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Application of the Double Diode Model of Photovoltaic Cells for Simulation Studies on the Impact of Partial Shading of Silicon Photovoltaic Modules on the Waveforms of Their Current–Voltage Characteristic

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Received: 17 April 2019; Accepted: 19 June 2019; Published: 24 June 2019

Abstract: Photovoltaics (PV) is the phenomenon of converting sun energy into electric energy by using photovoltaic cells. Furthermore, solar energy is the major renewable energy source. PV modules are systematically more efficient and manufacturing costs decrease at the same time. The PV module performance is affected by ambient temperature, humidity, wind speed, rainfall, incident solar radiation intensity and spectrum, dust deposition, pollution, and shading, which are environmental factors. The problem of partial shading of the generator often arises when designing photovoltaic installations. If it is not possible to avoid this phenomenon, its impact on the operation of the photovoltaic system should be estimated. The classical method is to measure the current–voltage characteristics, but it requires switching off the installation for the duration of the measurements. Therefore, this paper proposes a method using a computer simulation in the Matlab package with the implemented component "Solar Cell" for this purpose. Three cases of partial shading of photovoltaic modules with different degrees of shading were analyzed. The obtained results of the computer simulation were verified for two types of silicon PV modules: Mono- and polycrystalline.

Keywords: photovoltaics; PV cell; PV module; partial shading; current–voltage characteristics

1. Introduction

The process of conversion of sunlight directly into electricity using solar cells is called photovoltaics. Solar energy is one of the major renewable energy resources. Photovoltaics is a new interdisciplinary field of science and technology, and its electricity is currently the most commonly used form of energy. It is a rapidly growing alternative to the conventional fossil fuel electricity generation. Furthermore, it increasingly becomes an important renewable electricity source. However, since the first practical photovoltaic devices were demonstrated in 1954, it is a relatively new technology compared to other electric power generations [1–3]. Research and development of photovoltaics gained its first intensification from the space industry in the 1960s which required a power supply for contemporary satellites. The short-lived world oil crisis in the 1970s caused solar cells to become an alternative power generating technology. Their application quickly prompted the development of a terrestrial photovoltaic industry.

In the first section of the research, the general scope, is given and the genesis of our research is justified. The second section is a description of the research station, the simulation model, the methodology, and the scope of research. The third section presents the results of the research. The fourth and fifth sections are the discussions of the results, conclusions from our research, and guidelines for future research.

Different aspects of the partial shading influence on the performance of photovoltaics (PV) modules were analyzed in several available studies [4–9]. In several of them, the problem was also analyzed in the form of simulation results based on modeling [10–12], and simulations were based on models of single- or double-diode PV cells [13–15]. A novelty in this research is the application of the MATLAB/Simulink (version 2019a, MathWorks, Natick, MA, USA) "Solar Cell" component for simulation testing of the effects of partial shading on the course of the current–voltage (I–V) characteristic of the PV module.

The purpose of this research was not to perform the next implementation of the mathematical model of the PV cell, but only to present a method of partial shading modeling using a ready Matlab component that can be quickly adopted for other modules with a different internal structure (e.g., for PV modules built of halves of cells with a different connection of PV cells). Another novelty in this research was also the proposal to introduce the coefficient of the degree of shading as a comparative indicator in this type of research.

2. Materials and Methods

2.1. Model Background

The only effective way to determine the correct functioning of the PV module is to measure the full I–V characteristics [1,16,17]. Data sheets of PV modules provided by manufacturers contain numerical values for three points of I–V characteristic, determined in standard test conditions (STC). They also show the I–V characteristic curves for selected values of solar radiation intensity and PV module temperature. In the area of the measured typical I–V characteristic, we distinguished three main parts (Figure 1) [18,19]:

- Horizontal part—from the side of the vertical axis (sometimes slightly falling), characterized by an almost constant current at high voltage changes;
- Vertical, falling part—from the side of the horizontal voltage axis, characterized by a large decrease of the current value with a slight increase in voltage;
- Curve bend—transition area between the above-mentioned parts, in which the maximum power point is determined (point MPP in Figure 1).

