Front. Energy 2016, 10(2): 125–135
DOI 10.1007/s11708-015-0392-4

RESEARCH ARTICLE

Amir AHADI, Hosein HAYATI, Seyed Mohsen MIRYOUSEFI AVAL

Reliability evaluation of future photovoltaic systems with smart operation strategy

Abstract This paper investigates a new operation strategy for photovoltaic (PV) systems, which improves the overall reliability of the system as a result of the improvement in the reliability of the critical components. First, a mathematical model is proposed using the fault tree analysis (FTA) to estimate the reliability of the PV systems in order to find the suitable maintenance strategies. The implementations demonstrate that it is essential to employ smart maintenance plans and monitor the identified most critical components of PV systems. Then, an innovative analytical method based on the Markov process is presented to model smart operation plans in PV systems. The impact of smart operation strategy on the PV systems is then evaluated. The objective of this paper is to develop plans for improving the reliability of PV systems. A series of case studies have been conducted to demonstrate the importance of smart operation strategies for PV systems as well as the applicability and feasibility of the proposed method.

Keywords smart operation strategy, renewable energy, fault tree analysis (FTA), Markov model

1 Introduction

Due to the fluctuation in fuel prices as well as the major part fossil fuels played in environmental pollutions, renewable energy sources are becoming more popular [1]. These types of alternative sources have the potential to replace the existing fossil fuel. Therefore, renewable energy sources with green electricity generation are highly sought after. So far, solar energy has proved more practical compared to other types of renewable energy sources such as wind, hydro, wave and tidal energies.

Cost-reduction in production of PV modules, economic incentives that government offers and recent improvements in PV systems and their reliability will not only add to the speed of capacity increment of installed PV systems in the close future, but also make them more preferable in competitive energy market [2]. However, for several reasons, the reliability of the PV systems has been an issue for over a decade. Due to the complex nature of PV systems, the quantification of the reliability of an entirely PV generated station is yet to be solved [3,4]. The reliability of PV systems has attracted a lot of attention in recent years due to the meteoric growth of PV power installation in residential and commercial buildings as well as military bases [5]. Because of the various components with high malfunctioning probability (e.g. inverter), PV systems tend to fail much often [6]. Moreover, owning to the limited and intermittent nature of the energy source for PV systems, the reliability of the energy output from these systems is degraded [7]. The reliability preference of customers has also a great impact on the utilization of PV power [8]. Most of the components of a PV power system are vulnerable to working condition and their life-cycle is highly dependent on loads and ambient conditions [9]. However, new development makes it possible to design improved, innovative, smarter and more efficient systems. Smart operation strategies (e.g. smart monitoring) are one of these new developments aimed at overcoming issue of enormous and complex gird and satisfy consumers who require uninterrupted reliable service and do not tolerate any inconvenience. Smart monitoring is technically a system that makes use of two-way communications, sensing, and control technologies to better control the power system. One of the challenges is to improve the reliability of PV systems by use of smart monitoring, so that it continues its uninterrupted service for longer period of time [10]. Smart monitoring is a method that qualifies for this requirement. Smart monitoring with its enhanced

Received December 27, 2014; accepted April 16, 2015

Amir AHADI (✉), Hosein HAYATI, Seyed Mohsen MIRYOUSEFI AVAL
Young Researchers and Elite Club, Ardabil Branch, Islamic Azad University, Ardabil 5615731567, Iran
E-mail: amirahadi8@gmail.com

control and monitoring infrastructure provides a new kind of power management and is the best solution to problems of renewable energy and specially PV power generation plants. Some of the major advantages of smart monitoring are better compatibility with distributed energy production, ability to make use of renewable energy in large capacity, real time monitoring, demand response, self-healing and better communication to match the generation with demand [11]. Using secure and real time data flow, smart monitoring is able to improve the reliability of PV systems with proper decisions. Considering that the new smart plans such as smart monitoring is the real control system for future of PV systems, current techniques for assessment of the reliability of PV systems should be made compatible with them.

A lot of researches have been conducted and many papers have been presented in the field of reliability analysis of power system including renewable energy sources. For instance, issues of optimizing the use of isolated small PV generators have been discussed in Ref. [12]. The system level models for the reliability of PV systems using the Markov modeling concept was presented in Ref. [13]. In Ref. [14], a hierarchical reliability block diagram was developed to model the behavior of the PV system. In Ref. [15], Monte Carlo simulation was used to quantify the impact of inverter failure on total lifetime of a PV system. A technique called Latin hypercube sampling (LHS) was proposed in Ref. [16] to improve computation speed for obtaining the reliability indices. In this method, the failure rates of electronic elements in a PV system are treated as constants. However, these parameters actually vary with system states including solar insolation, ambient temperature, and load level [17]. There are many reliability modeling concepts for PV systems such as fault tree analysis (FTA), Monte Carlo, and Markov methods. FTA and reliability block diagram (RBD) schemes in assessment of a standalone PV system were investigated in Ref. [18]. In Ref. [19], the Monte Carlo method was proposed to calculate the optimum PV and battery size for a desired reliability taking account of the uncertainty of solar resource. This method was also used in Ref. [20] to conduct a more complex simulation such as a PV/wind hybrid system. The simulation of the stochastic behavior of a system in Markovian models was conducted by simulating the state change process as a Markov random process [21]. Markov reward models are used in a proposed method, which integrates the performance and reliability of an on-grid PV system in Ref. [8], with the assumption of only two different failure modes including string block and inverter failures. The Markov method is used to predict the radiation pattern of the sun by making use of the solar data from Corsica for over a 20-year period in Ref. [22]. The overall reliability of large-scale, grid-connected PV systems was studied in Ref. [23].

