



BNL-98066-2012-CP

***Extending Performance and Evaluating Risks of PV
Systems Failure Using a Fault Tree and Event Tree
Approach: Analysis of the Possible Application***

Alessandra Colli

*Presented at the 38th IEEE Photovoltaics Specialists Conference
Austin, TX
June 3-8, 2012*

May 2012

Sustainable Energy Technologies Department/Renewable Energy Group

Brookhaven National Laboratory

**U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy**

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

This preprint is intended for publication in a journal or proceedings. Since changes may be made before publication, it may not be cited or reproduced without the author's permission.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Extending Performance and Evaluating Risks of PV Systems Failure Using a Fault Tree and Event Tree Approach: Analysis of the Possible Application

Alessandra Colli

Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract — Performance and reliability of photovoltaic (PV) systems are important issues in the overall evaluation of a PV plant and its components. While performance is connected to the amount of energy produced by the PV installation in the working environmental conditions, reliability impacts the availability of the system to produce the expected amount of energy. In both cases, the evaluation should be done considering information and data coming from indoor as well as outdoor tests. In this paper a way of re-thinking performance, giving it a probabilistic connotation, and connecting the two concepts of performance and reliability is proposed. The paper follows a theoretical approach and discusses the way to obtaining such information, facing benefits and problems. The proposed probabilistic performance accounts for the probability of the system to function correctly, thus passing through the complementary evaluation of the probability of system malfunctions and consequences. Scenarios have to be identified where the system is not functioning properly or at all. They are expected to be combined in a probabilistic safety analysis (PSA) based approach, providing not only the required probability, but also being capable of giving a prioritization of the risks and the most dominant scenario associated to a specific situation. This approach can offer the possibility to highlight the most critical parts of a PV system, as well as providing support in design activities identifying weak connections.

Index Terms — Performance, Risk, Failure, Fault Tree, Event Tree.

I. INTRODUCTION

Systems work according to interactions between humans and plants (the operating organization), and between the operating organization and the surrounding environment (Fig.1). Interactions can be positive or negative. When they take a negative characteristic, then a system failure is expected. Most incidents/accidents in the energy sector are actually man-made [1], but negative interactions could be restricted to the plant technology alone. Negative interactions can be categorized in different ways, as shown in Fig.2. They can propagate in series or in parallel, and normally start from a component failure.

Components failures can proceed according to two processes:

- Repair-to-failure process (non-repairable components).
- Repair-failure-repair process (repairable components).

The interaction between the operating organization and the environment can be source of hazards for the system in terms of natural disasters or, as in the case of a PV system, in terms of variability of the incoming solar radiation as primary energy source.

The aim of this paper is to discuss a methodology to investigate PV system failures and develop a model capable of defining the system failure probability. The model can then be used to characterize the dominance of the various risks based on the combinations of possible scenarios, with the purpose to define performance at an improved level. A similar approach, using different tools, has been discussed in [3]; however, differences exist with the methodological approach outlined in this paper.

An issue to face in this process is connected to data availability. Reliability data for PV systems are difficult to find and the PV community is aware of this. Working groups such as Task 13 of the Photovoltaic Power System Programme of the International Energy Agency are actually working to establish a database of performance and reliability data in the PV area.

At the moment, it is still difficult to cover all the needed information and sometimes comparable data have to be taken from other energy sectors. A difficulty also originates from the consideration that PV systems involve passive systems, and their functional behavior has to be defined and quantified.

Despite the limitations associated with data availability, interesting issues could arise when defining the connections and interactions among different components in the system, especially when reaching a high level of details. The identification of how failures originate and how they propagate within the system is already a useful indication to understand how and where to intervene.

Additionally, failures and combinations of failures can be prioritized by qualitative ranking, to identify the most important risk contributions. The relative results offered by this qualitative evaluation are independent from the uncertainty associated with the data inserted in the model, but mainly depend on the exactness of the system modeling activity. This can already provide significant indications of the risk contribution of a specific element in the entire system.

When considering PV modules throughout this paper, the focus is on crystalline silicon PV, given their large presence on the market.

