Energy 93 (2015) 1308–1320

Contents lists available at ScienceDirect

Energy

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

A framework for the reliability evaluation of grid-connected photovoltaic systems in the presence of intermittent faults

Baoping Cai [a, b, *], Yonghong Liu [a], Yunpeng Ma [a], Lei Huang [a], Zengkai Liu [a]

[a] College of Mechanical and Electronic Engineering, China University of Petroleum, Qingdao, Shandong 266580, China
[b] Department of Systems Engineering and Engineering Management, City University of Hong Kong, Kowloon, Hong Kong

A R T I C L E I N F O

Article history:
Received 9 June 2015
Received in revised form
8 October 2015
Accepted 18 October 2015
Available online 6 November 2015

Keywords:
Dynamic Bayesian networks
Reliability evaluation
Intermittent faults
Photovoltaic systems

A B S T R A C T

A framework for the reliability evaluation of grid-connected PV (photovoltaic) systems with intermittent faults is proposed using DBNs (dynamic Bayesian networks). A three-state Markov model is constructed to represent the state transition relationship of no faults, intermittent faults, and permanent faults for PV components. The model is subsequently fused into the DBNs. The reliability and availability of three simple PV systems with centralized, string, and multistring configurations, as well as a complex PV system, are analyzed through the proposed framework. The sequence of the degree of importance of PV components is investigated using mutual information. The effects of intermittent fault parameters, including the coefficients of intermittent fault, permanent fault, and intermittent repair, on the reliability and availability are explored. Results show that the reliability and availability of the PV system with centralized configuration rapidly decrease, compared with those of the PV systems with string and multistring configurations. The sequence of the degree of importance of PV components is DC/AC inverter, DC/DC converter, DC combiner, and PV module arranged from the largest to the smallest. The finding indicates that the DC/AC inverter should be given considerable attention to improve the reliability and availability and to prevent their possible failures.

1. Introduction

Given the concerns about increasing environmental problems, the development and application of grid-connected PV (photovoltaic) power systems to reduce fossil fuel consumption and greenhouse gas emissions have aroused a great deal of interest [1–4]. However, PV systems usually work in extreme conditions, (e.g., desert), and the modules and balance-of-system components of these systems deteriorate because of environmental and operational stresses [5–7]. Therefore, the reliability and availability of these systems need to be quantitatively predicted.

A few studies have evaluated the reliability and availability of PV systems and their components using general reliability analysis methods, such as fault tree, Monte Carlo simulation, Petri nets, and Markov models. Each of these methods has its advantages and disadvantages in terms of reliability evaluation. Gautam et al. investigate the operational lifetime of large solar PV arrays for reliability evaluation with probability theory [8]. Urbina et al. analyze the reliability of a rechargeable battery in a PV power supply system; they construct the model by integrating artificial neural network to simulate the damage that occurs in deep discharge cycles [9]. For the simple configurations of PV systems, reliability function is derived for quantitative analysis to obtain failure rate, probability density function, and average useful life [10,11]. Chan et al. propose a method for optimizing the reliability of inverters in grid-connected PV systems using the design-of-experiments technique [12]. Monte Carlo simulation was also used to evaluate the reliability of a small isolated power system with solar photovoltaic and the customers' nodal reliability and reserve deployment with high PV power penetration [13–15]. Harb et al. introduce a stress-factor reliability method to calculate the mean time between failures of a PV module-integrated inverter using a usage model approach [16]. Zhang et al. present a systematic technique for assessing the reliability of grid-connected PV power systems with a state enumeration method by considering the variations of failure rate and the input power of components

* Corresponding author. College of Mechanical and Electronic Engineering, China University of Petroleum, Qingdao, Shandong 266580, China. Tel.: +86 0532 86983505x8701, +852 5226 4360.
E-mail addresses: caibaoping@upc.edu.cn, baoping.cai@cityu.edu.hk (B. Cai).

http://dx.doi.org/10.1016/j.energy.2015.10.068
0360-5442/

[17]. Katsigiannis et al. propose a fluid stochastic Petri nets-based method for the reliability assessment of small isolated power systems, including wind turbines, PV, and diesel generators [18]. Zini et al. present a method based on fault tree to evaluate the reliability evaluation of large-scale grid-connected PV systems; these researchers look into the effects of PV components on system reliability to improve the performance of diagnosis and maintenance [19,20]. Markov method was also used to evaluate the reliability and performance of standalone PV systems, grid-connected PV systems, and multiphase DC/DC converters deployed in PV applications [21–23].

An intermittent fault is a recurrent event that appears and disappears with the changes in operation conditions. Some functions or performance characteristics fail for a while, but they subsequently recover [24]. Intermittent fault strongly affects the reliability of electronic products, such as DC combiner, DC/DC converter, and DC/AC inverter, deployed in PV applications. In the past three decades, few studies have reported on reliability modeling and evaluation in the presence of intermittent faults. Prasad develops a Markov model for the reliability assessment of digital system subject to intermittent and permanent faults [25,26]. Considering the influences of permanent and intermittent faults, Cheng et al. present a reliability evaluation method using an improved neural network training algorithm and architecture [27]. In view of the influences of permanent and intermittent faults, Habib et al. introduce a neural network-based Markov and fault-tolerant model for the reliability assessment of a consecutive r-out-of-n: F system a consecutive *r*-out-of-*n*: F system [28]. The influences of the high occurrence rates of transient and intermittent faults on a microprocessor have also been examined using the generalized stochastic Petri net modeling [29].

