14th IMEKO TC10 Workshop Technical Diagnostics
New Perspectives in Measurements, Tools and Techniques
for system’s reliability, maintainability and safety
Milan, Italy, June 27-28, 2016

Reliability assessment of PV inverters

Mohamed Khalil[1], Payam Soulatiantork[2]

[1]DEIB, Politecnico di Milano, Milano 20133, Italy, mohamedmahmoud.khalil@polimi.it
[2] DEIB, Politecnico di Milano, Milano 20133, Italy, Payam.Soulatiantork@polimi.it

Abstract – **The target reliability levels of Photovoltaic inverters, that encounter Photovoltaic panels reliability, is a challenging issue. Currently a lot of efforts are carried out to improve the lifespan of photovoltaic inverter and reduce their outages. Special attention in this respect is given to the failure causes of inverters. In this paper, a complete FMECA analysis is presented to understand the root causes of these failures, estimate the local and final effects on generating energy, and recommended actions to avoid these failure modes. Additionally, an assignment of risk priority numbers is carefully considered to the each failure mode in order to prioritize the various hazards for a better maintenance strategies.**

I. INTRODUCTION

In a grid-connected PV plant, inverter represents an expensive and complex key component, and PV inverter (PVI) is the considered most mature compared to inverters of other renewable sources: wind, fuel cells and micro turbines. Unfortunately, the majority of PV system failures involves the inverters; an Investigation in [1] was carried out on 126 system that provided 190 failure events, and results shows that PVI dominates the outage causes of PV plants by 76%. Another surveys in [2-3] depicted that PVIs are the leading cause of PV systems. Moreover, [4] stated that 65 % of outages of 213 events for 103 PV systems were assigned to PVI. The previously mentioned studies and surveys show that PVI are still a weak link in the photovoltaic systems.

The reason is the life span of PVIs that are very low compared to PV modules; PVI has shown a field mean time between failures of 1 - 16 years with typical warranties lasting only 3 - 5 years [5]. A study in [6] has depicted that the mean time to first failure of the PVI is five years. Also, the Mean Time Between Failures (MTBF) is reported to be between 5- 10 years in [2].The declared lifetimes of PVIs are due to their operation in inhospitable environments, where they are exposed to extreme temperatures and frequent thermal cycling and load stress. As a result, the reasons behind the high failure rates can be traced into manufacturing quality, inadequate design, and defective components [7].

Although the different failure modes of PV have to be highlighted, in terms of their failure causes and actions to be followed to reduce these failures, it is depicted from literature that the main concern of the current studies is towards both reliability estimation of PVI and RAM improvement of current PVI. For instance, Harb et al. [8] discussed the reliability of PVI based on the stress-factor methodology, Koutroulis et al. [9] focused on reliability improvement of PVI during the design phase through the estimation of the useful life time of inverter’s critical components, and Pregeij et al. [10] showed the impact of inverter configuration on the PV system reliability and energy production. Fife et al. [11] presented the necessary field reliability indices to be estimated for PVIs. Another study [12] proposed Bayesian inference methodology to model the uncertainty hazard and repair rate of fielded PVIs. An approach based on Monte Carlo simulation is presented in [13] to assess the expected availability of a particular inverter design and make qualitative assessments of several potential approaches to increasing inverter reliability.

This work aims to identify all the possible PVI failure modes of greatest concern, list the causes of these failure modes, consider the consequences of each failure modes, and finally determine the recommended actions to limit these failures. The previously mentioned objectives can be fulfilled through Failure Mode Effect and Critically Analysis (FMECA), which is a key analytical tool that aims to understand the root causes of failures associated with the operation of critical components in crucial systems. Additionally each failure mode within FMECA analysis will be prioritized in terms of its severity, occurrence and detection. In a way, that can be used by decision makers and maintenance crews for a priority order of the maintenance tasks among components.

This paper is organized as follows, Section 2 presents in details the different failure modes of PVI and their root causes, Section 3 introduce FMECA concept, section 4 discusses FMECA analysis of PVI. Finally, section 5 includes conclusion.

