Analysis of Shading on the Performance of Solar Photovoltaic Systems

Pooja[1], Rajesh Kumar[2]

Department of Electrical Engineering, University Institute of Engineering and Technology, Maharshi Dayanand University, Rohtak, India,124001

Corresponding Author: Rajesh Kumar

Abstract

Solar PV systems offer numerous advantages, including a cost-effective and eco-friendly energy source. However, their efficiency can be compromised by shading from various sources such as tree leaves, debris, bird droppings, rain, clouds, or obstructions like poles. To address this, several methods have been employed, including string arrangements, bypass diodes, module-level power electronics (MLPE), DC optimizers, and microinverters, though these can be costly. This paper aims to explore a simpler, more affordable solution for reducing shading impacts: the use of reflectors. Reflectors not only enhance panel efficiency in shaded conditions but also improve performance under normal conditions. The study assesses the performance of PV panels with and without reflectors under various shading conditions. Future research could focus on innovative ways to reduce power loss from shading, such as advanced shading detection algorithms, smart tracking systems, or shading-resistant materials, to further improve efficiency.

Keywords: Photovoltaic panel, Shading, Reflector.

1. Introduction

Renewable energy comes from sources that naturally replenish, such as the sun, wind, and water, which are inexhaustible. In contrast, non-renewable energy derives from limited sources like coal, oil, and natural gas, which will eventually be depleted. Emphasizing renewable energy is crucial as it is sustainable and environmentally friendly. By transitioning to renewable sources, we can fulfill our energy requirements without exhausting finite resources. [1]

As global energy demand rises due to population growth and technological advances, finding a reliable, affordable, and long-lasting renewable energy source becomes essential. Solar energy is an excellent choice since it is abundant and free. The solar industry is expanding worldwide due to increasing energy needs and the depletion of traditional fossil fuels. Additionally, alternative energy sources can be costly. Utilizing solar power addresses long-term energy challenges while also benefiting the environment. [2]

The adoption of photovoltaic (PV) systems in renewable energy networks has surged in recent years due to environmental concerns and the need for sustainable energy solutions. Despite their advantages, PV systems face challenges from environmental factors that affect their performance. Shading, caused by objects like trees, buildings, clouds, or debris obstructing sunlight, can significantly impact energy production. Even partial shading leads to "mismatch losses," where shaded cells generate less electricity compared to unshaded ones, reducing the system's overall efficiency and energy yield.

Shading effects on PV panels are complex and can vary with the sun's position, seasonal changes, or nearby objects casting shadows. Shading can be dynamic, with moving shadows complicating the issue further.

Additionally, shaded cells can create hotspots from localized heating due to current flow discrepancies, potentially causing long-term damage to the PV panel. Shading can also accelerate module degradation through uneven wear and tear.

1.1 Photovoltaic cell

Photovoltaic cells are extraordinary devices that convert solar energy directly into electricity through the photovoltaic effect, or by first transforming solar energy into heat or chemical energy. When these cells are assembled into panels, they capture sunlight to generate solar power. These panels are effective at harnessing energy from sunlight, but photovoltaic cells can also operate with other light sources such as artificial or lamplight. The amount of electricity generated by a photovoltaic device depends on several factors including the type and size of the material, sunlight intensity, and light wavelength. As energy demands increase, solar photovoltaic systems are gaining popularity due to their ability to provide a sustainable and renewable energy source. [3]

Photovoltaic modules are made up of numerous cells connected in series. Although these cells are designed to have similar electrical characteristics, they may behave differently under less-than-ideal conditions, leading to mismatch losses within the PV system. Designing an effective PV system requires careful consideration of both energy production and efficiency. This involves assessing how the cells perform under varying conditions to optimize the system's design, improve its overall performance, and maximize its effectiveness. [4-8]

1.2 Partial shading-

Partial shading occurs when certain cells, modules, or arrays of solar panels receive reduced sunlight due to factors such as tree branches, dirt, bird droppings, rain, clouds, or obstructions like poles. This reduction in sunlight leads to decreased output from the shaded cells, resulting in what is referred to as “mismatch losses.” In these conditions, while the unshaded cells continue to function normally, the shaded cells experience increased current flow. To ensure the solar photovoltaic system operates efficiently and effectively, it is essential to minimize shading. [9-12] Shadows can cause significant energy losses in a solar panel system, particularly if the system is not designed properly. [13]

1.3 Hot-spot Phenomenon-

When a photovoltaic (PV) cell or a group of cells is shaded, it can create a problem known as a "hot-spot," which may cause irreversible damage and reduce overall power output. Shading leads to an imbalance in the irradiation levels across the PV cells within a module. The unshaded cells continue to operate at higher current levels, while the shaded cells experience reverse bias, causing them to dissipate power and increase in temperature. This localized temperature rise, referred to as a hot-spot, can result in permanent damage if the shading issue is not addressed before the temperature of the shaded cells reaches a critical level. [14-16]

