Assessment of Methods to Limit The Impact of Hot Spot Phenomenon on Photovoltaic Power

Trung Hieu Trinh*, Duc Anh Nguyen, Thi-Thanh-Quynh Nguyen, Dinh Truc Ha

Abstract—Most solar systems consist of small power, low voltage panels connected in series or parallel to increase voltage and power. However, connecting the panels in series can lead to certain operational limitations. In the case where the panels are partially shaded by clouds, trees, or damaged elements, the current flowing through the solar system is reduced to the level of weakest panel in the string. The paper introduces the distributed maximum power point tracking (DMPPT) model to obtain the maximum power of the solar system when working in shaded conditions. PSIM software is used to evaluate the performance of the DMPPT model for a solar system consisting of 4 TP250MBZ panels. The simulation results show that when the shading occurs, the use of the DMPPT model will obtain a higher power than the central maximum power point tracking model (CMPPT)

Index Terms—Photovoltaic System, Maximum Power Point Tracking, Partial Shading Condition, Boost Converter.

1. Introduction

THE temperature of the earth is increasing and hence, this leads to the climate change affecting human life directly. Many efforts have been made and agreements have been adopted to reduce the rate of global warming. At the 26^{th} meeting of the United Nations Framework Convention on Climate Change (COP26) in November 2021, 197 member countries of the Paris climate agreement committed to reducing the emissions of CO_2 to 45% by 2030 compared to 2010 and to zero by 2050 [1]. Therefore, the development of renewable energy is one of the most important solutions to achieve this goal. In particular, solar energy plays an important role to meet the increasing load demand. According to the International Energy Association (IEA), it is estimated that the total installed solar energy capacity in 2021 will increase by more than 22% compared to the data in 2020, the electrical energy output exceeds 1000TWh. To achieve the goal set out at COP26, the growth rate of solar energy must reach 25% in the period 2022-2030 [2]. In Vietnam, up to November 2021, the accumulated capacity of solar power has reached about 19,400MWp, which is equivalent to 16,500MW. This data included 9300MWp of rooftop solar power [3].

The basic components of a solar power system or a photovoltaic (PV) system include solar panels, energy storage (battery), DC/DC and DC/AC converters [2]. The structure of a PV system depends on factors such as the load, voltage level, and so on. Currently, due to economic factors, most PV systems do not use energy storage devices. Each solar panel has a small capacity and low voltage, and hence, to supply sufficient power to the loads or the grid, panels need to be connected in series and/or parallel to create higher voltage and power. For panels in series, under the ideal normal operating condition of a series of panels, the current flowing through the panels is the same. However, in actual operation, it is difficult for PV panels to remain the same parameters. The main reason is that the panels with different aging levels, dirt, cracks on the surface of the panels, one or a few panels in the string are damaged, shaded, etc. Therefore, when a solar panel in the string is damaged or shaded, the current generated by that panel is reduced and the panel becomes a semiconductor resistor to consume energy generated from healthy or unshaded panels in the chain. Part of the electrical energy that the weak solar panel receives from the stronger panel will be converted into heat. This energy heats the panel up and possibly leading to damage and fire. This phenomenon is known as the "hot spots" phenomenon. To protect the panels, we often use reverse diodes to connect in parallel with the elements of the panels (bypass diodes), as shown in Fig. 1. When hot spots appear on the panels, these diodes will work

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to allow the current of the system to pass through it, not through the weak solar panel.

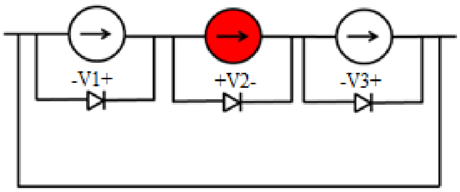

Fig. 1: Diodes connected in parallel with panels to protect solar panels

However, the phenomenon of "hot spots" will significantly reduce the photoelectric conversion efficiency of the system. To overcome this problem and to ensure the maximum power power point tracking of the PV system in this case, we can use the centralized maximum power point tracking (CMPPT) algorithm for the whole PV system or use multiple small DC/DC converters coupled together, maximum power point tracking is performed on each of these small converters and it is named distributed maximum power point tracking (DMPPT).