In the technical literature, several methods have been proposed based on the monitoring of the components of electrical distribution systems (eg. Ref. [24].). Although a wide variety of studies have been conducted on this topic, the real electrical architecture of modern large-scale, grid-connected PV systems employing smart monitoring requires further consideration.

This paper extends the analysis given in Refs. [11,23], and proposes a novel technique to evaluate the impact of smart monitoring on large-scale, grid-connected PV systems using the Markov method.

2 Overview of PV wireless remote monitoring and control system

Since the monitoring of photovoltaic systems is an essential part of the evaluation of the overall reliability of systems, a proper communication medium with high reliability is required to transfer critical information to and from components in order to control and monitor system status. Both wired and wireless communication technology is used in smart monitoring [25]. However, newer versions of wireless communication system have advantages of inexpensive product and installation, rapid deployment, widespread access, and mobile communication over wired and even older wireless technologies. Wireless communications used to have slower data rate, interference issues, and security concerns compared to wired communication, but several actions are initiated to address these issues [26]. Using smart monitoring, real-time component status is transmitted to data management and control center. Smart monitoring offers real-time monitoring, fault alarm, data analysis, and useful information which provide us with more control over photovoltaic system. Component failure (e.g. malfunctioning caused by aging and severe weather) might lead the system to blackout which, in turn, can damage industrial section and cause massive economical losses. Present control scheme [27] which is depicted in Fig. 1 requires a technician to be physically present in the electrical site and detect the failed component with his eyes and analyze the system state based on his experience and assumptions which can be time consuming and with error. However, as shown in Fig. 2, smart monitoring provides useful tools for advanced communication between management and components status through wired communications, satellite communication, wireless sensor networks (WSNs), or wireless automatic meter reading (WAMR) to prevent, predict or alarm components failure. Each communication system has its own pros and cons and the discussion of this problem is outside the scope of this paper. The PV systems components are exposed to climate change, unpredicted events, and degradation caused by aging effects, which will eventually lead to component failure and interruption in the system [23]. Thus, the PV system components should be permanently monitored.

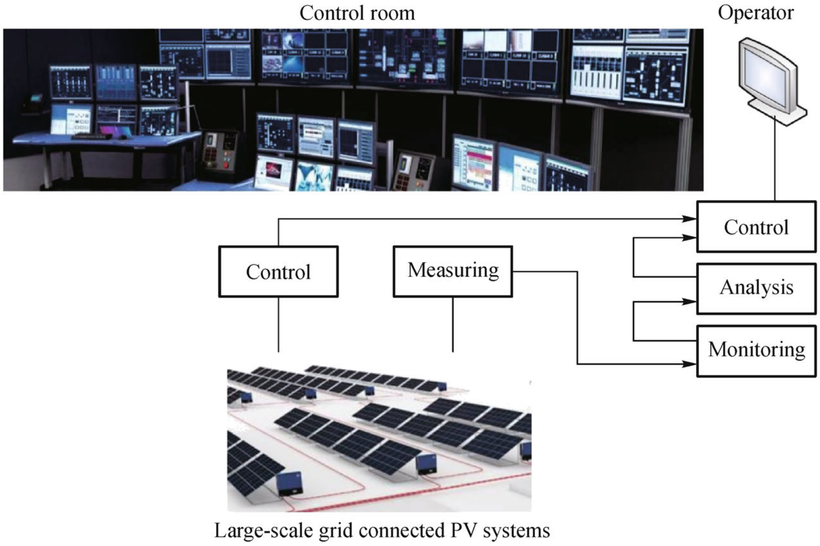

Fig. 1 Large-scale grid connected PV systems control scheme

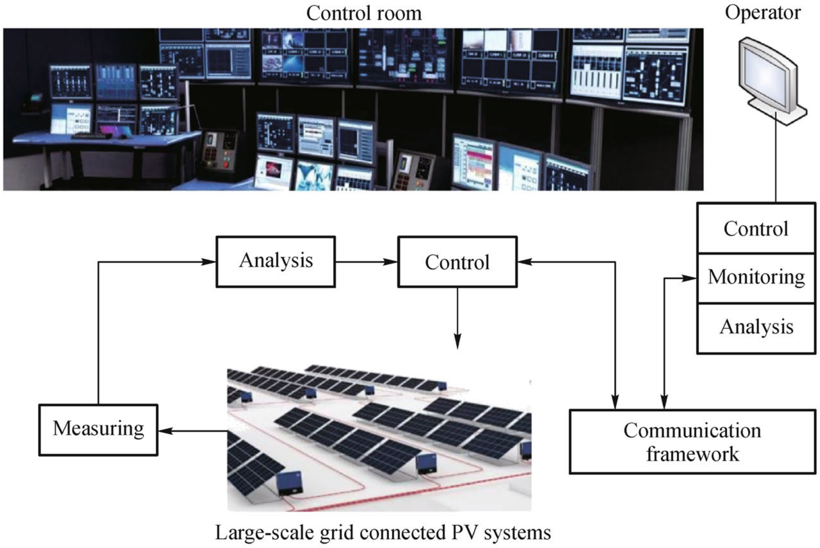

Fig. 2 Smart monitoring application for large-scale grid connected PV systems

3 Reliability analysis of PV systems

3.1 A general solution for reliability of PV systems

Fault tree analysis (FTA), which is a graphical design method based on minimal cut set is used to evaluate reliability of large-scale grid-connected PV systems. This method consists of drawing of a flowchart and association of every effective component on the reliability of the overall system to the top event. Minimal cut set is a method to translate the information in the FTA flowchart into equations and to obtain an overall percentage of the reliability of the system. FTA serves as a useful tool for calculating the probability of system failures by estimating the reliability and availability of the components within the system. The basic principle of the FTA method is the identification of undesired events and weather effects associated with undesired states (e.g. component failure). The undesired states of the system are shown by a rectangle which indicates a top event. A system may have more than one top event. The top event appears in a box that represents the failure event under investigation. For instance, the fact that “Energy reduces if solar radiation is reduced” is determined as a top event in this paper. By definition, a cut set represents a direct relation between basic events and the top event. A minimal cut set, in general, is the shortest path from a basic event to the top event. However, in this paper, it is defined as the component failure (i.e., basic event) with the highest effect on the overall system failure (i.e., top event). In other word, if one or all of the components are unavailable, a minimal cut set will cause the top event to occur. If all basic components are available, the top event will not occur. The minimal cut set is unique and finite for any fault tree.

