MATEC Web of Conferences **108**, 14007 (2017) DOI: 10.1051/matecconf/201710814007
ICMAA 2017

An Economic Solution to Optimize Performance of Photovoltaic Modules under Partial Shading

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Abstract. This paper investigates the effects of partial shading pertaining to photovoltaic (PV) modules and subsequently a solution that aims to minimize the effects and optimize the performance of PV modules is proposed. The concept of the solution is to integrate boost and buck converters into an electronic control system. The proposed system is simple and economic solution as it integrates cheap and easy available electronic components such as microcontrollers, capacitors, transistors and inductors. To validate the effectiveness of proposed system, a measuring instrument, namely NI cFP-1808 is used to perform the electrical characteristic analyses or known as I-V and P-V curve analyses. Furthermore, an outdoor experiment was conducted to examine the practicality of the proposed system in tackling real-world conditions. Experimental results showed that the proposed system improves the performance of the PV modules by 82.9% compared to the controlled experiment. In short, the effectiveness and practicality of the proposed system is proven with experiment results.

1 Introduction

Photovoltaic (PV) system has received prominent attention over the last decade as it offers great advantages such as low maintenance cost, absence of moving or rotating parts and freedom from environmental pollution [1,2]. Though the PV system has been widely implemented, there are still numbers of ongoing limitations that need to be investigated and improved. As an example, partial shading on PV system is one of the ongoing issue [3,4]. Partial shading is defined as the PV arrays that are partially shadowed by the neighboring trees, buildings, towers and even passing clouds [3]. Under partial shaded conditions, the PV characteristics get more complex with multiple peaks. A research from Germany shows that the effect of partial shading can reduce the output energy up to 20% [4].

Literature reveals that numbers of researches have been conducted to tackle partial shading conditions. These researches can be categorized into maximum power-point tracking (MPPT) methods [2], modeling and simulation based approaches [3, 5, 6], DC-DC converter [7]. In [2], a metaheuristic optimization algorithm namely, firefly algorithm, is used to track the maximum power point under partial shading condition in a PV system. A comprehensive study on MPPT methods has been discussed in [8, 9]. In [3, 5], MATLAB-based modeling and simulation approach studies the effect of shading patterns on PV panels pertaining to different configurations. In [6], PSpice-based modeling and simulation approach investigates the effects of bypass diode configurations on PV modules. In [7], a DC-DC converter is introduced to boost the output energy in partial shading condition. While many solutions pertaining to partial shading are available, an economic and simple solution is relatively new.

The aim of this paper is to propose an electronic system that improves the performance of photovoltaic modules under partial shading. It is worth-mentioning that the proposed system is built with cheap and easily available components such as microcontrollers, capacitors, transistors and inductors. The system consists of two parts namely, boost converter and buck converter. In general, the boost and buck converters are used to increase and decrease the output voltage level pertaining to input voltage, respectively. The performance of the proposed system is validated using a measuring instrument, namely NI cFP-1808. NI cFP-1808 is designed to measure electric current, voltage and power. Besides that, it can also perform the electrical characteristic analyses or known as I-V and P-V curve analyses with simple configurations.

In this paper, the partial shading effect is investigated through different shading portions. To effectively model the shading portion, an opaque tape with good thermal insulation is used to shade the PV cell. The materials used to shade the PV cell should be carefully considered else it may collect heat that will indirectly affect the performance of PV cell. The effectiveness and practicality of the proposed system is further evaluated with an outdoor experiment.

The rest of the paper is organized as follows. Section 2 introduces the notations with respective descriptions and some important equations. Section 3 presents the proposed system. Section 4 presents the experiment setup pertaining to two different investigations. Section 5 discusses the experiment results from different investigations. Finally, Section 6 presents the conclusion and future works.

2 Preliminaries

The related notations and their descriptions are listed in Table 1 as follows. As an example, V_{oc} represents open circuit voltage.