II. COMPONENTS FAILURE CAUSES

The reliable operation of PV inverter is based on its main components. The typical three phase PVI includes: IGBT Power modules, cooling fans, control software and DC link capacitors implemented on Printed Circuit Board (PCB) in addition to AC & DC contactors.

A. IGBT power module

IGBT power module consists of both IGBT and FreeWheeling Diode (FWD) that are connected to ceramic substrate through wire bonds. The ceramic substrate is then soldered onto cupper or AlSiC base plate, which acts as a mechanical support and ensures good thermal diffusivity then the base is coupled to heat sink, Thermal grease is placed between the base and heat sink to improve the cooling. The insulating gel improves the dielectric strength and acts as insulation.

IGBT

Because, IGBT is considered the heart of PV inverter, its failure is a common cause failure to the inverter. It has switching characteristics similar to a MOSFET and the high current and voltage capabilities of a bipolar junction transistor (BJT). It is depicted that the structure of MOSFET is the same as IGBT except the additional P+ layer

IGBT is a semiconductor device, so its predicated lifetime [9] is considered relatively high, 21.9 years, in case it is operated as a single device. Unfortunately, this does not exist in practical life. Ref. [9] summarized IGBT failure causes into four categories:

i) Thermal runway, ii) Ceramic substrate to base plate solder fatigue, the substrate solder refers to the delamination of the solder joint between base plate and the ceramic substrate, iii) Emitter wire bond fatigue, and iv) Partial discharge in insulating gel.

For a safety operation, it is necessary to operate IGBT at junction temperature less than 150o C in order to avoid fatigue in wire and solder bonding [14].

Freewheeling diodes

Although power diodes are usually assumed to have a reliable operation, (FWD) fails under various circumstances, especially during the turn-on transition of IGBTs in high switching frequency applications [15]. The FWD failures can be classified mainly into open and short circuit failure modes [15], the failure causes of open circuit mode are similar to failures of IGBT as they happen as a result of bonded wire liftoff or wire rupture after high short circuit, this mode is not severe to the IGBT; it will reduce only the output quality. Meanwhile, the short circuit mode is very severe to IGBT and its causes can be summarized into static high voltage breakdown, rising of leakage current, snappy recovery, reverse recovery dynamic avalanche, and high power dissipation.

B. DC link capacitor

Capacitors are widely used for dc links to balance the instantaneous power difference between the input source and output load, and minimize voltage variation in the dc link. In fact, the current conventional inverter designs need large electrolytic capacitors adjusted to the PV module itself to act as energy reservoirs. During their service life, they are subjected to different types of stresses: overvoltage, overheating, humidity, radiation, and vibration in addition to their irreversible ageing process. These stresses are summarized into three failure modes; ageing mode, open and short circuit modes.

C. Main AC/DC capacitor

The DC and AC contactor connect the PV inverter to the PV module and the grid in the morning and disconnect the PV inverter from the PV module and the grid in the evening or when the inverter has a fault [9]. Four failure modes are associated with the operation of contactors: i) the contactor fails to open or open late, ii) contactor opens by mistake, iii) high resistance of contactor, iv) and contactor fails to close

D. Cooling Fan

In inverters, forced air cooling through fans is used along with heat sinks to cool heat sources, e.g. semi-conductors. Fans usage aims to cool power devices on heat sinks the most efficient way. This requires a careful design and maintenance regulation to assure the proper air flow among different components. The failure of cooling fan can be due to mechanical or electrical failures.

The mechanical failure causes are a result of cage damage, bearing failures, and lubrication deterioration. Bearing failures are still the dominant reason for fans failures, and the bearing life is heavily dependent on retention of its lubricant.

The electrical failures includes cracks in printed circuit board the fan, wiring errors, and electrical overstress. Meanwhile, fan installation failures can be a consequence to Connector crimping, reversed airflow, and loosing cables. Acoustic failures of fans is due to loud noise from fan operation or fan blade interference with surrounds. Serviceability is due to improper access during maintenance, e.g. remote inverters at isolated sites.

E. Printed Circuit Board

Printed Circuit Board (PCB) mechanically supports and electrically connects electronic components using conductive tracks. It can be single sided, double sided or multi-layer. The design and the proper selection of PCB is essential for a better reliability and an improved performance. The major frequent failure causes of fielded PCB can be as a result of delamination between PCB’s layers, cracks in the boards, ion immigration, and component soldering.