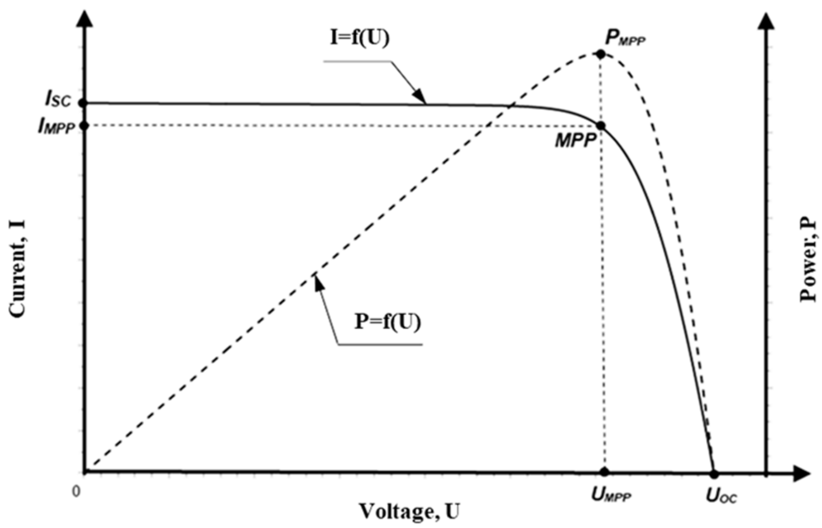

Figure 1. Correct course of the current–voltage (I–V) characteristic of the photovoltaics (PV) module and the interpretation of the maximum power point (MPP) (description of the markings is given in Table 1).

Table 1. Selected technical data of the PV modules according to the manufacturers.

Technical Data in STC:	IBC SOLAR MonoSol 260 EX	SUNTECH STP255-20/Wd
Solar Cell (6 inches ≈ 156 × 156 [mm])	Monocrystalline Silicon	Polycrystalline Silicon
No. of Cells	60	60
Maximum Power Point—P_{MPP}, [W_p]	260	255
Power Tolerance, [%]	0/+3	0/+5
Module Efficiency—η, [%]	15.8	15.7
Voltage in MPP—U_{MPP}, [V]	30.6	30.8
Current in MPP—I_{MPP}, [A]	8.51	8.28
Open Circuit Voltage—U_{OC}, [V]	38.8	37.6
Short Circuit Current—I_{SC}, [A]	9.24	8.76
Dimensions of PV Module, [mm]	1660 × 990 × 50	1640 × 992 × 35
NOCT, °C	48.4	45 ± 2
Temperature Coefficient of P_{MPP} - γ_T, [%/°C]	−0.43	−0.44
Temperature Coefficient of U_{OC} - β_T, [%/°C]	−0.31	−0.33
Temperature Coefficient of I_{SC} - α_T, [%/°C]	+0.042	+0.055

In the conditions of stable and even solar irradiance, the correctly measured I–V curve is characterized by a smooth shape and monotonic decrease of the current with increasing voltage and without any visible deviations or discontinuities. The shape of the I–V characteristic depends on the quality and technology of the cells making up the PV module. In the case of thin-film modules, particularly silicon (amorphous) modules, the curve is usually more rounded compared to the curves of modules made of crystalline silicon cells. Measurement of the I–V characteristic should be performed at radiation intensity not lower than 700 W/m^2 (according to IEC/PN-EN 60891 standard [20]), which allows for a more exact conversion of the electrical parameters obtained from the curve at the STC rated conditions. The direction of incidence of rays is also important, which is initially checked with the mechanical inclinometer. Deviations from the shape of the normal I–V characteristic shown in Figure 1 are anomalies which possible variants are shown in Figure 2. Various possible reasons for deviations of I–V characteristics were analyzed in the article [21], which were marked with arrows from 1 to 6 in Figure 2. The shape of the I–V curve denoted by the number 1 in Figure 2 indicates discrepancies within the range of the generated current between different areas of the PV module. The characteristic step shape is the effect of the bypass diode shunting the area responsible for the lower current. This situation can take place in a few cases:

- Partially shaded PV module, even partial shading of a single cell (about 20% of the surface) in the module can cause switching of the bypass diode, causing a clear indentation in the I–V curve (this case will be analyzed in detail in this research);
- PV module partially dirty or covered (e.g., with snow, frost, etc.);
- Damaged PV cells in the module.

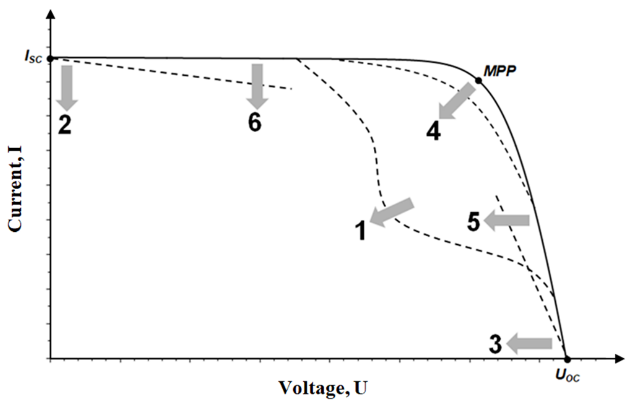

Figure 2. Anomalies in the course of I–V characteristics of the PV module. Possible deformations of the graphs are marked with arrows from 1 to 6.

