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A Comprehensive Analysis of Partial Shading Effect on Output Parameters of a Grid-connected PV System

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ABSTRACT

One of the issues of grid-connected photovoltaic systems is the effect of the partial shading on the key parameters and performance of the system. In practice, a share of the entire PV panel may shadded because of the various reasons, inevitably. In this case, the key parameters of the system output are affected with respect to the shading extent and paradigm. In this paper, the effects of the various partial shading patterns on the ouput of the system are examined. This is performed by deriving relevant equations and appropriate modeling of the system and defining different scenarios. The analysis on the system performance is carried out on the dominant output parameters including panel voltage, panel power, and total harmonic distortion (THD) of the inverter. Also, the study considers the effect of using bypass diodes in the panels or not. Addintionally, to compare derived conclusions, the study is implementd on a practical system. The set up is made up of a 7-level multi-level inverter, a Z-source converter, and 1 kW lateral circuitry. The real world test results of the study demonstrate a negligible deviation compared to the simulation results.

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1. INTRODUCTION

The shortage of fossil fuels in the world in the near future and the growing environmental concerons, have encouraged the use of renewable energy sources progressively [1]. In other hand, the use of photovoltaic energy as a renewable resource has been of great interest due to its technical, economic, and environmental issues being justified [2], [3].

The photovoltaic energy in Iran is employed to electrified remote villages in the form of off-grid systems. After that, some grid-connected systems have been installed in public buildings like mosques, schools, and governmet buildings. Recently, the development of photovoltaic power plants (in the range of 200kW and above) has been financed by involving entities especially Tavnir Co [4]. The use of this renewable energy is associated with the abundance of technical and economic challenges. One of these challenges is effects of partial shading of the panels. This phenomenon is caused by the shadow of clouds, trees, high buildings, transmission towers, power distribution poles, and so on. The partial shading engases panels, inverter, and total converter lead to deviation in the key output parameters of the system [5], [6].

In the literature, the effects of this phenomenon on various parameters of the photovoltaic system such as MPPT, transmitted power, total system losses, reliability, etc., are analyzed. In [7], Cuckoo Search (CS), the method used for MPPT is described during partial shading effect. The focus of the work is on the convergence rate, efficiency and capability of the CS method compared to the other conventional methods such as P&O and PSO. In [8], Improved Cuckoo Search (ICS) is the introduced method, which has a higher speed and capability during finding the maximum power point when partial shading occured. In [9], the improved Inc Cond (IC) method is used to reach the Global MPP (GMPP) while considering load variations and several peaks in I-V curve of the panels, in the form of partial shading. In [10], the DC-DC converter control method, connected to the panels is used to track the maximum power point. This method is applicable, both for the off-grid photovoltaic system and for the grid-connected system. In [11], the DPSO method is used to quickly reach the MPPT point in the presence of rapid shadow changes due to rapid changes in clouds. The general and partial effects of the fall shadow on panels arranged on a photovoltaic farm, using MATLAB software analyzes, are shown in [12]. In [13], a method is proposed to eliminate local maximum power point (LMPP) and to achieve GMPP. The effect of partial shading on the photovoltaic system and also the inverter outage from the network in critical situations is described in [14]. The proposed method is based on the measurement of the voltage and current of the panels. In [15], the effects of partial shading are analyzed using modeling of photovoltaic cells based on two diodes. In [16], a circuit model of the photovoltaic arrays is presented in terms of irradiance variations and effects of bypass diodes. In [17], the effects of using bypass diodes in different environmental conditions and partial shading are modeled in Pspice software. The model used in this simulation is a dual diode model. In [18], the analysis of the using bypass diodes with overlap configuration is described and probabilities and strategies for preventing double nominal current flows are formulated during partial shading. In [19], MPPT is performed taking into account the effects of bypass diodes while considering partial shading phenomenon (BD-MPPT). In [20], a comparison is made in terms of losses for the bypass diodes structure, in two modes including overlap and non-overlap. It is shown that, in overlap mode about one third of the associated system losses are related to the bypass diodes while in non-overlap mode there is power losses only in diodes in the partial shading mode.

In this paper, the effects of different shadow paradigms on the photovoltaic system output are investigated. This will be done by developing appropriate equations and modeling of the system through defining different scenarios. The system performance analysis is performed on the dominant output parameters such as panel voltage, panel power, and THD of the inverter. It also examines the effect of using bypass diodes on panels or not. To compare derived results, this study is accomplished on a practical system. The system is made up of a 1kW 7-level multi-level photovoltaic inverter. The actual test results in this study show a slight deviation from simulation results.

The paper excluding this introduction is organized as follows. The theory of partial shading is described in Section II. The theoretical simulation is performmed with the parameters of the actual panels in Section III. In Section IV, the effect of using bypass diodes to resolve the partial shading problem is investigated. In Section V, the actual test results of a grid-connected photovoltaic system with a power of 1 kW are shown. Discussion and conclusion of the work are also given in Section VI.

2. THEORY OF PARTIAL SHADING

To analyze the effect of partial shading on the photovoltaic systems, first, the photovoltaic panel cells should be modeled. The circuit models of photovoltaic cells are shown in full sun and in full shade (for one of the cells) in Figure 1 [21].