Based on the theory of probability and the minimal cut set, the reliability of the total system can be calculated using Eq. (1) [23],

$$R_{\text{tot}} = \exp\left(\sum_{i=1}^{n} m_i \lambda_i t_i\right), \tag{1}$$

where m_i is the total number of components, λ_i is the failure rate of component i, n is the total number of different components, and t is the study time of reliability analysis.

3.2 Reliability models of components with smart operation strategy

To analyze the advantages of implementing smart monitoring on the reliability of PV systems, with and without monitoring failure, a mathematical method based on the Markov chain is used. Correction and prevention measures of monitoring can help maintain the reliability of the grid, prevention measure of smart monitoring also decreases failure rate and repair time by creating new up state (Up) and down state (Dn) respectively, which, in turn, prevents dreadful failures and long-time blackouts. By creating the new Dn as well as higher repair rate, which means improved repair time, the correction quality of smart monitoring can help the operator to detect failure quickly and accurately [11]. New constant state states are created by smart monitoring according to the type of maintenance used. The Markov method is used to analyze the reliability of PV systems in terms of using smart monitoring.

The state-space diagram of the smart monitoring states is illustrated in Fig. 3. The approach in Ref. [11] is used to investigate the impact of monitoring on an electric distribution system.

The total availability by employing smart monitoring with n new states from the Markov chain can be obtained using

$$P_{\text{sm}} = \sum_{i=1}^{n-1} P_i, \tag{2}$$

where n refers to a part of the components which are not considered to be monitored, P_{sm} is the reliability of the component with smart monitoring, and P_i is the reliability of the component being in state i.

The failure rate with smart monitoring (λ_{sm}) can be presented by

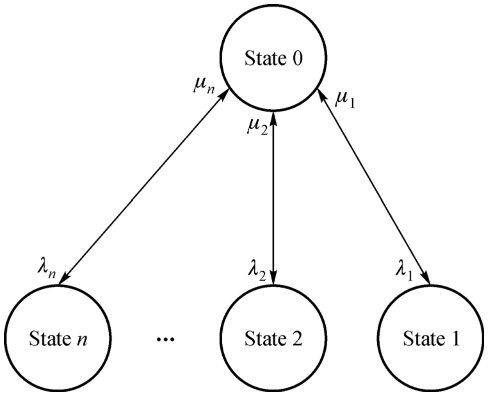

Fig. 3 Markov model for component of PV systems with smart operation strategy

$$\lambda_{\text{sm}} = \lambda_n, \tag{3}$$

where λ_n is the failure rate for the state n.

Furthermore, smart monitoring failures could be considered with a specific reliability model as

$$P'_{\text{sm}} \overset{\text{def}}{=} \{P_{\text{sm}} | \text{Smart monitoring success}\} + \{P_0 | \text{Smart monitoring unsuccess}\}. \tag{4}$$

The reliability model indicates $P'_{\text{sm}} = P_{\text{sm}}$, if smart monitoring is completely available. In other words, smart monitoring unavailability is equal to 0 (P_{u} = 0), and $P'_{\text{sm}} = P_0$, if this system encounters with one various failures and becomes fully unavailable or in other words (P_{u} = 1). This behavior can also be mathematically presented as

$$P'_{\text{sm}} = P_0 \times P_{\text{u}} + P_{\text{sm}} \times (1 - P_{\text{u}}). \tag{5}$$

The failure rate with monitoring failure can be calculated using

$$\lambda'_{\text{sm}} = \left[P_{\text{u}} \times \sum_{i=1}^{n-1} \lambda_i\right] + \lambda_n, \tag{6}$$

where λ'_{sm} is the failure rate with monitoring failure.

Moreover, the failure rate decrement can be expressed as

$$R_{\lambda} = \frac{\lambda_{\text{sm}}}{\lambda_0}. \tag{7}$$

All the smart monitoring techniques with reliability aspects are depicted in Fig. 4.

4 System under study

To calculate the reliability of the overall system, seven large-scale PV systems [23] with a nominal output power from 100 kW to 2500 kW, whose electrical structure is demonstrated in Fig. 5, are used. All of the systems are identical in PV module and inverter characteristics as listed in Ref. [23]. Increasing the nominal output power of the system requires more components. In Table 1, a number of PV systems with different nominal power output and the number of required components for each one are listed. The reliability of all seven PV systems was analyzed over one year and twenty years of operation with 8.5 h of operation per day. The failure rates for all of the components are in unit of failure/hour and listed in Table 2. The failure rates of SPDs are not taken into account for their negligible magnitudes.

5 Case studies and discussion

The FTA and the Markov method are used in the case studies to show the practicality of the proposed method.