2.2. Research Stand and Methods

The first stage of the research was the preparation of artificial shutters of 0.2 mm thick yellow polyethylene film (film used in the construction for the vapor barrier). The simulated shading included one, two, or three sections of the PV module, protected by separate shunt diodes (Figure 3). For all three types of shading, the tests were performed for double layer of polyethylene film.

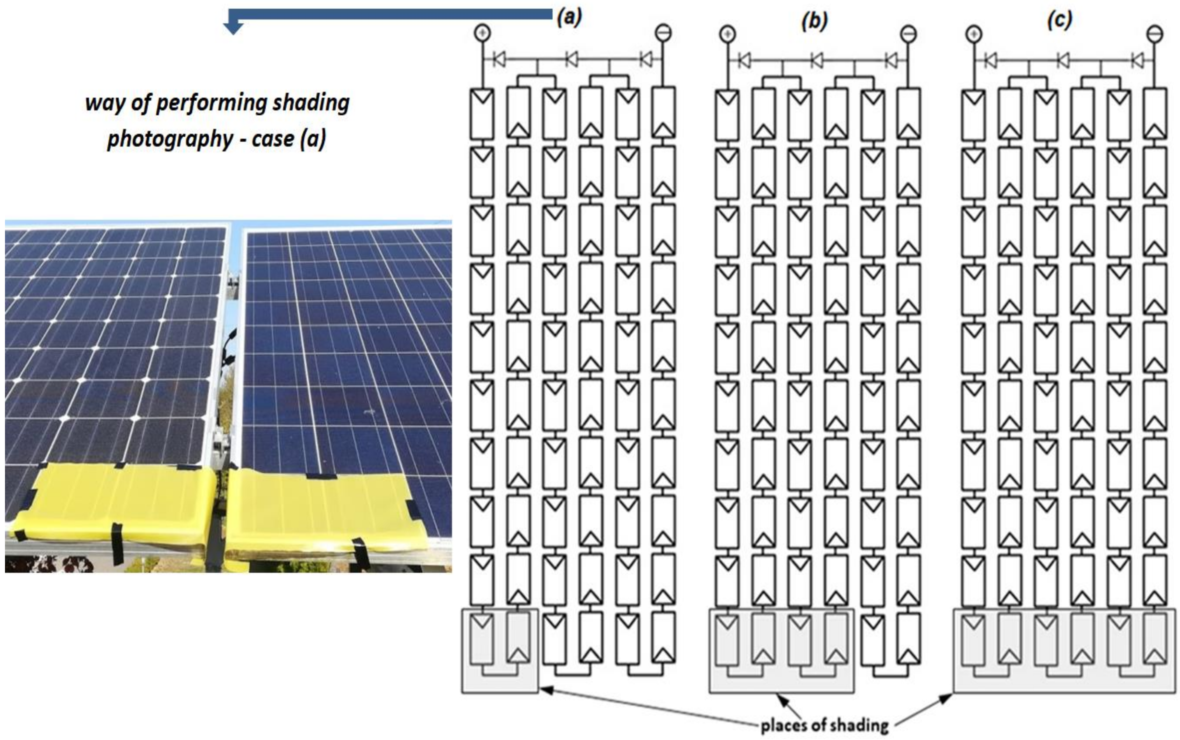

Figure 3. Diagram of the internal structure of typical silicon PV modules (60 pieces of PV cells) with marked spots of artificial shading of PV cells: (**a**) Two PV cells shaded (photography); (**b**) four PV cells shaded; (**c**) six PV cells shaded.

The second stage of the research was setting the parameters of the I–V 400 meter [22] used to measure the actual I–V characteristics of the PV modules: IBC SOLAR MonoSol 260 EX [23] and SUNTECH STP255-20/Wd [24]. The most important technical data of the modules are provided in Table 1.

The measurements of the real I–V characteristics were made for the PV modules mounted in the GPS location 52.478561 N and 19.672268 E (central Poland, near Plock). The PV modules were mounted in the azimuthal deviated by 2° from the direction of the South to the East and inclined at an angle of 33° to the horizontal (the location was determined using the mobile PV*SOL app), on 13 October 2018. In hours: 10:00 p.m. to 12:00 p.m.