2. Centralized maximum power point tracking model

Currently, most solar battery systems or solar farms use centralized maximum power point tracking (CMPPT) structure. In this model, a series of solar panels are connected to a centralized DC/AC converter. The function of maximum power point tracking (MPPT) is carried out at this converter via a control system. This centralized controller, as shown in Fig. 2, is responsible for capturing the maximum power for all panels in this string.

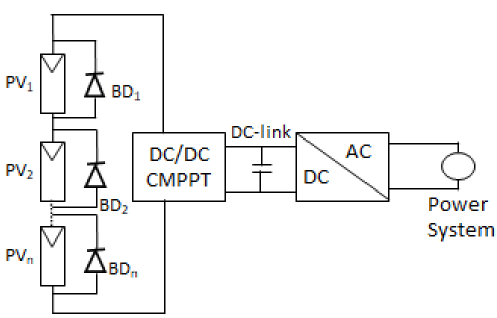

Fig. 2: A sample of PV system with CMPPT

From Fig. 1, we can see that under normal operating condition, the current generated by all panels is equal, and the bypass diodes are reverse biased, allowing the current to flow normally between the panels without any energy loss. In abnormal operating condition, let assume that the second panel is the weakest, then the panel will now apply a forward voltage to its own bypass diode. As a result, the current will pass through the bypass diode of the 2^{nd} panel protecting it from damage or explosion. The use of these reverse parallel bypass diodes helps the system to continue operating even if a panel fails, preventing the whole chain from losing power. However, this method is only to protect solar panels without considering the use of all the energy generated by the panels. If the panels in the series are only slightly damaged or shaded, this can result in a significant power loss and a decrease in the overall electrical energy output of the PV systems.

Moreover, when there is partial shading or local damage, the I-V and P-V characteristic curves of the PV system will be changed. During such conditions, these characteristic curves exhibit local maximum power points (LMPP), as shown in Fig. 3. The number of these LMPP depends on the difference of radiations placed on the PV system. Among these LMMPs, there is a specific point with the highest value known as the global maximum power point (GMPP), as depicted in Fig. 4. Taking a PV system consisting of 4 panels connected in series as an example, the I-V and P-V characteristics of this PV system are shown in Fig. 3 and Fig. 4. We can see from these figures, with three different radiation levels hitting the panels, three LMPP occur, with one of them being the GMPP. Consequently, it becomes challenging for a conventional MPPT controller to track this GMPP [4-5].

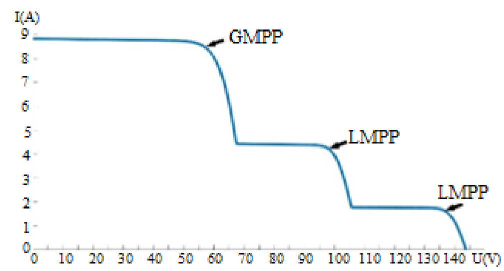

Fig. 3: I-V curve of a PV system with obscuration

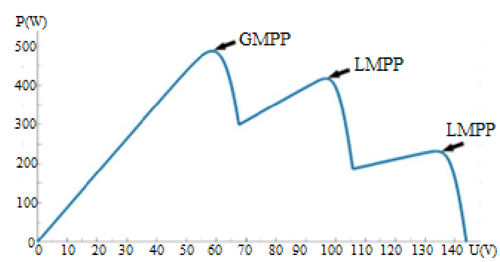

Fig. 4: P-V curve of a PV system with obscuration

In order to solve the above problem, there are currently many proposals and applications of methods to track the global maximum power point. Each method has distinct advantages and disadvantages. Gray Wolf Optimization algorithm for high performance, low oscillation and parameters to be adjusted [6]. The Artifical Bee Colony Optimization algorithm has the advantages of simplicity and fast calculation speed [6]. Likely, the Variable-Step Newton-Raphson algorithm has the advantage of fast stability and little oscillation [6]. However, most of them have complicated calculation processes, the high cost of installation and use [6]; they are developed from complex mathematical models and formulas; and so, it makes controllers hard to operate properly such as low reliability, slow response and easy to track LMPP point [4, 5, 6, 7, 8]. Moreover, when we use the GMPPT algorithms, the power generated by all the panels in the PV system will not be used fully because the weak panel is shorted by protection diodes or the current flowing the PV system is equal to that of the weakest panel in this string.