5.1 Case study 1: Reliability estimation of large-scale PV systems using FTA

This case study aims to evaluate the reliability of large-scale PV systems and help identify the most critical PV system components. A mathematical model for cut sets is presented using the FTA. Such methods significantly help convert fault trees into Boolean models and mathematical equations. Table 3 represents the reliability of the overall system for one year as well as for 20 years of operations. It can be clearly seen that the reliabilities of the component decrease as the PV power output increases. Furthermore, the probability of 0% means that there is one top event which causes the overall system to go to the failure state. From Table 3 and the method described in the previous section, the most critical components can be extracted. The list of critical components and their solutions are reported in Table 4 in the order of the influence they have on the overall reliability of the system. The component with more failure rate should be quickly repaired or replaced after the

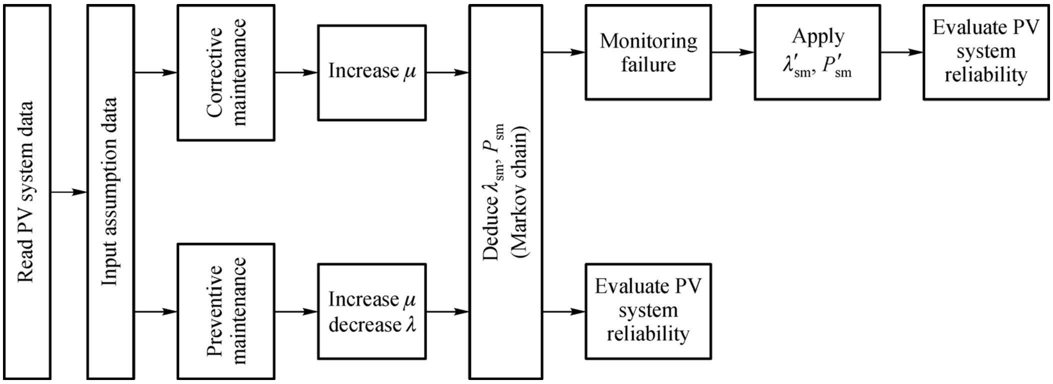

Fig. 4 Flowchart for PV system reliability assessment with smart operation strategy

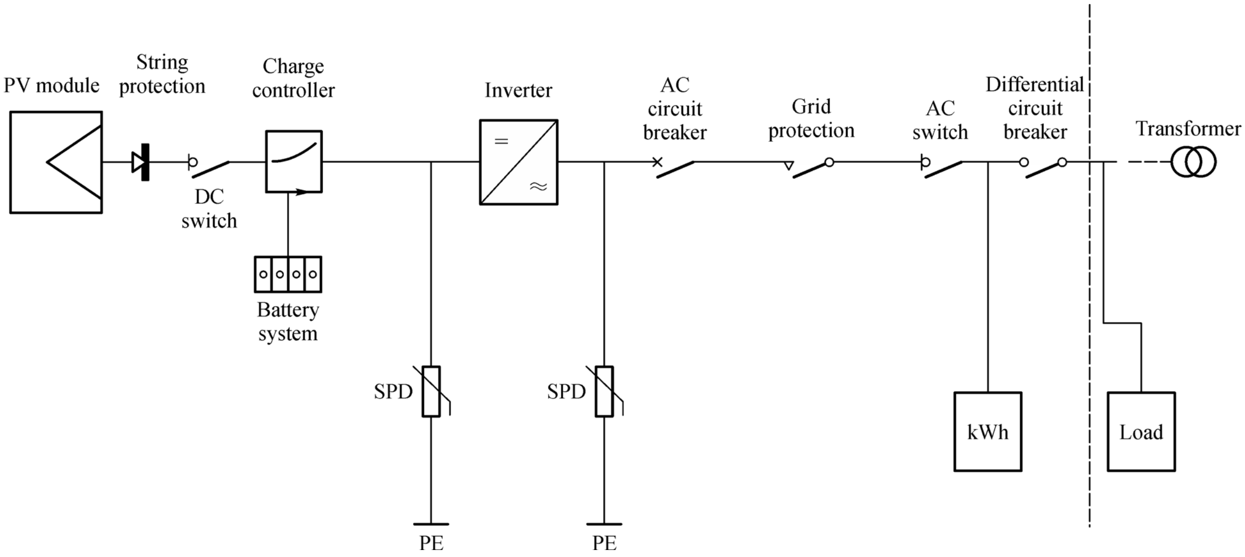

Fig. 5 Single line diagram of system under study

Table 1 Number of components for each PV system

Component	Power/kW						
	100	200	500	1000	1500	2000	2500
PV modules	437	874	2166	4351	6517	8702	10868
String protection	23	46	114	229	343	458	572
DC switch	3	6	15	27	42	57	72
Inverter	1	2	5	9	14	19	24
AC circuit breaker	1	2	5	9	14	19	24
Grid protection	1	1	1	1	1	1	1
AC switch	1	1	1	1	1	1	1
Differential circuit breaker	1	1	1	1	1	1	1
Connector (couple)	874	1748	4332	8702	13034	17404	21736
Battery system	16	30	76	150	224	298	372
Charge controller	1	1	1	1	1	1	1

Table 2 Component failure rates

Component	Failure rate/$10^{-6}h^{-1}$	Reference
PV modules	0.0152	[28]
String protection	0.313	[29] Sect.6-2
DC switch	0.2	[29] Sect.22-1
Inverter	40.29	[23]
AC circuit breaker	5.712	[29] Sect.14-5
Grid protection	5.712	[29] Sect.14-5
AC switch	0.034	[29] Sect.14-1
Differential circuit breaker	5.712	[29] Sect.14-5
Connector (couple)	0.00024	[29] Sect.17-1
Battery system	10.9589	[30]
Charge controller	5.4794	[30]

failure occurs. Although the monitoring of all components of the PV system can improve the reliability of the system, it is neither economical nor practical. So a component with the most critical failure status and expense has to be chosen. The solar inverter qualifies for this category which also may be totally unavailable under long-term operations as reported in Table 4. Several mentioned reasons for the advantages of implementing smart monitoring of the solar inverter are the case studies of this paper.