The connection diagram of the meter during measurements is shown in Figure 4. The connection of the I–V 400 meter [22] was made using the four–wire method according to the IEC/PN-EN 60891 [20] standard. The temperature sensor (PT300N) of the PV modules was glued to the inner surface of the module in its central part. The solar radiation intensity sensor (HT304) was connected in accordance with the technology of the PV modules (monocrystalline or polycrystalline silicon) and mounted exactly in the assembly plane of the module. With the I–V 400 meter, measurements can also be carried out in conditions deviating from the optimal radiation for the PV module, i.e., below the 700 W/m^2 value. This is important when conducting tests to check the effect of shading on the functioning of the PV modules with different solar spectrum. Before measuring the I–V characteristics of the PV modules with partially shaded cells according to the scheme shown in Figure 3, the amount of solar radiation that was passed through the two-layered shutter material was measured. The value of this reduced radiation intensity ($E_{s1} \div E_{s3}$) was introduced into the appropriate section of the PV cells of the simulation model shown in Figure 5.

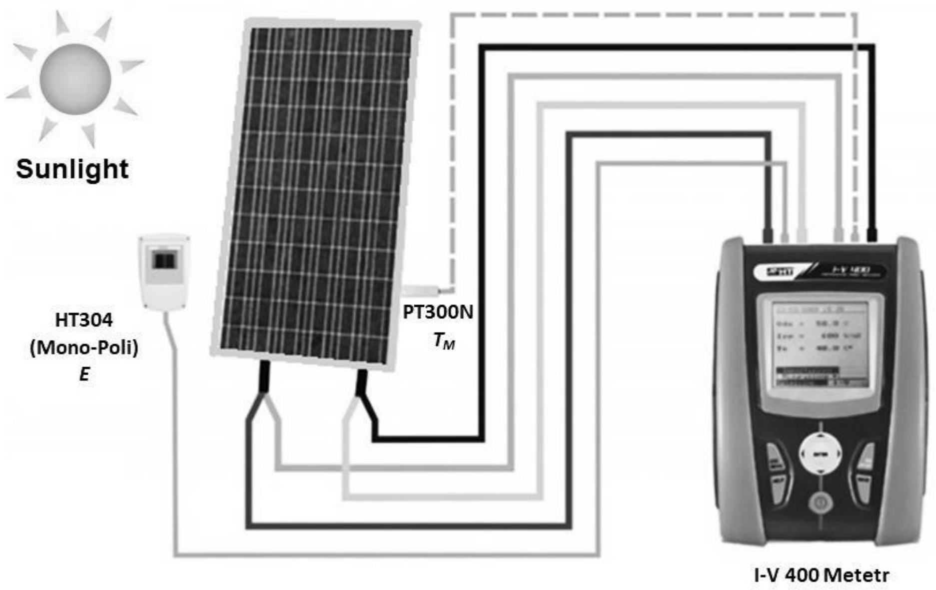

Figure 4. Method of measurement of I–V characteristics using the I–V 400 meter [22].