3. Distributed maximum power point tracking model

To overcome the above problems, the distributed control model of maximum power point tracking (DMPPT) is used [9, 10], as shown in Fig. 5. In this model, the small DC/DC converters completely replace the bypass diodes and are controlled to track maximum power point of the connected panel.

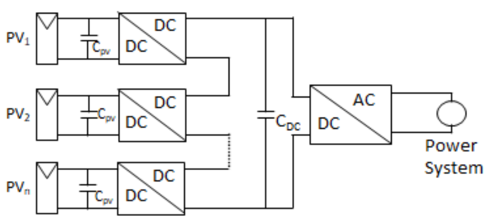

Fig. 5: A sample model of distributed maximum power point tracking control

The structure and efficiency of each DC/DC converter plays a decisive role in the successful application of the DMPPT control model. The structures of DC/DC converters such as buck, boost, buck-boost, and etc. . . are considered and evaluated for their application in the PV energy conversion systems [11]. The chosen structure should possess high conversion efficiency, be capable of series connection for voltage boosting, easy to control, compact in size for integration into the solar cell system. From the above objectives, the Boost structure was chosen to be used in the DMPPT model – Fig. 6.

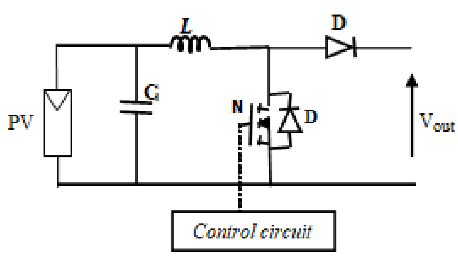

Fig. 6: Structure of Boost converter

The structure of Boost converter consists of a main switching element using Nmosfet and diodes. This structure offers several benefits. First of all, we only need to use one control pulse to control the Nmosfet. Furthermore, by using the Nmosfet as the main switching element, we can save energy or obtain a small power loss in the circuit because Nmosfet usually has a low conductive resistance. Moreover, this Nmosfet can switch at high frequency so we can design inductor with small size, suitable for integrating converter into solar panel. In addition, the relationship between input voltage and output voltage of this structure is linear, making it easier to perform MPPT [12].

For PV systems with a large scale, consisting of many panels, the series and/or parallel connection of the panels is done at the output of each small DC/DC – Fig. 7. This connection ensures the balance of current and voltage during the operation of this system. The overall efficiency of this conversion system is equal to the efficiency of each DC/DC converter.

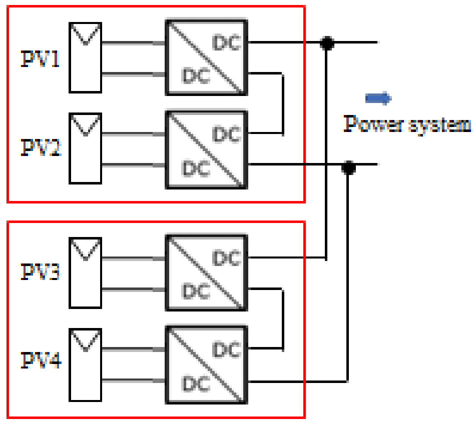

Fig. 7: Connection of converters in the DMPPT control model for a large scale PV system

4. Operating simulation of CMPPT and DMPPT model

To evaluate the performance of the two above models, this research uses PSIM software to simulate their operation. A PV system using for simulation includes 4 PV solar panels of TP250MBZ which is manufactured by TATA Power Solar System brand and its specific parameters are shown in Table 1.

TABLE 1: Specific parameters of a PV panel

Maximum power: P_{max} (Wp)	235,74
Open-circuit voltage: V_{oc} (V)	36,8
Voltage at P_{max}: V_{MPP} (V)	28,33
Short-circuit current: I_{sc} (A)	8,83
Current at P_{max}: I_{MPP} (A)	8,32

This research uses the structure of controller that tracks the maximum power according to the Perturb and Observe (P& O) algorithm because of its simplicity and fast speed to integrate into the converter using the DMPPT model [13]. The controller structure is implemented in PSIM software as shown in Fig. 8.

This controller collects data of the output voltage, U, and current, I, of each panel. When the radiation at the panels changes, it affects the output power of each panel. The controller will open/close the keys $dP > 0$ or $dP < 0$ for increasing or decreasing the output power of the panel, respectively. As a result, the voltage applied to each panel is changed by adjusting the phase angle control of Nmosfet and this makes the power output of panel reach to the maximum value.