5.2 Case study 2: Markov model for solar inverter with smart operation strategy

The solar inverter is one of the most important, expensive, and complex components in a PV system which may fail due to component failures and aging as follows:

1) Capacitor failures: Voltage stress, continuous operation under maximum voltage conditions, frequent short-term voltage transients, current stress, internal temperature increment due to continuous high current flow, thermal stress on component terminals, improper charge and discharge rates, operating in improper temperature, mechanical stress, and vibrations.

2) Inverter bridge failures: Operation beyond its rated operating limit, over-current and overvoltage, thermal shock, thermal overload, extremely cold operating temperature, and other malfunctioning components.

3) Mechanical failures: Component stress, contamination at contacts, and extreme temperature condition.

In this case study, the failure statuses of the capacitor and inverter bridge are monitored. Table 5 lists the failure distribution to different parts of a solar inverter. As shown in Table 5, the ratio of failure for the capacitor is greater than that of other parts. The Markov model of the inverter with 4 monitoring states is displayed in Fig. 6. The failure rates of the inverter could be calculated from Table 5. The failure rate of the inverter without smart monitoring is

Table 3 Reliability of overall system for a period of 1 year and 20 years of operations

Reliability	Power/kW						
	100	200	500	1000	1500	2000	2500
1 year/%	78.3716	64.9282	36.9896	16.6818	6.5229	2.5457	0.9954
20 years/%	0.7641	0.0177	0	0	0	0	0

Table 4 Critical component priorities

Priority	Component	Reliability status	Coordinated maintenance
1	Inverter	Critical	Continuously maintenance
2	String protection	Intense	Continuously & Periodical maintenance
3	PV modules	Critical	Continuously maintenance
4	AC circuit breaker	Critical	Continuously maintenance
5	DC switch	Normal	Periodical maintenance
6	Charge controller	Normal	Periodical maintenance
7	Grid protection	Normal	Periodical maintenance
8	Differential circuit breaker	Normal	Periodical maintenance
9	Connector (couple)	Normal	Periodical maintenance
10	AC switch	Normal	Periodical maintenance
11	Battery system	Normal	Periodical maintenance

Table 5 Ratio of failure for solar inverters

Type of failure	Failure rate/%
Capacitor failure	60
Inverter bridge failure	35
Mechanical failure	5

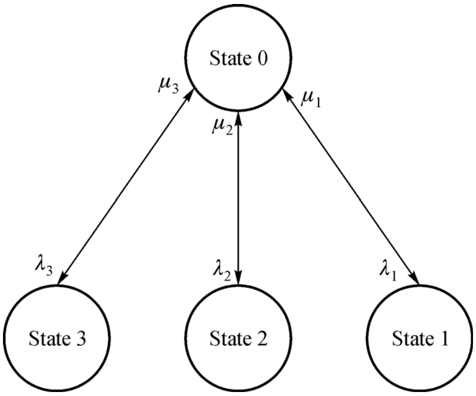

Fig. 6 Markov chain for solar inverter

40.29×10^{-6} failures/hour. From the Markov chain, λ_1, λ_2, λ_3, λ_4, and the repair rate of the inverter can be obtained considering 24 h of maintenance because of the forced outage and 12 h for preventive actions, as reported in Table 6. In this section, the availability and the failure rate of the inverter with smart monitoring are evaluated using the previous equations. Following this, the reliability of the overall PV system and the availability of the inverter in presence with monitoring are estimated. The steady-state probability with the inverter monitoring for 3 new states using the Markov method can be obtained as

$$\begin{pmatrix} \mathrm{d}P_0/\mathrm{d}t \\ \mathrm{d}P_1/\mathrm{d}t \\ \mathrm{d}P_2/\mathrm{d}t \\ \mathrm{d}P_3/\mathrm{d}t \end{pmatrix} = \begin{pmatrix} -(\lambda_1+\lambda_2+\lambda_3) & \mu_1 & \mu_2 & \mu_3 \\ \lambda_1 & -\mu_1 & 0 & 0 \\ \lambda_2 & 0 & -\mu_2 & 0 \\ \lambda_3 & 0 & 0 & -\mu_3 \end{pmatrix} \begin{pmatrix} P_0(t) \\ P_1(t) \\ P_2(t) \\ P_3(t) \end{pmatrix}. \tag{8}$$

Table 6 Failure and repair rates for solar inverter

State	Failure rate/$10^{-6}\mathrm{h}^{-1}$	Repair rate/failure$\cdot\mathrm{h}^{-1}$
State 0	$\lambda_0 = 40.29$	$\mu_0 = 0.04166$
State 1	$\lambda_1 = 24.174$	$\mu_1 = 0.0833$
State 2	$\lambda_2 = 14.1015$	$\mu_2 = 0.0833$
State 3	$\lambda_3 = 2.0145$	$\mu_3 = 0.04166$

Further simplifications based on the frequency balance approach in Ref. [31] can be expressed as

$$\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ \lambda_1 & -\mu_1 & 0 & 0 \\ \lambda_2 & 0 & -\mu_2 & 0 \\ \lambda_3 & 0 & 0 & -\mu_3 \end{pmatrix} \times \begin{pmatrix} P_0(t) \\ P_1(t) \\ P_2(t) \\ P_3(t) \end{pmatrix}. \tag{9}$$

From the transition rates listed above, state probabilities are deduced to be

$$P_0 = 0.0020,\ P_1 = 0.5703,\ P_2 = 0.3327,\ P_3 = 0.0950,$$

where P_3 refers to a part of the inverter that is not monitored. The availability, failure rate, and failure rate decrement of the inverter with smart monitoring are calculated below, respectively.

$$P_{\mathrm{sm}} = 0.0020 + 0.5703 + 0.3327 = 0.9050,$$

$$\lambda_{\mathrm{sm}} = 2.0145,$$

$$R_{\lambda} = \frac{40.29}{2.0145} = 20.$$

For instance, $R_{\lambda} = 20$ indicates that failure rate of the inverter is significantly decreased to 5%. The reliability of the overall system and the availability of the inverter for this case study are tabulated in Tables 7 and 8, respectively.