Current PCBs are composed of woven glass fiver that are bonded together with an epoxy, afterwards the board is cured through combination of temperature and pressure, which causes the glass fibers to melt and bond together, thereby giving the board strength and rigidity [16].

Overheating during PCB’s operation is the leading reason for the delamination of the board. Also, soldering repairs has its significant contribution on the delamination on PCBs long term operation [17]. These factors will reduce board integrity and allow moisture in between the board layers.

Solder fracture and cracks can occur internally within the solder or at the area where solder joins another surface, their dimensions are very small in size in terms of μm and both types occur frequently in the field. Ion immigration is a phenomena that occurs in the presence of moisture, where metallic positive electrode is oxidized into a soluble form, and the resulted positively charged ions migrates towards the negative electrodes forming a dendrite metallic deposits that grow towards the anode and result in short circuit bridges[18]. Three factors contributes mainly in the occurrence of this phenomena which are: environmental factor that is the main source of contaminants, electrical potential, and moisture or high humidity [17].

F. Control Software

Various control methods are available for grid connected PV inverters, starting from conventional methods using voltage and current double-loop, open control loops, PI current loop control till modern sophisticated methods as sliding mode control [19]. The proper selection of the exact control strategy is very crucial for the ultimate performance of the inverter. The control software should be designed to adapt the operating voltage range, output power level, operating hours, and change in temperature, health monitoring facility, and the most proper actions for the different PV panels and grid faults. Moreover, the selection of the best Maximum Power Point Tracker (MPPT) scheme is a necessity; the reliability of MPPT scheme has a significant impact on the whole inverter's reliability.

III. FMECA CONCEPT

FMECA is considered as a first step for improving the system reliability through failure analysis, and it is one among several methods used for risk assessment and management by selecting the most proper maintenance strategies to enhance the system performance. FMECA is composed of two separate analyses, the Failure Mode and Effects Analysis (FMEA) and the Criticality Analysis (CA). More details on FMECA is available in [20-21].

A. FMEA

FMEA is a bottom-to-up analysis, it starts with gathering information on the failures of the subsystems at the lowest level of the system, the function and the impact of the each subsystem failure in the whole system. IEC-60182 [20] defined FMEA as a systematic methodology of the system analysis to identify the potential failure modes, the various failure causes and the effect of each failure mode on the whole system performance. The working of FMEA should include: a list of equipment failure modes, reasons of these failures, local effects that refer to the consequences of each possible failure on the system element, final effects that describe the impact of that possible failures on the whole system and an alternative provision or recommended corrective actions to avoid these failures.

B. CA

CA is the second part of FMECA that focus mainly on the prioritization of the failures by giving each failure mode a number that express how risky it is. Thus, it will be clear for maintenance management to plan their future activities starting with failures with highest risk. The evaluation of this number can qualitative, based on experience gained from field and site background, or quantitative that requires a database or previous field surveys. Both the qualitative and quantitative methodologies are managed by assigning each failure mode to a Risk Priority Number (RPN), defined by RPN = O × S × D, where S represents a scale for the failure severity and the risks behind the failure occurrence., O denotes the probability of failure mode occurrence, and D means detection, and represents the possibility to recognize the failure before the system or the customers are affected.

The criteria for selecting severity, occurrence, and detection values depends on standards. In this paper, a quantitative analysis based on IEC-60182 [20] evaluation criteria is applied to PVI.

IV. PVI FMECA ANALYSIS

As far as the use of the FMEA is concerned, Table 1 is illustrated to highlight all the possible PVI components outage modes and their failure causes. The impact of each failure modes is addressed in terms of the local effect, limited only to the component itself, and final effect, reflecting the impact on the overall inverter operation. Moreover, a lot of attention is given to the best preventive measures necessary to limit and avoid these outage modes through design and operating phase. It is worth noting from the Table 1 how significant is the design management on the operation phase and overall performance of PVI, in terms of environmental, mechanical, electrical, and thermal stresses.