BN (Bayesian network) and DBNs (dynamic BNs) are probabilistic graphical models that represent a set of random variables, including their conditional dependencies through directed acyclic graphs [48]. Since these models were first proposed by Pearl [49], they have been considered powerful tools for handling uncertainty information and have therefore received increasing attention in the field of reliability evaluation. Our previous work systematically investigates the reliability modeling and evaluation methodology using BNs and DBNs taking into account common cause failure, imperfect coverage, imperfect repair, and preventive maintenance [30–32]. However, to the best of our knowledge, the application of either BNs or DBNs to the evaluation of the reliability of grid-connected PV systems, especially in the presence of intermittent faults, has not been reported. Correspondingly, many critical issues on this subject should be investigated.

This study focuses on the reliability and availability evaluation of grid-connected PV systems in the presence of intermittent faults using the DBNs method. The rest of the paper organized into five sections. Following the Introduction, Section 2 describes the configuration of grid-connected PV systems. Section 3 develops the DBN-based framework for the reliability evaluation of PV systems. Section 4 presents the reliability evaluation results and discussions. Finally, Section 5 summarizes the whole study.

2. Description of grid-connected PV systems

A grid-connected PV system consists of PV modules and balance-of-system components. The PV modules can be arranged in different configurations that directly affect the structure and topology of the balance-of-system electronic components [33,50,51]. Different configurations of PV modules have been proposed during in the past, such as centralized, string, multistring, and modular configurations [34–36]. The balance-of-system components of PV systems include string protection, DC combiner, DC/DC converter, DC/AC inverter, DC disconnect, AC disconnect, grid protection, and others [6,19,37–39,41].

In this study, three PV system configurations, i.e., centralized, string, and multistring configurations, are analyzed to compare their respective system reliabilities in the context of intermittent faults of electronic components. For simplicity, only a few electronic devices are considered, including PV module, DC combiner, DC/DC converter and DC/AC inverter [42]. Other electronic devices, such as controller, DC disconnect, AC disconnect, grid protection, are excluded from the study, as shown in Fig. 1.

For example, in consideration of the PV system with a centralized configuration illustrated in Fig. 1(a), the PV array composed of two strings of two modules each connects a series-parallel configuration. Subsequently, the DC voltage level is combined together in a DC combiner, converted from DC to DC in a DC/DC converter and from DC to AC in a DC/AC inverter, and is finally fed into the electricity grid system. A centralized configuration is mainly used in PV plants, which have a nominal power higher than 10 kW, a high power conversion efficiency, and low cost. However, the MPPT (maximum power point tracking) efficiency of this central structure sharply decreases in a partial shading condition because it can hardly individually draw the maximum power from each module, thereby decreasing total efficiency [34].

PV module is the packaged, connected assembly of PV cells and is considered the most reliable component in PV systems [6]. DC combiner is used to combine multiple source circuits into a single source, which consists of various electronic devices, e.g., PV fuse, string sensor, DC surge protector, signal surge protector, etc. DC/DC converter and DC/AC inverter are among the vulnerable components in PV systems because they contain semiconductor modules. These components connect the switching components and capacitors. All these components, i.e., PV module, DC combiner, DC/DC converter, and DC/AC inverters, suffer permanent and intermittent faults, which seriously affect the reliability of PV system.

String configuration can connect different PV modules of the same type in every string. If the string voltage does not have the appropriate value, then a boost DC/DC converter or a step-up transformer (usually placed on the AC side) is required [33]. Fig. 1(b) provides a simple PV system with string configuration. The distinguishing feature of this system is that each string has its own DC/DC converter to convert the voltage level and DC/AC inverter to convert DC electricity into an AC output. If a centralized system has the same total capacity as an *n*-string PV system, then the capacity of each string converter and inverter is only one-*n*th of that of the centralized converter and inverter. This event leads to failure rate that significantly varies for different converter and inverter. Fig. 1(c) illustrates a PV system with multistring configuration, wherein the string has its own DC/DC converter to convert the voltage level, but only has one DC/AC converter to convert the DC electricity into an AC output. The string and multistring structures have been used in low power ranges because of their enhanced MPPT efficiency. However, in these configurations, the electrical characteristic difference resulting from PV module's tolerance, partial shading, and reflection problems still hinders the maximum power generation of each module [34].

In this study, a complex system is used to demonstrate the proposed methodology. As shown in Fig. 2, the system comprises a micro-inverter PV system and two strings. The micro-inverter and PV module are integrated as one electrical device, which is directly connected to a distribution grid through an AC bus. The micro-inverter system is adopted to achieve high modularity, easy installation, and enhanced safety. The two PV strings are connected to an AC combiner.