As is mentioned in Case study 1, the reliability of the system decreases under long-term operations. The reliability of the systems is also decreased in larger PV systems due to the increment in the number of components. However, it is intuitively observed clearly from Tables 7 and 8 that the smart monitoring has significantly improved the reliability of the system and corrected the availability of the inverter regarding long-term operations. For instance, the inverter in a 100 kW PV system without smart monitoring has a probability of availability of 88.2497% in one year operation, while the probability of the inverter of a 2.5 MW system has been decreased into approximately 4.9787%. In addition, for 20 years of operation, the reliability of the inverter declines quickly. For a 100 kW and 2.5 MW system, the reliability of the inverter is 8.2085% and 0%, respectively. However, when the smart monitoring is employed, the reliability of the inverter is improved to approximately 99.3770% and 86.0708% for a 100 kW and 2.5 MW system after one year operation, respectively. Additionally, for a 2.5 MW system, the inverter was reliable by about 4.9787% in 20 years of operation. Employing monitoring for the inverters can also improve the reliability of the overall system. For a 2 MW system, after one year of operation, the reliability of the overall system is improved by approximately 92.96%. It is worth noting that, deduced from the increasing pattern of reliability improvement in Tables 7 and 8, the impact of smart monitoring on the reliability of the overall system is greater in bigger and more complex systems.

5.3 Case study 3: Monitoring failure

The evaluation of the advantages of implementing smart monitoring on the reliability of the system in Case study 2 reveals that there is a great improvement in the availability of the inverter and reliability of the overall PV system. Smart monitoring, identical to other components, has failure rate due to aging or operational failure. The impact of smart monitoring failure is evaluated in this section. This impact is estimated by increasing the availability (P_{u}) of smart monitoring, gradually from $P_{\mathrm{u}} = 0$ (smart monitoring is completely available) to $P_{\mathrm{u}} = 1$ (PV system has no smart monitoring) in Eq. (10) and then to evaluate the reliability of the associated system. The results indicate that the unavailability of smart monitoring worsens the reliability of the system as well as the availability of the inverter, which is a strong evidence for effectiveness of smart monitoring. The trial and monitoring failure are considered for the inverter, as shown in Figs. 7 and 8. It can be commonly seen from the inductive results that the reliability of the PV system and the availability of the inverter have been deteriorated by increasing the unavailability of monitoring, compared to those of the Case studies 1 and 2.

6 Conclusions

In the first part of the paper, a mathematical model using FTA has been used to evaluate the reliability of the

Table 7 Reliability of inverter with and without smart operation strategy

Inverter reliability	Power/kW						
	100	200	500	1000	1500	2000	2500
Without monitoring (1 year)/%	88.2497	77.8801	53.5262	32.4653	17.3775	9.3015	4.9787
With monitoring (1 year)/%	99.3770	98.7578	96.9233	94.5303	91.6219	88.8030	86.0708
Without monitoring (20 years)/%	8.2085	0.6738	0.0004	0.0000	0.0000	0.0000	0.0000
With monitoring (20 years)/%	88.2497	77.8801	53.5262	32.4653	17.3775	9.3015	4.9787

Table 8 Reliability of overall PV system with and without smart operation strategy

Inverter reliability	Power/kW						
	100	200	500	1000	1500	2000	2500
Without monitoring (1 year)/%	78.3716	64.9282	36.9896	16.6818	6.5229	2.5457	0.9954
With monitoring (1 year)/%	88.2533	82.3337	66.9794	48.5728	34.3914	24.3043	17.2084
Without monitoring (20 years)/%	0.7641	0.0177	0	0	0	0	0
With monitoring (20 years)/%	8.2152	2.0491	0.0330	0.0001	0	0	0

components as well as the overall large-scale PV systems. The method serves as a useful tool to identify the most critical components which leads to the determination of various maintenance strategies. The implementation of smart grid technologies offers opportunities to improve the reliability of electric power distribution system. Moreover, a novel method using the Markov model has been proposed and illustrated for analyzing the smart monitoring effects on the reliability of large-scale, grid connected PV systems. Due to the smart monitoring investment costs which may themselves increase the operation costs and also the fact that monitoring all the critical components of a

