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Investigation of Partial Shading in PV Array Configuration and Partial Shading with Boost Converters

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ABSTRACT
Most of the energy used today comes from fossil fuels. The constant exploitation of fossil fuels creates an adverse effect on the environment. With the trend of an increase in energy demand in recent years, there is a widespread utility of sustainable energy sources to meet the energy demands. So, the use of sustainable energy sources is the need of the hour. Among the sustainable energy sources, solar energy is the prominent non- polluting energy that can be used for the cause. Photovoltaic (PV) cells and modules are being used to obtain electricity from solar energy. For high power applications, PV arrays are used in place of PV modules. But PV arrays suffer from Partial shading (PS) due to the presence of building shade, nearby trees, birds' droppings, electric poles, etc. PS affects the PV modules negatively which reduces the overall efficiency of the array. To enhance the PV array efficiency, reconfiguration techniques are being widely used. In this paper, five different array configurations such as Series-Parallel (SP), Total Cross Tied (TCT), Bridge Link (BL) and Honeycomb (HC) are considered for analysis. Six cases of shading conditions are considered for investigation using a 5×5 PV array. For PV array modelling KC200GT PV module parameters have been used and simulated in MATLAB/Simulink software. The performance of PV array has been analysed considering maximum power, shading loss (SL), mismatch loss (ML) and fill factor (FF).

Keywords: PV array configuration, partial shading, fill factor, mismatch loss, shading loss

Introduction

Solar energy being a prominent renewable energy is used widely to suffice the ever growing energy demand. As the energy is sustainable, renewable and infinite and is easily available it is used in large scales to generate power [1]. PV cell is the vital component for the conversion of solar energy into electricity. Partial Shading (PS) is a negative factor which has a diminishing effect on the efficiency of the PV array. PS occurs due to various reasons such as clouds, the shadow of buildings and trees, birds' droppings and electrical pole etc. Because of the shadings due to the above conditions, different amount of modules of a PV array tend to receive different amount of irradiation which leads to the PV

module producing power which is less compared to the desired maximum power thereby causing power loss [2]. The power lost due to partial shading needs to be minimized and to achieve that, different PV configurations are implemented as Series- Parallel (SP), Total Cross Tied (TCT), Bridge Link (BL), Honey Comb(HC) [3][4].
In this paper a PV array of 4×4 configuration is used and the performance of the implemented PV array configurations are analyzed under six shading cases. For the analysis and modelling of the PV array, KYOCERA KC200GT PV module has been used [5]. The study has been conducted for Series, SP, TCT, BL and HC configurations. Performance of different configurations has been analyzed in terms of losses due to shading and mismatch as well as fill factor.

PV MODULE MATHEMATICAL MODELLING

Mathematical modelling of a PV cell presented in Fig.2 is done to establish a proper working model of a PV module. From the existing diode models, single diode model is the convenient and most popular one used for designing the PV cell/module and is prominently used. Single diode model as described in [6] is shown in Fig.1.

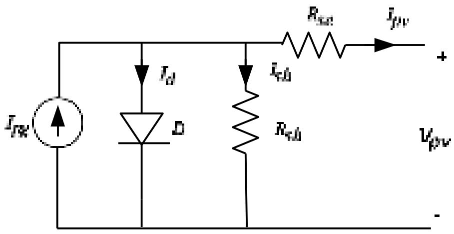

Fig. 1 Single diode PV module

Ipg and *Io* refer to the array photo current and saturation current respectively, *a* is the diode's quality factor and *Vt* is the cell's thermal voltage. When modules are connected in parallel manner it gives the increased output current and if it is connecting in series manner will give the increased output voltage. In the I- V characteristics curve the three parameters of great importance are open-circuited voltage (*Voc*), short circuited current (*Isc*), and maximum power point (*Pmax*). The photovoltaic current generated is difficult to calculate without knowing the series or parallel resistances. The linear dependence of the photogenerated current with respect to the temperature and solar irradiation. $I_{pg,n}$ is the current generated due to light at nominal condition (25^0C and 1000 W/m^2), $\Delta T=T-T_n$ (*T* refers to the actual temperature and T_n refers to the nominal temperature in ^{0}K), *G* is irradiation falling on the surface of the PV cell and G_n is nominal irradiation of 1000W/m^2. To further improve the model the saturation current is mentioned.
To model the PV module in the MATLAB/Simulink, the parameters of KC200GT PV module is considered which consists of 54 number of cells. The PV module's simulation.

