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Simulation study on the degradation process of photovoltaic modules

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ABSTRACT

Degradation decreases photovoltaic power delivery capacity over time. Studies on photovoltaic degradation are usually based on accelerated tests or filed tests which are time-consuming and require much effort. This paper investigates the degradation process of photovoltaic modules by simulation studies. A circuit-based model is employed to describe photovoltaic characteristics to environmental conditions and to the aging factors of photovoltaic modules. Analysis of each aging factor shows that the decrease of short-circuit current, the main reason of power loss, is mainly caused by optical degradation. The decay of fill factor mainly due to degradation of parasitic resistances worsens the power output. The statistical analysis of photovoltaic characteristic parameters based on a great number of photovoltaic modules with the same technology indicates that the degradation process can be very complicated depending on the degradation patterns of aging factors. Generally, the power loss tends to increase and the mismatch among photovoltaic modules becomes more remarkable through the time.

1. Introduction

Photovoltaic (PV) module is considered as the most reliable component in a PV system, and its life time is expected to be more than 20 years. Degradation, however, decreases the PV power delivery capacity over time [1]. A thorough understanding of PV module degradation is required to make better use of PV module during its life time.

Studies on PV degradation often investigate the degradation modes, mechanisms, and degradation rates. The reported degradation modes include cell cracks, hot spots, glass soiling, ethylene vinyl acetate (EVA) browning, delamination, coating oxidation, etc., for crystalline silicon PV modules operated over 20 years in Italy [2]. These degradation models were also observed in PV modules of other technologies and exposed to various climates. In [3], Malvoni et al. studied the long-term performance loss of a 960 kWp PV system in the Mediterranean climate and concluded that the PV system demonstrated good performance compared to other plants located in the same climate. Kichou et al. [4] investigated the degradation modes and degradation rates of thin-film PV modules exposed to relatively dry and sunny climate in Spain. Bouraiou et al. [5] investigated the impacts of high temperature and the other climatic factors in the Saharan environment on the performance of PV modules installed in the desert region in south of Algeria. Chandel et al. [6] presented the performance degradation of mono-crystalline-silicon PV generator after 28 years of exposure at a western Himalayan in India, and the main defects observed in PV modules were encapsulant discoloration, delamination, oxidation of front grid fingers, and glass breakages. In [7], Jordan et al. concluded that hot spot was the most important degradation mode for crystalline modules installed in the last 10 years while the glass breakage and absorber corrosion dominated the degradation models for thin-film PV technologies. It was also concluded that PV modules exposed to hot and humid climates show considerably higher degradations modes than those in desert and moderate climates. These degradation modes decrease the light approaching the semiconductor junction and worsen the internal electrical properties of PV modules leading to the loss in power production. In [8], the long-term performance degradation rates of 12 PV systems with different technologies including monocrystalline silicon, multicrystalline silicon, amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) were investigated and the degradation rates varied significantly among these technologies. In [9], nearly 2000 degradation rates were reviewed showing a median annual performance degradation rate of 0.5% and that location and PV technology were most influential factors determining degradation rate. Accelerated tests and outdoor tests which are time-consuming and require substantial efforts are the most frequently applied approaches to study degradation of PV modules. It took hundreds of hours to run the thermal cycling stress test to estimate the degradation rate of multi-

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Nomenclature

I_{pv}	light-generated current
R_s	series resistance
R_p	shunt resistance
I_0	diode reverse saturation current
a	diode ideality factor
V_T	thermal voltage
N_s	cells in series of a PV module
k	Boltzmann constant
q	electron charge
T	PV cell temperature
I	terminal current of a PV module
V	terminal voltage of a PV module
I_{sc}	short-circuit current
V_{oc}	open-circuit voltage
G	solar irradiation
$I_{pv,ref}$	I_{pv} at reference conditions
T_{ref}	T at reference conditions
G_{ref}	G at reference conditions
k_I	temperature coefficient of I_{sc}
k_V	temperature coefficient of V_{oc}
τ	transmittance of a PV module
P_{max}	maximal power
FF	fill factor
t	the index of time
$\tau(t)$	τ at time t
$R_s(t)$	R_s at time t
$R_p(t)$	R_p at time t
$I_{pv}(t)$	I_{pv} at time t
$V(t)$	V at time t
$I(t)$	I at time t
μ_0	initial mean value
σ_0	initial standard deviation
$\mu(t)$	mean value at time t
$\sigma(t)$	standard deviation at time t
A	variation rate of μ
B	variation rate of σ

crystalline silicon PV modules under well controlled conditions in [10]. The outdoor experiments could last from several years to more than 20 years. Hence, a simple and fast approach to investigate the degradation of PV performance over time regardless of the PV technology and the installed location is of great value.