2. Methods to Reduce Partial Shading Losses:

One traditional approach to lessen the effects of partial shading is to use bypass diodes, which are connected in parallel with PV cells or modules. [17-19] However, while these diodes help mitigate shading impacts, they can complicate the PV characteristic curve by creating multiple peaks under partial shading conditions. This can lead to inaccuracies in traditional maximum power point tracking techniques. [20-23]

• An alternative method involves using individual DC/DC power converters with separate maximum power point (MPP) controllers for each PV module. This setup allows for optimal power extraction from each module and enables module-level maximum power point tracking (MPPT). [24]

• Another proposed solution is the use of AC modules, which feature separate DC-to-AC conversion for each module. This approach ensures that shading affects only the power output of the shaded module. However, these systems can be costly due to the need for individual components for each module and may require independent voltage control, leading to power losses during the switching process. [25-27]
• Additionally, optimizing the arrangement of PV arrays has been suggested as a method to minimize the negative effects of partial shading.

3. Literature Review

Many researchers have studied the effects of shading on solar cells. They not only explored the effects of shading on solar cells but also provided various techniques and methods to minimize its impact. The studies conducted by numerous researchers are depicted in table below as table 1.

Table:1 Earlier investigations based on the effects of shading on PV panel

S. No.	Author/year	Description	Methodology	Outcomes	References
1	Volker Quaschning /1996	Calculations are performed to determine the properties and behaviour of solar generators when they are partially shaded.	Numerical algorithm	Only 2% shaded, but a 70% performance loss. Bypass diode reduce it from 70% to 55%.	[28]
2	Atsushi Kajihara /2005	To explore the equivalent circuit model and its behaviour when subjected to partial shading conditions.	MPPT method	60% boost in power generation with MPPT METHOD.	[29]
3	Hiren Patel /2008	Studying the I-V and P-V characteristics of a PV array under partial shading condition.	MATLAB – based Modelling and simulation	The way the PV array is set up has a significant impact on the maximum power that can be generated when the system is partially shaded.	[30]
4	R.Ramaprabha /2009	Exploring the detrimental effects of partial shading on the performance of	PSPICE Simulation model	When the level of shading increases, the power dissipated by the shaded cells	[31]

		a PV module.		also goes up.	
5	SrinivasaVemuru /2012	How using bypass diodes affect the performance of solar cells when they are shaded	MATLAB	68.5% power drops when bypass diode is not used.	[32]
6	Yu Mon ThandarHtet	Four different configurations (SP, TCT, BL, and HC) were proposed to minimize the mismatch losses.	MATLAB/SIMULINK is used to create models of the photovoltaic array configurations.	TCT configuration is most effective in reducing mismatch losses when the PV array is exposed to partial shading.	[33]
7	KashifIshaque /2012	To enhance the capability of tracking the maximum power point for a photovoltaic system when it is subjected to partial shading conditions.	deterministic particle swarm optimization (DPSO) method	Average efficiency reaches 99.5%	[34]
8	Yunlin Sun /2013	Various shading phenomenon affecting a grid connected PV system were categorized and examined in detail.	Different positions of shading are considered to understand their distinct impacts on identical solar panels.	Shading affects the electrical characteristics of solar panel, with variations observed based on the position of shading.	[35]
9	SmitaPareek /2013	The various interconnection configurations SP ,TCT and BL are discussed	MATLAB/SIMULINK	By aligning the chosen scheme with the shading pattern, we can tap into more power potential.	[36]
10	Ekpenyong /2013	The impact of shading on PV cells.	The investigation is conducted with and without bypass diodes.	Uneven lighting in a series string can cause significant power loss.	[37]

11	Alberto Dolara /2013	Impact of partial shading on poly crystalline and mono crystalline PV modules operations	The impact of shading on a single pv cell with both vertical and horizontal shading profiles.	When the shading profile is varied from 0 to 100%, there is a consistent decrease in the generated current.	[38]
12	Ali Murtaza /2014	Explore the challenges of partial shading on PV array and proposes an improved BD-MPPT technique.	MATLAB/SIMULINK	With the help of the BD-MPPT technique, the efficiency can exceed 96.6%	[39]
13	Indu Rani Balasubramanian /2014	Examine how different shading patterns impact the power transferred to the load.	Boost converter is used as MPPT	Maximum power is delivered to load when a GP is tracked in output curve. (Efficiency 63.2%)	[40]
14	Sathyanarayana P /2015	It aims to systematically investigate how shading influences the power output, fill factor, and efficiency of solar panels.	Two types of shading experiments, namely uniform and non-uniform, were conducted.	Uniform shading-linear decrease in short circuit current and power output. Non-uniform shaded cell experience decreased current, power and efficiency.	[41]
15	SmitaPareek /2016	PV arrays were studied when they were partially shaded to understand their performance under such conditions.	PV arrays interconnected in series-parallel (SP) style simulated and analysed using MATLAB/Simulink for performance evaluation under partial shading conditions.	Partial shading losses in PV arrays were minimized by connecting shaded modules in series, which was found to outperform parallel connection.	[42]
16	Smita Pareek /2016	A novel method for forecasting module interconnection in TCT-	Introduce a unique approach for predicting module interconnection in TCT connected PV arrays	Enhance the efficiency and performance of PV system.	[43]