LITERATURE SURVEY

In this paper, we have presented the study of the energy performance of six possible configurations for photovoltaic Arrays under different partial shading scenarios, namely: Series (S), parallel (P), series parallel (SP), Total Cross Tied (TCT), Bridge Linked (BL) and Honey Comb (HC) The simulation results indicate that all six configurations give the same maximum power under conditions without shading. The choice of the optimal configuration of the PV array in the case of partial shading depends on the scenario of the latter in the case when a row or a column is entirely (uniformly or not) shaded (S1 and S2), all the configurations give the same maximum power except the P configuration The four configurations SP, TCT, BL and HC give the same maximum power when a column is entirely and uniformly shaded (S3). Finally, the TCT configuration is the one which gives the best performance when a column is entirely and unevenly shaded as well as during a random distribution of shading (S4 and S5).

This paper has described the configuration of a portable PV power system that produced maximum power under rapidly change partial shading conditions such as would be encountered in portable applications. Under complex irradiance conditions, the power generating capability of the proposed PV system was approximately twice that of a conventionally configured series system. The developed approach is broadly applicable, but is perhaps most valuable in PV systems having high single- cell voltages where direct input to a high efficiency converter is most practical.

PROPOSED METHOD

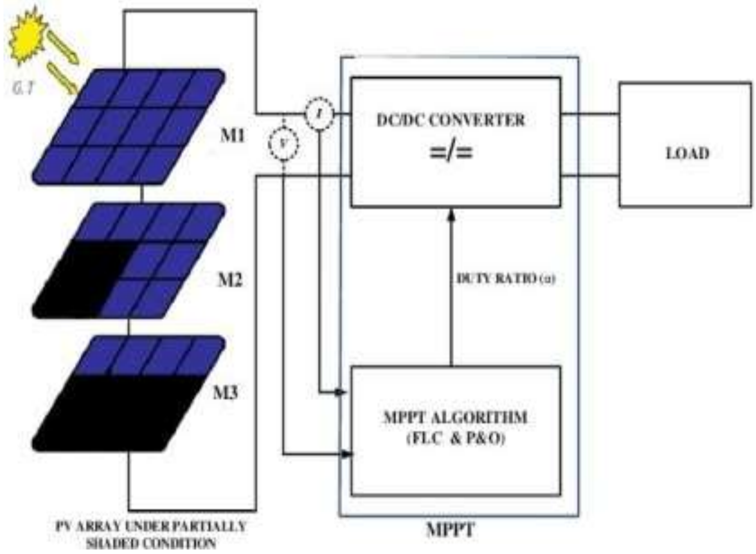

Fig. 2 Block Diagram of Solar Photovoltaic System under Partially Shaded Condition photovoltaic system. Solar Cells work on the principle of conversion of energy from light (photons) to electricity (current)

In this paper analysis is done to determine the efficiencies of the mentioned PV array configurations of 5x5 array involving six different shading conditions. For the shading conditions considered the different shading patterns.

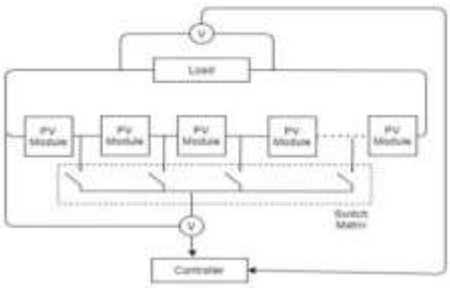

Fig.3 Block diagram of Partial shading in PV systems

The solar irradiation values used for testing are: 500 Watt/m^2, 700 Watt/m^2, 900 Watt/m^2, and 1000 Watt/m^2. The PV configurations are modelled in the similar way of shading pattern on the PV modules. considered shading cases are described below as Case-1 to Case-6.