Table 1. List of notations

Notations	Descriptions
V_{OC}	Open circuit voltage
I_{SC}	Short circuit current
V_{pm}	Maximum power voltage
I_{pm}	Maximum power current
FF	Fill factor
P_{max}	Maximum power
P_{in}	Input power
η	Efficiency of photovoltaic (PV) cell
ΔI_{SC}	Declined percentage for I_{sc}
ΔI_{pm}	Declined percentage for I_{pm}
ΔP_{max}	Declined percentage for P_{max}

Besides several important definitions and equations used in this paper are defined as follows.

Fill factor, FF is defined as the ratio of maximum obtainable power to the product of the open-circuit voltage and short-circuit current. FF can be calculated using Eq. (1).

$$FF = \frac{I_{mp} \times V_{mp}}{I_{SC} \times V_{OC}} \tag{1}$$

Maximum power, P_{max} is product of V_{OC}, I_{SC} and FF as simplified in Eq. (2).

$$P_{max} = V_{OC} I_{SC} FF \tag{2}$$

The efficiency of a PV cell is an important parameter to compare the performance of PV cell. It is defined as the fraction of energy output from the PV cell to input energy from the sun which can be simplified into Eq. (3)

$$\eta = \frac{P_{max}}{P_{in}} \tag{3}$$

where the input power per meter square of PV cell is 1 kW/m^2.

3 The proposed system

The proposed system consists of two parts, i.e., buck converter and boost converter. Both converters are similar in design. The general concept of the converters is illustrated in the block diagram as shown Figure 1. It comprises three modules namely, voltage regulator, pulse width modulation (PWM) generator and inductor-based switching regulator (SR). The first module is used to maintain a constant voltage at 10V. The second module is known as PWM to generate 40 kHz frequency and the third module is used to step up/down of voltage source.

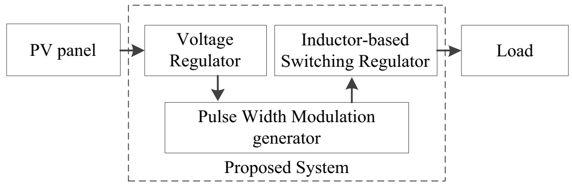
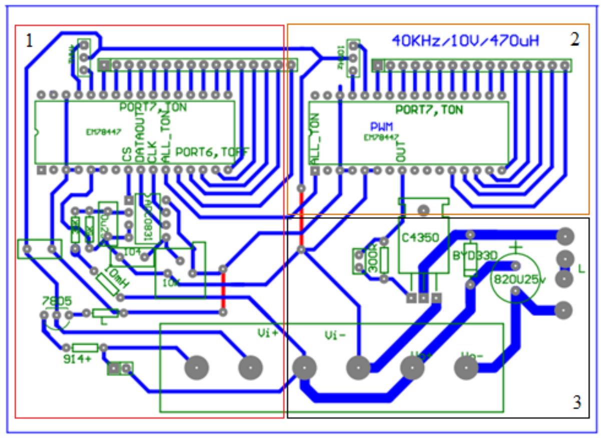
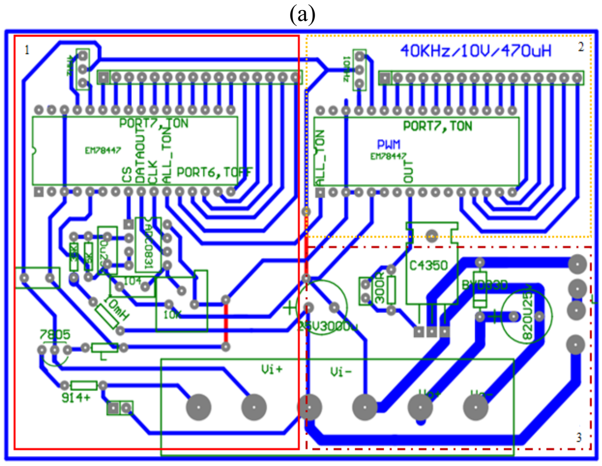


Figure 1. Block diagram of the proposed system

The three modules are integrated and designed in a single printed circuit board (PCB). An example of PCB layout for the proposed buck Converter is depicted in Figure 2.