Considering CA, quantitative CA approach is followed up in this paper based on a survey carried out by SunEdison Company that operates more than 600 PV systems in four continents with 1500 in-service inverters from 16 vendors and more than 2.2 million PV modules from 35 manufacturers [3]. The surveyed period is during interval January 2010 and March 2012 for 350 systems. The most significant failure modes of PVI inverters in SunEdison survey are shown in Table 2. Inverter tickets are issued whenever there is a reported failure with PVI. Accordingly, both the percentage of tickets and KWh lost reflects the occurrence (O) and severity (S) of CA. The detection (D) is measured according to the probability of identifying the failure before the system is affected. This can be carried out through the different field indicators.

It is depicted from Table 2 that control software is the dominant cause of PVI failures followed by PCB board. Meanwhile, the largest power losses were assigned to failures by PCB boards followed by control software.

It is worth to mention that control software contribution is high; as it also includes failures where inverter shuts down without a fault code and without being forced to disconnect due to grid outage [3].

Table 2. frequency of tickets & associated energy loss for each PVI failure mode [3]

Specific failure **a**rea	Percentage of tickets	Percentage of KWh lost
Control software	28%	15%
PCB board	13%	22%
AC contactors	12%	13%
DC contactor	4%	1%

Fans	6%	5%
IGBT modules	6%	5%
Capacitors	3%	7%

The criticality analysis in Table 1 shows that PCB recorded the largest RPN; since it is very hard in the field to detect failure causes of PCB.

On the contrary, the control software has a high detection possibility; because the changes in generated electricity can be easily observed with a strong power and energy metering, moreover the protection scheme is tested frequently in the site during the scheduled maintenance activities.

AC/DC contactors have a significant RPN because of their high assigned severity value in SunEdison survey; generally improper operation of the contactor subjects the human's life to danger and contribute in fault propagation in grid. In the field, AC/DC contactors have moderate detection facility during routine protection tests only.

Both cooling fans and DC link capacitors have low RPN because of their insignificant impact on power interruption, low failure frequency, and high possibilities to be recognized in the field. The DC link capacitor symptoms of failures are limited to RF noise during operation, and dissipation factor test during maintenances besides ESR monitoring during its operation [22]. The Results of CA is summarized in Fig. 1.

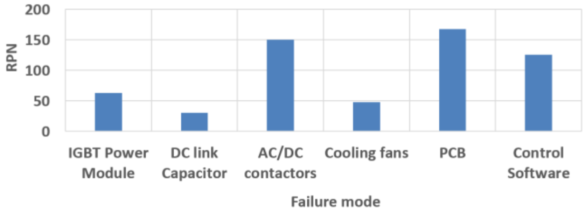

Fig. 1 RPN for inverters' failure modes

V. CONCLUSION

Reliability of inverters is still inadequate, but improvements are being in progress. A 5-year warranty has currently become a norm in the industry, whereas 2-year warranties were most common just a few years ago. Unfortunately, these longer warranties are still controversial; manufacturers claim that they have gained sufficient experience of the PVI failure causes based on field experience, and they developed their design plans, incorporate higher quality components. Meanwhile, industry experts believe that these warranties are mere marketing tools.

The main objective of this work is to provide the manufacturers and decision-makers in utilities a guide, through FMEA, for the reason and impact of feasible hazards that could interrupt PVI operation and result in losses of power in addition to the prioritizing of these hazards, through CA, for a better maintenance strategies.

References

[1] Maish, A.B.; Atcitty, C.; Hester, S.; Greenberg, D.; Osborn, D.; Collier, D.; Brine, M., "Photovoltaic system reliability," Photovoltaic Specialists Conference, Conference Record of the Twenty-Sixth IEEE , pp.1049-1054, 1997.

[2] A review of PV inverter technology cost and performance projections, Navigant Consulting, Burlington, MA, NREL subcontract Rep. NREL/SR-620-38771, Jan. 2006.

[3] Golnas, A., "PV System Reliability: An Operator's Perspective," IEEE Journal of Photovoltaics, vol.3, no.1, pp.416-421, Jan. 2013.

