Long-term Aging Pattern Characterization for Photovoltaic Panels using the Superellipse Model

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Abstract

A long-term assessment of the behavior and characteristics of photovoltaic (PV) panels is essential before the installation of large-scale PV farms. While the industrial standard for the lifespan of most PV panels is 25-30 years, their conversion efficiency and maximum output power significantly decrease due to solar cell degradation. Researchers have suggested incorporating aging laws and degradation rates with the conventional single-diode model to carry out these long-term aging pattern assessments. However, the accuracy of this approach is still reliant on the accurate estimation of the electrical parameters of the single-diode model. Hence, this paper introduces a new simplified approach that utilizes the superellipse model, which is easy to fit, to forecast the behavior of these nonlinear devices under accelerated test conditions.

1 Introduction

In the past, the electrical circuit-based model of photovoltaic (PV) panels has been widely used to predict the nonlinear performance and characteristics of these complex systems [1]. However, the effectiveness of the single-diode model implemented in most commercial software packages such as MATLAB and PSIM is highly dependent on accurately estimating the electrical fitting parameters.

Despite these limitations, researchers have been able to conduct accelerated aging pattern characterization of PV panels under various conditions by incorporating theoretical and mathematical equations governing the effects of solar degradation and aging laws into their models [2]. However, the complexity of these equations and the number of fitting parameters make long-term assessment of PV panels a tedious and time-consuming task.

The superellipse model is an empirical model that has been introduced to accurately reconstruct the nonlinear characteristics of the I-V curve under varying ambient conditions [3]. Since this model inherits all the constraints described in the datasheet, it is useful for evaluating the long-term assessment of these nonlinear systems. Therefore, this paper proposes a simplified and explicit equation for predicting the nonlinear behavior of PV panels under the influence of degradation.

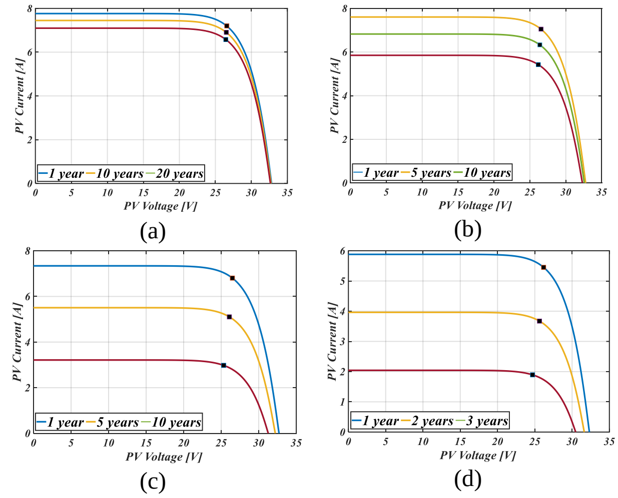

Fig. 2 Reconstruction of the I-V characteristic curve for the KC200GT PV panel operating under the effect of degradation (a) nominal (b) crack (c) dust (d) discoloration.

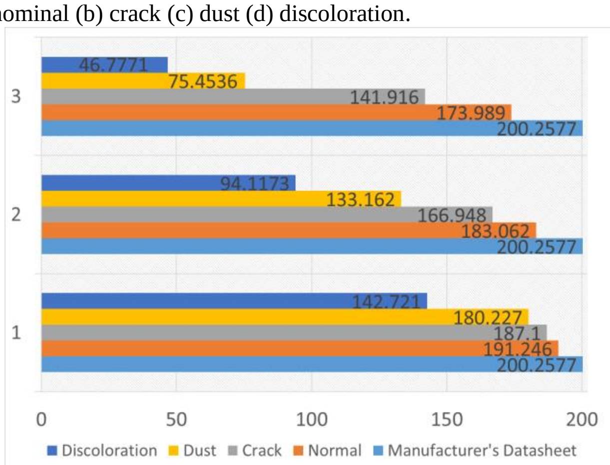

Fig. 2 Estimated maximum power for the KC200GT PV panel operating under different degradation conditions – normal $(\alpha_{opt} = 0.45\ \%/yr)$, crack $(\alpha_{opt} = 2.5\ \%/yr)$, dust $(\alpha_{opt} = 5.88\ \%/yr)$, discoloration $(\alpha_{opt} = 24.6\ \%/yr)$.

2 Proposed Method

By establishing a theoretical and mathematical relationship between the geometric shape of the superellipse and the graphical characteristics of the I-V curve, the explicit equation describing the improved empirical model has been defined as [1,3]

$$i = I_{sc}^{*} \cdot \left[1 - \left(\frac{v}{V_{oc}^{*}}\right)^{m}\right]^{\frac{1}{n}} \quad (1)$$

where V_{oc}^* and I_{sc}^* are its open circuit and short circuit points, and m and n are the fitting parameters of the superellipse model.

