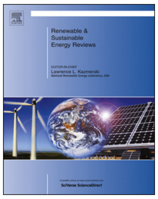
Renewable and Sustainable Energy Reviews 50 (2015) 804–809

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Failure mode and effect analysis for photovoltaic systems

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ARTICLE INFO

Article history:
Received 18 May 2014
Received in revised form
27 March 2015
Accepted 2 May 2015

Keywords:
FMEA
Photovoltaic systems
Reliability

ABSTRACT

Failure mode and effect analysis (FMEA) is an inductive and conservative system reliability analysis approach, here applied to photovoltaic system. A system is a complex combination of components and sub-components, where technical and disciplinary interfaces apply in their mutual interactions. FMEA processes the individual analysis of each system's sub-component with the task to identify the various failure modes affecting each part, along with causes and consequences for the part itself and the entire system. In the proposed analysis the system's component and sub-components have been identified from the design of the Northeast Solar Energy Research Center (NSERC) photovoltaic research array located at Brookhaven National Laboratory's (BNL). The complete FMEA analysis is presented, along with the applied ranking scales and final results. The approach is discussed in its benefits and limitations, the latter mainly identified in the limited amount of open source information concerning failure probabilities for the photovoltaic system parts.

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1. Introduction

Electric utilities and grid operators face major challenges from an accelerated evolution towards an extensive integration of variable renewable energy sources into the electric power grid, such as solar photovoltaic (PV). The integration of such a variable energy source into the existing, sometimes weak or overloaded, electric grid requires an adequate risk-informed decision making approach. The ideal grid integration design for PV systems should optimize the mutual benefits between the grid and the PV system itself; this has to take into consideration the PV source variability, availability, reliability, as well as the stability of the electric grid. The aim is to reduce or promptly intervene with outages and impairments affecting the PV system, to improve the confidence in this renewable energy source.

So far, the most of the photovoltaic-related reliability analysis has focused on modules [1] and balance of system (BOS) separately [2]. Only in recent years the shift of focus to grid integration has required considering the entire system. The purpose of this paper is to present and discuss the complete results of a failure modes and effects analysis (FMEA) developed for a PV system [3]. To the author's knowledge, there are no complete and detailed FMEA analyses for PV systems including risk ranking information published to date. This work represents part of the background investigations needed to develop a probabilistic risk analysis (PRA) for PV systems [4], to investigate safety-related and energy-production-related risks. For this reason, the FMEA has been preferred to other methods, such as Taguchi [5,6].

The system under analysis is a simplified model having all the principal components and sub-components as from the design of the Brookhaven National Laboratory's (BNL) Northeast Solar Energy Research Center (NSERC) research array. The analysis aims

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http://dx.doi.org/10.1016/j.rser.2015.05.056
1364-0321/

to identify the failure modes affecting the system's sub-components and to list possible causes and effects.

Despite the approach is now common for PV applications, FMEA analyses have been performed in other renewable energy areas, such as wind energy [7,8].

2. The FMEA process

Failure modes and effects analysis (FMEA) is an established semi-qualitative reliability engineering approach to systematically evaluating system design on a component-by-component basis to identify failure modes and their effects on system function and other system components. It can support fault tolerant design, testability, safety, logistic support and related functions. This bottom-up technique has been an essential tool for industries such as the aerospace and automobile industries, the semiconductor industry [9], and the nuclear industry [10,11]. Government agencies (such as the Air Force and the Navy) require that an FMEA is performed on their systems to ensure safety as well as reliability. The automotive industry has adopted the use of FMEA to support the design and manufacturing/assembly of automobiles.

Kumamoto and Henley [12] recommend several uses for the FMEA:

1) Identification of critical components for fail-safe design, failure-rate reduction or damage containment.
2) Identification of components requiring particularly stringent quality control.
3) Formulation of special requirements to be included in specifications for suppliers.
4) Formulation of special procedures, safeguards, protective equipment, monitoring or warning systems.
5) Distribution of project funds across these areas.

Although there are various types of FMEA (design, manufacturing process, equipment, system) and for different applications (hardware to software), the principal aim of this approach is to support the early identification of potential problems and address them before accidents happen.