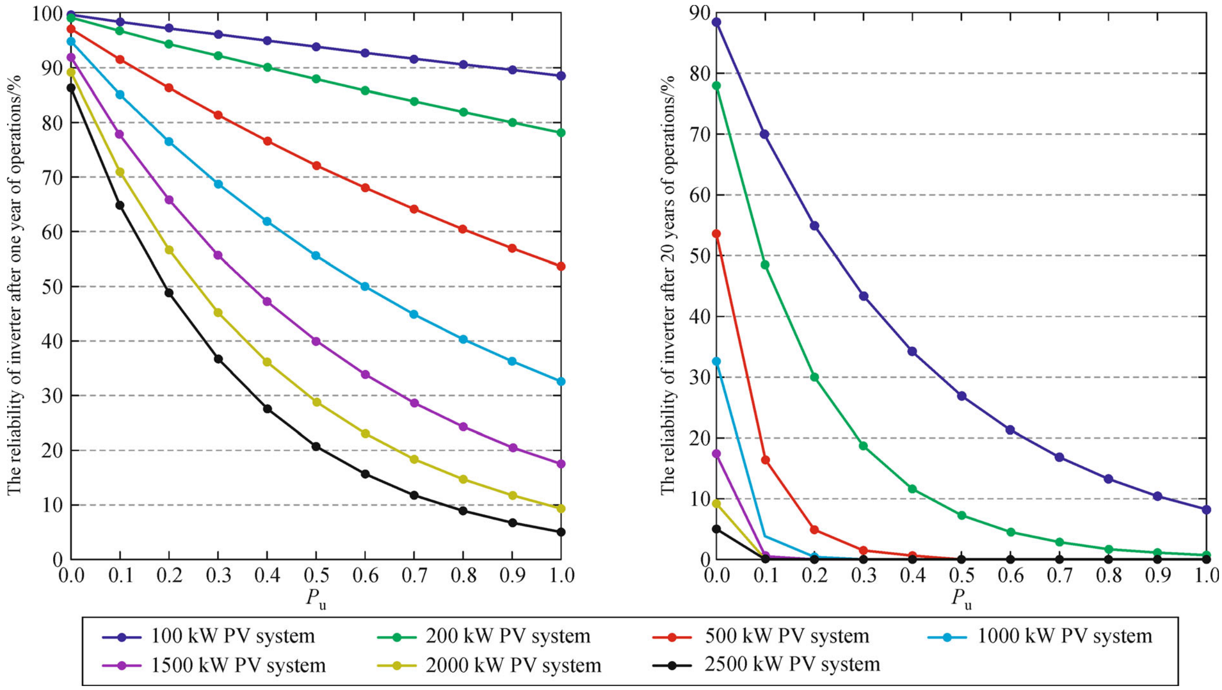

Fig. 7 Impacts of operational failure for solar inverter considering P_u

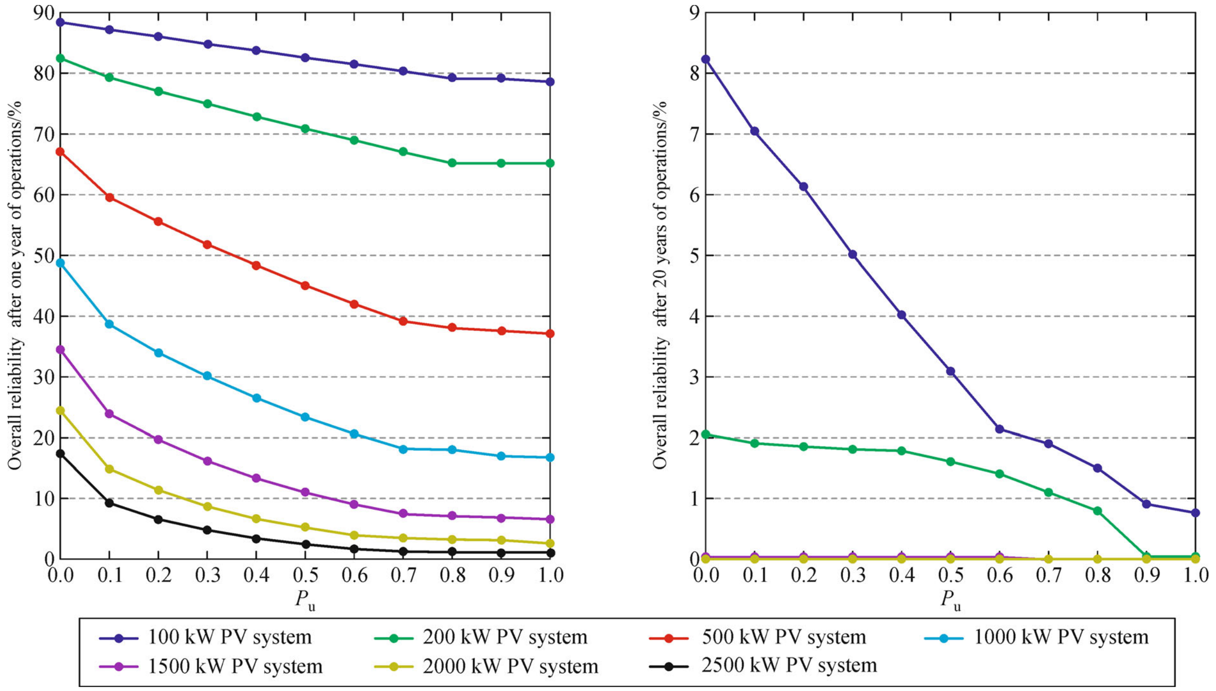

Fig. 8 Variation of reliability of overall PV system regarding inverter monitoring and considering P_u

PV system is not economical and practical, only solar inverters is chosen to be monitored. It is revealed from the various case studies with and without considering the monitoring deficiency that the proposed method significantly improves the reliability of the system by providing more awareness of components condition. The proposed model reduces the complexity of using analytical methods, provides a comprehensive model for reliability evaluation, and assists operators and planners to evaluate the reliability benefits brought by smart monitoring of PV systems. However, it is worth noting that the PV modules might be arranged in a particular series-parallel combination, thereby affecting the reliability of overall systems. In addition, the output power of PV systems is affected by the variability of solar radiation and ambient temperature, where the uncertainty of solar radiation may affect the overall reliability of the system.