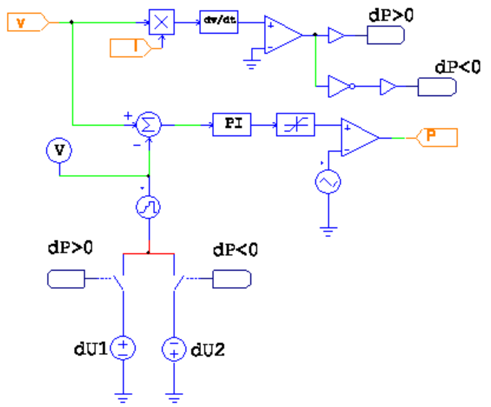

Fig. 8: Diagram of P&O algorithm in PSIM software

The P& O algorithm combined with artificial intelligence [4, 14] is used for the CMPPT model. This algorithm helps the PV system to operate at the GMPP when the radiation at the different panels is different. The function blocks of the algorithm are taken from the software's library.

5. Simulation results

5.1. Centralized maximumpower point tracking control

The simulation diagram of CMPPT model in PSIM software is shown in Fig. 9. In which, 4 PV panels are connected in series and connected to a DC/AC converter. Each panel is protected by bypass diodes. To evaluate the impact of the power difference of the panels on the overall power of the PV system, we suppose that the radiation of the 4^{th} panel is different from the rest of the panels, taking in the case of a cloud as an example. The radiation of panels in this case is shown in Fig. 10. In this figure, the radiation hitting four panels,S1, S2, S3 and S4 respectively has the same value of $1000W/m^2$. By the time t = 0.1s the shading occurs, the radiation hitting the fourth panel S4 decreases to smaller than the radiation of other panels. The voltage at the shaded panel VD4 gradually decreases with radiation as Fig. 11. The current generated by this panel Ipv_4 will also be smaller than the current of other panels Ipv_1, Ipv_2, Ipv_3, as shown in Fig. 12. This decrease leads to the current of the other panels operating equal to the current of the 4^{th} panel and it causes the power output of the whole PV system to decrease accordingly – Fig. 13. Up to time t = 0.215s, the voltage of the 4^{th} panel is low, the bypass diode D_4 starts working to protect this panel, and hence, it makes the system current turn back to the original value of 8.82A as before shading. However, the power output of the PV system has now decreased from the initial value of 942.8W to only 700W, which is the maximum power output of 3 unshaded panels minus the loss on diodes D_4. The MPPT controller always adjusts the voltage applied to the panel so that the panel can generate maximum power.