The FMEA presented in this work has the task to identify failure modes along with possible causes and effects for a grid-connected PV plant. The FMEA process followed along this study is shown by the block diagram in Fig. 1. It requires to identify the system model, its components, sub-components, requirements, descriptions, and, when useful, also functional diagrams. Failure modes are investigated at the system's sub-component level, according to the desired level of depth in the analysis. For each failure mode a severity (S), occurrence (O) and detection (D) rating is defined and rated according to subjectively defined scales, based on available information and supported by expert opinion and evaluation. The rating system involves expert opinion and a level of subjectivity which is typical of rating systems based on a scales defined by the user.

The combination of the three ratings defines an overall risk measure, the risk priority number (RPN), which indicates the relevance of each failure mode in affecting the PV system. Villacourt [13] describes this approach in relation to the semiconductor industry. The RPN is calculated for each failure mode according to the following equation [5,6, 13, 14]:

$$\text{RPN} = S \times O \times D \tag{1}$$

A high RPN is a critical indicator for corrective action considerations on identified sub-components. The RPN simplifies the computation of the criticality number adopted in the failure mode effect and criticality analysis (FMECA) by requiring only the probability of failure (occurrence) and the severity classification; however, the RPN extends the criticality number approach by incorporating the detection likelihood rating. This is crucial in evaluating PV systems since system downtime directly leads to power supply interruption and financial losses when energy purchase agreements or feed-in tariffs are in place. Thus, quick, efficient detection of failures is critical, and the RPN is implemented such that the detection of failures is a conscious goal of the FMEA application.

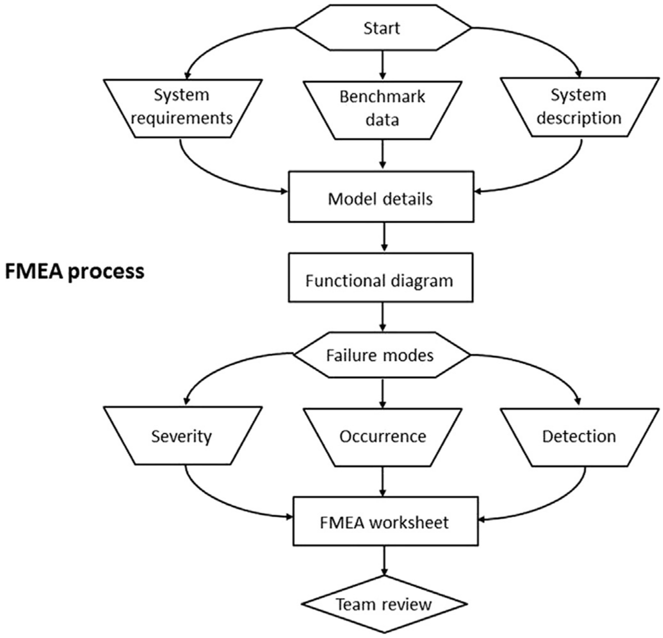

Fig. 1. Block diagram representing the FMEA process followed along this study.

The FMEA is a systematic, inductive, and conservative technique for failure analysis and it is here performed ahead of the development of more complex system-level methods such as fault trees (FT) and event trees (ET) analysis, combined into the probabilistic risk analysis (PRA). In further research developments at BNL, we will use the FMEA primarily as an investigation to support the development of a PRA model and identify elements and failures to be represented in the PRA in relation to the rest of the system. A fundamental difference between the FMEA and PRA is actually that the former is focusing on individual components, while the latter is modeling the interactions between components in the entire system, thus providing a holistic overview.

3. The system model and its components

To perform the FMEA analysis, the PV system will be represented by a simplified model reporting all the components as by design. Fig. 2 shows the simplified model used for the FMEA and based on the BNL's NSERC photovoltaic research array configuration. The diagram shows that the system is mainly built in 3 blocks: (i) source system, (ii) string combiner, and (iii) power conditioning system.

The NSERC array design is in real much more complex than the simplified model shown in Fig. 2, which has the only purpose of identifying the sub-components to consider in the FMEA. In its present development the NSERC array reaches a rated power of 518 kW_p and includes a total of 1672 PV modules, rated 310 W_p each. The modules are arranged in strings of 19 modules each. Combiner boxes merge 11 strings to reach the input of a single inverter's module. The 3 plant inverters are actually modular, and allow the independent management of each set of 11 strings. All