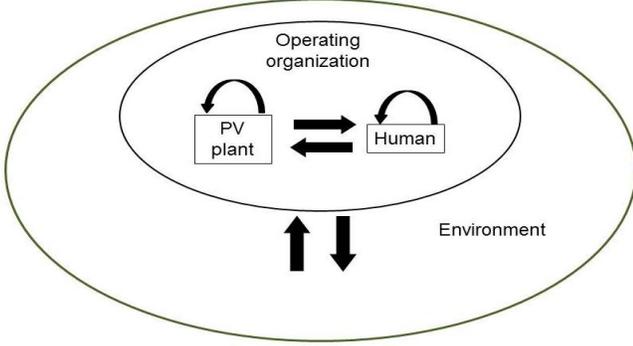


Fig. 1. Interactions between the system operating organization (PV plant and humans) and the environment.

Why	How	When	Where
<ul style="list-style-type: none"> •Mechanical, functional, interface failure. •Primary, secondary, command failure. •Basic, intermediate failure. •Parallel, cascade failure. •Direct, indirect, root causes. •Main, supplemental cause. •Inducing factors. •Hardware-, human-, system-induced failures. 	<ul style="list-style-type: none"> •Random, wearout, initial failure. •Demand, run failure. •Persistent, intermittent failure. •Active, latent failure. •Omission, commission error. •Independent, dependent failure. 	<ul style="list-style-type: none"> •Recovery failure. •Initiating, enabling event. •Routine, cognitive error. •Lapse, mistake. 	<ul style="list-style-type: none"> •Internal, external events. •Active, passive failure.

Fig. 2. Categorization of negative interaction as in [2].

II. A PROBABILISTIC PERFORMANCE DEFINITION FOR PV SYSTEMS

Let's define this concept starting from the definition of risk. Although several definitions exist, risk is expressed in terms of consequences and probabilities associated to specific scenarios [4]. The same logic can be applied to evaluating the probabilistic performance of a PV system.

The performance ratio (PR) of a PV system is defined in [5] as:

$$PR \equiv \frac{Y_f}{Y_r} \quad (1)$$

where Y_f is the final yield over a certain time τ , defined as the energy production E in kWh divided by the peak power P_p in kWp, and $Y_r = H/G$ over time τ , where respectively H is the in-plane insolation (in kWh/m²), and G is the irradiance at standard test conditions (STC) (1 kW/m²).

What we could call probabilistic performance (PR_{PROB}) of a PV system is the PR combined with the probability of the system to provide performance, thus being operable and available, given a specific scenario or combination of scenarios.

$$PR_{PROB} \equiv PR * p(PR) \quad (2)$$

This formulation allows taking into account both performance (as it is usually meant and defined in IEC 61724 [5]) and probability connected to the intrinsic reliability of PV systems, as well as the risks from other external accidental or voluntary events and the variability of solar irradiance, providing probabilistic information on the chance that the system is working properly and under the optimal conditions.

The outlined concept is applicable to existing PV fields, but could be additionally applied in design activities, to support choices and solutions. Assigning a numerical value to (2) requires the steps outlined ahead.

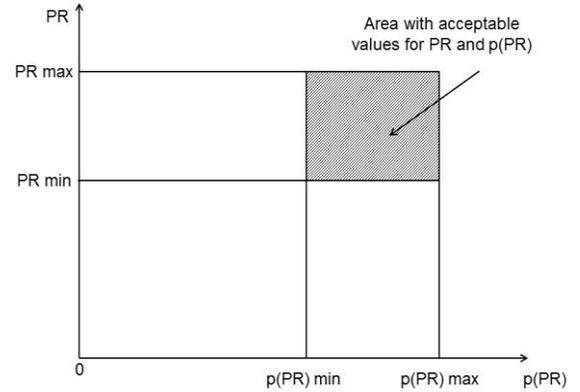


Fig. 3. Setting appropriate limits for PR and $p(PR)$ enables an area of acceptable operation for a PV plant to be defined.

As shown in Fig. 3, an area of acceptable system operation can be defined, which will be useful to determine the expected energy production, the economic impact of feed-in tariffs, and help in managing the system interconnection with the electricity grid. Respecting specific performance limitations taking into account a series of possible altering factors is the answer to understand when the system will be available or not, under specific uncertainty criteria that will be defined in the calculation process for each specific case.