Indeed, a PV plant usually consists of dozens or hundreds of PV modules. Degradation process can provoke mismatch among PV modules. It is interesting that the standard deviation of peak power of 42 crystalline silicon PV modules after 12-year operation in Southern Europe slightly decreased compared to initial value in [11]. However, the standard deviation of peak power of 191 PV modules after 11 years of field exposure to a cool and coastal environment in California, USA, showed a greatly increase [12]. This mismatch of peak power among PV modules may cause a variety of problems to the PV system [13], such as the presence of multiple local maxima of the PV plant which can mislead the maximal power point tracking (MPPT) algorithm failing to extract the most power from the array. A better understanding of the distribution of power output of PV modules will benefit the PV management system, and help improve the prediction accuracy of PV power production over time.

Simulation provides an easy and fast approach to study the characteristics of PV modules [14]. Such studies are often used to investigate response of PV modules to environmental factors [15] and to develop MPPT algorithms [16]. Nowadays, simulation is also applied to analyze the influence of degradation on PV module characteristics. Doumane et al. [17] investigated power loss of a PV module over years based on an equivalent electrical circuit by tuning the circuit parameters associated with the aging of PV modules, and this work was conducted in a deterministic manner. However, a PV plant is composed of dozens or hundreds of PV modules and the aging process of each module could be quite different. A PV array is usually composed of PV modules with the same technology. Hence, it will be of great value to investigate the degradation process considering a great number of PV modules with the same technology that the electrical properties of PV modules are considered independent and identically distributed in statistics.

The aim of this paper is to investigate the degradation process of PV module performance by simulation considering a great number of PV modules with the same technology. The investigation will concentrate on the statistical analysis on the degradation of PV characteristic parameters for the considered PV modules through the time. To this end, a circuit-based model is developed to describe the general electrical characteristics of PV modules in Section 2. In Section 3, the effects of each aging factor on PV module performance are analyzed relying on the circuit-based model. This is followed by simulation study on the degradation process of a great number of PV modules over a long period under assumptions that the considered PV modules with the same technology are independent and their electrical properties follow the same probability distribution. Results show that the degradation process can be very complicated depending on the aging patterns of related factors. Generally, the mismatch among PV modules become more remarkable through the time. The conclusion and perspective are provided in Section 4.

2. Modeling of photovoltaic module characteristics

A PV cell is a semiconductor device fabricated in a thin wafer or layer that converts solar power to electricity. And a PV module usually consists of dozens of PV cells in series. The equivalent circuit of a PV module in Fig. 1 shows a good compromise between complexity and accuracy in modeling PV characteristics, and it is widely used to express the electrical characteristics of a PV module. The light-generated current I_{pv} is proportional to the effective irradiance and is affected by cell temperature. The diode expresses the exponential *I-V* characteristics of a PV module. The equivalent series resistance R_s and equivalent shunt resistance R_p present the power loss due to the parasitic resistances in practical PV modules. The equivalent series resistance R_s includes resistances from metallic contacts, cell solder bonds, cell-interconnection bars, junction-box terminations, and inner diode. The shunt resistance R_p represents any parallel high-conductivity shunts across the solar cell p-n junction or on the cell edges. In general case, the value of R_p is much higher than that of R_s, while in ideal case the value of R_p is infinite and the value of R_s is zero.

According to Kirchhoff laws, the *I-V* characteristics depicted in Fig. 1 can be mathematically expressed as:

$$I = I_{pv} - I_0\left[\exp\left(\frac{V+R_sI}{aV_T}\right)-1\right]-\frac{V+R_sI}{R_p} \tag{1}$$

where I_{pv} is the light-generated current; I_0 is the diode reverse

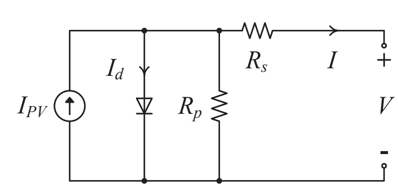

Fig. 1. The schematic of PV module equivalent circuit.