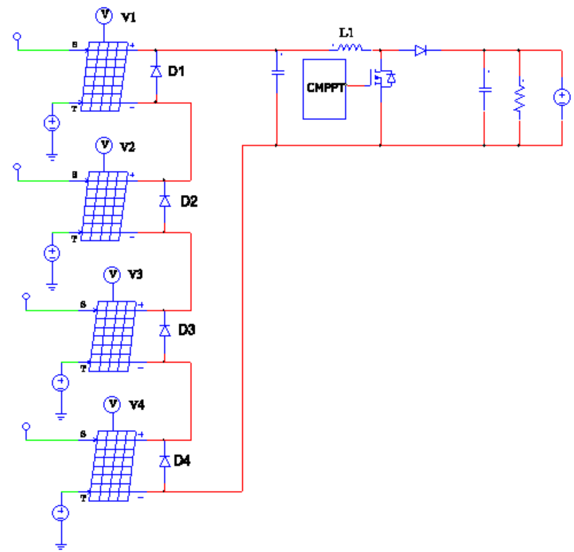

Fig. 9: Diagram of CMPPT used for simulation

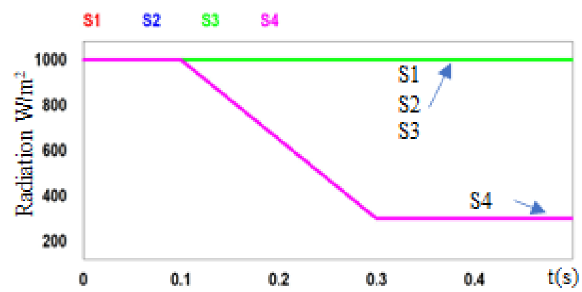

Fig. 10: The radiation of panels

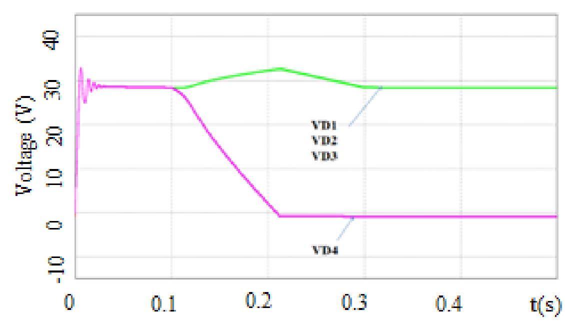

Fig. 11: The terminal voltage of panels

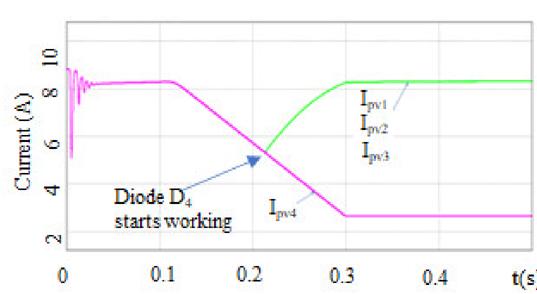

Fig. 12: The current output of panels

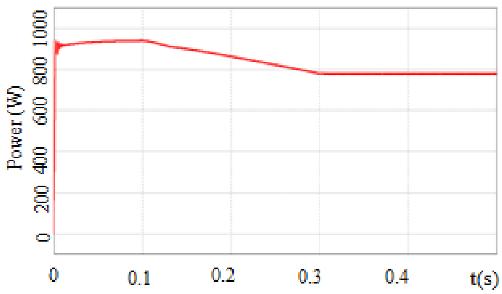

Fig. 13: Power output of PV system

Simulation results of different shading cases which make power output of the 4^{th} panel reduce by 20%, 50%, 70% and 100%, respectively, are shown in Table 2.

TABLE 2: Power output of PV system at different shading levels by using CMPPT model

Shading cases of the 4^{th} panel	20%	50%	70%	100%
Power output of PV system (W)	832	700	700	700

From the simulation results, it is easy to see that when the 4^{th} panel is only shaded by 20%, the maximum power output of the PV system is obtained when the panels work with a current equal to the current of the 4^{th} panel and the bypass diode D_4 is not active. In the cases of 50%, 70% and 100% shading, the global maximum power point is reached when bypass diode D_4 is active. The power output of the PV system in these cases is the power output in total of the remaining 3 panels.

5.2. Distributed maximum power point tracking control

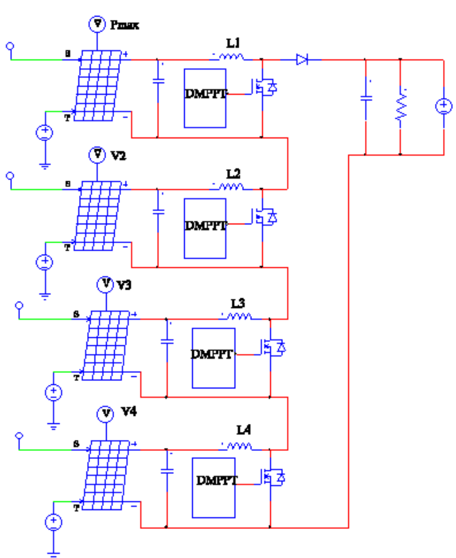

Fig. 14: Diagram of DMPPT used for simulation

The objective of this section is to evaluate the DMPPT model. The conditions of radiation and parameters of the panels are the same as in subsection 5.1. However, in this model, each PV panel is connected to an individual Boost converter, the output side of the converters are connected in series and connected to the grid through a inverter as Fig. 14. The radiation applied to the panels is shown as Fig. 10. When the radiation applied to the 4^{th} panel is decreased, the current generated from this panel is decreased. However, since each panel is connected to a separate DC/DC converter, it does not affect the currents of the remaining panels in string, as in Fig. 15. The power output of the PV system is the sum of the power output of 3 panels including the 1^{st}, 2^{nd}, 3^{rd} panel and the partial power output of the 4^{th} panel as Fig. 16.