(a)



(b)

Figure 2. PCB layout diagram of the proposed (a) buck Converter (b) boost Converter

The buck converter consists of few electronic components such as two microcontrollers, EM78447, two crystal oscillators (i.e., 4MHz and 10MHz), Analog to Digital convertor (ADC), capacitors, transistors, inductors and etc. As in Figure 2, it is observed that the square outline labeled with "1" indicates the voltage regulator module, "2" indicates the PWM generator module and "3" indicates the inductor-based SR module. In general, the circuit connection for both converters is similar, except for the configuration in third module. The difference for boost and buck inductor-based SRs is indicated in Figure 3. Technically, the buck inductor-based SR reduces a DC voltage to a lower DC voltage and boost inductor-based SR provides an output voltage that is higher than the input. With these boost and buck inductor-based SR, voltages can be regulated consistently. It is worth-mentioning that the inductor-based SR is beneficial as it has minimal power loss and provides high power efficiency [10].

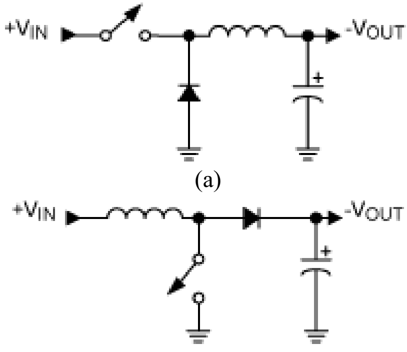


Figure 3. Inductor-based switching regulators (a) buck and (b) boost [11]

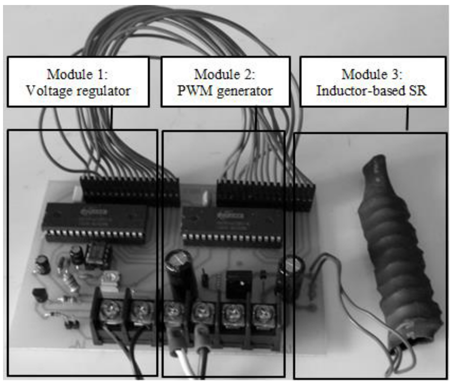


Figure 4. The proposed buck converter

4 Experiment setup

In this experiment, a PV cell is an electrical device with dimension 19.5×52 mm that converts the light energy into electricity energy. Therefore, the total power generated from a PV cell per meter square is 1.014W. A PV module is a packaged, connected assembly via the arrangement of 5×4 PV cells i.e., 5 cells in row and 4 cells in column as illustrated in Fig.5 (a). The total area of a PV module that occupy with PV cell is 20×19.5×52 mm or 20280 mm^2. Total power generated from a PV module is 20.28W. A PV array is defined as numbers of PV modules connected in serial/parallel. This research used a notation "SxPy XXX" to explain the connection of PV array where S and P indicate serial and parallel connections, respectively while x and y indicates the number of PV modules that connect in either serial or parallel connection and XXX indicates the shaded portion. For examples, "S1P1 6.25" represents a single PV module with 6.25% shaded portion and "S3P1 25" represents three PV modules connected in serial with 25% shaded portion.

It is worth-mentioning that our experiment focuses on two investigations, (1) investigate the effects of different shaded portions pertaining to a PV module and (2) investigate the practicality of the proposed method in improving the performance of PV module under partial shading effects. These two investigations are presented in detail as follow.

