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Studying the Impact of Shading on the Energy Characteristics of a Solar String

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Abstract. *The current article presents an analysis of the impact of shading on the characteristics of a solar string, with and without the presence of bypass diodes. A solar string consisting of four solar modules was used for this purpose. Experiments were sequentially conducted by connecting one, two, and four bypass diodes. The study was conducted in laboratory conditions using an artificial light source while maintaining the cell temperature mode. The obtained results were analyzed concerning the volt-ampere characteristics, power characteristics, and the coefficient of performance of the photovoltaic string. All the obtained characteristics are compared with the characteristics of the non-shaded solar string.*

Keywords: solar, string, cell, shading, diode

1. Introduction

With increasing energy demands and technological advancements, technologies that convert renewable energy sources are finding more frequent applications for energy production. Given the distribution of energy potential on a global scale and the accessibility of the used technologies, solar energy proves to be one of the fastest-growing sectors for energy production (**Hannah Ritchie et al., 2020**).

Most commonly, solar energy is utilized for the production of electrical and thermal energy (**Ang et al., 2022**). A widely used technology for generating electrical energy is based on the photovoltaic effect (**Saiprakash et al., 2021**), involving the use of solar cells and solar modules (**Abdelaziz et al., 2022**).

A technology using the photovoltaic effect is characterized by relatively low conversion efficiency. Several factors further influence its efficiency, such as solar module temperature (**Parthiban & Ponnambalam, 2022**), the type and orientation of solar modules (**Al-Ghussain et al., 2023**), meteorological factors, pollution, and shading caused by objects located near the solar modules or a group of modules (**Bernadette et al., 2021**).

The shading effect is characterized by partial or complete restriction of the sunlight reaching the solar panels (**Abdelaziz et al., 2022**), (**Fialho et al., 2014**). During shading, one or more cells of the photovoltaic module switch to a dark mode and behave like a diode. In this mode, the cell or cells are connected in the opposite direction compared to the other participating cells in the solar module (**Smets et al., 2016**). As a result, there is a partial or complete reduction in the generated energy, as well as thermal stress on the shaded cell or cells (**Wang & Hsu, 2011**).

One way to limit the shading effect is by using bypass diodes, commonly applied by one or several diodes for a solar module (**Calcabrini, et al., 2022**). Other applicable methods are related to orienting the solar modules in space (**Iskandar et al., 2018**) and dynamically reconfiguring the photovoltaic system (**Chaaban et al., 2015**), (**Sai Krishna & Moger, 2019**).

The aim of this article is to analyze the influence on the characteristics of a solar string under conditions of partial shading, both with and without the addition of bypass diodes.

2. Experimental Setup

The experiments were conducted using a specially prepared stand. The stand is composed of four solar modules, each consisting of four silicon cells. The illumination of the modules, or rather the cells,

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is carried out through an artificial light source. The light source is made from halogen lamps MR16. The maintenance of the cell's temperature mode is achieved by forced cooling using fans.

The stand provides the capability to connect in parallel one, two, or four bypass diodes to the string of solar modules, according to the diagram presented in Fig. 1. For this purpose, rectifier diodes 1N4007 were used.

The conditions under which the experiments are conducted are as follows:

- Maintaining a constant cell temperature;
- Maintaining a constant light flux;
- Loading the string is performed using adjustable resistance, providing a range of loading from open-circuit to short-circuit point.

The experimental studies are structured into the following groups and conducted according to the diagram presented in Fig. 1:

- Operation of the string without bypass diodes, with and without shading (all the switches are open);
- Operation of the string with one bypass diode, with and without shading (switch S7 is closed, and the other are open);
- Operation of the string with two bypass diodes, with and without shading (the switches S5 and S6 are closed, others are open);
- Operation of the string with four bypass diodes, with and without shading (the switches S1, S2, S3 and S4 are closed, others are open).

The shading process was implemented by completely shading one module from the solar string.