		connected PV arrays.			
17	Minh Quan Duong / 2017	How different configurations of bypass diodes impact the performance of photovoltaic systems when subjected to varying degrees of shading.	The analysed bypassconfiguration of a PV module was implemented using PSpice.	The system setup and the extent of shading have a significant impact on the operational performance of PV modules.	[44]
18	Mohammad Abdullah Al Mamun / 2017	To explores the effects of shading on PV performance using a 90W module.	Experiments were conducted with varying shading levels (0% to 80%)	10% increase in the shaded area can cause a 12.41 W decrease in power output and a 2.3% decrease in electrical efficiency.	[45]
19	R. Ahmad / 2017	Examined the influence of partial shading on the PV array connected in series – parallel configuration.	MATLAB/SIMULINK model is used	Maximum no. of bypass diodes, or LMs in the PV array does not exceed the number of modules connected in series, regardless of the type of partial shading pattern.	[46]
20	Monadhil Al-Chaderchi /2018	To investigate the impact of shading on various string configuration within a PV panel.	MATLAB/SIMULINK	With each subsequent cell shaded, there was a consistent 25% reduction in both voltage and power.	[47]
21	Nikesh Sharma /2018	To suggest solutions that can be used to rearrange photovoltaic arrays in order	Extends the reconfiguration technique for TCT interconnected PV arrays.	The addition of HRPVA and FRPVA increased the power generated from	[48]

		to minimize the loss of power caused by partial shading.		2758.2 W to 3724.8 W, resulting in a 35.04% increase compare to TCT.	
22	João Paulo N. Torres /2018	It examined the impacts of partial shading on solar cell strings and temperature on the performance of various PV modules.	PSPICE software	partial shading can significantly reduce the overall power output of solar cell.	[49]
23	Mona Sharma /2019	Investigates the various configurations of 4*4 solar photovoltaic panel arrays and their effect on the system performance and efficiency.	Four shading patterns were investigated for PV panel in the SP,TCT,HC and BL configuration ,these are single row shading, double row shading, oblique shading and quarter array shading	The performance of TCT configuration is good as compare to SP configuration in the presence of shading.	[50]
24	Mustafa Hamid Al-Jumaili /2019	Analyse how different levels of simulated shading affect the electrical characteristics of a solar module.	solar module tester (SMT) simulator is used	Shading a single cell can cause a 57% decrease in power.	[51]
25	MarkapuramSrinivasaRao /2020	Incorporating aluminium reflectors on the solar array system to observe shading effects on performance parameters.	Aluminium reflectors are used on the solar array system.	Current efficiency increased to 21.84%, Pmax reached 22.34%, and solar irradiation rose by 5.29%.	[52]
26	J.C. Teo /2020	Investigating how the forward voltage of bypass diode affects the maximum power of a photovoltaic	Implemented different shading patterns and adjusted the forward voltages of the bypass diode in the PV sting.	Maximum power decreased by 16.8%.	[53]

		system when it is exposed to partial shading.			
27	Chidurala Saiprakash /2021	Comparative analysis conducted on different 6*6 PV array configurations.	MATLAB-Simulink	TCT configuration is less affected by partial shading and achieves high maximum power and fill factor.	[54]
28	Ankur Kumar Gupta /2021	Bypass diode is replaced with an efficient electromagnetic relay for higher efficiency under partial shading.	Using electromagnetic relay instead of bypass diode	The proposed method has minimal power losses (150 mW) under partial shading, compared to the bypass diode (550 mW)	[55]
29	Paolo Bernardoni /2021	Explore the potential of Luminescent Solar Concentrator (LCS) panels for BIPV applications under normal and shading conditions.	Simulated LCS panel performance and compared with experimental measurements using organic dyes and high performance solar cells.	LCS panels, with reflective films, showed high efficiency than traditional PV system.	[56]
30	Muhammad Iqbal /2022	To create a system that enhances the voltage of a solar cell by utilizes a reflector to counteract the negative effects of shading.	Mirror reflectors are placed in front of solar panel to increase sunlight exposure.	Adding a reflector system at a 70^0 angle has been proven to greatly enhance voltage output.	[57]
31	Mona Sharma /2023	Reconfiguration technique is used	Utilized a set of reconfiguration rules to select shaded panel location, offering multiple reconfiguration options.	Calculated performance enhancement ratios for various shading patterns: 25% for short wide, 6.4% for short narrow, 5.9% for long narrow.	[58]

4. Methodology

Partial shading is a critical factor that can significantly reduce the power output of a PV panel. Of all the variables influencing panel performance, shading has the most profound effect on diminishing its power generation. The efficiency of a PV panel can be calculated using the below formula.