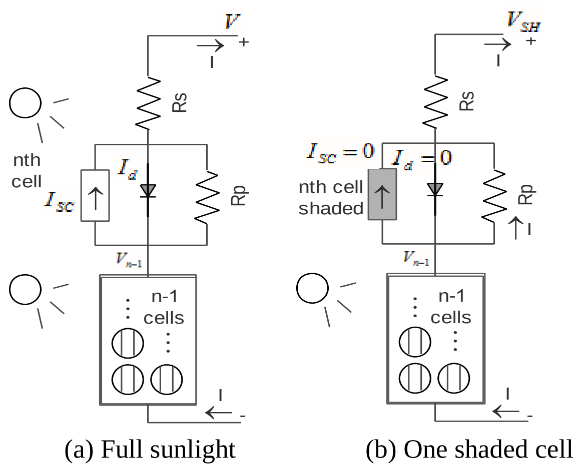


Figure 1. (a) Circuit model of cells, in full sunlight mode; (b) Circuit model of a cell under shade

According to circuit laws (for Figure 1):

$$V_{SH} = V_{n-1} - I(R_P + R_s) \quad (1)$$

$$V_{n-1} = \left(\frac{n-1}{n}\right)V \quad (2)$$

$$V_{SH} = \left(\frac{n-1}{n}\right)V - I(R_P + R_s) \quad (3)$$

And so, the difference between the voltages is equal to:

$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right)V + I(R_P + R_s) \quad (4)$$

$$\Delta V = \frac{V}{n} + I(R_P + R_s) \quad (5)$$

And with a reasonable approximation:

$$\Delta V \cong \frac{V}{n} + IR_P \quad (6)$$

After extracting the equations, the effects of this phenomenon on the I-V curve of the panels is examined, in different states. As shown in Figure 2, in the case of one of the cells in the full shadow state, the I-V curve of the panels change. Also, with the expansion of the above equations, for a state in which *m* cells are shaded, this voltage difference is equal to:

$$\Delta V = m(\frac{V}{n} + I(R_P + R_s)) \quad (7)$$

And with an approximation:

$$\Delta V \cong m(\frac{V}{n} + IR_P) \quad (8)$$

I-V curves of typical cells are shown in Figure 3 for different modes of 0.5, 1, and 2 cells in full shadow. As Figure 3 shows, the I-V curve of the panels is severely damaged by this phenomenon. In the following, partial shading is simulated in different situations, in real panels.

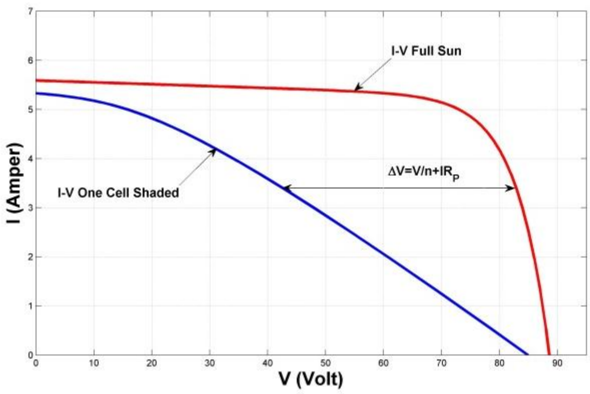


Figure 2. I-V curve of typical cells, in full sun, and full shadow (for a cell)

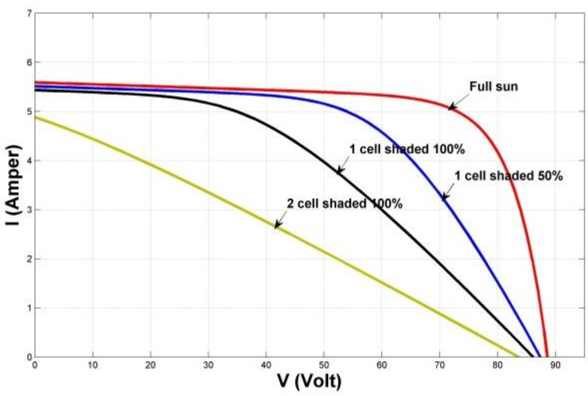


Figure 3. I-V curves of typical cells, in full sun, and 0.5, 1 and 2 shaded cells

3. SIMULATION ON CHARACTERISTICS OF THE REAL PANELS

The panels used for simulation are selected from the project of 1kW photovoltaic system connected to the grid and have electrical characteristics according to Table 1. Standard conditions (STC, AM1.5, Iradiance Level = 1kW/m^2, Tamb = 25 °C) from Solar One and the Hanwha Solar One-Qidong-SF 160-24-1M180 [22] are considered.

Table 1. Electrical characteristics of the used panels

Char acteristic	V alue		Characteristic	V alue
P_{MP}	180 W		FF	72.7 %
V_{OC}	44.3 V		Number of Bypass Diodes	3
I_{SC}	5.59 A		Number of Cells	72
V_{MP}	35.4	0	R_P	130Ω
I_{MP}	5.11 A	1	R_s	0.0125Ω
η	14.1 %	2	Cells type	M ono

The both panels are series, in three-stage, to achieve sinusoidal output, in structure Figure 4 (structure used in the project), which is 7-level Z-source multi-level inverter. The output of the panels is increased by the Z-source converter, and its expected output is shown in Figure 5.

The magnitude of the increased voltage of each stage is obtained from the following equations [23]:

$$V_1 = \frac{V_{mp_1}}{1-2D_1} \quad , \quad V_2 = \frac{V_{mp_2}}{1-2D_2} \quad , \quad V_3 = \frac{V_{mp_3}}{1-2D_3} \qquad (9)$$

Where *Di* is duty cycle. The block diagram of the output signal generation and a sample of actual generated voltage and the harmonic analysis of the inverter's output voltage (before the filter) for the structure of Figure 4 is shown in Figure 6.