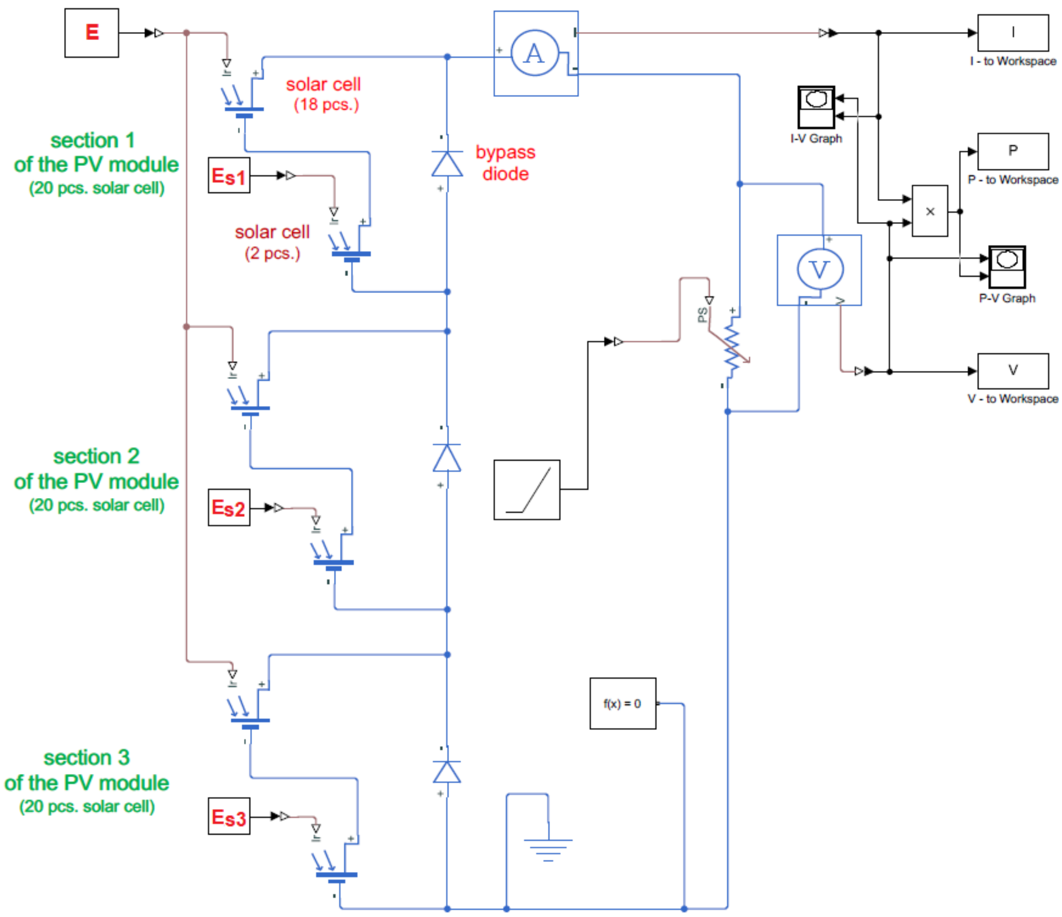

Figure 5. Simulation model of the I–V characteristics of PV module in the MATLAB/Simulink.

To better illustrate the amount of shading method, a coefficient of shading degree k_{sh} was introduced, which was defined according to the following relationship:

$$k_{sh} = \frac{E - E_{sh}}{E} \cdot 100, \quad (1)$$

where E_{sh} means E_{s1}, E_{s2}, or E_{s3} according to Figure 5, respectively. The results of the calculation of this coefficient are given in column number four of Table 2.

Table 2. Conditions of experimental measurements, performed with the I–V 400 meter on 13 October 2018, between 10 and 12 p.m., with an average ambient temperature of 14.5 °C.

Marking of Measurement: M-mono, P-poly Crystalline PV Module:	Temperature of the PV Module T_M, [°C]	Number of Shaded PV Cells in the Module, [pcs.]	Coefficient of Shading Degree: k_{sh}, [%]
P1 (Figure 6)	34.1	2	60.1
P2 (Figure 7)	34.4	4	58.9
P3 (Figure 8)	34.3	6	60.8
M1 (Figure 9)	33	2	56.8
M2 (Figure 10)	33.1	4	58.4
M3 (Figure 11)	33	6	38.8

A total of three measurements were carried out for the mono- and polycrystalline silicon PV module. The "Solar Cell" component of the Matlab/Simulink engineering calculations was used to simulate the effect of shading on the waveforms of the I–V characteristics of the PV modules. The "Solar Cell" component was developed on the basis of the dual diode mathematical model of a PV cell [25]. A simplifying assumption was made that the temperature of the PV module was constant. This assumption was due to the fact that the temperature sensor was glued to one point on the inner surface of the PV module. Detailed analysis of the temperature distribution, e.g., on the performed thermograms, showed some differences that were revealed in the case of prolonged shading. The ambient temperature was relatively constant during the measurement which was measured at the beginning and end of the measurements and stayed the same (14.5 °C). Sky condition during measurements: Sunny and cloudless.

The parameters of the PV modules from Table 1 and the same weather parameters (module temperature and radiation intensity) as in the measurements using the I–V 400 meter were used for the simulation.