III. FAILURE MODES IN PV SYSTEM

First of all, defining the probability of a PV system to provide performance means that the complementary probability of the system to fail has to be expressed.

The first step in this direction involves the identification of the system to analyze (Fig. 4) and the causes (voluntary or not) of failure, along with the effects that they have. Literature has been considered (such as [6]) covering this area. Table I

provides an overview in this direction; it has been created for a system utilizing crystalline silicon PV modules, which are currently used in the majority of PV plants.

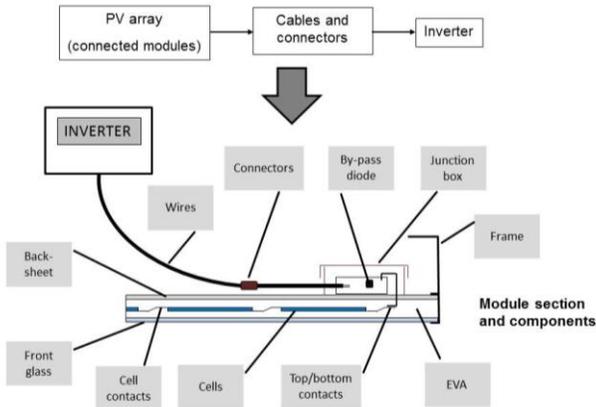


Fig. 4. Basic model of a PV system, including the section of module and the definition of the main components.

TABLE I

POSSIBLE FAILURE MODES AND EFFECTS IN A PV SYSTEM.

Part	Possible causes	Possible failure modes	Possible effects
Module	Damages from frame, distortion, mounting brackets, thermal expansion/contraction, excessive snow load, vandalism, delamination, front/back damages, cell physical damage from metallization process, cracks (glass, over/around cells), metallization distortion, corrosion of contacts interconnecting cells or at top/bottom of module, visual changes, changing colors, corrosion, increased module	Moisture ingress, loss of circuit, cell overheat, thermal damages to encapsulant, cells and contacts, shorts/open circuit in module, possible arcing and overheating of junction box	Reduced energy output depending on damage severity, increased degradation, module failure, array interruption, array/inverter matching problems, possible fire.

	degradation, high cell/module temperature, hot-spots, burns/damages on back-sheet, damages at the junction box, by-pass diode failure.		
Cables	Manufacturing defects, malfunctions or bad connections, aging, maintenance, damages from animals.	Cracks, pulling out of cables, ruptures, contacts corrosion, overheat, short/open circuit, possible arcing, complete loss of output.	Reduced energy output or no output, human safety, possible fire.
Inverter	Inverter failure (stress, aging), low efficiency (also for MPPT), sizing mismatch, faulty switches, capacitor degradation, cable damage (also for aging), ground connection failure, insulation fault, overheating, arcing damage, corrosion of contacts, grid fluctuation, accidental switch-off.	Incorrect sizing, poor/incorrect tracking algorithm, low performance, intermittent operation, open circuits, higher resistance in circuits, physical damage to cabling, overheating, moisture ingress.	Reduced energy output or no output, degraded power quality, damages to specific parts, human safety, possible fire.
General	Thefts, damages due to animals or vandalism, extreme weather conditions, clouds variability, lightning, natural disasters, shading.	Removal of modules, physical component damage, thermal/electrical/mechanical stress and damages, loss of circuit integrity, shadings, seasonal effects.	Reduced energy output or no output, human safety.

IV. FTA AND ETA FOR RISK EVALUATION

In a system where different interconnected components function together, fault tree analysis (FTA) and event tree analysis (ETA) can be helpful in consistently and systematically identifying interdependencies in order to assess potential risks [2, 7]. Together they are normally identified as probabilistic safety assessment (PSA).

The approach will start from FTA to analyze an undesired state of the system by combining a series of lower level events, and will be completed with an ETA to quantify consequences.

The dominance of various failure risks and the categorization of events and scenarios are allowed by the evaluation of the minimal cutsets and through the use of Fussell-Vesely importance in combination with Shannon entropy.