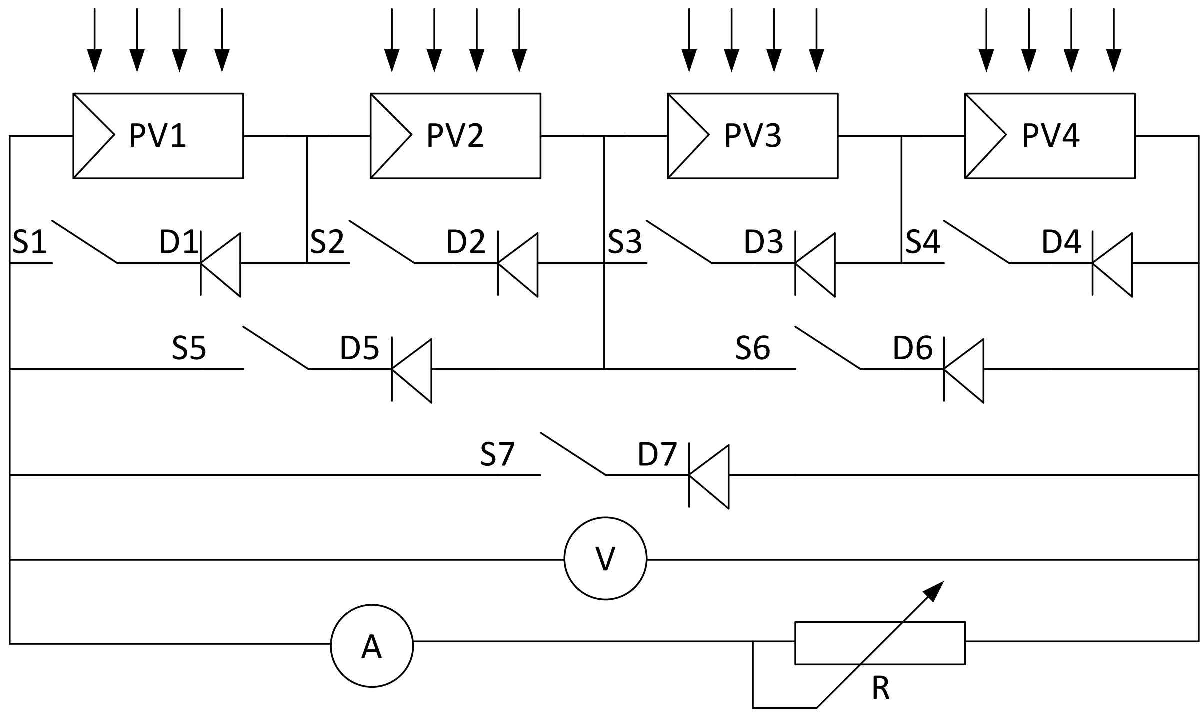

Fig. 1. Circuit diagram of the experimental setup.

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3. Results and Discussion

For all the described experimental groups, volt-ampere characteristics, power characteristics, and the coefficients of performance have been obtained. For the purpose of comparison and analysis of the obtained results, values on the graphs are presented in relative units.

Figures 2, 3, and 4 illustrate the graphical results for the following several cases - without shading and bypass diodes; without shading and with one bypass diode; without shading and with two bypass diodes; without shading and with four bypass diodes.

According to the presented results, it is noted that the inclusion of bypass diodes in cases of no shading does not significantly affect the energy characteristics of the modules. Minor differences in the characteristics are mainly attributed to relatively small variations in maintaining the temperature mode, disparities among individual modules due to imperfections in their manufacturing, as well as the uneven distribution of the light flux.

