Applied Energy 199 (2017) 264–280

Contents lists available at ScienceDirect

Applied Energy

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

Economic evaluation of maintenance strategies for ground-mounted solar photovoltaic plants

Lennart Peters, Reinhard Madlener *

Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics/E.ON Energy Research Center, RWTH Aachen University, Mathieustraße 10, 52074 Aachen, Germany

HIGHLIGHTS

- A generic model for the economic analysis of PV maintenance strategies is proposed.
- We investigate open-field PV plants of different size and with variable components.
- We compare immediate corrective maintenance with alternative maintenance strategies.
- Immediate corrective maintenance is found to be the most cost-effective strategy.
- Higher costs per service trip and larger PV plants favor periodic maintenance.

ARTICLE INFO

Article history:
Received 13 January 2017
Received in revised form 8 March 2017
Accepted 20 April 2017

Keywords:
Photovoltaics
Ground-mounted solar PV
Corrective maintenance
Germany

ABSTRACT

We propose a generic model which allows to evaluate the economic viability of alternative maintenance strategies for differently sized photovoltaic plants with variable components. We thoroughly review the existing literature on reliability, maintenance and maintenance strategies for PV plants. The model is applied to fixed-tilt ground-mounted solar PV plants in Germany of three different sizes: 1, 10, and 100 MW_p. The PV plants are set up in a central inverter configuration with the following components: AC/DC switch, circuit breaker, and inverter. The analysis compares immediate corrective maintenance with maintenance strategies of different periodicity (weekly, bi-weekly, and monthly). Simulations take the driving time of the service team and the operation of a spare parts inventory into account. We further analyze the impact of hourly spot prices in contrast to constant prices (feed-in tariffs). We find that corrective maintenance is the most cost-efficient strategy. If the service journey takes six hours instead of one hour, corrective maintenance becomes more expensive than weekly periodic maintenance. For a three-hour journey, the size of the PV plant matters. If corrective maintenance is adopted, the establishing of a spare parts inventory should be considered. When volatile hourly spot prices are considered, we find that opportunity costs are lowest (highest) when service teams operate at 8 pm (8 am), irrespective of the day of the week, whereas maintenance events scheduled for Wednesdays at 8 am or 2 pm are, given current EPEX spot prices, the most cost-efficient in terms of total costs.

1. Introduction

Growing environmental concerns have led to a change in the energy markets worldwide. Ambitions to reduce fossil fuel consumption and greenhouse gas emissions led to record additions for the second consecutive year for wind and solar photovoltaic (PV) energy in 2015. The share of renewable energy sources had increased to 23.7% of global electricity production by the end of 2015, with wind and PV accounting for 77% of new installations. The total capacity of PV installations worldwide has now reached 227 GW, 40 GW of which is in Germany [1]. German government

Abbreviations: AC, alternating current; BOS, balance of system; CBM, condition-based maintenance; CDF, cumulative density function; CM, corrective maintenance; DC, direct current; EPEX, European stock exchange; MC, Monte Carlo; MPPT, maximum power point tracking; MTBF, mean time between failure; O&M, operations and maintenance; PDF, probability density function; PM, periodic maintenance; PV, photovoltaics; PV-RPM, photovoltaic reliability and performance model; QMO, quantitative maintenance optimization; SNL, Sandia National Laboratory; TRY, test reference year; UB_{95}, upper bound of the 95% confidence interval.

* Corresponding author.
E-mail address: RMadlener@eonerc.rwth-aachen.de (R. Madlener).

http://dx.doi.org/10.1016/j.apenergy.2017.04.060

Nomenclature

c_{dr}	costs per man-hour of driving
c_w	costs per man-hour of work
C_f	fixed costs
$CF(t)$	cash flow in period t
$E(G(t), T_u(t))$	electricity production per module in period t
$f(t)$	probability density function at time t
$F(t)$	cumulative density function at time t
$G(t)$	solar irradiance in period t
$h(t)$	hazard rate function at time t
i	discount rate
$n_{ar}(t)$	number of offline arrays in period t
n_{arrays}	number of arrays
n_{mod}	number of modules per array
$p_{el}(t)$	sales price of electricity in period t
Pr	probability
P_{STC}	nominal power of a solar module under standard test conditions
$R(t)$	reliability function at time t
$R_x(25a)$	prob. that component x will not fail within 25 years
t	time
t_{dr}	time of the journey to the PV plant
$t_{n,offline}$	offline hours of array n
t_{repl}	time consumption for the replacement of an item
$t_{lifetime}$	lifetime of the simulated PV plant
$T_a(t)$	ambient temperature in period t
T_c	solar cell temperature
T_{NOCT}	normal operating cell temperature
T_{STC}	solar cell temperature under standard test conditions
V	present value
β	shape parameter of the Weibull function
β_P	solar cell power temperature coefficient
η	scale parameter of the Weibull function
λ	failure rate

