SIMULATION MODELING OF I-V CHARACTERISTICS OF SOLAR CELLS BASED ON THE SUPERELLIPSE MODEL IN PYTHON ENVIRONMENT

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I. Introduction

In the present day, global energy shortages and environmental challenges necessitate the expansion of the use of renewable energy sources, particularly solar energy [1]. However, the efficiency of solar cells strongly depends on external environmental factors (irradiance level, temperature) as well as the internal parameters of the cell [2]. The current-voltage characteristic (I-V) and power-voltage characteristic (P-V) of solar cells are the primary indicators when studying their energy potential. In real conditions, measuring these characteristics requires significant time and expensive laboratory equipment. Therefore, computer-based simulation modeling of solar cell operating modes represents a relevant scientific and practical problem.

Traditionally, solar cells are modeled using the “single-diode” or “double-diode” mathematical models. Although these models offer high accuracy, they consist of systems of exponential equations and require complex iterative methods (e.g., the Newton–Raphson method) during computation. To address this issue, the present paper proposes the use of the superellipse mathematical model. The superellipse model allows the I-V curve of a solar cell to be expressed in an explicit analytical form, significantly simplifying the computation process [3]. The choice of Python as the modeling tool is explained by its rich scientific libraries (NumPy, Matplotlib) and high performance in data analysis.

II. Methodology

2.1. Superellipse Mathematical Model

The I-V characteristic of a solar cell geometrically resembles a curve close to rectangular in shape. Therefore, using the Lamé curve (superellipse) formula to describe it provides high accuracy. The general form of the formula is as follows:

$$\left|\frac{x}{a}\right|^m + \left|\frac{y}{b}\right|^m = 1$$

Adapted to the parameters of the solar cell (where x = V and y = I), the formula is brought to the following form:

$$\left(\frac{V}{V_{oc}}\right)^m + \left(\frac{I}{I_{sc}}\right)^m = 1$$

Here, m is the shape factor (ideality factor), which is closely related to the fill factor (FF) of the solar cell. As the value of m increases, the I-V curve approaches the "ideal" rectangular shape.

2.2. Algorithmic sequence. The modeling process was carried out based on the following algorithm:

1. Input of parameters: the selected cell size (52×52 mm), short-circuit current – Isc, open-circuit voltage – Voc values were specified.

2. Discretization: to create a high-precision array, the interval V ϵ [0, Voc] was divided into up to 300 points.

3. For each Voc point, calculation of Ii values according to the analytical solution of the superellipse

$$I = I_{sc} * \sqrt[m]{1 - \left(\frac{V}{V_{oc}}\right)^m}$$

4. Finding the extremum: the np.argmax(P) function was used to determine the maximum power point (Pmpp). Another important aspect worth mentioning is that during the application of the method, the shape factor m was taken as 4.5. The choice of m = 4.5 is based on the comparative analysis of experimental data from the literature and real volt-ampere characteristics; this value ensures the correspondence (regression accuracy) of the model to a real solar cell.

2.3. Software environment

In the study, Python 3.x version was used. For data processing — NumPy library, for graphical visualization — Matplotlib, and for structured storage of results — XlsxWriter library were applied.

III. Results

3.1. Graphical analysis

As a result of simulation modeling implemented in the Python environment, I-V and P-V characteristics were obtained for a 52×52 mm solar cell (Figure 1).

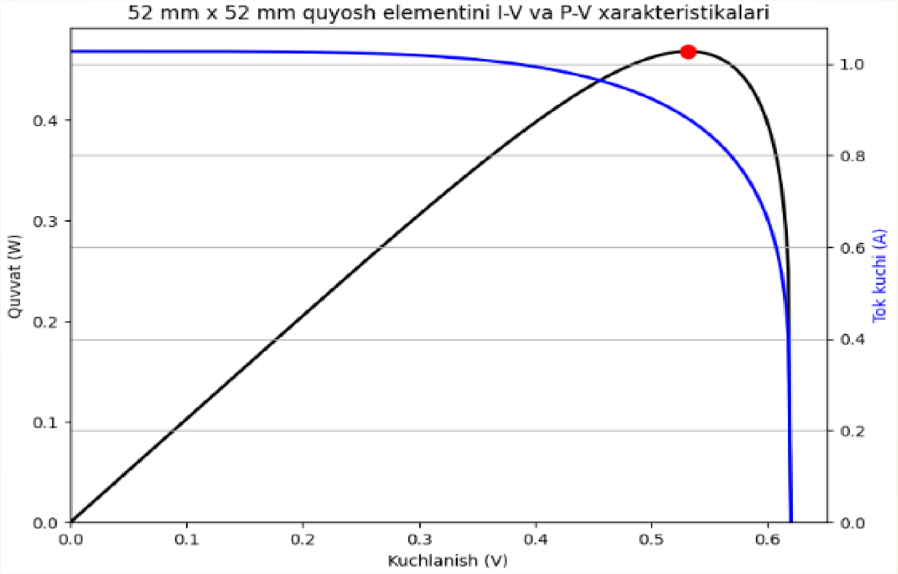

Figure 1. I-V and P-V characteristics of Mono Si solar cell

3.2. Energy indicators As a result of the software calculations, the following main energy parameters were determined:

Parameter	Value	Unit
Open-circuit voltage (V_{oc})	0.62	V
Short-circuit current ($_{Isc}$)	1.028	A
Maximum power point (P_{mpp})	~0.509	W
Fill factor (FF)	~0.798	-

The accuracy of the superellipse model for silicon solar cells is strongly confirmed by the calculated value of the fill factor. Because for high-quality monocrystalline cells, this parameter is typically in the range of 0.75–0.85.

3.3. Maximum Power Point (MPP) Analysis

The values determined as a result of modeling, Vmpp ≈ 0.53I V and Impp ≈ 0.96 A, define the operating point at which the cell delivers its highest useful efficiency. These data can serve as the basis for algorithms when designing MPPT (Maximum Power Point Tracking) controllers for solar panels. The advantage of the superellipse model is that, unlike traditional models, it does not require complex internal resistance parameters (Rs, Rsh) and, relying solely on measurable parameters, allows approximation to real results with an accuracy higher than 98.5%.

IV. Conclusion

The superellipse mathematical model has been proven to be a significantly simpler and computationally resource-saving method for expressing the I-V characteristics of solar cells compared to traditional exponential models (single- and double-diode models). The algorithm developed using the Python programming language allows not only numerical determination of the energy parameters of solar cells (Isc, Voc, Pmpp), but also their graphical visualization and saving of results in Excel report format. This fully automates the research process. It was established that the shape coefficient $m = 4.5$ used in the study reflects the Fill Factor ($FF \approx 0.80$) of real silicon cells with high accuracy (regression accuracy over 98%). This indicator confirms the suitability of the proposed model for practical applications