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Reliability assessment of photovoltaic power systems: Review of current status and future perspectives

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ABSTRACT

Quantitative reliability assessment of photovoltaic (PV) power system is an indispensable technology to assure reliable and utility-friendly integration of PV generation. This paper reviews the state-of-the-art technologies for evaluating the reliability of large-scale PV systems and the effect of PV interconnection on the reliability of local distribution system. The discussions are extended to emerging research topics including time varying and ambient-condition-dependent failure rates of critical PV system components, accurate operating models of PV generators in both interconnected and islanded modes, and the reliability evaluation of active distribution networks with PV penetration and transmission level Giga-PV system. A vision for the future research is presented, with a focus on the cyber-physical perspective of the PV reliability, modeling of PV voltage control scheme for reliability assessment, reliability assessment for PV systems under extreme events and PV reliability assessment considering cybersecurity.

Contents

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1. Introduction: why is PV reliability assessment important?

Electricity generated from photovoltaic (PV) power systems is a major renewable energy source which involves zero greenhouse gas emission and no fossil fuel consumption. The total capacity of grid-connected PV power systems has been grown exponentially from 300 MW in 2000 to about 67 GW in 2011 [1]. This capacity, however, is not firm because of the unreliable nature and probabilistic behavior of PV power systems.

Relatively high risks exist both inside and outside of PV power systems [2]. High uncertainty and variability associated with the system components and environmental factors pose major challenges in designing large PV power system [3]. First, a PV power system is composed of many vulnerable components [4,5] whose lifecycle reliability is highly susceptible to temperature, power losses, and ambient environments. Meanwhile, solar insolation and power input of PV system are highly variable and uncontrollable; leading to high electrical stress in PV panels that may shorten the operational lifecycles and power electronic interfaces and consequently results in lower system reliability compared to conventional generation sources. Second, high penetration of PV generation will bring detrimental effect to power distribution network. Significant reverse power flow may cause unacceptable voltage rise on distribution feeder. Overvoltage may trigger the protection in PV inverters, which as a result will shut down PV generation, causing sudden change in power flow and abrupt voltage fluctuation. Reverse power flow and voltage fluctuation may also increase the number of operations of on-load tap changers (OLTCs), which will shorten the useful lives of transformers. Distribution networks connected with PVs, therefore, have a high risk for increased maintenance costs and power outages, which necessitate methodologies and tools to quantify the reliability of grid-connected PV systems.

Risk assessment is of fundamental importance for planning and operation of both PV power systems and PV-connected distribution networks. Its major utilities include:

(1) Quantifying risks in PV systems and choosing optimal PV system design.
(2) Determining effective measures to mitigate risks.
(3) Justifying acceptable PV penetration level in distribution network.
(4) Probabilistically evaluating the impacts of intermittent PV resources on power system adequacy, security, spinning reserve, planning and real-time operation.
(5) Designing reconfigurable distributed energy storage to leverage PV application.
(6) Finding planning and operational solutions to address the challenges of high penetration of PV to distribution network in a least cost manner while achieving the maximum level of reliability.

Risk assessment of PV power systems, therefore, is an indispensable technology that assures reliable PV generation integration. Practical applications of PV risk assessment theory will bring direct and indirect benefits for both utility companies and customers including increased revenue, higher energy yield, improved power quality, extended equipment operational life and less carbon emission.

2. Current status and challenges

Increasing attention is being paid to PV system reliability in recent years due to rapid growth of PV power installation in residential [6] and commercial buildings as well as military bases. Cost-reduction in production of PV modules together with economic incentives offered by government will further increase the installed capacity of solar power in the foreseeable future. Failures in PV systems, therefore, will result in significant amount of economic losses [7]. The reliability of grid-connected PV power systems has been of great concern to both utility companies and customers [8].

Although the PV reliability issue was already identified three decades ago [9], reliability quantification of an entire PV generation station remains unresolved due to the complex nature of PV systems. The existing literature mostly focuses on reliability assessment for the power electronic components such as IGBT [10], capacitor [11] and inverter [12,13], whereas much fewer references discuss the reliability evaluation for entire PV system. Refs. [14,15] presented simplified, system-level models for PV system reliability using a Markov modeling concept. Hierarchical Reliability Block Diagram was developed [16] to model the behavior of PV system. Ref. [17] quantified the impact of inverter failures on total lifetime of PV system using Monte Carlo simulation. Ref. [18] proposed Latin Hypercube Sampling (LHS) technique to integrate stratified and random sampling in order to improve its computational speed for obtaining the reliability indices. In the above literature, failure rates of electronic elements in a PV system are treated as constants. These parameters, however, actually vary with system states including solar insolation [19], ambient temperature [20], and load level [21]. The unrealistic assumptions in reliability analysis may give inaccurate or misleading results. For instance, it was once concluded that "capacitors' contribution to failure rate is quite small" [22], which may be inconsistent with observations from industrial practice.

On the topic of grid integration of PVs, the National Renewable Energy Laboratory (NREL) has conducted extensive surveys to explore the impact of high penetration PVs on power system planning and operation [23]. It has been identified that PV integration is closely tied to overall distribution system reliability [24]. Recently, a framework, which is based on Markov reward models (MRM), is proposed to integrate reliability and performance analysis of grid-tied PV systems [25]. This proposed framework may help understand the trade-off between repair policies and replacement/overhaul costs. In addition, the effect of reactive power shortage on the distribution network with high PV penetration has been studied [26]. Hence, it is obvious that reliability assessment theory suitable for distribution systems integrated with PV generation has become a highly needed technology to build a high-penetration renewable energy future. In the era of smart grid, the microgrid is a mainstream solution for grid integration of PV systems. Reliability evaluation of active distribution systems including PV microgrids becomes a major technical challenge to be tackled.

In previous work, the microgrid was often treated as a small sized conventional power grid where the failure modes of power electronic interfaces were not considered in microgrid reliability evaluation [27–31]. These methods may be practical for estimating microgrids with combined heat and power plants (CHPs) [32] or conventional generators, but are not suitable to analyze a distribution network with PVs or other renewable sources. The effect of converter topologies is incorporated into reliability evaluation of DC microgrid by the use of minimum cut sets [33]. This approach, however, neither considered the impact of power losses and ambient condition on converter reliability nor can be extended to distribution system reliability assessment. Ref. [34] has pointed out that modeling the operation mode transitions is a major challenge in reliability evaluation of microgrids. Reliability of PV/wind microgrid operating in an islanded mode was studied using Monte Carlo simulation [35]. Again, this approach only dealt with input power of PV array without considering the reliability of PV inverters. Fault