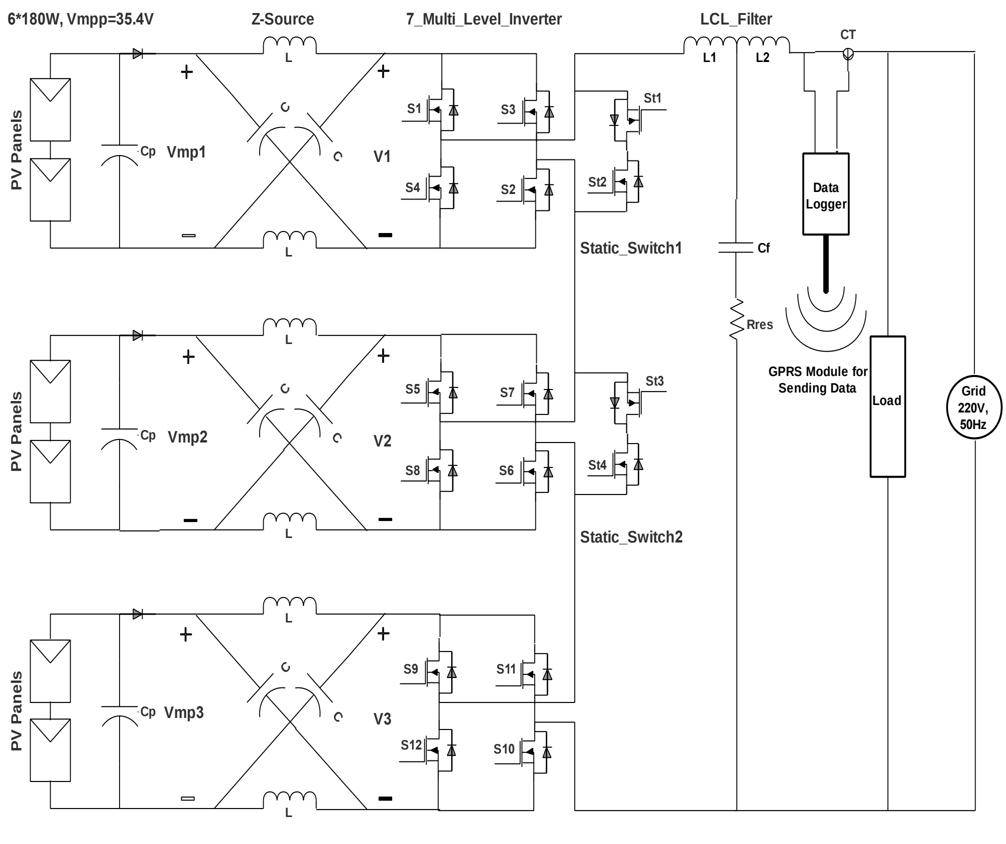


Figure 4. The structure used to inject the power of the panels into the grid

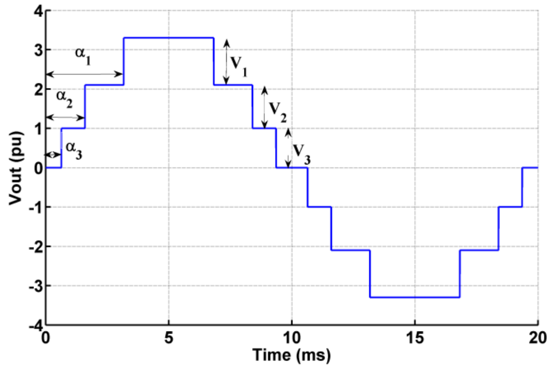
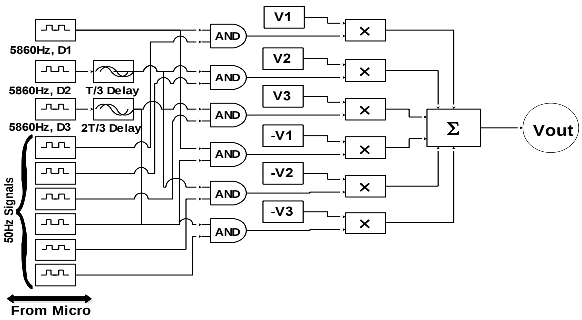
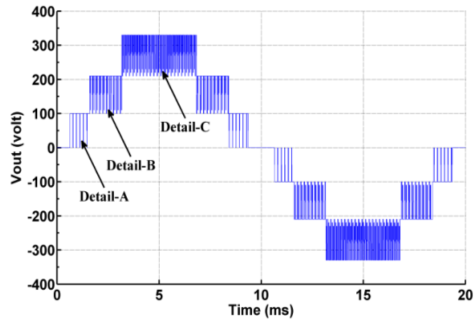


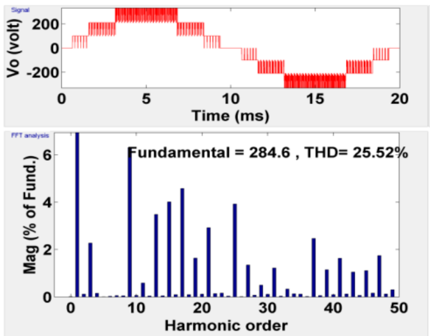
Figure 5. Required 7-level output with unequal voltage levels