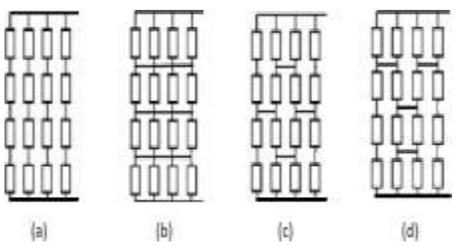

Fig. 4 PV array configurations (a) S P (b) T C T (c) B L (d) H C configuration

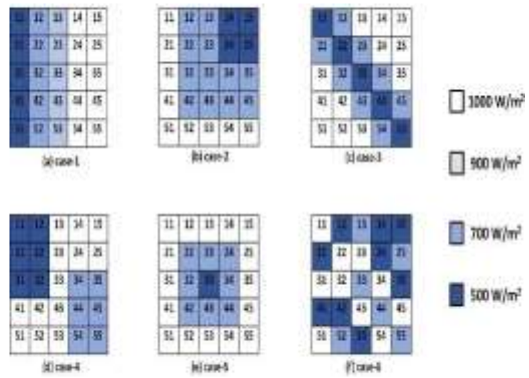

Fig. 5 Different partial shading conditions for PV arrays (a) case-1, (b) case- 2, (c) case-3, (d) case-4, (e) case-5, (f) case-6

Case 1. In this case, the solar irradiation of the starting column from the left side of the PV string is 500 Watt/m^2 and the column adjacent to it receive 700 Watt/m^2, the third column collects an irradiance value of 900 Watt/ m^2 and the rest two columns receive an irradiation value of 1000 Watt/ m^2.
Case 2. In this case, four modules in the top right corner in an array receive 500 Watt/m^2 and the twelve modules adjacent to it receive 700 Watt/m^2 and the rest modules receive an irradiance value of 1000 Watt/m^2 of irradiation.
Case 3. As shown in Fig.5 (c), the left diagonal modules in an array receive an irradiance value of 500 Watt/m^2 and the adjacent to the diagonal modules, those have an irradiance value of 700 Watt/m^2 and the rest modules receive irradiation of 1000 Watt/m^2.
Case 4. In this configuration, six modules to the top left corner receive irradiation of 500 Watt/m^2 while the six modules to the bottom right corner receive irradiation of 700 Watt/m^2.
Case 5. Here the shading affects in middle of the array so the center most module receives irradiation of 500Watt/m^2 and the modules adjacent to it receive irradiation of 700 Watt/m^2 and rest of the modules receive an irradiation of 1000 Watt/m^2.
Case 6. In this configuration, the shading pattern is random with irradiation values: 500 Watt/m^2, 700 Watt/m^2, 1000 Watt/m^2 distributed all around the array.

SOFTWARE

Matlab 2017a is a powerful numerical computing environment and programming language widely used in engineering, science, and mathematics. Here's a brief introduction to its key features and capabilities:
Interactive Environment: Matlab provides an interactive environment where you can perform computations, visualize data, and write programs all within the same interface.
Matrix-Based Operations: Matlab is particularly strong in handling matrices and arrays, making it well-suited for linear algebra computations, signal processing, and image processing.
Built-in Functions: It comes with a vast library of built-in functions for mathematical operations, statistical analysis, optimization, signal processing, and more.
Visualization: Matlab offers extensive plotting and visualization capabilities for creating 2D and 3D plots, histograms, surface plots, and more. The plots can be customized extensively to suit your needs.
Programming: You can write scripts and functions in Matlab to automate tasks, perform complex calculations, or develop algorithms. Matlab supports a wide range of programming constructs like loops, conditional statements, and function definitions.

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Toolboxes: Matlab offers various toolboxes that extend its functionality for specific domains such as control systems, image processing, signal processing, machine learning, and optimization. These toolboxes prov ide additional functions and specialized tools tailored to specific applications.

Integration: Matlab can be easily integrated with other programming languages like C/C++, Python, and Java. It also supports integration with external libraries and software packages.

Simulation and Modeling: Matlab includes tools for simulating dynamic systems, designing control systems, and modeling physical phenomena. It is widely used in academia and industry for simulation and modeling tasks.

Parallel Computing: Matlab supports parallel computing, allowing you to speed up your computations by distributing them across multiple cores or processors.

Documentation and Community: Matlab provides extensive documentation, including help files, examples, and tutorials. Additionally, there is a large online community of users and developers who contribute tips, tricks, and solutions to common problems.

Overall, Matlab 2017a is a versatile and powerful tool for numerical computing, data analysis, visualization, and algorithm development across a wide range of disciplines. Whether you're a student, researcher, or professional, Matlab can help you tackle complex computational tasks efficiently and effectively.

