International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:8, No:9, 2014

Characteristics of Different Solar PV Modules under Partial Shading

Hla Hla Khaing, Yit Jian Liang, Nant Nyein Moe Htay, Jiang Fan

Abstract**—**Partial shadowing is one of the problems that are always faced in terrestrial applications of solar photovoltaic (PV). The effects of partial shadow on the energy yield of conventional mono-crystalline and multi-crystalline PV modules have been researched for a long time. With deployment of new thin-film solar PV modules in the market, it is important to understand the performance of new PV modules operating under the partial shadow in the tropical zone. This paper addresses the impacts of different partial shadowing on the operating characteristics of four different types of solar PV modules that include multi-crystalline, amorphous thin-film, CdTe thin-film and CIGS thin-film PV modules.

Keywords**—**Partial shade, CdTe, CIGS, multi-crystalline (mc-Si), amorphous silicon (a-Si), bypass diode.

I. INTRODUCTION

IN the new trend of integrated PV systems, it is difficult to avoid partial shading of array due to neighboring obstructions (e.g. building, tree, and telegraph pole, etc) throughout the day in all the seasons. This makes the study of partial shading of modules a key issue to the performance of a PV array. PV arrays in some applications are often subject to partial shading and rapidly changing shadow conditions. In a series connected solar photovoltaic modules, performance is adversely affected if all its cells are not equally illuminated. All the cells in a series array are forced to carry the same current even though a few cells under shading produce less photon current. The shaded cells may get reverse biased, acting as loads, draining power from fully illuminated cells [1]-[7]. If the system is not appropriately protected, hot-spot problem (premature failure problem) can emerge and in several cases, the system can be irreversibly damaged. To protect the system from such premature failure, modules are generally connected with “bypass diodes” in parallel with the cell. If the PV current cannot flow through one or more cells, it will flow through bypass diode instead. The bypass diode conducts when total current exceeds the current of the defective cell. In practice, bypass diodes are connected across groups of cells. The group size is typically 10 to 20 cells. The maximum power dissipation in the shaded cell is approximately the same as the generating capability of all cells in the group. To avoid failure of the bypass diodes, the cell temperature is recommended to keep low. In higher voltage application, bypass diodes may be placed across groups of cells to prevent mismatched or shaded cells from inhabiting production of power by rest of the cells [8]-[10].

Shading obstructions can be defined as soft or hard sources. If a tree branch, roof vent, chimney or other item is shading from a distance, the shadow is diffused or dispersed. These soft sources significantly reduce the amount of light reaching the cell(s) of a module. Hard sources are defined as those that stop light from reaching the cell(s), such as a blanket, tree, branch, bird dropping, or the like, sitting directly on top of the glass. If even one full cell is hard shaded the voltage of that module will drop to half of its un-shaded value in order to protect itself. If enough cells are hard shaded, the module will not convert any energy and will become a tiny drain of energy on the entire system [1]. In this paper, the hard sources are analyzed as it highly affects the performance of PV module. Moreover, it addresses the impacts of partial shadow on the operating characteristics of four different types of solar PV modules that include multi-crystalline silicon (mc-Si), amorphous thin film silicon (a-Si), Cadmium Telluride (CdTe) thin film, Copper Indium Gallium Selenide (CIGS). Among the four types of PV modules, three types of PV modules (mc-Si, a-Si and CIGS) are equipped with bypass diodes, while CdTe module does not require bypass diode. The experiments on the characteristics of the four PV modules were performed at the solar PV test-bed in Singapore Polytechnic when different partial shades were applied to the PV module along the different sides of PV module. The experimental data show that partial shadows covering the solar module along length-side resulted in greater power losses than those along breadth-side. Moreover, the experiments on the performance of mc-Si module, when bypass diodes breakdown, were undertaken. It is found that the malfunction of bypass diode significantly reduces the power output of PV module. Comparing to a PV module equipped with bypass diode, CdTe module without bypass diodes presents better performance when operating under the partial shade.

II. PV MODULES UNDER TEST

Four types of PV modules were selected to undergo the partial shading tests that are a-Si, CIGS, CdTe and mc-Si PV modules. Table I gives the main parameters of each PV module. The special features of selected PV modules are illustrated below.