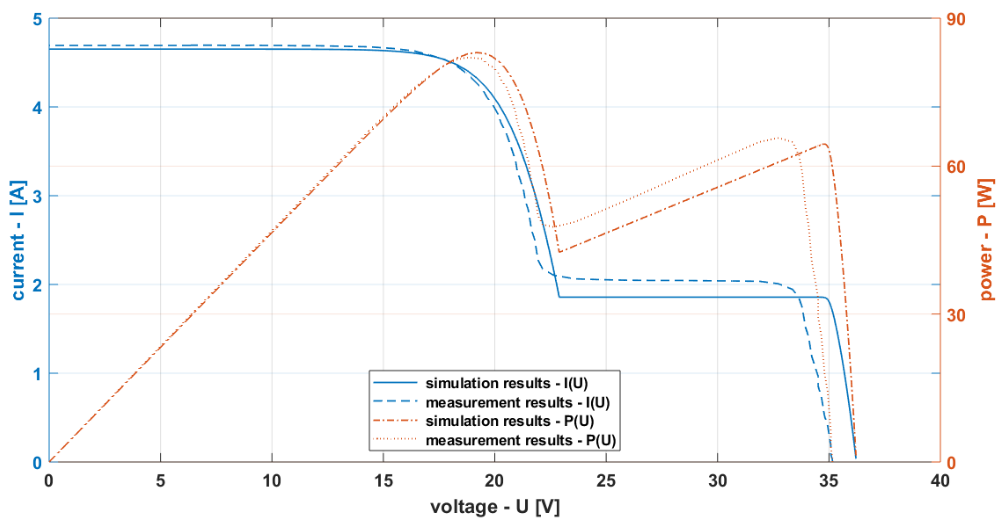

Figure 6. I–V characteristics of PV module STP255-20/Wd made with partial shading. For detailed comparison of measurement and simulation results, see Table 2. Marking of measurement point P1 (two PV cells were shaded; the exact measurement time was 10:24 a.m.

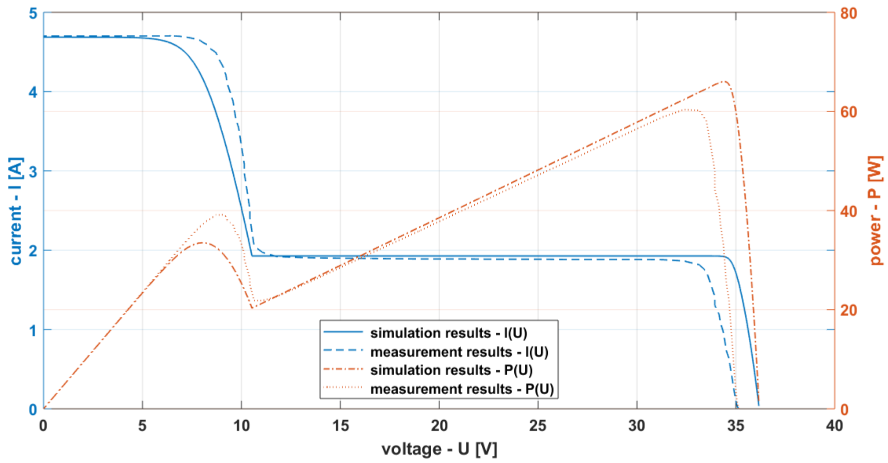

Figure 7. I–V characteristics of PV module STP255-20/Wd made with partial shading. For detailed comparison of measurement and simulation results, see Table 2. Marking of measurement point P2 (four PV cells were shaded; the exact measurement time was 10:36 a.m.).

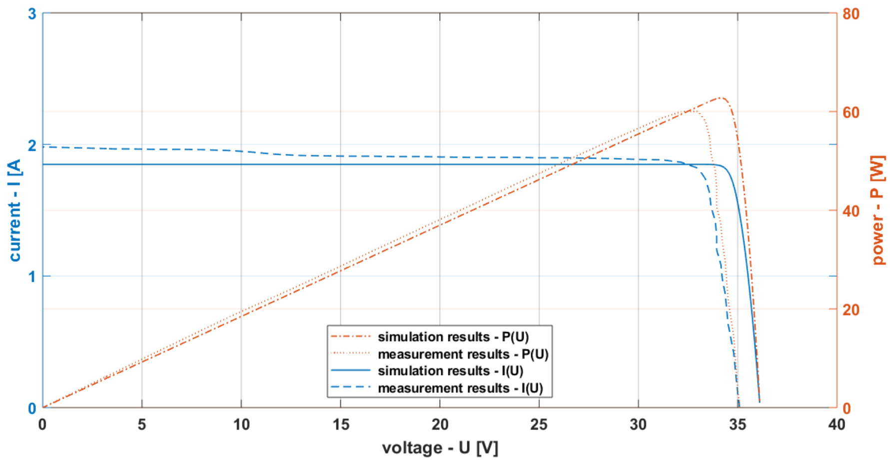

Figure 8. I–V characteristics of PV module STP255-20/Wd made with partial shading. For detailed comparison of measurement and simulation results, see Table 2. Marking of measurement point P3 (six PV cells were shaded; the exact measurement time was 10:49 a.m.).