References

1. Xu J, Yang Y, Cai B, Wang Q, Xiu D. All-ceramic solar collector and all-ceramic solar roof. Journal of the Energy Institute, 2014, 87 (1): 43–47
2. Chiradeja P, Ramakumar R. An approach to quantify the technical benefits of distributed generation. IEEE Transactions on Energy Conversion, 2004, 19(4): 764–773
3. Enslin J H R, Snyman D B. Combined low-cost, high-efficient inverter, peak power tracker and regulator for PV application. IEEE Transactions on Power Electronics, 1991, 6(1): 73–82
4. Song J, Krishnamurthy V, Kwasinski A, Sharma R. Development of a Markov-chain-based energy storage model for power supply availability assessment of photovoltaic generation plants. IEEE Transactions on Sustainable Energy, 2013, 4(2): 491–500
5. Landgrebe A R, Donley S W. Battery storage in residential applications of energy from photovoltaic sources. Applied Energy, 1983, 15(2): 127–137
6. Singh C, Kim Y. An efficient technique for reliability analysis of power systems including time dependent sources. IEEE Transactions on Power Systems, 1988, 3(3): 1090–1096
7. Ristow A, Begovic M, Pregelj A, Rohatgi A. Development of a methodology for improving photovoltaic inverter reliability. IEEE Transactions on Industrial Electronics, 2008, 55(7): 2581–2592
8. Dhople S V, Dominguez-Garcia A D. Estimation of photovoltaic system reliability and performance metrics. IEEE Transactions on Power Systems, 2012, 27(1): 554–563
9. Hong Y Y, Lian R C. Optimal sizing of hybrid Wind/PV/Diesel generation in a stand-alone power system using Markov-based genetic algorithm. IEEE Transactions on Power Delivery, 2012, 27 (2): 640–647
10. Kanchev H, Lu D, Colas F, Lazarov V, Francois B. Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications. IEEE Transactions on Industrial Electronics, 2011, 58(10): 4583–4592
11. Ahadi A, Ghadimi N, Mirabbasi D. An analytical methodology for assessment of smart monitoring impact on future electric power distribution system reliability. Complexity, 2015, 21(1): 99–113
12. Shrestha G B, Goel L. A study on optimal sizing of stand-alone photovoltaic stations. IEEE Transactions on Energy Conversion, 1998, 13(4): 373–378
13. Collins E, Dvorack M, Mahn J, Mundt M, Quintana M. Reliability and availability analysis of a fielded photovoltaic system. In: 2009 34th IEEE Photovoltaic specialists conference (PVSC). Philadelphia, USA, 2009, 2316–2321
14. Pregelj A, Begovic M, Rohatgi A. Impact of inverter configuration on PV system reliability and energy production. In: Conference record of the 29th IEEE Photovoltaic specialists conference. Publisher: IEEE, 2002, 1388–1391
15. Meyer E L, van Dyk E E. Assessing the reliability and degradation of photovoltaic module performance parameters. IEEE Transactions on Reliability, 2004, 53(1): 83–92
16. Shu Z, Jirutitijaroen P. Latin hypercube sampling techniques for power systems reliability analysis with renewable energy sources. IEEE Transactions on Power Systems, 2011, 26(4): 2066–2073
17. Rodriguez C, Amaratunga G A J. Long-lifetime power inverter for photovoltaic AC modules. IEEE Transactions on Industrial Electronics, 2008, 55(7): 2593–2601
18. Theristis M, Bakos G C, Papazoglou I A. Development of a reliability model for the estimation of the loss of load probability and cost for an off-grid PV system. In: Proceedings of 27th European Photovoltaic Solar Energy Conference. Frankfurt, Germany, 2012, 4245–4248
19. Arun P, Banerjee R, Bandyopadhyay S. Optimum sizing of photovoltaic battery systems incorporating uncertainty through design space approach. Solar Energy, 2009, 83(7): 1013–1025
20. Kishore L, Fernandez E. Reliability well-being assessment of PV wind hybrid system using Monte Carlo simulation. In: Proceedings of International Conference on Emerging Trends in Electrical and Computer Technology. Nagercoil, India, 2011, 63–68
21. Modarres M, Kaminskiy M, Krivtsov V. Reliability Engineering and Risk Analysis: A Practical Guide, 2nd ed. Boca Raton, FL, USA: CRC, 2010
22. Poggi P, Notton G, Muselli M, Louche A. Stochastic study of hourly total solar radiation in corsica using a Markov model. International Journal of Climatology, 2000, 20(14): 1843–1860
23. Ahadi A, Ghadimi N, Mirabbasi D. Reliability assessment for components of large scale photovoltaic systems. Journal of Power Sources, 2014, 264: 211–219
24. Lei H, Singh C, Sprintson A. Reliability modeling and analysis of IEC 61850 based substation protection systems. IEEE Transactions on Smart Grid, 2014, 5(5): 2194–2202
25. Liu N, Chen J, Zhu L, Zhang J, He Y. A key management scheme for secure communications of advanced metering infrastructure in smart grid. IEEE Transactions on Industrial Electronics, 2013, 60 (10): 4746–4756
26. Iyer G, Agrawal P, Monnerie E, Cardozo R. Performance analysis of wireless mesh routing protocols for smart utility networks. IEEE International Conference on Smart Grid Communications, 2011, 114–119
27. Zhang P, Li F, Bhatt N. Next-generation monitoring, analysis, and control for the future smart control center. IEEE Transactions on

Smart Grid, 2010, 1(2): 186–192

28. Oozeki T, Yamada T, Kato K, Yamamoto T. An analysis of reliability for photovoltaic systems on the field test project for photovoltaic in Japan. In: Proceedings of ISES Solar World Congress, 2007, 1628–1632
29. Reliability prediction of electronic equipment, MIL-HDBK-217F, 217F Notice 1, 217F Notice 2. Washington DC, USA: Department of Defense 1991, 92–95
30. Nkhonjera L K. Simulation and performance evaluation of battery based stand-alone photovoltaic systems of Malawi. Dissertation for the Master’s Degree. Environmental Sustainable Development, National Central University, 2009
31. Billinton R, Allan R N. Reliability Evaluation of Engineering Systems: Concepts and Techniques. 2nd ed. Springer, 1992