[4] Dhere, N.G., "Reliability of PV modules and balance-of-system components," Photovoltaic Specialists Conference, 2005. Conference Record of the Thirty-first IEEE, pp.1570-1576, 3-7 Jan. 2005.

[5] Flicker, Jack; Kaplar, Robert; Marinella, Matthew; Granata, Jennifer, "PV inverter performance and reliability: What is the role of the bus capacitor?," 38th IEEE on Photovoltaic Specialists Conference (PVSC), Volume 2,pp.1-3, 3-8 June 2012.

[6] Federal Office for Education and Science, Mean Time Before Failure of Photovoltaic modules, Final report BBW 99.0579, June 2003.

[7] Kaplar, R.; Brock, Reinhard; DasGupta, Sandeepan; Marinella, M.; Starbuck, A.; Fresquez, A.; Gonzalez, S.; Granata, J.; Quintana, M.; Smith, Mark; Atcitty, S., "PV inverter performance and reliability: What is the role of the IGBT?," 37th IEEE Photovoltaic Specialists Conference (PVSC), pp.001842-001847, 19-24 June 2011.

[8] Harb, S.; Balog, R.S., "Reliability of Candidate Photovoltaic Module-Integrated-Inverter (PV-MII) Topologies—A Usage Model Approach," IEEE Transactions on Power Electronics, vol.28, no.6, pp.3019-3027, June 2013.

[9] Ma, Z.J.; Thomas, S., "Reliability and maintainability in photovoltaic inverter design, "in proceedings of Reliability and Maintainability Symposium (RAMS), pp.1-5, 24-27 Jan. 2011.

[10] Pregelj, A.; Begovic, M.; Rohatgi, A., "Impact of inverter configuration on PV system reliability and energy production," Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, pp.1388-1391, 19-24 May 2002.

[11] Fife, J.M.; Scharf, M.; Hummel, S.G.; Morris, R.W., "Field reliability analysis methods for photovoltaic inverters," 35th IEEE Photovoltaic Specialists Conference (PVSC), pp. 002767-002772, 20-25 June 2010.

[12] Battistelli, L.; Chiodo, E.; Lauria, D., "Bayes assessment of photovoltaic inverter system reliability and availability," in proceedings of International Symposium on Power Electronics Electrical Drives Automation and Motion (SPEEDAM), pp.628-634, 14-16 June 2010.

[13] Ristow, A.; Begovic, M.; Pregelj, A.; Rohatgi, A., "Development of a Methodology for Improving Photovoltaic Inverter Reliability," IEEE Transactions on Industrial Electronics, vol.55, no.7, pp.2581-2592, July 2008.

[14] Herrmann, T.; Feller, M.; Lutz, J.; Bayerer, R.; Licht, T., "Power cycling induced failure mechanisms in solder layers," 2007 European Conference on Power Electronics and Applications, pp.1-7, 2-5 Sept. 2007.

[15] R. Wu, F. Blaabjerg, H. Wang, M. Liserre," Overview of catastrophic failures of freewheeling diodes in power electronic circuits," European Symposium on Reliability of Electron Devices, Failure Physics and Analysis, Microelectronics Reliability, Volume 53, Issues 9–11, Pages 1169-1828, September–November, 2013.

[16] Clive Max Maxfield, Bebop to the Boolean Boogie: An Unconventional Guide to Electronics, Chapter18: Printed Circuit Boards (PCBs), pp. 251–276, Newnes press, 2009.

[17] Keenan, E.; Wright, R.G.; Mulligan, R.; Kirkland, L.V., "Terahertz and laser imaging for printed circuit board failure detection," in proceedings of AUTOTESTCON 2004 , pp.563,569, 20-23 Sept. 2004. doi: 10.1109/AUTEST.2004.1436955

[18] Reid, M.; Punch, J.; Rodgers, B.; Pomeroy, M.J.; Galkin, T.; Stenberg, T.; Rusanen, O.; Elonen, E.; Vilen, M.; Vakevainen, K., "Factors that influence ionic migration on printed wiring boards," in the proceedings of 43rd Annual IEEE International Reliability Physics Symposium, pp.300-304, April 17-21, 2005.