Solar cell degradation mostly impacts the optical transmittance of the front layers of PV panels, leading to decreased output power. A mathematical equation connecting the optical transmittance of the panel and its incident solar irradiance has been established in literature [2]

$$G_{deg}(t) = \tau(t).G_o(t)$$
$$\tau(t) = \tau_o(-\alpha_{opt}.t + 100\,\%) \quad (2)$$

where $\tau(t)$ is the optical transmittance of the PV panel decreasing according to a time (t) in years, and the subscript o refers to its nominal values i.e., standard test condition (STC).

Thus, by incorporating (2) into the equations describing (V_{oc}^*, I_{sc}^*) in (1), new mathematical expressions for estimating the key point values and for the reconstruction of the full range of the I-V curve can therefore be rewritten as

$$\begin{aligned} I_{sc(deg)}^* &= I_{scn}\tau(t).[1+\beta_I(T-T_n)] \\ V_{oc(deg)}^* &= V_{ocn} + NA_n\frac{kT}{q}In(\tau(t)) + \beta_V(T-T_n) \\ I_{mp(deg)}^* &\approx I_{mpn}\tau(t).[1+\beta_I(T-T_n)] \\ V_{mp(deg)}^* &\approx V_{mpn} + NA_n\frac{kT}{q}In(\tau(t)) + \beta_V(T-T_n) \end{aligned} \quad (3)$$

$$i = I_{sc(deg)}^*.\left[1-\left(\frac{v}{V_{oc(deg)}^*}\right)^m\right]^{\frac{1}{n}} \quad (4)$$

Similar to [1,3], by applying the datasheet constraints into (4), a two-dimensional simultaneous equation is derived whose roots become the optimum fitting parameters of the superellipse model.

$$\begin{aligned} I_{mp(deg)}^* &= I_{sc(deg)}^*.\left[1-\left(\frac{V_{mp(deg)}^*}{V_{oc(deg)}^*}\right)^m\right]^{\frac{1}{n}} \\ I_{mp(deg)}^* &= \frac{mI_{sc(deg)}^*}{n}\left(\frac{V_{mp(deg)}^*}{V_{oc(deg)}^*}\right)^m\left(\frac{I_{mp(deg)}^*}{I_{sc(deg)}^*}\right)^{\frac{1}{n}} \end{aligned} \quad (5)$$

Table 1 MPP values of the reconstructed PV characteristic curves for the KC200GT PV panel.

PV Panel Condition	Year	$V_{mp}[V]$	$I_{mp}[A]$	$P_{mp}[W]$
Manufacturer's Specification	STC	26.2795	7.6203	200.2580
Nominal/Normal	1	26.5709	7.1975	191.2460
$\alpha_{opt} = 0.45\,\%/yr$	10	26.5125	6.9047	183.0620
	20	26.4446	6.5794	173.9890
Crack	1	26.5417	7.0493	187.1000
$\alpha_{opt} = 2.5\,\%/yr$	5	26.3895	6.3263	166.9480
	10	26.1727	5.4223	141.9160
Dust	1	26.4920	6.8050	180.2270
$\alpha_{opt} = 5.88\,\%/yr$	5	26.0876	5.1044	133.1620
	10	25.3302	2.9788	75.4536
Discoloration	1	26.1802	5.4515	142.7210
$\alpha_{opt} = 24.6\,\%/yr$	2	25.6248	3.6729	94.1173
	3	24.6936	1.8943	46.7771

3 Simulation Results

According to literature, the KC200GT PV panel is widely utilized in evaluating the performance of PV models under various ambient and test conditions. By directly substituting the required key point values under specified ambient conditions into (5), the fitting parameters of the proposed model can therefore be easily extracted using the Leverberg-Marquardt algorithm [1,4] as $(m = 12.710, n = 0.937)$.

To evaluate the long-term performance of these PV panels, the degradation rates as specified in [5] for PV panels operating under normal operation $(\alpha_{opt} = 0.45\,\%/yr)$, cracks $(\alpha_{opt} = 2.5\,\%/yr)$, dust $(\alpha_{opt} = 5.88\,\%/yr)$ and discoloration $(\alpha_{opt} = 24.6\,\%/yr)$ are carried out using the MATLAB R2023b software environment (see Figs. 1 and 2).

As such, this improved superellipse model equations presents a simplified and easy alternative to estimating or predicting the behavior of PV panels operating under individual effect of solar cell degradation as summarized in Table 1.

4 Conclusion

This paper introduced a simplified method for predicting the long-term performance of photovoltaic (PV) panels. By integrating the superellipse model with the basic equation and laws governing solar cell degradation, an improved superellipse model is established. In the future, this simplified analytical approach will be further extended to predict the combined effects of solar degradation on PV panels with different cell materials.

5 Acknowledgments

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