METHODOLOGY

When it comes to partial shading with boost converters, the methodology extends to examining how boost converters can help overcome shading effects by optimizing power extraction from shaded panels. This involves analyzing converter efficiency, voltage regulation, and overall system performance under varying shading conditions. Experimental testing, simulation studies, and theoretical analysis are common approaches in such investigations.

EXPERIMENTAL RESULTS

The analysis of performance of different array configurations is analyzed by MATLAB/Simulink. From obtained simulation values, PV characteristics of array configurations for different shaded condition are determined.

Analyzing all the configurations it is observed that every configuration has its different maximum power under the different conditions of partial shading. In the all shaded cases among all configurations the TCT configuration gives maximum power with the S-P power being the lowest.

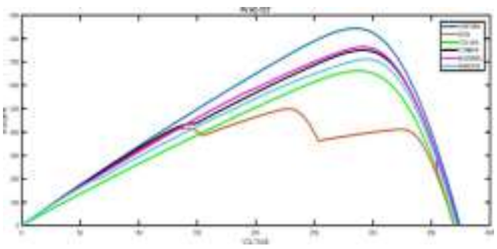

Fig. 6 PV characteristics plot for different shading conditions in SP

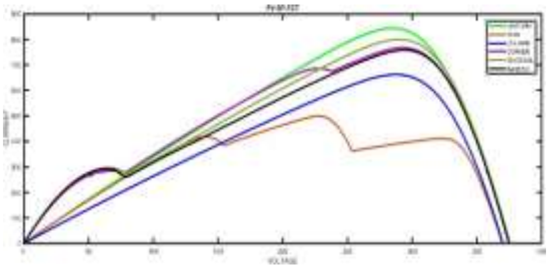

Fig. 7 PV characteristics plot for different shading condition in TCT

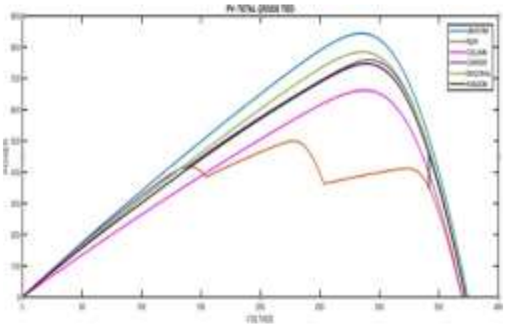

Fig. 8 PV characteristics plot for different shading condition in HC

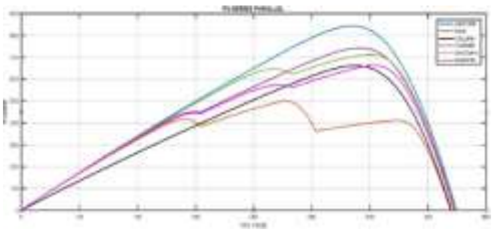

Fig. 9 PV characteristics plot for different shading condition in BL

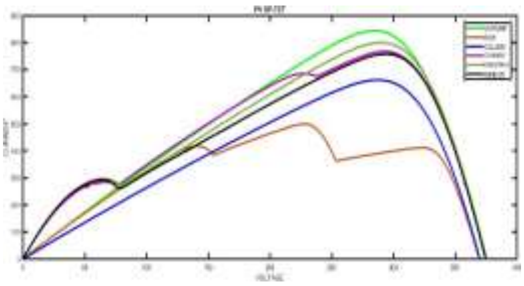

Fig. 10 PV characteristics plot for different shading condition in BL-TCT

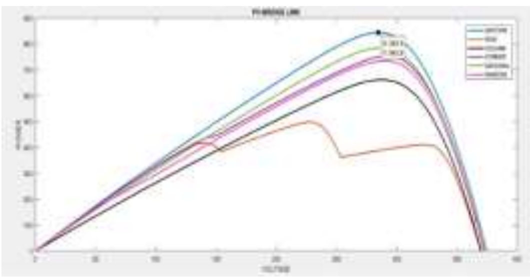

Fig. 11 PV characteristics plot for different shading condition in HL-TCT

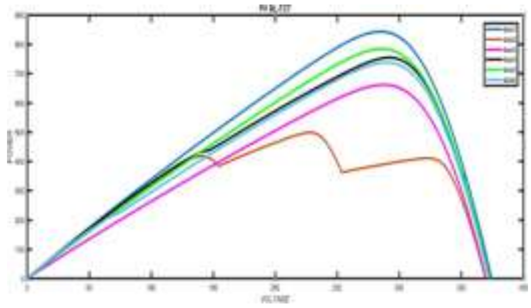

Fig. 12 PV characteristics plot for different shading condition in SP-TCT

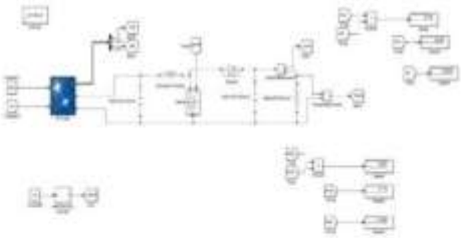

Fig. 13 PV array with Boost converter

TABLE 1. Boost converter output

IRRADIANCE	Solar panel output	Boost converter output
1000	25.03	61.75
900	22.69	55.1
800	20.32	49.98

Table 2 Simulation Results Of Considered Array Configurations Under Different Shading Conditions

Shading Cases	Configuration s	Pmax (W)	Vmax (V)	Imax (A)
Case-1	S-P	842.9	284.5	2.963
	TCT	842.9	284.5	2.963
	BL	842.9	284.5	2.963
	HC	842.9	284.5	2.963
Case-2	S-P	498.3	227.6	2.189
	TCT	498.3	227.6	2.189
	BL	498.3	227.6	2.189
	HC	498.3	227.6	2.189
Case-3	S-P	661.1	287.8	2.297
	TCT	661.1	287.8	2.297