(a)



(b)



(c)

Figure 6. (a) Block diagram of the output voltage, (b) a sample of generated real voltage, (c) its harmonic analysis

The output voltage and analyzes in the above section are related to the case in whcich the panels are exposed to full solar radiation. But this is not always the case and for various reasons in many installed photovoltaic systems. In practice, partial or general shading occurs due to different factors. In the following, this effect on the output voltage of the structure of Figure 4 is investigated. First, the structure of the used panels must be known and analyzed. The equivalent circuit of the above panels is shown in Figure 7. As seen in the figure, the panel has only 3 bypass diodes, which is very low with respect to 72 cells. Also, both cells are parallelized together in the panel. In this photovoltaic system, the panels are arranged in two-in-series, which ultimately obtains an equivalent circuit by 180-watt panels, as shown in Figure 8. By solving the circuit equations of the photovoltaic cells, the I-V curve equation of the two-series panel, which is used in this project, will be obtained. According to the following equation:

$$I_P = I_{SC} - I_0\left(e^{\alpha(V_P+R_S I_P)} - 1\right) - \frac{(V_P+R_S I_P)}{R_P} \quad (10)$$

Given that, are used two series panels, so the equivalent of the series and parallel of the resistors is equal to:

$$R_P = 2 * 130 = 260\ \Omega\,,\ \ R_S = 2 * 0.0125 = 0.025\ \Omega$$

By setting the values of the panels in equation 10, three equations and three unknowns are obtained:

$$\begin{cases} 0 = I_{SC} - I_0(e^{\alpha(44.3)} - 1) - \frac{(44.3)}{260} \\ 5.59 = I_{SC} - I_0(e^{\alpha(0.025*5.59)} - 1) - \frac{(0.025*5.59)}{260} \\ 5.11 = I_{SC} - I_0(e^{\alpha(35.4+0.025*5.11)} - 1) - \frac{(35.4+0.025*5.11)}{260} \end{cases}$$

The I-V curve of the panels is obtained by solving nonlinear equations using MATLAB software.

$$I_P = 5.5905 - 4.8388 * 10^{-7} * (e^{0.18284(V_P+0.025I_P)} - 1) - \frac{(V_P+0.025I_P)}{260} \quad (11)$$

The curve of Equation (11) is shown in Figure 9. In the following (four senarios-Figure 10, Figure 11, Figure 12 and Figure 13), shadow effects on the photovoltaic panels are introduced, theoretically, and regardless of bypass diodes (blue curve), in comparison with the full sun state (red curve).

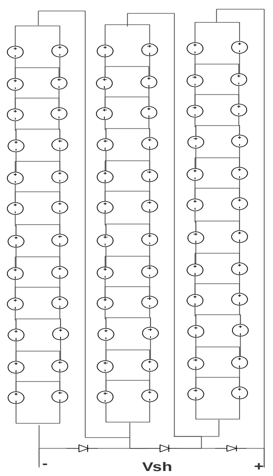


Figure 7. The equivalent circuit of 180 watts panel used in the photovoltaic project

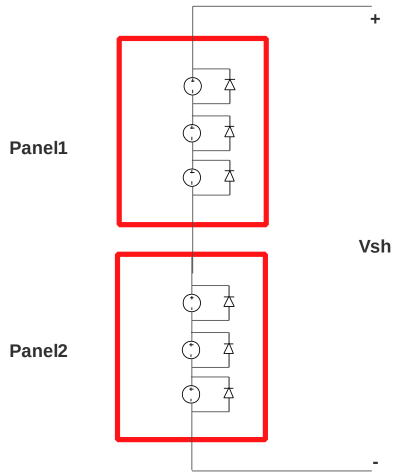


Figure 8. Equivalent circuit of two series 180 watts of the panels

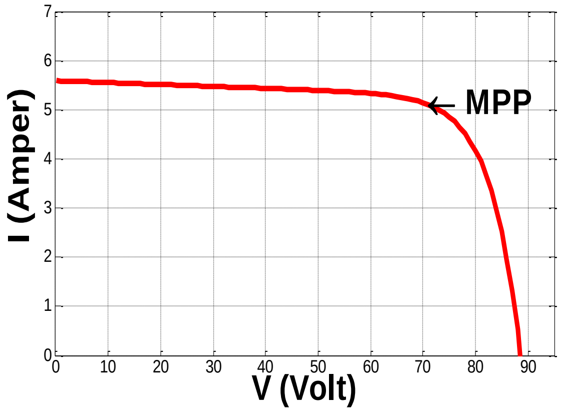


Figure 9. I-V curve of two-series panels used in the project

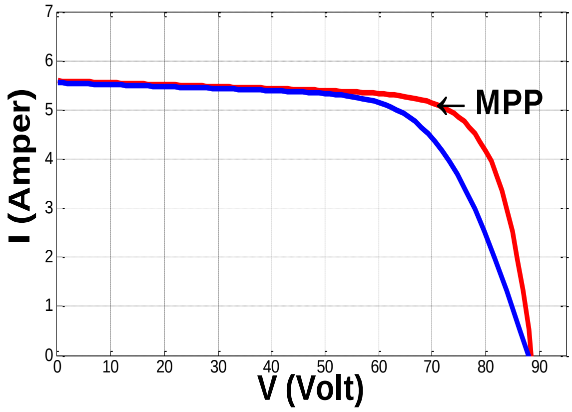


Figure 10. Shaded curve of the panel, with 50% destruction of one cell

a. 50% of one cell is shaded (in the panel introduced, the word cell, that is, the parallel combination of two real cells)
b. 1 cell is completely under shadow
c. 2 cells are completely under shadow
d. 12 cells are completely under shadow

