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Reliability assessment for components of large scale photovoltaic systems

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HIGHLIGHTS

- This paper presents a complete and real structure of the large-scale PV systems.
- FTA is used to analyze the effects of a battery system on the system reliability.
- We estimate total component reliability and overall reliability for the PV system.
- Increasing nominal power output of the PV system will decrease Reliability.
- The critical components with priority for the PV system are revealed.

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ABSTRACT

Photovoltaic (PV) systems have significantly shifted from independent power generation systems to a large-scale grid-connected generation systems in recent years. The power output of PV systems is affected by the reliability of various components in the system. This study proposes an analytical approach to evaluate the reliability of large-scale, grid-connected PV systems.

The fault tree method with an exponential probability distribution function is used to analyze the components of large-scale PV systems. The system is considered in the various sequential and parallel fault combinations in order to find all realistic ways in which the top or undesired events can occur. Additionally, it can identify areas that the planned maintenance should focus on. By monitoring the critical components of a PV system, it is possible not only to improve the reliability of the system, but also to optimize the maintenance costs. The latter is achieved by informing the operators about the system component's status. This approach can be used to ensure secure operation of the system by its flexibility in monitoring system applications. The implementation demonstrates that the proposed method is effective and efficient and can conveniently incorporate more system maintenance plans and diagnostic strategies.

1. Introduction

Analyzing the reliability of PV power systems is important for planning and long-term operation, because the analysis helps predict system behavior over time and devise appropriately timed maintenance plans. It is a significant factor for the operator to be able to assess system reliability under long-term operations in order to optimize decisions in design, engineering, procurement, construction, and service [1].

PV and wind systems produce electric power, which involves zero greenhouse gas emissions and fossil fuel consumption. The total capacity of grid-connected PV power systems has grown exponentially, from 300 MW in 2000 to approximately 67 GW in 2011 [2]. PV power generation will become the main focus of future energy development. As a clean energy, its application has gradually changed toward large-scale, grid-connected systems. It significantly influences the reliability, economics and operational stability of such systems [3]. The largest PV system with a generation capacity of 80 MW was installed in Sarnia, Ontario, Canada, in 2010 [4]. Additionally, the European PV Technology Platform Group

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Nomenclature

I_{ph}	internal equivalent current source
V_t	thermal voltage of the array
q	the electron charge of 1.602×10^{-19} Coulomb
T_j	the temperature of the pn junction
G	solar irradiation
ΔT	temperature deviation from the reference value
T_n	reference temperature
I_{sr}	the reference reverse saturation current
MPP	maximum power point
I_{SC}	PV short-circuit current
$V_{mpp,max}$	maximum MPP voltage of the inverter
μ_I	PV temperature coefficient of I_{SC}
I_{mpp}	PV current at the maximum power point
$I_{DC,max}$	maximum input DC current of the inverter
$F(t)$	failure probability function
ACS, DCS	AC or DC switch
CB	AC circuit breaker
INV	inverter
CON	connector
CC	charge controller
FV	Fussel–Vesely
$Pr(E)$	failure probability
P_{TOP}	the probability of top event
P_{MCS_i}	the probability of occurrence of MCS_i
$P_{B1}, P_{B2}, \ldots P_{Bn}$	the failure probabilities of basic events
M	number of batteries in parallel
T	the system's time to failure
$\lambda_{Battery}$	failure rate of the battery system
I_s	reverse saturation current
N_s	cells connected in series
k	the Boltzmann constant of 1.38×10^{-23} J K^{-1}
a	the permittivity of the diode
K_i	temperature coefficient (mA °C^{-1})
G_n	the reference irradiation
E_g	bandgap energy of the semiconductor
P_{max}	maximum output power of a PV cell
$V_{mpp,min}$	minimum MPP voltage of the inverter
V_{mpp}	PV voltage at the maximum power point
V_{oc}	PV open-circuit voltage
μ_v	PV temperature coefficient of V_{oc}
V_{max}	maximum operating voltage of the inverter
$R(t)$	reliability probability function
$f(t)$	probability density function
GP	grid protection
SPD	surge protection device
BD	blocking diode
PV	photovoltaic cell
BS	battery system
DCB	differential circuit breaker
$1 - Pr(E)$	reliability probability
MCS_i	minimal cut set i
m	the number of basic events in the largest minimal cut set
n	the number of minimal cut sets
N	total number of batteries
E_i	the event that component i operates without failure
$\lambda_{Charge-Controller}$	failure rate of the charge controller

reports that PV systems are predicted to reach network parity in most of Europe in 2019 [5].

In recent literature, evaluating the reliability of solar PV has been a point of interest.

In Ref. [6], the investigators analyzed the reliability of solar PV power system designs using failure mode effect analysis (FMEA) and fault tree analysis (FTA), and also calculated the failure rates of the PV array and inverter. In Ref. [7], the investigators estimated reliability equations from the FTA but did not analyze the reliability probability functions. The maximum reliability of PV arrays with optimal interconnection of PV modules was investigated in Ref. [8–10]. In Ref. [11], the researchers evaluated the reliability of an electric power generation system, including a PV system, by considering the load under the assumption that none of the system components ever failed. The researchers in Ref. [12] proposed a new method for the calculation of the optimal configuration of large-scale PV systems. In Ref. [13], FTA and Markov chain method are jointly used to evaluate the behavior of PV system. The energy cost of PV system is estimated and applied to PV system designs. The investigators in Ref. [14] studied the reliability of battery voltage regulators (BVRs) used in PV systems and calculated the overall system reliability. In Ref. [15], the investigators proposed a model using Monte Carlo for the analysis of reliability of rechargeable batteries in photovoltaic power supply systems. In Ref. [16], the researchers discussed the PV inverters used in PV systems, presenting their experimental results. The reliability of PV systems was estimated in various small-scale field tests described in Refs. [17–19].

Although a wide variety of studies have been conducted about the large-scale, grid-connected PV systems [20–27], the real electrical architecture of modern large-scale, grid-connected PV systems with battery backup requires further consideration.

This paper presents a technique for analyzing the reliability of large-scale, grid-connected PV systems using an exponential distribution based on FTA method and considering the presence of a battery system and charge controller. It is necessary to point out that changing the function from exponential distribution to, for example, accelerated life tests (ALTs) with Log-normal, Weibull or mixed-Weibull distributions did not alter the output of the proposed method. In addition, if the repair interval of the system components is sufficiently less than a critical value and does not influence the system operation, then the repair time could be ignored. Thus, in this study, it was assumed that any failures could not be repaired [7], [11], and [28–32]; therefore, if a component failed, the overall PV system was assumed to be in failure mode and the repair is finished during a short time. However, the overall system remaining in operation during that time, because the electric power of distribution system is sufficient for loads to use. It is also important to point out that in order to define the critical components, the scope of this paper is focused on the reliability evaluation of PV systems based on unrepairable components. It is assumed the repair time of the system failure is too short and the loads could be incorporated with the distribution system during failure. However, the proposed method is applicable when the repair and the common-cause degradation are considered.

The remainder of the paper is organized as follows. Section 2 describes the electrical structure of large-scale grid connected PV systems. Section 3 proposes the reliability modeling formulation. The case studies are presented in Section 4. Finally, the conclusions are provided in Section 5.