For a fault tree, the Fussell-Vesely formula gives the importance of a basic event as the ratio between the top event unavailability based only on the minimal cutsets (MCSs) where the basic event 'i' is included, and the top event unavailability including all MCSs:

$$I_i^{FV} = \frac{Q_{TOP}(MCS_{including(i)})}{Q_{TOP}} \quad (3)$$

Shannon defined the entropy in communication theory as:

$$H = -K \sum_{i=1}^n p_i \cdot \log(p_i) \quad (4)$$

In (4) p represents the probability and K a positive constant. Quantities H "play a central role in information theory as measures of information, choice and uncertainty" [8]. Entropy allows assessing the level of disorder in the transmission of signals. On the basis of this formula Shannon could define the number of bits to be transmitted in a specific signal. Shannon's theorem is also considered by Jaynes [9] when treating probability theory. Jaynes defines probability distributions as carriers of incomplete information. The entropy H is identified as a reasonable measure of the amount of uncertainty represented by a probability distribution.

On the base of these discussions, and referring also to [10], the calculation of the Shannon entropy follows the formula:

$$|H| = |w_i \cdot q_i \cdot \ln(w_i \cdot q_i)| \quad (5)$$

In the entropy equation, q_i are probabilistic values connected to the basic event, while w_i are calculated according to the Fussell-Vesely formula. Actually, in this application, the Fussell-Vesely importance acts like a weighting factor for the corresponding basic event. The entropy evaluation gives information about the uncertainty associated with a specific element in connection to the process. In fact the evaluation considers not only the single

basic event under evaluation (with the term q_i), but also its interconnection within the process (with the term w_i).

The values resulting from the application of the Shannon entropy allow performing a relative ranking. A verbal categorization of the basic events can be done following ranking levels high (H), medium (M), and low (L). If required by the context of the application, very high (VH) and very low (VL) levels could also be introduced.

A preliminary application of the approach described in this paper (excluding the consideration of clouds variability) has given interesting results. Some relative results are shown in Table II for some failures/impact.

The qualitative results shown in Table II are just indicative of an initial evaluation still to be developed in details. However, they offer an idea of what we could expect when working in a condition of high input data uncertainty.

The possibility to use appropriate data for input in the model, would allow reaching the expected possibility of a quantitative evaluation, leading to the definition of the system performance limits as shown in Fig. 3.

TABLE II
PRELIMINARY RESULTS OF AN INITIAL PV SYSTEM PSA MODEL [11]. THE IMPACT OF EACH SINGLE FAILURE IS EVALUATED FOR INFLUENCE ON THE PRODUCTION LOSS, THE IMPACT ON THE WHOLE SYSTEM, AND THE RISK THAT THE PROBLEM IS ACTUALLY HAPPENING.

Failures	Impact on production loss	Impact on category of importance for the whole operation of the installation	Risk impact
Mechanical cell failures due to internal or external causes	Low	Medium	High
Electrical arcs	Medium	Medium	High
Grounding failure	Medium	Medium	High
Inverter	High	High	Low
Junction box failure (except arches)	High	High	Low
Mechanical support of cells	High	High	Low
Fire detection and prevention	Low	High	High

The probability derived from the PSA calculation is actually the probability of the system not being able to provide the expected performance for a certain scenario, or combination of scenarios. Thus it is:

$$p(\text{nonPR}) \equiv (1 - p(\text{PR})) \quad (6)$$

The probability used in (2) for the system being available is actually the complement to the probability of being unavailable due to malfunctions or damages.

V. CONCLUSION

The paper discusses a methodology for developing an integrated overview of the performance and reliability of a PV system. Up until this time, the paucity of comprehensive reliability data for large solar PV systems, particularly utility-scale installations, performing over a wide range of operating environments and applications, has limited the development of practical reliability models for PV systems. These efforts have been hampered by minimal access to detailed component-level reliability data. Quality data, possibly coming from the industries or research laboratories, could offer the possibility to obtain relevant results applying the approach described in this paper.

Despite the uncertainty associated with the data, useful results from the component interactions can be defined. A qualitative ranking of the basic events can be obtained, using an approach that avoids subjectivity by using the PSA-dependent Fussell-Vesely importance as a weighting factor in Shannon entropy.

The validated use of PSA techniques in the energy sector is mainly limited to the nuclear environment, with applications also in the oil and gas sector. However, such a methodology could be widely used with all energy systems and especially in the assessment of new technologies subject to accidental events.