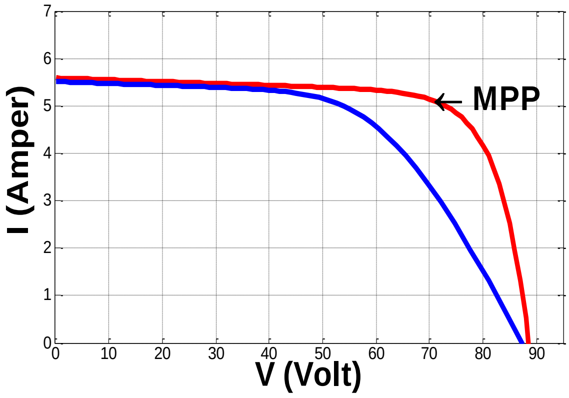


Figure 11. Shaded curve of the panel, to the extent of the destruction of one cell

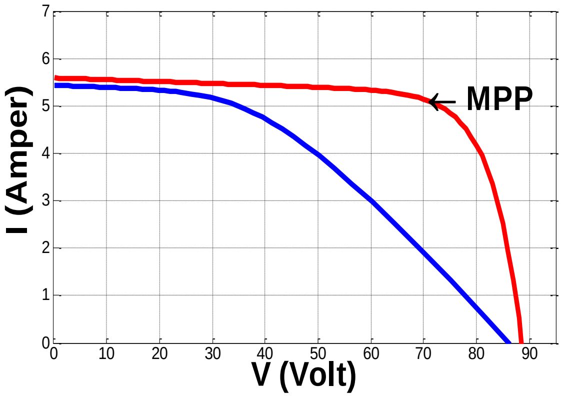


Figure 12. Shaded curve of the panel, to the extent of the destruction of two cells

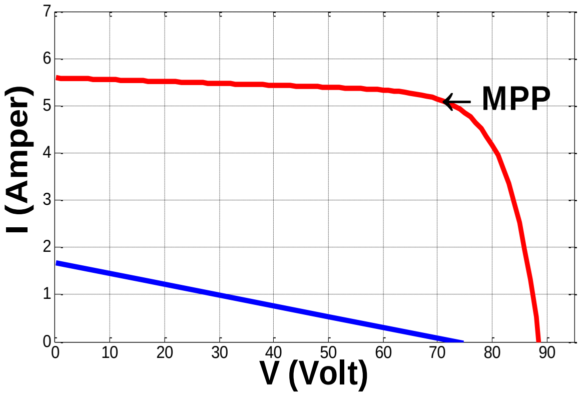


Figure 13. Shaded curve of the panel, to the extent of the destruction of 12 cells

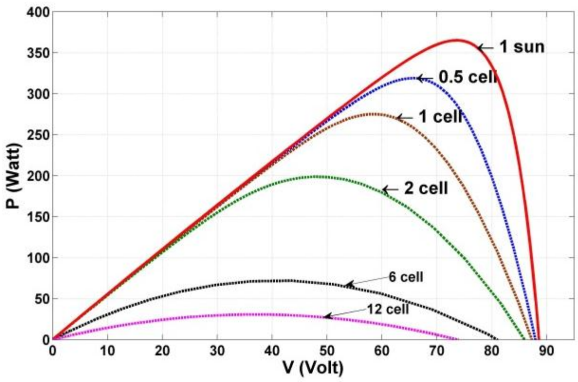


Figure 14. P-V curves in different states of partial shading

In Figure 14, the curves of P-V are shown in various partial shading conditions. As can be seen, the reduction of the output power which are specified, by increasing the number of degraded cells. The I-V curves of the series panels along with the MPPT points and the area of its realization are shown in different shaded conditions in Figure 15. As the figure shows, reaching the MPPT point of more than 12 shaded cells is not feasible [24].

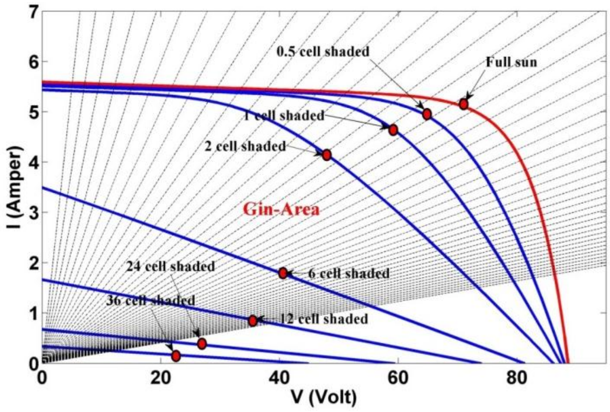


Figure 15. I-V curve, MPP points, and area of inverter input conductivity range, under different shaded conditions (without bypass diodes)

In Table 2, the MPPT point voltage and the maximum extracted power of the panels are presented in terms of the number of shaded cells. The decreasing trend of these values is quite obvious in tables and figures, by increasing the number of shaded cells. The maximum extraction power of panels, in different shades, is plotted in the graph, in Figure16.