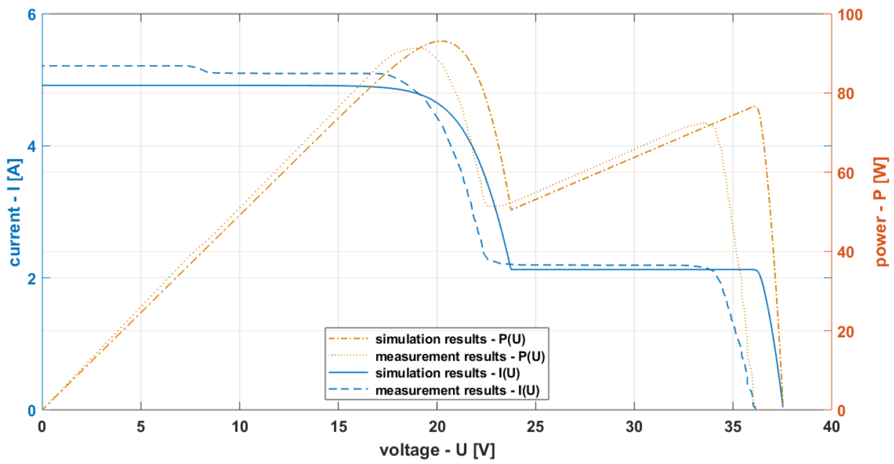

Figure 9. I–V characteristics of PV module MonoSol 260 EX made with partial shading. For detailed comparison of measurement and simulation results, see Table 2. Marking of measurement point M1 (two PV cells were shaded; the exact measurement time was 11:08 a.m.).

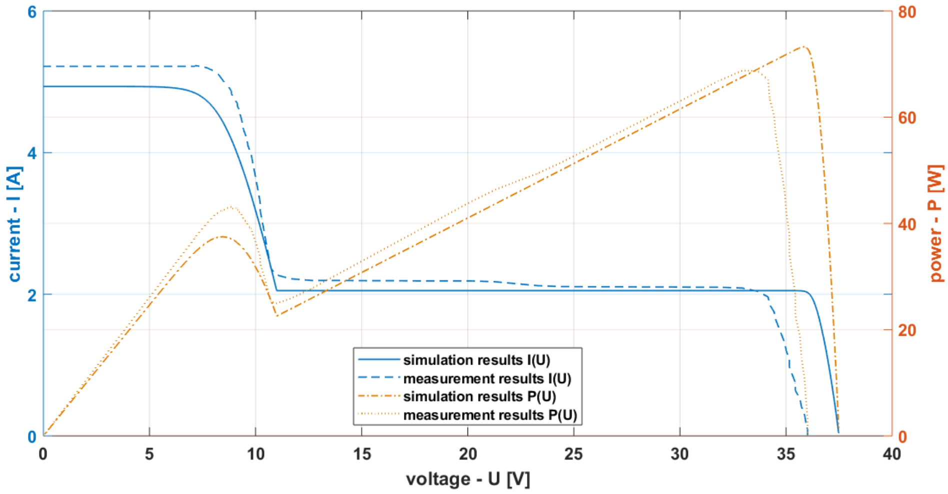

Figure 10. I–V characteristics of PV module MonoSol 260 EX made with partial shading. For detailed comparison of measurement and simulation results, see Table 2. Marking of measurement point M2 (four PV cells were shaded; the exact measurement time was 11:22 a.m.).