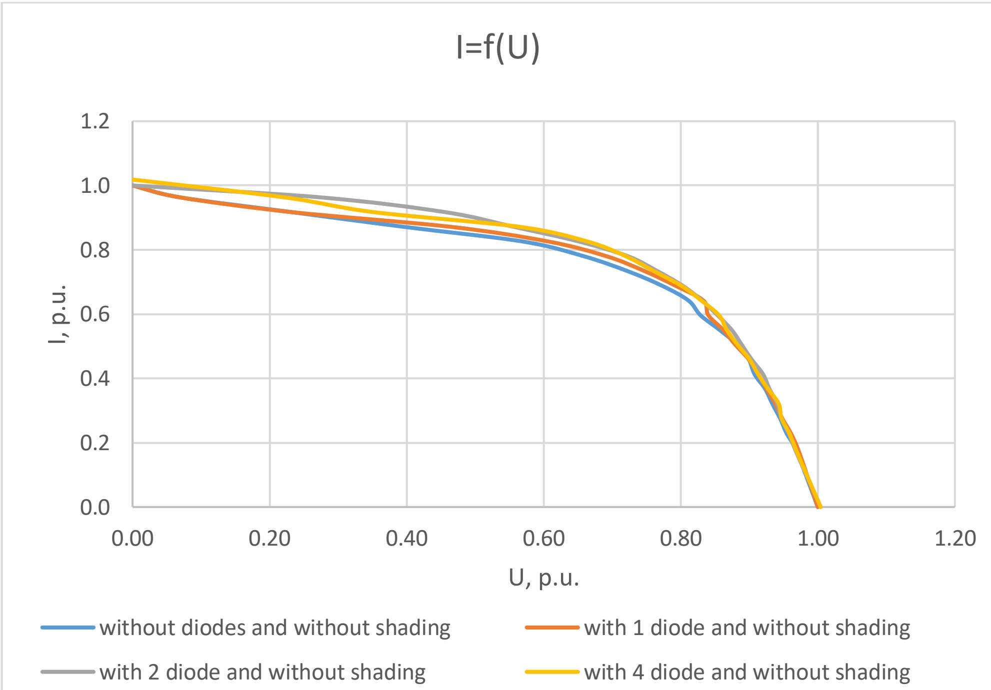

Fig. 2. Solar string volt-ampere characteristics without shading.

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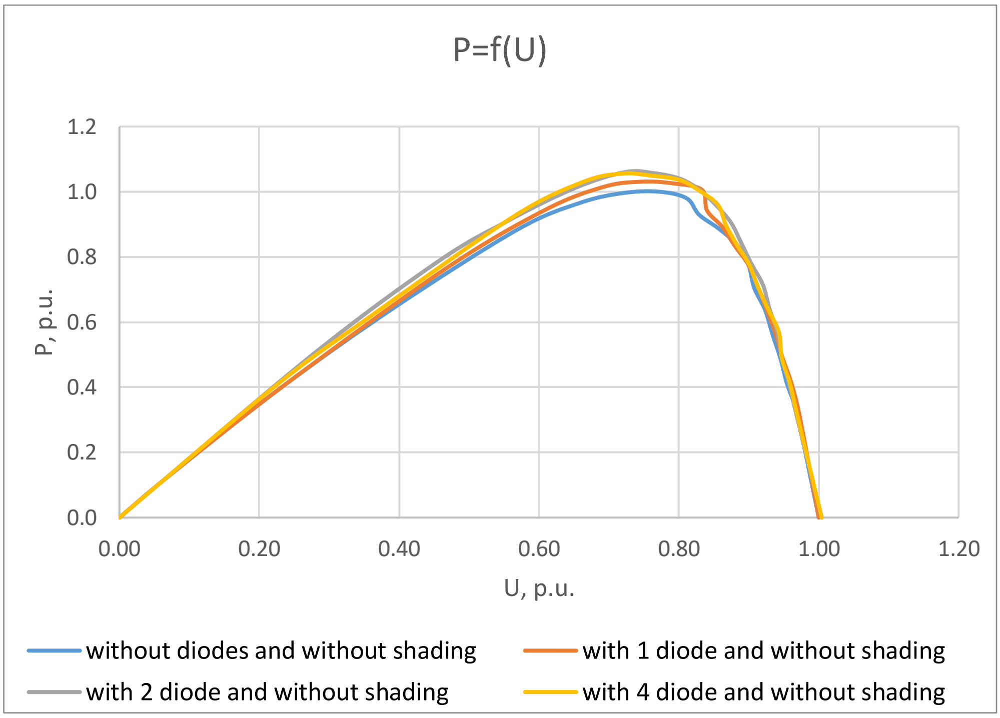

Fig. 3. Solar string power characteristics without shading.