	BL	661.1	287.8	2.297
	HC	661.1	287.8	2.297

Case-4	S-P	741.1	294	2.52
	TCT	758.5	291.1	2.606
	BL	752.6	293.7	2.562
	HC	746.2	292.4	2.552
Case-5	S-P	710.6	301.4	2.358
	TCT	783.7	286.7	2.733
	BL	789.4	288.2	2.718
	HC	713.5	300.7	2.373
Case-6	S-P	662	304.9	2.172
	TCT	746.3	289	2.582
	BL	734.2	290.5	2.527
	HC	714.3	296.1	2.412

From results obtained after the study it is observed that the Total Cross Tied (TCT) configuration gives optimum performance under all the described partial shading conditions. As compared to other considered configurations, TCT gives maximum output power. The shading losses obtained for a given shading case are the same for all configurations. To analyses the performance of the different array configuration, the performance parameters like shading losses, mismatch losses and Fill factor are calculated and tabulated. Losses due to shading and mismatch.

Shading loss (SL)

SL is the difference between maximum power of PV array under STC (standard test condition) and the sum of the individual PV module in an array during partial shading condition as mentioned in Eq. (4) below [4].

$$PSL = P_{m,irc} - P_{m,ind} \qquad (4)$$

PSL: Shading loss in power, $P_{m,irc}$: Maximum power available at STC, $P_{m,ind}$: the amount of individual available power from each PV module in an array during partial shading condition. The total power of an array under STC condition is 4999.19 W for all given configurations. $P_{m,ind}$ for each given case is the same for all the PV array configuration. The shading losses obtained for a given shading case are the same for all configurations. From the table it is observed that case 5 has the least shading loss and case 6 having the highest value of loss amongst all shading cases.

TABLE III. SHADING LOSSES (W) FOR DIFFERENT SHADING CONDITIONS OF ARRAY CONFIGURATIONS

	case 1	**case 2**	**case-3**	**case 4**	**case 5**	**case 6**
Series	900	1119.97	980.07	960	580.15	1259.94
S-P	900	1119.97	980.07	960	580.15	1259.94
TCT	900	1119.97	980.07	960	580.15	1259.94
BL	900	1119.97	980.07	960	580.15	1259.94
HC	900	1119.97	980.07	960	580.15	1259.94

Fig. 14 Graphical representation of shading loss

Mismatch Loss (ML)

ML is termed as, difference between the amount of available power of individual PV module in an array during shading condition and the global maximum power as mentioned in Eq. (5) below [4].