$$\eta = P_{max}/ P_{in} = \{(I_{sc} * V_{oc} * FF)/P_{in}\} * 100\% \quad (1)$$

η = Efficiency of output power

P_{max} = Max. output power

P_{in} = input power of PV panel
I_{sc} = short circuit current
V_{oc} = open circuit voltage
FF = fill factor

5. Case Study

Table: 2 Electrical characteristics of PV panel

Maximum Power	40 Wp
Vmax	18.69V
Imax	2.30 A
Voc	22.68V
Isc	2.49A
FF(%)	76.21
Efficiency(%)	15%

The analysis of the experiment is conducted on a 40W PV panel from GENUS, which has the specifications mentioned in table 2. The efficiency of PV panel is analysed with and without a mirror, both in shaded and unshaded condition.

5.1 Case- 1 Efficiency of PV panel without shading

Table: 3Detailed findings without shading

Without Shading(Without Mirror)						
Area	**Time**	**Solar intensity**	**Voltage**	**Current**	**P_{in}**	**Efficiency**
0.216	10:00AM	372.1	20.07	0.85	80.3736	16.1312
0.216	11:00AM	542.4	18.69	1.071	117.1584	12.9849
0.216	12:00PM	482.7	18.61	1.125	104.2632	15.2609
0.216	1:00 PM	517.2	18.69	1.205	111.7152	15.3214
0.216	2:00 PM	436.2	18.44	1.001	94.2192	1.5023
0.216	3:00 PM	262.9	18.54	0.68	56.7864	16.8728
0.216	4:00 PM	175.2	18.41	0.466	37.8432	17.2292
0.216	5:00 PM	135.7	18.11	0.385	29.3112	18.0784

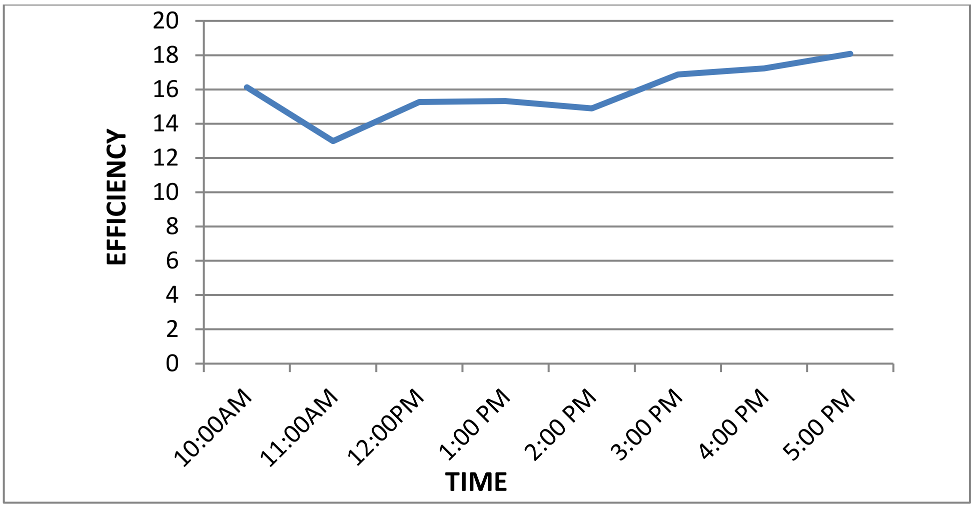

Fig. 1.Efficiency of PV panel without shading without mirror

Table: 4 Detailed findings without shading with mirror

Without Shading (With Mirror)						
Area	**Time**	**Solar intensity**	**Voltage**	**Current**	**Pin**	**Efficiency**
0.216	10:00AM	391	22.1	0.98	84.456	19.489533
0.216	11:00AM	570	20.5	1.095	123.12	13.856481
0.216	12:00PM	497	21.1	1.3	107.352	19.419107
0.216	1:00 PM	538	20.5	1.351	116.208	18.112849
0.216	2:00 PM	460	20.2	0.99	99.36	15.296377
0.216	3:00 PM	290	20.3	0.88	62.64	21.674074
0.216	4:00 PM	198	20.22	0.6	42.768	21.558923
0.216	5:00 PM	158	20.11	0.5	34.128	22.391585