4.1 Investigate the effects of different shaded portions

A PV module pertaining to different shaded portions (i.e., 6.25%, 12.5%, 18.75% and 25%) as shown in Figure 5, is investigated under a controlled experiment. The performance of the PV module is examined by using a photovoltaic module tester (SPI-SUN SIMULATOR 350i). SPI-SUN SIMULATOR 350i detects the efficiency of PV module. The tester uses 1.3M Xenon lights to test PV module with dimension 2200mm × 1200mm. Technically, its requirements can meet with ASTM E927 Class A rating which is a standard specification for solar simulation used for photovoltaic testing. SPI-SUN SIMULATOR 350i measures the important parameters of PV module such as V_{oc} , I_{sc}, V_{pm}, I_{pm}, $P_{\max}$, FF, η, ΔI_{sc}, ΔI_{pm}, $\Delta P_{\max}$. Also it provides important visualization i.e., I-V and P-V characteristic curves. The results and discussions from this experiment are further discussed in Section 5.1.

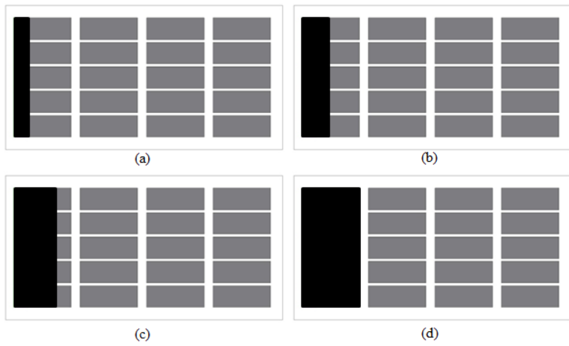


Figure 5. A PV module with different shaded portions (a) 6.25% (b) 12.5% (c) 18.75% (d) 25%

4.2 Investigate the proposed system pertaining to shaded portion

To validate the practicality of the proposed system, an outdoor experiment is essential. The experiment was conducted on a sunny day from 0540 until 1840, at rooftop of Mold and Die Department, National Kaohsiung University of Applied Science, Taiwan. The setup of the experiment is shown in Figure 6. It consists of two groups of experiment, namely experiment and control groups. Both groups use three PV modules connected in serial (i.e., S3P1, in short). One of the three PV modules is shaded with 18.75%, i.e., a total of 6.25% shaded portion for a PV array connected in S3P1. Besides that, both groups are controlled and applied that the same PV material and configurations, i.e., monocrystalline silicon, tilt angle 23.5° and azimuth angle 175° with 5° facing south east.

The results from the experiment and control groups are collected using data acquisition system (i.e., National Instruments, NI cFP-1808). NI cFP-1808 has Input and

Output (I/O) interface for Ethernet and RS232 networks. It can be easily read via the networked host PC. On the other hand, the solar irradiance of this experiment is measured using solar power meter (TEES-1333R) as depicted in left-corner of Figure 6.

Subsequently, the results from both groups are analyzed and compared. In this way, the practicality of the proposed system pertaining to shading effect of PV is validated. The results and discussions from the experiment are further discussed in Section 5.2.

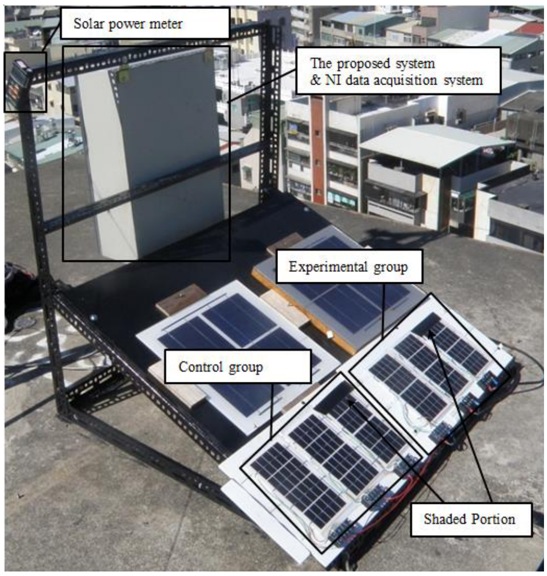


Figure 6. Setup for outdoor experiment

5 Results and discussions

The experimental results of the two investigations are presented in two sub-sections as follows.