Table 2. Output parameters of the system in different modes of partial shadings

Number of cells under shadow	Maximum power extracted (W) (in MPPT)	MPPT point voltage By V
0	360	70.8
0.5	319	65.7
1	275	59.1
2	198	47.6
6	72	40.5
12	31	35.6
24	10	27.3
36	4	20.1

As shown in Figure 16, as the number of shaded cells increases, the extraction power of the panels decreases sharply.The above curve is very similar to the following function:

$$P_{MP} = \frac{\alpha}{n^2+\beta} \quad (12)$$

Where, n is the number of shaded cells, and α, β are constants. In this panel, we can approximate the output power with a very good approximation, by the following equation:

$$P_{MP} = \frac{3240}{n^2+9} \quad (13)$$

Total power to the grid and the output voltage of the Z-source converter and the output voltage THD of the inverter, are shown in Table 3 at various modes of partial shading.

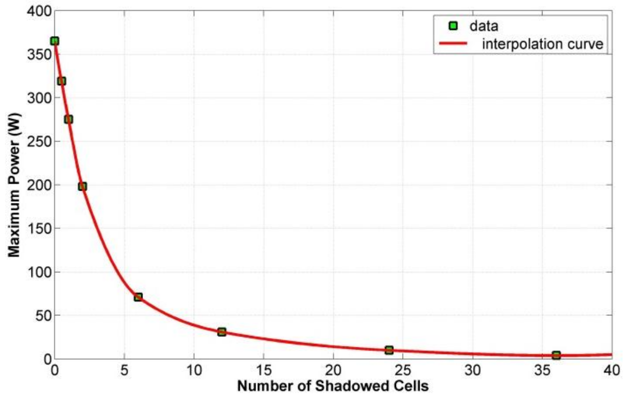


Figure 16. Maximum power extraction curve of the panels, in terms of the number of shaded cells

Table 3. Output power values, Z-source voltage and THD of the output signal according to the type of partial shading

N umber of cells under shading	PPT voltage V	M point By	To tal power injected into the grid (W)	Outp ut voltage of the Z- sour ce (V)	HD%	T
0	.8	70	10 80	120	5.52%	2
0 .5	.7	65	10 39	111. 35	5.20%	2
1	.1	59	99 5	83.4 7	4.96%	2
2	.6	47	91 8	67.2 3	5.36%	2
6	.5	40	79 2	57.2	5.84%	2
1 2	.6	35	75 1	50.2 8	6.29%	2
2 4	.3	27	73 0	38.5 6	7.28%	2
3 6	.1	20	72 4	28.3 9	8.38%	2

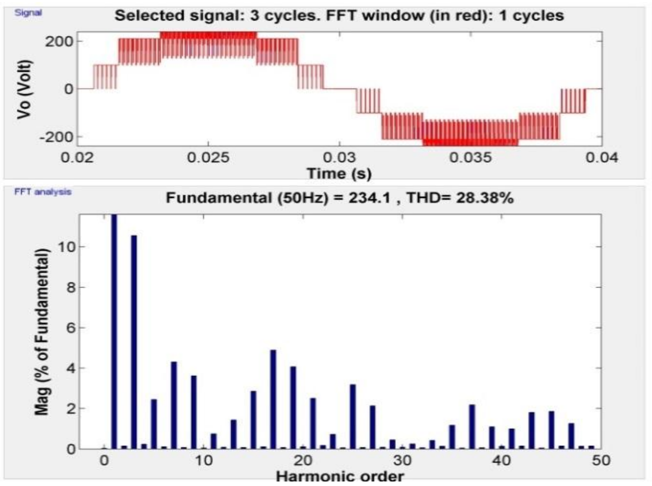


Figure 17. Output voltage waveform analysis, in row 8 of Table 3

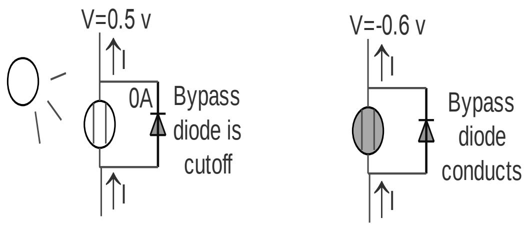
As Table 3 shows, by increasing the number of under shading cells, the output voltage of the Z-source converter decreases and it reduces the fundamental harmonic amplitude of the output waveform, and in general, causes an increase in the THD of the output voltage. The generation waveform analysis for row 8 (when a panel is generally in full shadow) is shown in Figure 17. Also, in addition to reducing the power of injection into the grid, this effect raises the loss of the system which is by no means desirable. Using bypass diodes is a solution that is provided by panels makers to minimize the effects of partial shading on photovoltaic panels described in detail in the next section.

3. BYPASS DIODES

The panel manufacturers use panels bypass diodes, parallel to the cells, to prevent loss of power during partial shading, as in Figure 18. The I-V curves of a typical panel, with and without bypass diodes is shown in Figure 19. The modified I-V and P-V curves using bypass diodes related to row 6 of Table 3 are shown in Figure 20 and Figure 21. As it is evident in the diagram, the use of the bypass diodes plays a very important role in preventing a large deterioration of the I-Vand P-V curves of the panels. The correction values of Table 2, after considering the bypass diodes are shown in Table 4.

As shown in Figure 13, we can see that when the 12 cells exit the circuit, then the I-V curve of the panels is severely eliminated and the power is reduced to the load. And yet, in practice and in such an event, the bypass diodes enter the circuit and improve the I-Vand P-V curves, as in Figure 20 and Figure 21.