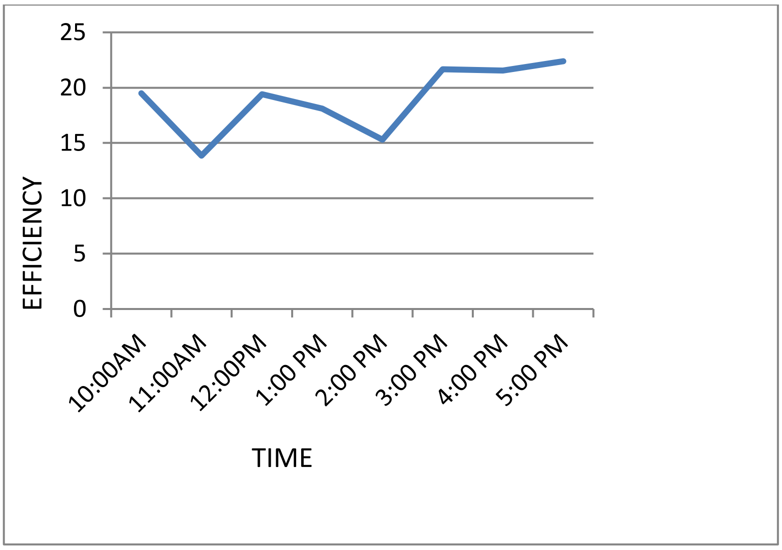

Fig. 2.Efficiency of PV panel without shading with mirror

The analysis of the above two graphs shows that employing a mirror enhanced the current, voltage, and efficiency of the PV panel. The maximum efficiency of panel without mirror is 18.07 .And with mirror it is improved to 22.39.

5.2 CASE 2. Efficiency of PV panel with and without mirror under 50% of shading

Table: 5 Detailed findings with 50% of shading without mirror

50% of Shading(Without Mirror)						
Area	**Time**	**Solar intensity**	**Voltage**	**Current**	**P_{in}**	**Efficiency**
0.216	10:00AM	372.1	15.83	0.006	80.3736	0.0898116
0.216	11:00AM	542.4	15.24	0.01	117.1584	0.098861
0.216	12:00PM	482.7	13.26	0.002	104.2632	0.0193311
0.216	1:00 PM	517.2	15.11	0.007	111.7152	0.0719555
0.216	2:00 PM	436.2	15.11	0.008	94.2192	0.0975054
0.216	3:00 PM	262.9	14.21	0.002	56.7864	0.0380359
0.216	4:00 PM	175.2	13.87	0.003	37.8432	0.0835648
0.216	5:00 PM	135.7	13.12	0.001	29.3112	0.0340184

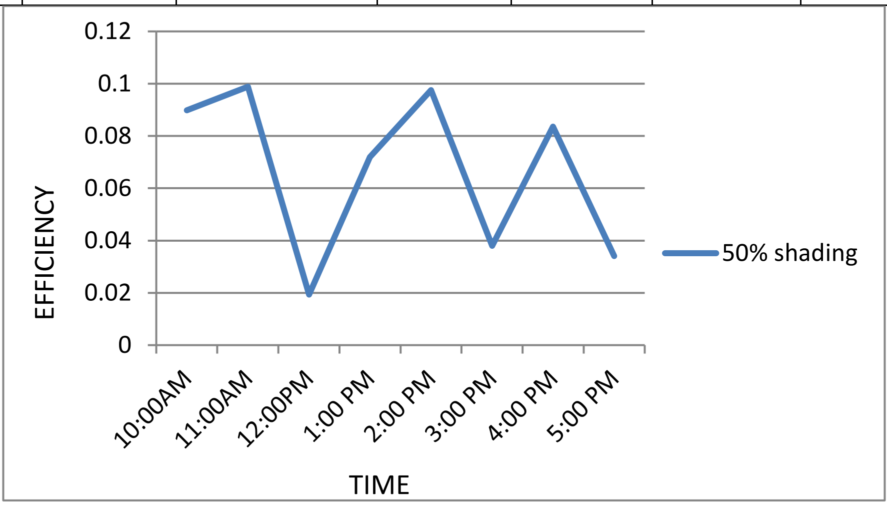

Fig. 3.Efficiency of PV panel under 50% of shading without mirror

Table: 6 detailed findings with 50% of shading with mirror

50% Shading (With Mirror)						
Area	**Time**	**Solar intensity**	**Voltage**	**Current**	**Pin**	**Efficiency**
0.216	10:00AM	391	16.61	0.016	84.456	0.2391513
0.216	11:00AM	570	15.7	0.015	123.12	0.1453704
0.216	12:00PM	497	14.9	0.01	107.352	0.1054848
0.216	1:00 PM	538	15.51	0.015	116.208	0.152153
0.216	2:00 PM	460	15.41	0.015	99.36	0.1768056
0.216	3:00 PM	290	14.34	0.007	62.64	0.1217893
0.216	4:00 PM	198	14.3	0.008	42.768	0.2032922
0.216	5:00 PM	158	13.52	0.005	34.128	0.1505391