In [12] the relevance of PSA is discussed for new applications within the nuclear field, but also for modeling risks in non-nuclear energy systems: the main result of such an analysis is the discovery that the issues encountered in the use of the PSA approach in nuclear and non-nuclear applications are similar. Additionally, the application of PSA in the PV manufacturing industry as described in [7].

In this paper, PSA is considered a tool to be used in combination with decision theory and energy technology insights in order to deal with complex issues like the energy availability for grid dispatch (a context close to security of energy supply).

It is clear that there is a variety of benefits in using PSA. First of all is the possibility to assess the level of risk associated to a certain installation; moreover, the focus on the design, identifying its weaknesses, makes PSA a valid instrument for evaluation, improvement, and training of involved human resources.

For those reasons, the probabilistic safety analysis has become an important supplement to deterministic analysis in the evaluation and improvement of the safety level of a

facility. It can be considered an added value, both for existing areas of application and for new fields.

The use of PSA, in combination with the appropriate development of key parts in the model (e.g., definition of end states), could lead to the identification of consequences and risks for a specific installation. This could give an important contribution in the evaluation of new energy systems, where incidents are maybe rare, or maybe not reported in databases, or maybe listed but not disclosed to the public; in any case, difficultly available for assessing risk.

REFERENCES

- [1] S. Hirschberg, G. Spiekerman, R. Dones, "Project GaBE: Comprehensive Assessment of Energy Systems. Severe Accidents in the Energy Sector", First edition, Paul Scherrer Institut, 1998.
- [2] H. Kumamoto, E.J. Henley, "Probabilistic Risk Assessment and Management for Engineers and Scientists", IEEE Press, 1996.
- [3] M. Mundt, S. Miller, E. Collins, J. Stein, R. Sorensen, J. Granata and M. Quintana, "Simulation of Time-Varying Throughput by Combining Availability and Solar Irradiance Models", International Applied Reliability Symposium (ARS), San Diego, California, June 7-9, 2011.
- [4] S. Kaplan and B.J. Garrick, "On The Quantitative Definition of Risk", Risk Analysis, Vol. 1, No. 1, 11-27, 1981.
- [5] International standard IEC 61724, "Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data Exchange and Analysis", 1998.
- [6] S. Kurtz, J. Granata, and M. Quintana, "Photovoltaic-Reliability R&D toward a Solar-Powered World", Society of Photographic Instrumentation Engineers (SPIE) Solar Energy and Technology Conference, San Diego, California, August 2-6, 2009.
- [7] A. Colli, D. Serbanescu, B.J.M. Ale, "PRA-Type Study Adapted to the Multi-crystalline Silicon Photovoltaic Cells Manufacture Process", in "Safety, Reliability and Risk Analysis: Theory, Methods and Applications", Martorell et al. (Eds.), Taylor & Francis Group, London, ESREL 2008.
- [8] C.E. Shannon, "A Mathematical Theory of Communication", from The Bell System Technical Journal, Vol. 27, pp. 379-423, 623-656, July, October, 1948.
- [9] E.T. Jaynes, "Probability Theory: The Logic of Science", edited by G. Larry Bretthorst, ISBN-13: 9780521592710, ISBN-10: 0521592712, DOI: 10.2277/0521592712, published April 2003.
- [10] D. Serbanescu, "A new approach to decision making in different phases of PSA studies", in proceedings of the International symposium Use of probabilistic safety assessment for operational safety PSA '91, IAEA -NEA-OECD, Vienna, 1991.
- [11] A. Colli, D. Serbanescu, "Towards reliability analysis for PV systems", presentation at the IEA PVPS Task 13 meeting in Chambéry, 25-26 October 2010.
- [12] D. Serbanescu, A. Colli, A.L. Vetere Arellano, "On some aspects related to the use of integrated risk analyses for the decision making process, including its use in the non-nuclear applications", in "Safety, Reliability and Risk Analysis: Theory, Methods and Applications", Martorell et al. (Eds.), Taylor & Francis Group, London, ISBN 978-0-415-48513-5, for ESREL 2008 & 17th SRA Europe Annual Conference, 22-25 September 2008, Valencia, Spain.