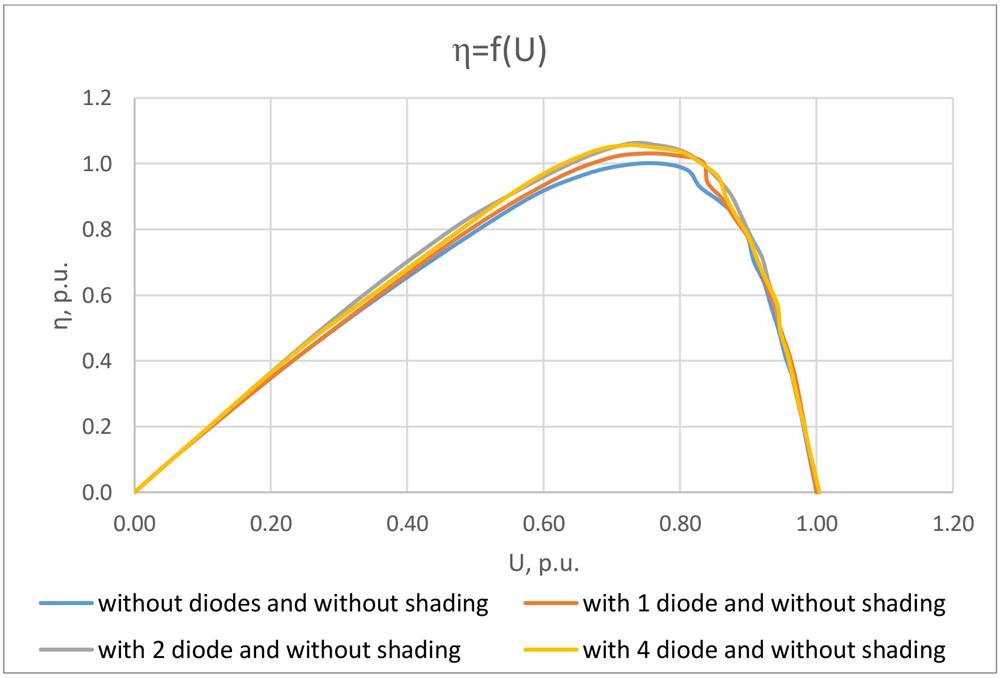

Fig. 4. Solar string efficiency characteristics without shading.

Figures 5, 6, and 7 illustrate the graphical results for the following several cases - without shading, without bypass diode; with shading and with one bypass diode; with shading and with two bypass diodes; with shading and with four bypass diodes. From the presented results, a clear reduction in the generated electrical power and efficiency of the string is noted. In cases of shading on one of the modules in the string, without and with connection of one bypass diode, the characteristics overlap. This means that the presence of only one bypass diode does not influence the reduction of the shading effect.

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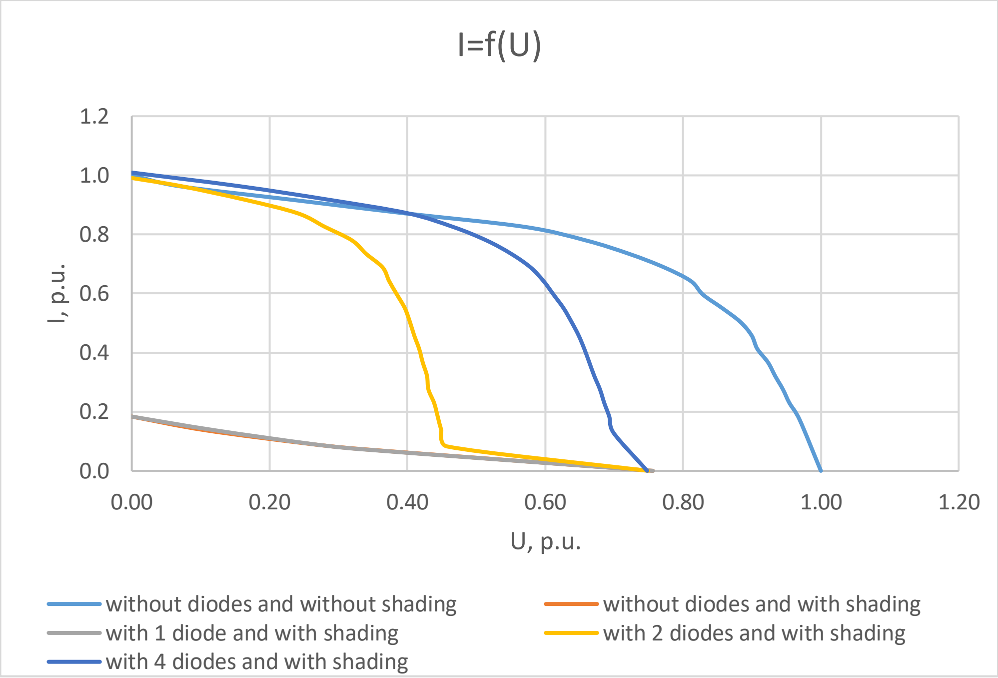

Fig. 5. Comparison between solar sting volt-ampere characteristics with and without shading.