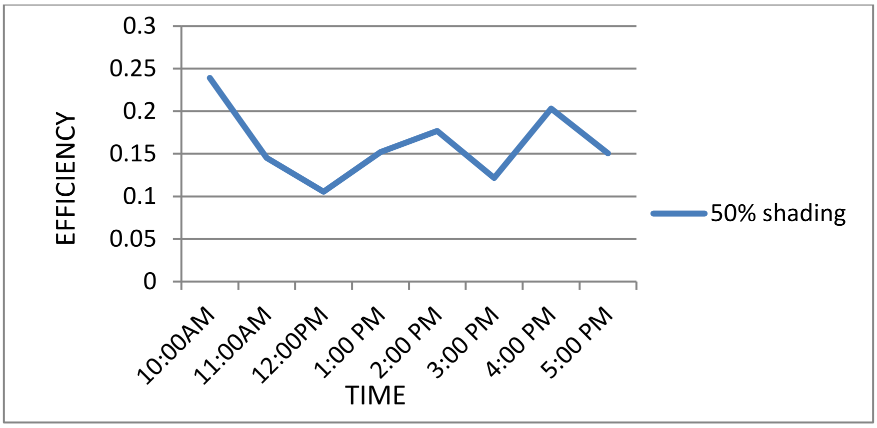

Fig 4. Efficiency of PV panel under 50% of shading with mirror

The maximum efficiency of solar panel under 50% of shading without mirror is 0.098. And with mirror it is improved to 0.239.

6. Conclusion

this study demonstrates that mirrors significantly enhance the efficiency of solar panels, both with and without shading conditions. The analysis of multiple studies reveals that solar panels equipped with mirrors show an increase in both current and voltage, thereby enhancing their overall efficiency. Without a mirror, the efficiency of the panels can reach up to 18.07%, but with a mirror, it can improve to 22.39%. This demonstrates that mirrors help mitigate the efficiency losses caused by shading, resulting in a notable improvement in the solar cells' performance.

References

1. Swami, R. (2012). Solar cell. *International Journal of Scientific and Research Publications*, *2*(7), 1-5.
2. Kannan, N., &Vakeesan, D. (2016). Solar energy for future world:-A review. *Renewable and sustainable energy reviews*, *62*, 1092-1105.
3. Sharma, N., Pareek, S., Chaturvedi, N., &Dahiya, R. (2018, March). Multiple Solutions for Reconfiguration to Address Partial Shading Losses in Solar Photovoltaic Arrays. In *IOP Conference Series: Materials Science and Engineering* (Vol. 331, No. 1, p. 012018). IOP Publishing.
4. Dolara, A., Grimaccia, F., Leva, S., Mussetta, M., Faranda, R., &Gualdoni, M. (2012). Performance analysis of a single-axis tracking PV system. *IEEE Journal of Photovoltaics*, *2*(4), 524-531.
5. Kadri, R., Andrei, H., Gaubert, J. P., Ivanovici, T., Champenois, G., & Andrei, P. (2012). Modeling of the photovoltaic cell circuit parameters for optimum connection model and real-time emulator with partial shadow conditions. *Energy*, *42*(1), 57-67.
6. Rehman, S., & El-Amin, I. (2012). Performance evaluation of an off-grid photovoltaic system in Saudi Arabia. *Energy*, *46*(1), 451-458.
7. Wang, J. C., Shieh, J. C., Su, Y. L., Kuo, K. C., Chang, Y. W., Liang, Y. T., ... & Jiang, J. A. (2011). A novel method for the determination of dynamic resistance for photovoltaic modules. *Energy*, *36*(10), 5968-5974.
8. Jiang, J. A., Wang, J. C., Kuo, K. C., Su, Y. L., Shieh, J. C., & Chou, J. J. (2012). Analysis of the junction temperature and thermal characteristics of photovoltaic modules under various operation conditions. *Energy*, *44*(1), 292-301.