Pml =Pm, ind - PGMPP. (5)

Pml: Mismatch loss, *Pm, ind*: Power due to sum of individual PV module in an array during partial shading condition. *PGMPP*: Global maximum power point. The losses due to mismatch are calculated in Watts. which gives an idea about the configuration which can provide optimum performance with less power loss.

TABLE IV. Under shading conditions, mismatch loss(w) of PV array configurations.

	case 1	case 2	case 3	case 4	Case 5	case 6
S-P	45.58	465.92	1021.62	534.89	1475.34	1537.65
TCT	45.38	311.52	82.22	334.99	348.04	281.05
BL	46.68	735.82	591.82	441.79	363.34	793.25
HC	45.98	391.92	873.12	457.59	354.74	525.65

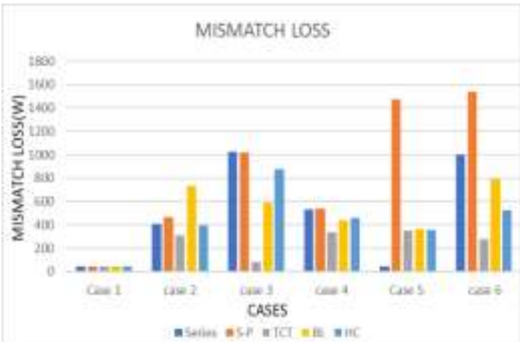

Fig. 15 Graphical representation of mismatch loss

Fill Factor (FF)

FF is termed as, ratio of generated maximum power of the array under partial shading condition ($Vmax \times Imax$) to the generated power at nominal operating conditions ($VOC \times ISC$) as mentioned in Eq. (6) below. Fill factor calculated for all configurations.

TABLE V. FILL FACTOR FOR ARRAY CONFIGURATIONS UNDER SHADING CONDITIONS

	case 1	case 2	case 3	case 4	case 5	case 6
S-P	0.73	0.51	0.44	0.52	0.54	0.35

TCT	0.73	0.53	0.69	0.62	0.60	0.76
BL	0.73	0.46	0.58	0.56	0.60	0.49
HC	0.73	0.51	0.49	0.53	0.60	0.50

TABLE VI. Available maximum power(gmpp) for array configurations under different shading condition

	case 1	**case 2**	**case 3**	**case 4**	**case 5**	**case 6**
S-P	4053.6	3413.3	2989.5	3504.3	2943.7	2201.6
TCT	4053.8	3567.7	3936.4	3704.2	4069.0	3458.2
BL	4052.5	3143.4	3427.3	3597.4	4055.7	2946.0
HC	4053.2	3487.3	3146.0	3581.6	4064.3	3213.5

CONCLUSION

An extensive study of the partial shading effect on configurations of the S-P, T-C-T, B- L, HC array was conducted. To accomplish this, MATLAB/Simulink has been used to simulate each 5x5 array configuration for different shading cases. From the results obtained it is observed that under uniform irradiance conditions all the defined array configurations produce the equal amount of maximum power. But due to partial shading condition, the PV array performance is degraded for each partial shading case. After the analysis of different partial shading condition and comparing all the configurations in terms of shading losses, mismatch losses, fill factor and maximum power it has been observed that the TCT configuration gives the optimum performance under all shading conditions.

FUTURESCOOPE

Here's a more specific future scope for investigating partial shading in PV array configuration and its interaction with boost converters: Develop sophisticated simulation models to accurately capture the dynamic behavior of partially shaded PV arrays and boost converters under various shading conditions, including changes in irradiance and temperature gradients. Research and develop intelligent control algorithms for boost converters that dynamically adjust their operating parameters in response to partial shading, aiming to maximize power output and minimize losses. Experiment with novel hardware implementations, such as integrated PV modules with built-in boost converters or distributed power electronics architectures, to efficiently manage partial shading effects at the module level. Conduct field experiments and long-term monitoring of PV installations in real-world conditions with partial shading scenarios to validate the effectiveness of proposed solutions and refine simulation models. Explore the integration of PV arrays with other renewable energy sources, energy storage systems, and smart grid technologies to create hybrid energy systems capable of mitigating partial shading effects and optimizing overall energy production. Perform comprehensive economic analyses to evaluate the cost-effectiveness and return on investment of implementing partial shading mitigation techniques with boost converters, considering factors such as system lifetime, maintenance costs, and energy yield improvement.

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