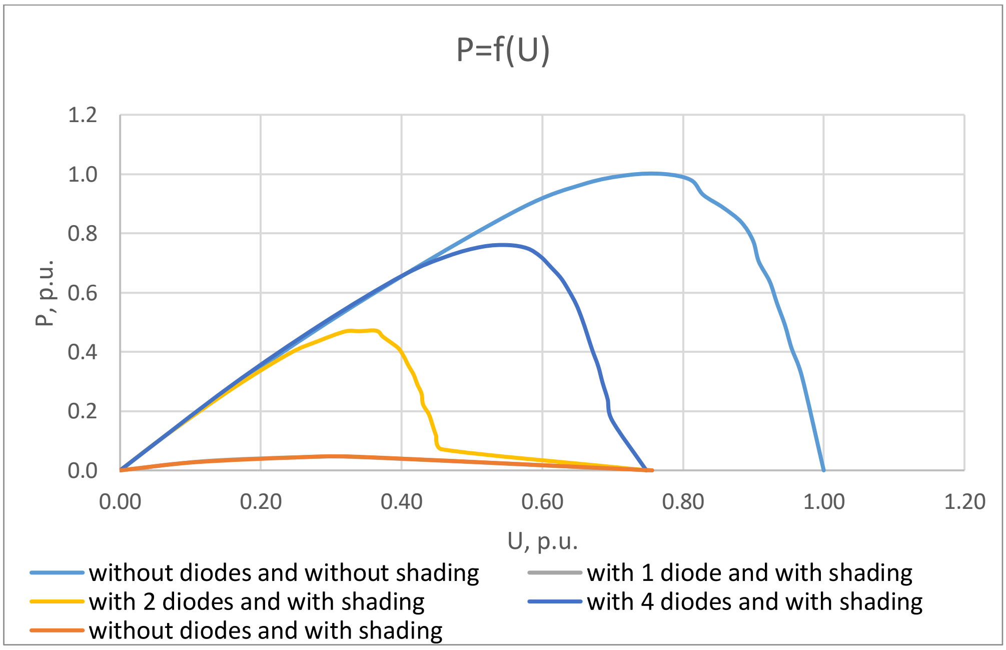

Fig. 6. Comparison between solar sting power characteristics with and without shading.

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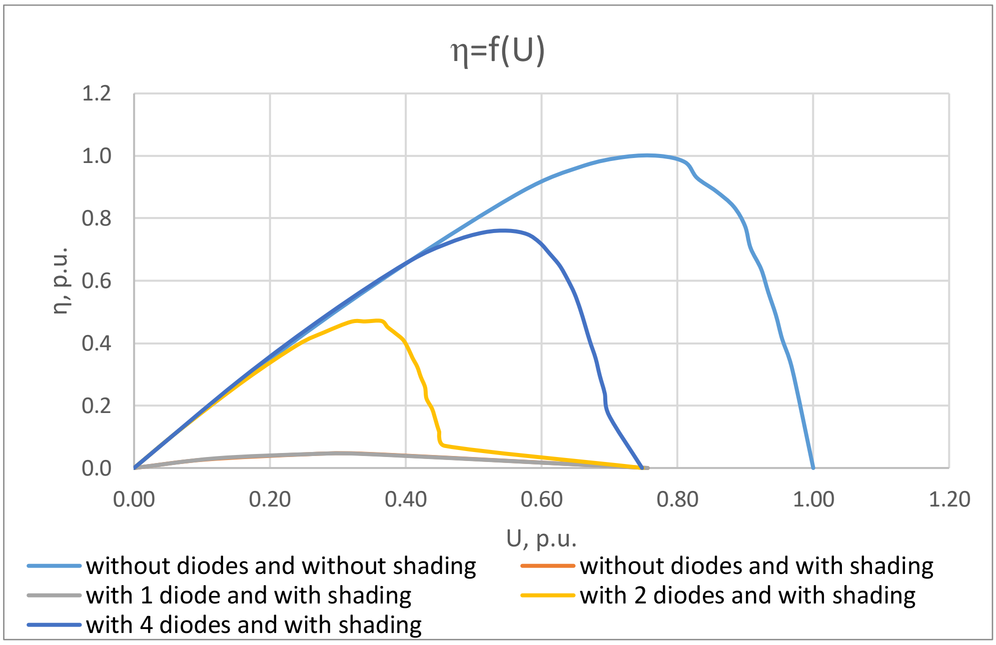

Fig. 7. Comparison between solar sting efficiency characteristics with and without shading.

In instances involving more than one bypass diode, the reduction of power is less pronounced. When two diodes are connected, only two out of the four modules are simultaneously bypassed, whereas by connection of four diodes, only the shaded module is bypassed.

4. Conclusion

The presented article includes experimental results regarding the electrical characteristics of a solar string composed of four solar modules. Various scenarios, with and without shading of one solar module, were implemented, and results were compared when one, two, and four bypass diodes were used. As a result of the conducted research, it is demonstrated that shading has the least impact when an equal number of bypass diodes are employed as the number of participating solar modules. The obtained results can also be applied to the characteristics of solar cells within the structure of a solar module under conditions of partial shading.

Based on the results obtained from the experimental studies, a model of the solar string under the specified conditions is yet to be developed. In future work, the influence of the type of bypass diode on the energy characteristics of the solar string will also be investigated.

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