A. Amorphous with 2 Bypass Diodes (UniSolar, US-42)

UniSolar US-42 solar panel uses Triple Junction amorphous thin film silicon cell technology, resulting in a robust, durable

---

Hla Hla Khaing, Yit Jian Liang, and Nant Nyein Moe Htay were students with the School of Electrical and Electrical Engineering, Singapore Polytechnic, Singapore.
Jiang Fan (Dr.) is with the School of Electrical and Electronic Engineering, Singapore Polytechnic, Singapore (phone: 65-68790629; fax: 65-67721974; e-mail: jiangfan@sp.edu.sg).

as well as flexible and light-weight cell. Modules are encapsulated in UV-stabilized polymers (includes EVA and fluoro-polymer Tefzel similar to Teflon), framed with anodized aluminum, and backed with Galvalume steel for stiffness. Bypass diodes are connected across each cell, allowing modules to continue to produce power when partially shaded. Compared to mono- and multi-crystalline modules, amorphous modules are virtually unbreakable and tolerant of both heat and shade.

TABLE I
PARAMETERS OF THE DIFFERENT TYPES OF PV MODULES

Type	a-Si	CIGS	CdTe	mc-Si
$P_{max}(W_p)$	42	60	48	120
$V_{oc}(V)$	23.8	25	90	21.7
$V_{mpp}(V)$	16.5	17.5	63.8	16.7
$I_{sc}(A)$	3.17	4.5	0.94	7.8
$I_{mpp}(A)$	2.54	3.5	0.78	7.2

The US-42 a-Si PV module has 22 cells connected in series and two bypass diodes are installed so that each bypass diode is connected to 11 cells in parallel as shown in Fig. 1.

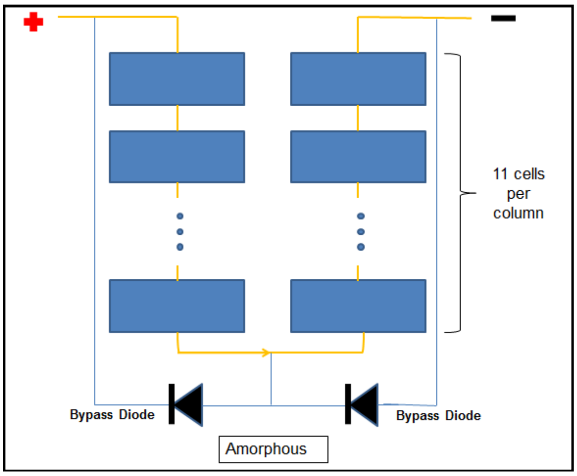

Fig. 1 Connection of bypass diodes in a-Si PV module

A. Copper Indium Gallium Selenide with 1 Bypass Diode (CIGS, GSE-60)

The GSE Solar Power Module uses high efficiency thin-film Cop per Indium Gallium Selenide (CIGS) solar cells encapsulated in advanced polymers. This is the next generation of solar power modules intended for off grid applications needing reliable lower wattage power designed to last for years. The GSE line of solar power modules are designed for off grid applications providing reliable power.

B. Cadmium Telluride Thin-Film without Bypass Diode (WK-65)

WK-65 is a Cadmium Telluride (CdTe) thin-film frameless solar module using a proprietary advanced deposition process; the semiconductor film is uniform providing consistence performance. CdTe is a direct band-gap semiconductor, which permits conversion of solar energy into electricity more efficiently by the way of increased watts per gram of material than the indirect band-gap semiconductor used historically. It will generally produce more electricity under real world conditions than solar modules with comparable power ratings. More importantly, there is no bypass diode in this module as there are 108 of small cells connecting in series.

C. Multi-Crystalline Silicon Modules with and without Bypass Diodes

Similar to Mono-crystalline PV cell, mc-Si PV cell is a typical semiconductor wafer consisting of N-layer, P-N junction and P-layer. Although it comprises of different grains of silicon, it is still able to produce a decent output [6]. With the increasing of its efficiency and the reducing of its price, mc-Si PV module has become the most popular PV product in the existing market.

The 120Wp mc-Si PV module consists of 36 PV cells connected in series and is equipped with 2 bypass diodes, each connecting 18 PV cells as shown in Fig. 2. As shown in Fig. 2, the 36 cells of mc-Si PV module are placed on the substrate in 4 collumns along its length-side and each bypass diode is connected to 18 cells string. To evaluate the impact of faulty bypass diodes in the module, the module without bypass diodes were tested under different shadowing conditions.