programs and subsidies have helped to integrate PV power plants into today's energy market. Through technical progress and scale and learning effects, the investment costs of PV plants have been reduced by 75% since 2006 [2]. Additional cost reductions in production in combination with incentives offered by the government will further increase the installed capacity of PV in the foreseeable future [3]. Stakeholders are interested in low operation and maintenance (O&M) costs, while at the same time they rely on the ability of the PV plant to produce the expected amounts of electricity in order to secure the invested capital. The selection of a cost-efficient maintenance strategy is therefore a process that needs to be evaluated in the light of technical and economic conditions.

The optimal maintenance strategy for a PV plant depends on multiple factors. PV plant size, component configurations, location, global irradiation, etc. are important criteria to factor in when selecting a strategy. Nowadays, most PV plants are operated with a corrective maintenance strategy in combination with preventive maintenance carried out according to the component manufacturer's guidelines. With increasing size of the PV plants, the number of components also rises. Avoiding any failures at all is a very unlikely scenario. In the case of a failure, corrective maintenance is usually carried out right away in order to achieve a high availability of the PV plant even though a strategy that leads to high availability might not always be coherent with the most cost-efficient strategy.

The objective of this paper is to develop a generic model for the evaluation of different maintenance strategies, which can be applied to PV plants configured in various ways. Further, the model supports decision makers when selecting a cost-efficient maintenance strategy. The model simulates three sizes of a ground-mounted open-field PV plant and its components over a lifetime of 25 years. The focus of this investigation is on fixed-tilt PV plants, which in 2016 accounted for some 77% of the total new installed PV capacity in Germany [4]. Components are selected and failures simulated with respect to failure data available in the literature. The focus of this paper is on the economic evaluation of possible actions following any failure of components. Corrective maintenance which is carried out right after the detection of a failure is compared to periodically scheduled maintenance events as a form of deferred corrective maintenance. Resulting O&M costs and opportunity costs stemming from lost revenues are evaluated and compared. Restrictions arise from the limited availability of failure data in the literature, but the model is implemented in a flexible way so that the number and characteristics of the components can be adjusted when more detailed and reliable data become available. In this study a central inverter configuration is investigated and the following components are considered: AC/DC switch, circuit breaker, and inverter. The meteorological data used are specific to Germany. The model is an event-based simulation which is implemented in MATLAB. The failure times for the components are randomly selected from their probability distributions, and the resulting O&M and opportunity costs are hence also random. Monte Carlo simulation is used to produce probability distributions of the results. This way, all possible outcomes and their probabilities can be evaluated and discussed.

Section 2 gives an introduction to the theoretical background of reliability modeling, maintenance classification, and optimization theory, respectively. Section 3 provides a state-of-the-art literature review on reliability, maintenance as well as maintenance strategies for ground-mounted PV plants. Section 4 describes the model developed and its sub-models for PV plant reliability, the service team operations, and the economic evaluation. The selected input parameters for the model are described and discussed in Section 5. The resulting histograms are discussed and maintenance strategies evaluated in Section 6 with respect to the mean values, median, and the upper bound of the 95% confidence interval. Section 7 concludes and gives an outlook on possible further investigations.

2. Theoretical background

2.1. Reliability modeling

2.1.1. Probability functions

Reliability is defined as "the ability of an item to perform its required function without failure, under given environmental and operational conditions and for a stated period of time" [5]. In reliability modeling, the time of failure of an item is a random variable, which can be described by various probability functions. The *probability density function* (PDF) $f(t)$ describes the relative likelihood of a random variable taking on a given value, e.g. the time to failure. The probability of a failure occurring before some specified time t can be expressed by the *cumulative density function* (CDF), $F(t)$. It relates to its PDF by:

$$F(t) = \int_0^t f(t)dt. \tag{1}$$