In this section, the simulation of the previous section (Figure 15) is presented in the presence of bypass diodes. As shown in Figure 22, Figure 23, Figure 24, and 36 shaded cells, the previous simulation, where MPPT could not be achieved, MPPT will be achieved in this case. In general, we can say that, in the presence of bypass diodes, the MPPT realization algorithm is realized in many cases of the partial shading.



(a) Full sun (b) Full shadow

Figure 18. Use of bypass diodes, to prevent loss of power, in panels, in a- Full sun modes, and b-Full shadows

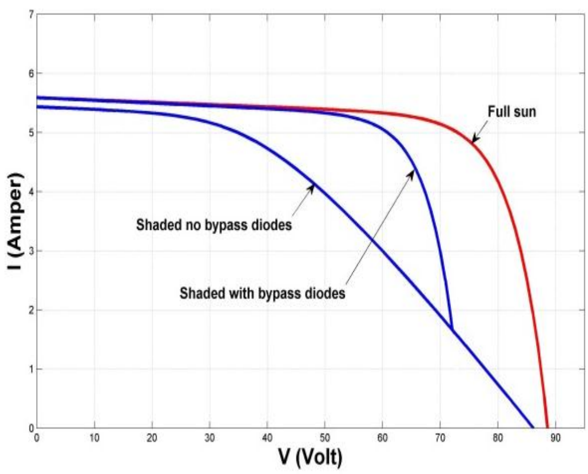


Figure 19. I-V Curve of a typical panel, with and without bypass diodes

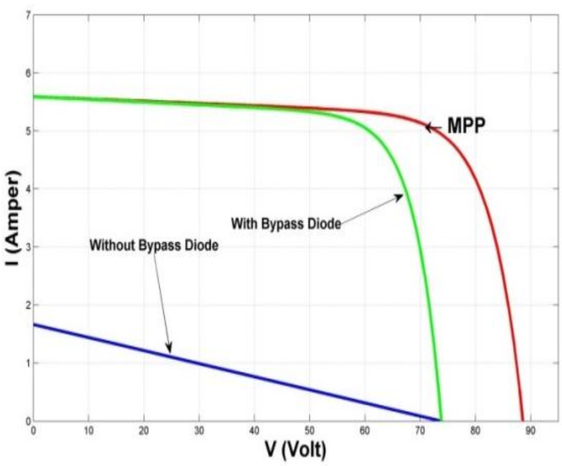


Figure 20. The effect of using bypass diodes to prevent the power loss, when the 12 cells are exited from the circuit (I-V curve)

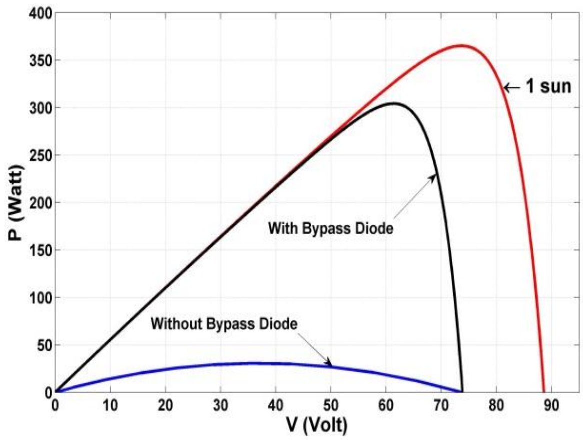


Figure 21. The effect of using bypass diodes to prevent the power loss, when the 12 cells are exited from the circuit (P-V curve)

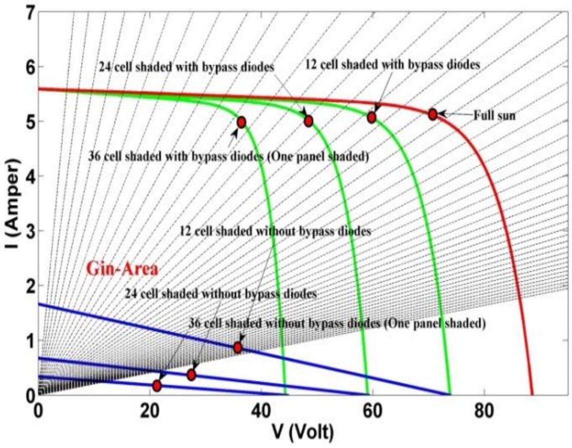


Figure 22. I-V Curve, MPP Points, and inverter input conductivity range, under different conditions of partial shading (with bypass diodes)

Table 4. Maximum extracted output power of the panels, per stage, with bypass diodes

Numbe r of cells under shading	Maximum extracted output power (W) (MPPT)
0	360
0.5	319
1	275
2	198
6	72
12	300
24	240
36	180

4. REAL TEST RESULTS

Further, the actual partial shading test on the panels is described and its effect on the Voc (open circuit voltage) is described. The setup of the structure of Figure 1 is shown in Figure 23 [22]. A sample of power and energy produced by this system without shading over a period of one day is shown in Figure 24. The effect of partial shading testing in the real system, and its comparison with the simulation results, is performed, as shown in Figure 25. The actual voltages (Voc) of one of the under shading panels will be shown in various ways. The open circuit voltage of the panel, while divided, is shown in Figure 26 at intervals of 1/6 of the panel surface, and in the longitudinal direction.