9. Spertino, F., &Akilimali, J. S. (2009). Are manufacturing $ I $–$ V $ mismatch and reverse currents key factors in large photovoltaic arrays?. *IEEE Transactions on Industrial Electronics*, *56*(11), 4520-4531.
10. Patel, H., &Agarwal, V. (2008). MATLAB-based modeling to study the effects of partial shading on PV array characteristics. *IEEE transactions on energy conversion*, *23*(1), 302-310.
11. Ghitas, A. E., &Sabry, M. (2006). A study of the effect of shadowing location and area on the Si solar cell electrical parameters. *Vacuum*, *81*(4), 475-478.
12. Drif, M., Perez, P. J., Aguilera, J., & Aguilar, J. D. (2008). A new estimation method of irradiance on a partially shaded PV generator in grid-connected photovoltaic systems. *Renewable energy*, *33*(9), 2048-2056.
13. PVresources (n.d) Shading analysis. [Online] http://www.pvresources.com/en/siteanalysis/shadinganalysis.php (Accessed 29 April 2017.
14. Kovach, A., &Schmid, J. (1996). Determination of energy output losses due to shading of building-integrated photovoltaic arrays using a raytracing technique. *Solar Energy*, *57*(2), 117-124.
15. Garcìa, M. A., Herrmann, W., Böhmer, W., &Proisy, B. (2003). Thermal and electrical effects caused by outdoor hot-spot testing in associations of photovoltaic cells. *Progress in photovoltaics: research and applications*, *11*(5), 293-307.
16. Yang, H., Xu, W., Wang, H., & Narayanan, M. (2010, June). Investigation of reverse current for crystalline silicon solar cells—New concept for a test standard about the reverse current. In *2010 35th IEEE Photovoltaic Specialists Conference* (pp. 002806-002810). IEEE.
17. Pareek, S., &Dahiya, R. (2014). Output power comparison of TCT & SP topologies for easy-to-predict partial shadow on a 4× 4 PV field. *Applied Mechanics and Materials*, *612*, 71-76.
18. Chen, K., Tian, S., Cheng, Y., &Bai, L. (2014). An improved MPPT controller for photovoltaic system under partial shading condition. *IEEE transactions on sustainable energy*, *5*(3), 978-985.
19. Tey, K. S., &Mekhilef, S. (2014). Modified incremental conductance algorithm for photovoltaic system under partial shading conditions and load variation. *IEEE Transactions on Industrial Electronics*, *61*(10), 5384-5392.
20. Patel, H., &Agarwal, V. (2008). Maximum power point tracking scheme for PV systems operating under partially shaded conditions. *IEEE transactions on industrial electronics*, *55*(4), 1689-1698.
21. Rani, B. I., Ilango, G. S., &Nagamani, C. (2013). Enhanced power generation from PV array under partial shading conditions by shade dispersion using Su Do Ku configuration. *IEEE Transactions on sustainable energy*, *4*(3), 594-601.
22. Ishaque, K., & Salam, Z. (2013). A review of maximum power point tracking techniques of PV system for uniform insolation and partial shading condition. *Renewable and Sustainable Energy Reviews*, *19*, 475-488.
23. Qi, J., Zhang, Y., & Chen, Y. (2014). Modeling and maximum power point tracking (MPPT) method for PV array under partial shade conditions. *Renewable Energy*, *66*, 337-345.
24. Bidram, A., Davoudi, A., &Balog, R. S. (2012). Control and circuit techniques to mitigate partial shading effects in photovoltaic arrays. *IEEE Journal of Photovoltaics*, *2*(4), 532-546.
25. Rodriguez, C., &Amaratunga, G. A. (2008). Long-lifetime power inverter for photovoltaic AC modules. *IEEE Transactions on Industrial Electronics*, *55*(7), 2593-2601.
26. Ji, Y. H., Jung, D. Y., Kim, J. H., Won, C. Y., & Oh, D. S. (2010, June). Dual mode switching strategy of flyback inverter for photovoltaic AC modules. In *The 2010 International Power Electronics Conference-ECCE ASIA-* (pp. 2924-2929). IEEE.
27. Roman, E., Alonso, R., Ibañez, P., Elorduizapatarietxe, S., &Goitia, D. (2006). Intelligent PV module for grid-connected PV systems. *IEEE Transactions on Industrial electronics*, *53*(4), 1066-1073.

28. Quaschning, V., &Hanitsch, R. (1996). Numerical simulation of current-voltage characteristics of photovoltaic systems with shaded solar cells. *Solar energy*, *56*(6), 513-520.

29. Kajihara, A., &Harakawa, A. T. (2005, December). Model of photovoltaic cell circuits under partial shading. In *2005 IEEE International Conference on Industrial Technology* (pp. 866-870). IEEE.

30. Patel, H., &Agarwal, V. (2008). MATLAB-based modeling to study the effects of partial shading on PV array characteristics. *IEEE transactions on energy conversion*, *23*(1), 302-310.

31. Ramaprabha, R., &Mathur, B. L. (2009). Impact of partial shading on solar PV module containing series connected cells. *International Journal of Recent Trends in Engineering*, *2*(7), 56.

32. Vemuru, S., Singh, P., &Niamat, M. (2012, May). Modeling impact of bypass diodes on photovoltaic cell performance under partial shading. In *2012 IEEE international conference on electro/information technology* (pp. 1-5). IEEE.

33. Htet, Y. M. T., Ya, A. Z., &Thar, H. A. Performance analysis of solar photovoltaic array configurations to reduce mismatch losses under partial shaded conditions.

34. Ishaque, K., & Salam, Z. (2012). A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. *IEEE transactions on industrial electronics*, *60*(8), 3195-3206.

35. Sun, Y., Li, X., Hong, R., &Shen, H. (2013). Analysis on the Effect of Shading on the Characteristics of Large-scale on-grid PV System in China. *Energy Power Eng*, *5*(04), 215-218.

36. Pareek, S., &Dahiya, R. (2014). Output power maximization of partially shaded 4* 4 PV field by altering its topology. *Energy Procedia*, *54*, 116-126.

37. Ekpenyong, E. E., &Anyasi, F. I. (2013). Effect of shading on photovoltaic cell. *IOSR J. Electr. Electron. Eng*, *8*, 2278.

38. Dolara, A., Lazaroiu, G. C., Leva, S., &Manzolini, G. (2013). Experimental investigation of partial shading scenarios on PV (photovoltaic) modules. *Energy*, *55*, 466-475.