[19] Qunhai Huo; Li Kong; Tongzhen Wei; Guowei Zhang; Lingzhi Kong, "A new method for the photovoltaic grid-connected inverter control," . Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies(DRPT), pp.2626-2629, 6-9 April 2008.

[20] IEC-60182, Analysis techniques for system reliability- Procedure

for failure mode and effects analysis (FMEA), 2006.

[21] MIL-STD-1629A, Procedures for Performing a Failure Mode, Effects and Criticality Analysis, Nov. 1980.

[22] Vichare, N.M.; Pecht, M.G., "Prognostics and health management of electronics," IEEE Transactions on Components and Packaging Technologies, vol.29, no.1, pp.222-229, March 2006.

Table 1. FMECA of PVI

Item	**Component failure**	**outage mode**	**Possible outage cause**	**Local effect**	**Final effect**	**Compensating provision against failure**	**S**	**O**	**D**	**RPN**
PVI	IGBT Power Module	- Thermal runway, - Ceramic substrate to base plate solder fatigue, - Emitter wire bond fatigue, - Partial discharge. - FWD is short circuited.	- High operating Temperature - Long power cycles - Big thermal mismatch between the components - Moisture	- Cracks formation and delamination formation in solder layers. - Wire bonding cracks and wire lift off. - Voids in encapsulation and Insulation failure of insulating gel.	- Damage of IGBT power module and power interruption	- Lowering thermal resistance between IGBT and heat sink, - improve chip thickness and bonding technology, - Using high wire material purity with larger diameter - Operating IGBT power module at temperature less than 150°C - Implementing Fault Prognosis techniques in condition monitoring	3	3	7	63
	DC link Capacitor	- Capacitor open circuit. - Capacitor short circuit. - Ageing.	- Moisture absorption. - Heat contraction of dielectric film - Successive over currents self-healing - dielectric losses	- Connection instability - Oxidation of evaporated metal and reduction of electrode area. - Change of insulation and electric behavior of DC link capacitor	- Replacing DC link capacitor & PVI power interruption	- A proper overload protection scheme. - Healthy monitoring of ESR - Frequent measurement of tan delta	3	2	5	30
	AC/DC contactors	- Fails to open or open late. - Opens by mistake - Fails to close. - Contactor high resistance	- Bad system configuration - Human mistakes - Tripping coil ageing - Rust deposits, Oxidation and polluted electric contacts.	- During ON-state: high power losses & degradation of contactor. - Protection failure of inverter	- Overheating, arcs, and fire - Damage of inverter	- Periodic visual inspection - Preventive maintenance to carry out contactor electrical tests - A proper design for protection.	6	5	5	150
	Cooling fans	- Mechanical mode - Electrical mode	- Cage damage. - Bearing failures. - Lubrication deterioration. - Wiring errors. - Electrical overstress. - Installation failures. - Dust and dirt on fan and its heat sink. - Excessive vibration	- Reversed Air flow. - Fan failure. - Poor cooling performance. - Loud noise from fan's operation. - Other components' cables loosing.	- Excessive heat. - Damage of PVI's components.	- A careful design. - Improving serviceability. - Temperature sensors for cooling monitoring & protection - Implementing Precursor Monitoring approach.	4	3	4	48
	PCB	- Delaminated layers - Board cracks - Ion immigration - Components soldering	- Overheating & moisture between wafer layers - Thermal expansion coefficient mismatch between components and PCB - Environmental contamination	- Board integrity is reduced - Resistive heating & damage of components' solder joints. - Short circuit bridges in between the PCB's components.	- Inverter Replacement & interruption of power	- Proper board design - improving field sealing of Inverter components and PCB - Regular visual inspection & board tests	7	4	6	168
	Control software	- Poor PVI performance. - Fails to trip with grid outages - Unknown tripping flags.	- Improper setting parameters. - Poor tracking algorithm - Insufficient sensor networks. - Unfrequented cleaning of Photovoltaic panels	- Unreliable MPPT scheme	- Inefficient operation of inverter - Power losses	- Improving inverter data acquisition level. - Implementing smart monitoring system - Schedule tests on PVI protection. - Deployment of sufficient electrical and environmental sensors. - Following up a firmly scheduled cleaning maintenance.	6	7	3	126