5.1 Results pertaining to different shaded portions

Through SPI-SUN SIMULATOR 350i, PV without shaded portion obtains V_{oc} is 12.35V, I_{sc} is 350.8mA, V_{pm} is 10.25V, I_{pm} is 327.9mA, P_{max} is 3.362W, FF is 0.776 and η is 16.58%. While the rest of the results for 6.25%, 12.5%, 18.75%, 25% are tabulated in Table 2. It is obvious that the efficiency of PV cell decreases drastically with the increase of shaded portions as in row "η" it is observed that efficiency drop from 16.58% to 13.18%, 8.955%, 4.655% and 0% for shaded portions of 6.25%, 12.5%, 18.75%, 25%, respectively. Also, it is observed that the declined percentages pertaining to I_{pm} i.e., ΔI_{pm} are increasing with respective to increase in shaded portions.

I-V and P-V characteristic curves in Figure 7 further illustrate the effect of different shaded portions. Again, the effect is significant as the increasing of shaded portions will lead to reduce in both current (A) and power (W), correspondingly. When the shaded portion is up to 25%, it is observed that the power generated is reduced drastically to about 0W.

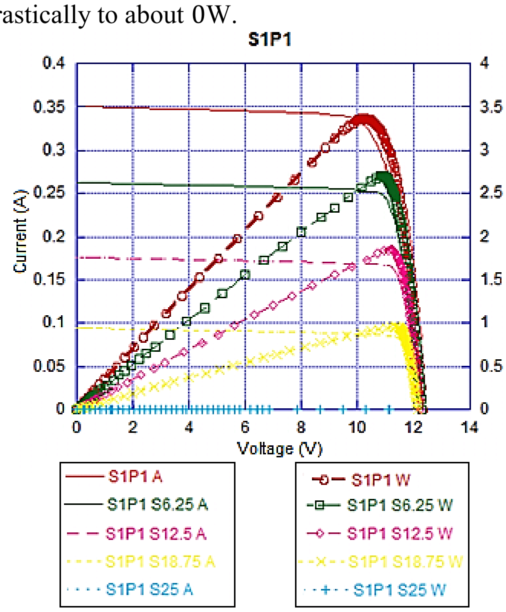


Figure 7. I-V and P-V characteristic curve of a PV module tested under different shading percentages

Further to this, other configurations such as S2P1 and S3P1 are investigated. The results are tabulated in Table 2. The results obtained from S2P1 and S3P1 are in line with the observations in S1P1. It is observed that the efficiency of PV cell reduces with the increase of shaded portions. It indicates that the increase of shaded portions significantly reduce the efficiency of PV module. Such deduction is also applicable to different configuration of PV module. As such, a research that improves the performance of the PV modules under partial shading is important.

Table 2. Experimental results of different PV configurations pertaining to different shading percentages