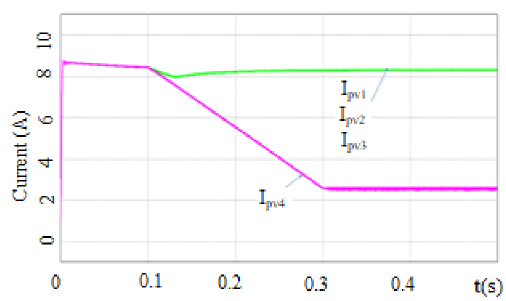

Fig. 15: Current output of each panel

From the simulation results, we can see that although the current generated from the panels may be different, the current of the PV system is not limited by the shaded PV panel thanks to the use of DC/DC converters installed at each panel. Therefore, all the power generated by the panels will be supplied to the connected grid without being limited by the shading or damage of any panels. Table 3 shows the simulation results of different shading cases corresponding to the reduction of 20%, 50%, 70% and 100% of the power output of the 4^{th} panel.

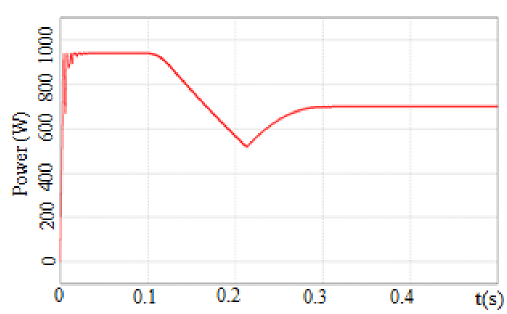

Fig. 16: Power output of PV system

TABLE 3: Power output of PV system at different shading levels by using DMPPT model

Shading cases of the 4^{th} panel	20%	50%	70%	100%
Power output of PV system (W)	898.9	828.6	780	700

TABLE 4: Daily electrical energy of the two models

Shading cases of the 4^{th} panel		20%	50%	70%	100%
CMPPT model	**Power output of PV system (W)**	832	700	700	700
	Daily energy capture (Wh)	4604	4472	4472	4472
DMPPT model	**Power output of PV system (W)**	832	700	700	700
	Daily energy capture (Wh)	4671	4600	4552	4472
Difference in power from two models (Wh)		67	128	80	0

5.3. Discussion of the results achieved by the two models

From Table 2, Table 3 in subsection 5.1 and 5.2, respectively, we can see that when the PV system is partially obscured, the DMPPT model gives a higher power output than that with the traditional CMPPT model. Connecting each panel to an individual DC/DC converter makes the maximum power point tracking of each panel independent. The current of the PV system is not limited by the minimum current of the shaded PV panel in the PV system, therefore we can obtain the maximum power output of the PV system. At this time, the inverter only performs the task of converting DC into AC and supplying to the grid.

Obviously, with the DMPPT model, the power output of the panels at the time of shading is better than that of the CMPPT model. However, to evaluate the daily electrical energy obtained from the PV system in the two above models, we need to consider additional factors such as total hours of sunshine, hours of shading, and the performance of converters in the two models. Table 4 shows the energy obtained from two simulation models with the number of sunny hours in a day is 5h and the time of shading is 1h. Based on the difference in power obtained and the efficiency of the converters, we can choose the appropriate model for the PV system.

The DMPPT model is suitable for the PV systems placed in partially shaded locations for a certain period of time. However, because the DMPPT model uses more DC/DC converters than the CMPPT model, the reliability of this model is lower and the cost is higher than that of the CMPPT model. In order to improve reliability and reduce costs when using the DMPPT model, it is necessary to integrate small DC/DC converters into the panels during production.

6. Conclusion

This research presents a DMPPT model using a Boost DC/DC converter to achieve the maximum power point tracking of the PV system in case of partial shading or slight damage. The effectiveness of the DMPPT model is proven by simulating and evaluating the power output captured of the PV system when we use the DMPPT model and the CMPPT model. Simulation results in PSIM software shown that when shading occurs, the use of DMPPT model makes the PV system obtain a higher power ourtput than that of the traditional CMPPT model. Therefore, the application of the DMPPT model is absolute necessary for optimizing the use of energy. However, to apply the model widely, it is necessary to have an advanced technology to manufacture DC/DC converters and integrate them into the panels to improve the reliability and reduce the conversion system's overall cost.

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