39. Murtaza, A., Chiaberge, M., Spertino, F., Boero, D., & De Giuseppe, M. (2014). A maximum power point tracking technique based on bypass diode mechanism for PV arrays under partial shading. *Energy and Buildings*, *73*, 13-25.

40. Balasubramanian, I. R., IlangoGanesan, S., &Chilakapati, N. (2014). Impact of partial shading on the output power of PV systems under partial shading conditions. *IET power Electronics*, *7*(3), 657-666.

41. Sathyanarayana, P., Ballal, R., Sagar, P. L., & Kumar, G. (2015). Effect of shading on the performance of solar PV panel. *Energy and Power*, *5*(1A), 1-4.

42. Pareek, S., &Dahiya, R. (2016, March). Series-connected shaded modules to address partial shading conditions in SPV systems. In *AIP Conference Proceedings* (Vol. 1715, No. 1). AIP Publishing.

43. Pareek, S., &Dahiya, R. (2016). Enhanced power generation of partial shaded photovoltaic fields by forecasting the interconnection of modules. *Energy*, *95*, 561-572.

44. Duong, M. Q., Sava, G. N., Ionescu, G., Necula, H., Leva, S., &Mussetta, M. (2017, June). Optimal bypass diode configuration for PV arrays under shading influence. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-5). IEEE.

45. Mamun, M. A. A., Hasanuzzaman, M., &Selvaraj, J. (2017). Experimental investigation of the effect of partial shading on photovoltaic performance. *IET Renewable Power Generation*, *11*(7), 912-921.

46. Ahmad, R., Murtaza, A. F., Sher, H. A., Shami, U. T., &Olalekan, S. (2017). An analytical approach to study partial shading effects on PV array supported by literature. *Renewable and Sustainable Energy Reviews*, *74*, 721-732.

47. Al-Chaderchi, M., Sopian, K., Salameh, T., Zhang, D., &Alghoul, M. A. (2018). Enhancing the performance of PV panel undergoing shading effects. *International Journal of Power Electronics and Drive Systems*, *9*(4), 1937.

48. Sharma, N., Pareek, S., Chaturvedi, N., &Dahiya, R. (2018, March). Multiple Solutions for Reconfiguration to Address Partial Shading Losses in Solar Photovoltaic Arrays. In *IOP Conference Series: Materials Science and Engineering* (Vol. 331, No. 1, p. 012018). IOP Publishing.

49. Torres, J. P. N., Nashih, S. K., Fernandes, C. A., &Leite, J. C. (2018). The effect of shading on photovoltaic solar panels. *Energy Systems*, *9*, 195-208.

50. Sharma, M., Pareek, S., & Singh, K. (2019, August). Comparative study of different configuration techniques to address the outcome of partial shading conditions on solar photovoltaic system. In *IOP Conference Series: Materials Science and Engineering* (Vol. 594, No. 1, p. 012031). IOP Publishing.

51. Al-Jumaili, M. H., Abdalkafor, A. S., &Taha, M. Q. (2019). Analysis of the hard and soft shading impact on photovoltaic module performance using solar module tester. *Int. J. Power Electron. Dri. Syst*, *2088*, 1015.

52. Rao, M. S., &Agrawal, M. (2020, February). Performance analysis of partial shading on Solar Photovoltaic System under Aluminium Reflectors. In *2020 IEEE International Students' Conference on Electrical*, *Electronics and Computer Science (SCEECS)* (pp. 1-6). IEEE.

53. Teo, J. C., Tan, R. H., Mok, V. H., Ramachandaramurthy, V. K., & Tan, C. (2020). Impact of bypass diode forward voltage on maximum power of a photovoltaic system under partial shading conditions. *Energy*, *191*, 116491.

54. Saiprakash, C., Mohapatra, A., Nayak, B., &Ghatak, S. R. (2021). Analysis of partial shading effect on energy output of different solar PV array configurations. *Materials Today: Proceedings*, *39*, 1905-1909.

55. Gupta, A. K., Maity, T., Anandakumar, H., &Chauhan, Y. K. (2021). An electromagnetic strategy to improve the performance of PV panel under partial shading. *Computers & Electrical Engineering*, *90*, 106896.

56. Bernardoni, P., Mangherini, G., Gjestila, M., Andreoli, A., &Vincenzi, D. (2021). Performance optimization of luminescent solar concentrators under several shading conditions. *Energies*, *14*(4), 816.

57. Iqbal, M., Ihsanto, E., &Mohammednour, A. B. (2022). Improvement of output voltage from shading interference on solar cell using a reflector system. *Journal of Integrated and Advanced Engineering (JIAE)*, *2*(2), 70-76.

58. Sharma, M., Pareek, S., & Singh, K. (2023). Robust reconfiguration strategies for maximum output power from large-scale photovoltaic arrays under partial shading conditions. *PhysicaScripta*, *98*(3), 035215.