Parameters	S1P1 with different shading percentages					S2P1 with different shading percentages					S3P1 with different shading percentages				
	0%	6.25%	12.5%	18.75%	25%	0%	6.25%	12.5%	18.75%	25%	0%	6.25%	12.5%	18.75%	25%
V_{OC}	12.35	12.30	12.24	12.14	11.24	24.76	24.72	24.70	24.51	17.50	37.15	37.10	37.08	37.02	29.72
I_{sc}	350.8	262.5	176.7	94.40	1.100	350.7	351.6	351.0	350.8	350.9	350.9	350.8	351.0	350.9	350.7
V_{pm}	10.25	11.23	11.32	11.11	6.181	6.662	5.293	3.707	3.037	3.017	10.00	8.185	6.368	6.347	6.340
I_{pm}	327.9	238.1	160.4	85.00	0.600	20.52	20.80	20.51	9.393	9.331	30.76	31.61	19.69	19.60	19.81
P_{max}	3.362	2.673	1.816	0.944	0.004	324.6	254.5	180.7	323.4	323.4	325.1	259.0	323.5	324.0	323.3
FF	77.62	82.78	83.98	82.46	27.55	76.73	60.89	42.75	29.09	49.13	76.72	62.90	48.93	48.60	60.83
η	16.58	13.18	8.955	4.655	0	16.43	13.05	9.140	7.488	7.438	16.28	13.32	10.47	10.43	10.42
ΔI_{sc}	0	25.17	49.63	73.09	99.69	0	−0.257	−0.086	−0.029	−0.057	0	0.029	−0.029	0	0.057
ΔI_{pm}	0	32.13	51.08	74.08	99.82	0	21.60	44.33	−0.370	−0.37	0	20.33	0.492	0.338	0.554
ΔP_{max}	0	20.49	45.99	71.92	99.88	0	20.55	44.36	54.41	54.71	0	18.15	36.32	36.53	36.60

5.2 Results pertaining to outdoor experiment

The results of the outdoor experiment are summarized in Table 3. The maximum solar irradiance of the day is 960 Wh/m^2 at time 12:22:58. The maximum power collected through the experiment and control groups are 5.089W and 2.742W, respectively. The maximum power collected through the experiment group is higher than the control group. This is the first evidence that the proposed method installed in experiment group has improved the power efficiency of PV modules under partial shading.

Further to this, the cumulative total generated power from the experiment group is 30.0Wh compare to the control group 16.4Wh. It shows that the proposed system improved the total accumulated power by 13.6Wh, i.e., the overall power efficiency improves by 82.9%. Besides that, the performance of both groups is visualized in Figure 8. The cumulative total generated power of the experiment group is always higher than the control group throughout entire the experiment.

Table 3 Results of outdoor experiment

Details	Results
Duration of experiment	05:40:00~18:30:00
Maximum solar irradiance	960Wh/m^2 (12:22:58)
Maximum power collected through the experiment group	5.089Wh (12:22:58)
Maximum power collected through the control group	2.742Wh (12:22:58)
Cumulative total solar irradiance	4921Wh/ m^2
Cumulative total generated power from experiment group	30.0Wh
Cumulative total generated power from control group	16.4Wh
Percentage of power restored via the proposed system	**82.9%**

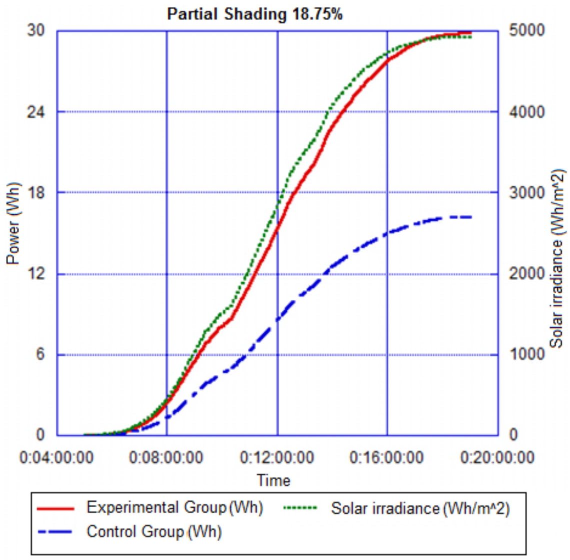


Figure 8. Cumulative generated power and solar irradiance

6 Conclusion and future works

In this research, the effects of different shading portions are investigated. The results show that the performance of PV cell is significantly affected. As such, a new solution that optimizes performance of photovoltaic modules under partial shading is proposed. Through the experiment, the proposed system has proven to improve the performance of the PV modules by 82.9%. It is worth-noting that the proposed solution is important as it is simple and economic.

In future, it is important to further investigate the practicality of the proposed system pertaining to PV array. It is interesting to investigate the durability of the proposed system in real implementation.

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