648, Aug. 2009.
[38] Di Piazza, M.C.; Serporta, C.; Tine, G.; Vitale, G., "Electromagnetic compatibility characterisation of the DC side in a low power photovoltaic plant," Industrial Technology, 2004. IEEE ICIT '04. 2004 IEEE International Conference on , vol.2, no., pp.672,677 Vol. 2, 8-10 Dec. 2004.

[39] Yaroslav Smirnov, “RF disturbances produced by high-power photovoltaic solar plants”, Master’s thesis, Department of Electrical Engineering, Lappeenranta University of Technology, 2011.
[40] Bazzi, A.M.; Kim, K.A.; Johnson, B.B.; Krein, P.T.; Dominguez-Garcia, A., "Fault impacts on solar power unit reliability," Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE , vol., no., pp.1223,1231, 6-11 March 2011.
[41] Harb, S.; Balog, R.S., "Reliability of Candidate Photovoltaic Module-Integrated-Inverter (PV-MII) Topologies—A Usage Model Approach," Power Electronics, IEEE Transactions on , vol.28, no.6, pp.3019,3027, June 2013.
[42] Mohammed khorshed Alam, Faisal Khan, Jay Johnson and Jack Flicker, “PV Ground-fault Detection using Spread Spectrum Time Domain Reflectometry (SSTDR)” accepted for publication in ECCE 2013.
[43] Kazuhiko Kato, “PV module failures observed in the field- solder bond and bypass diode failures”, 28th EU PVSEC 2013, Paris, France.
[44] Wohlgemuth, J.H., "Reliability testing of PV modules," Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference - 1994, 1994 IEEE First World Conference on , vol.1, no., pp.889,892 vol.1, 5-9 Dec 1994.
[45] Spanoche, S.A.; Stewart, J.D.; Hawley, S.L.; Opris, I.E., "Model-Based Method for Partially Shaded PV Module Hot-Spot Suppression," Photovoltaics, IEEE Journal of , vol.3, no.2, pp.785,790, April 2013.
[46] Molenbroek, E.; Waddington, D. W.; Emery, K.A., "Hot spot susceptibility and testing of PV modules," Photovoltaic Specialists Conference, 1991., Conference Record of the Twenty Second IEEE , vol., no., pp.547,552 vol.1, 7-11 Oct 1991.
[47] J. Munoz, E. Lorenzo, et. al., “An Investigation into Hot-Spots in Two Large Grid-Connected PV Plants”, Prog. Photovolt: Res. Appl. 2008; 16:693–701.
[48] Ye Zhao, “Fault Analysis in Solar Photovoltaic Arrays”, MSc Thesis dissertation, Department of Electrical and Computer Engineering, Northeastern University, December, 2010.
[49] C. Furse, Y. C. Chung, C. Lo, P. Pendayala, “A Critical Comparison of Reflectometry Methods for Location of Wiring Faults”; Smart Structures and Systems, vol 2, Issue 1, pp. 25-46, 2006.
[50] NFPA70, "Article 690 - Solar Photovoltaic Systems of National Electrical Code," ed, 2011.