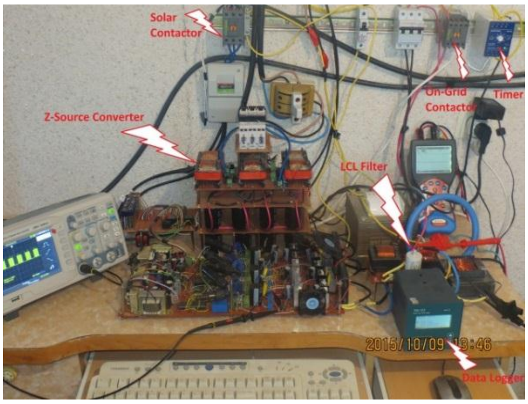


Figure 23. SETUP of 1kW photovoltaic system connected to the grid

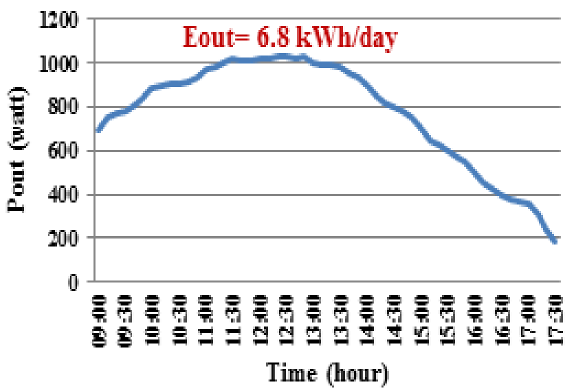


Figure 24. An example of the power and energy generated by the photovoltaic system during a day

The open circuit voltage shown in cross-section in the 1/12 intervals of the panel are shown in Figure 27. Figures 26 and 27 are almost linear. In Figure 26, the 2P3 voltage number which means that 2/3 of the panel surface is exposed to sunlight, is equal to 33.6 V, which, if it is to be summed up, with a 41.1 V series of a healthy panel with a total of 75 V it is produced, as shown in Figure 13, which is the simulation of the same state, indicating approximately the same number at the Voc point (74 V). The comparison of theoretical and practical state of the open circuit voltage of the panels for two partial shading longitudinal and transverse modes is shown in Figure 28. As Figure 28 shows, the differences between simulation and measurement are small and negligible. This suggests that panel modeling is done correctly and other results related to THD, maximum power voltage, and extraction powers of the system have high accuracy and similarity with simulation results.

(a) A full panel (b) Two third of a panels (c) One-eighth of a panels

Figure 25. How to test under shading panels

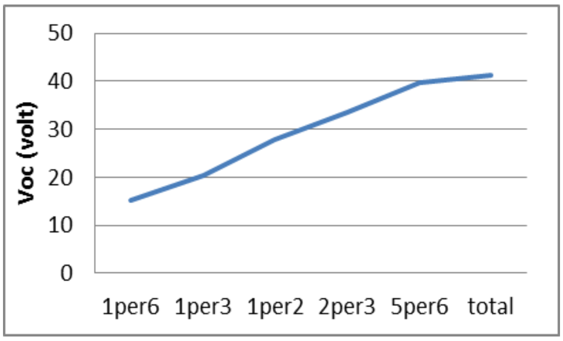


Figure 26. Voltages of the open circuit panel, in the longitudinal section under shading

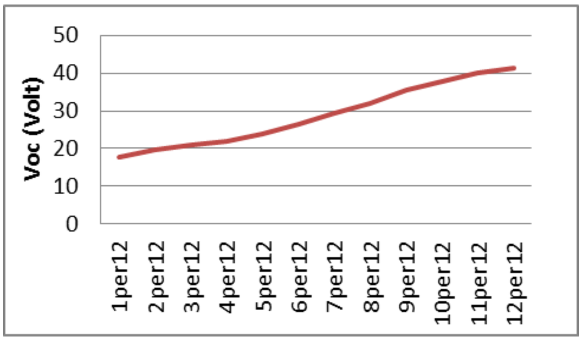


Figure 27. Open circuit voltages of panels, under shading

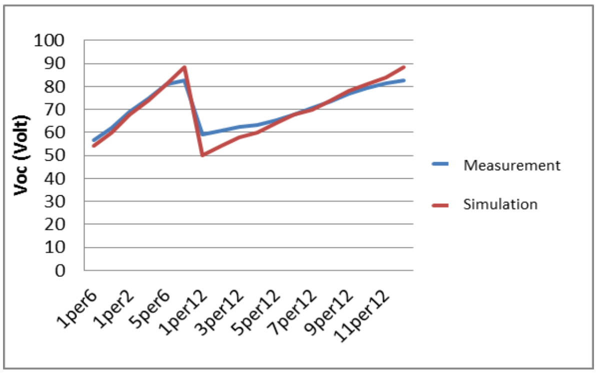


Figure 28. Comparison of open circuit voltages for panels, in the case of longitudinal and transverse shading

5. CONCLUSION

In this paper, the theoretical and practical aspects of the effect of partial shading on the photovoltaic system panels connected to a typical grid are investigated. As illustrated, simulation results under the shading of real panels after obtaining the I-V curve equation are in good accordance with the results of the measurements and this shows calculations and modeling accuracy. These effects are investigated on the parameters of open circuit voltage, voltage of MPP, maximum output power, THD voltage, and the role of bypass diodes in their improvement in the presence of various partial shadings. The results will give the designer an appropriate understanding of the function of photovoltaic systems in various conditions, including partial shading.

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