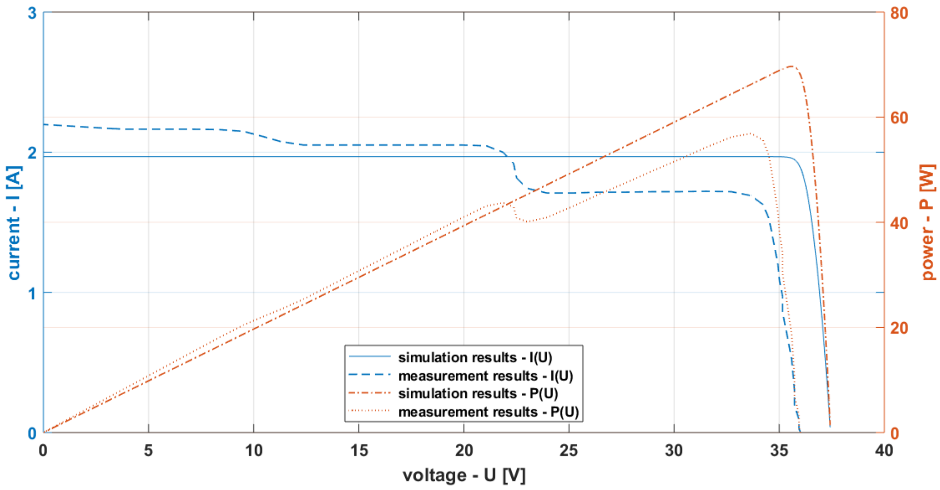

Figure 11. I–V characteristics of PV module MonoSol 260 EX made with partial shading. For detailed comparison of measurement and simulation results, see Table 2. Marking of measurement point M3 (six PV cells were shaded; the exact measurement time was 11:41 a.m.).

3. Results

This research compared the I–V characteristics of the polycrystalline PV module (STP255-20/Wd) (Figures 6–8) with the characteristics of the monocrystalline PV module (MonoSol 260 EX) (Figures 9–11), which were obtained as a result of computer simulations and measurements. The research of the PV modules was performed for three cases of partial shading and for two-layer shutters made of a polyethylene film. A summary of all cases of the research is shown in Table 2.

Calculation and verification typical indicators of the fill factor of the I–V curve and the efficiency of the PV module for cases with shading of PV cells was unjustified, because the maximum power point (MPP) in the diagrams of Figures 6–11 was ambiguous and was characterized by the occurrence of local extremes. Adoption of the fill factor and efficiency of the PV module for the maximum power value would lead to large errors resulting from the interpretation of these values, causing their significant under-reporting.

4. Discussion

In the case of shading of two PV cells in both tested modules, comparable results were obtained from measurements and simulations, regardless of the degree of shading (Figures 6 and 9). Similar compliance was observed for four shaded PV cells (Figures 7 and 10). Surprising results were obtained for shading six PV cells. For the PV module made of monocrystalline silicon, a slightly different course of characteristics was observed for the measurements made with the meter (Figure 11). In this case, the study on the simulation model would not properly characterize the operation of the bypass diodes. Characteristics of I–V have shapes similar to standard ones, which do not reflect the structure of the PV module shown in Figure 3.

Assuming as a measure of comparison of simulation and measurement results, the maximum relative error was estimated at around 10%. However, in this verification, it was important to reproduce the shape of the current–voltage characteristics (I–V), which was confirmed. The relative error of verification was estimated for two points of I–V characteristics in the diagrams shown in Figures 6–11: For I_{sc} (short circuit current) and for V_{oc} (open circuit voltage). The MPP (maximum power point) was not compared because it shifted significantly during the partial shading of the PV module.

5. Conclusions

The obtained results of simulation tests in the form of I–V characteristics were positively verified by the results of real measurements. Both the shapes of the characteristics in Figures 6–11 as well as the values of the characteristic points were correspondingly correct. The characteristic of the obtained results was: The smaller the shading, the greater the compliance of the measurement results and simulations.

The results of the conducted research indicated that the MATLAB/Simulink "Solar Cell" module (double diode model) for simulation studies on the effect of partial shading of solar modules made of silicon was a sufficiently accurate test method for practical applications. The conducted simulation tests were a quick method that did not require turning off the PV generator during their execution. The presented results show the effect of partial shading in typical cases, such as shading of tree leaves or contamination due to bird excrement. They are dangerous because in the long term they can lead to hot spots of solar modules.

In future studies, it could be possible to model any shape and degree of partial shading of the PV module using the "Solar Cell" component after appropriate modification of the simulation scheme. In the future, an index of the level and size of the partial shading of the PV modules should also be developed to determine the effect of shading on particular parameters of the PV module. This indicator will allow to accurately determine the efficiency losses of PV modules with different types of shading. It is also necessary to carefully check the effect of the bypass diode parameter on the results of model tests, which was particularly evident in the case of shading six PV cells.

Author Contributions: Conceptualization, M.T.S.; methodology, M.T.S.; investigation, M.T.S.; data curation, M.T.S.; writing—original draft preparation, M.T.S.; writing—review and editing, M.T.S., J.W., and K.J.W.; visualization, M.T.S.; supervision, K.J.W.; funding acquisition, J.W. and K.J.W.

Funding: The APC was funded by the Town of Płock through the Mayor's Research Grants Programme "Collaboration with Universities".

Conflicts of Interest: The authors declare no conflict of interest.

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