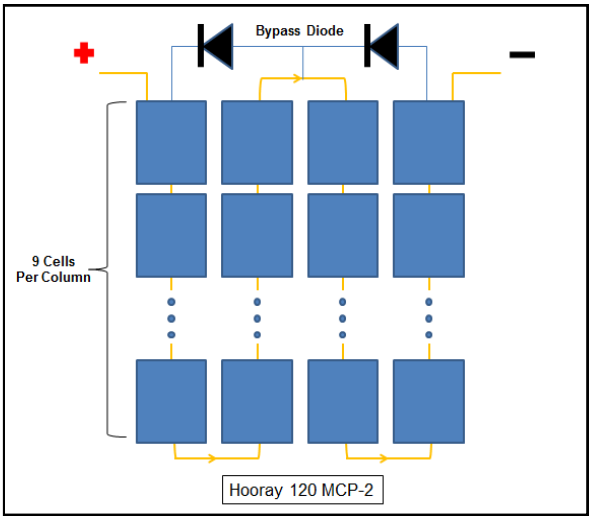

Fig. 2 Cells connection of mc-Si PV module with bypass diodes

III. PARTIAL SHADING TEST

In the experiments, the HT Solar I-V trace, a full PV system Analyzer, was used for measuring the I-V and P-V curves. Since the minimum power required for using HT Solar I-V trace is 50W, and the output of panels that investigated are small, two similar types of solar panels are connected in series to get a desire voltage and output power for the I-V tracer.

Fig. 3 illustrates the wire connections of panels, irradiance meter, temperature sensor and Solar I-V tracer. During the measurement, some parameters need to be taken note that include the speed of irradiance changing, solar cell temperature and the parameters of PV modules entered into the instrument.

Different patterns of shadows were applied on the PV modules to investigate the effects of various shading areas on its power output. Thanks to the different connection of the cells and by-pass diodes in a PV module, the shadows covering the modules along its length-side or breath-side can result significant impact on the power output of PV module. Therefore two measuring patterns, i.e. shading the PV modules along the length-side and the breadth-side, were implemented to shade the area of a PV module from 10% to 60% in step of 10% accordingly.

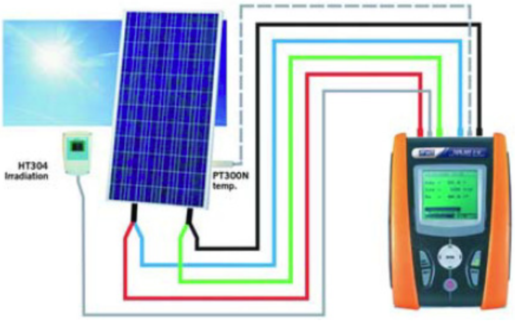

Fig. 3 The measurement of partial shading on solar system

IV. RESULTS OF PARTIAL SHADE TESTS

A. *Performances of PV Modules under Shading*

The experiments were conducted to obtain I-V and P-V curves of 4 types of PV modules under different shade conditions along both length-side shadow and breath-side of a module. As the testing data set for each PV module are similar, here are only the results of a-Si PV module described.

Fig. 4 presents the I-V curves and P-V curves of the a-Si PV module respectively under different partial shadows along the length. As shown in the diagram, the voltage drop of PV module is relatively even when the shadow on the module varied from 10% to 70%, about 2V drop corresponding to every 10% shadow increase. From the I-V curves, it is noticeable that the voltage of the PV module drops faster than its current with the increasing of shading area. The 'indents' of I-V curves and double power peaks of P-V curves in the figure are observed when more than 40% of PV module is shaded due to the conduction of the bypass diode to bypass current over the string of PV cells having partial shadow.

When the shadow falls on the same PV module along its breath-side, the performance of the module differs from that when the module was shaded along its length-side. Fig. 5 presents the I-V and P-V curves of the module measured when shading the module along the breath-side. It is noticeable that shading along the breath-side of module has more impact on the performance of a-Si module than shading along its length-side. Hence, it is recommended that if the shadow is not avoidable to the a-Si PV array with similar module, system installer should arrange the modules carefully to avoid the occurrence of shading along the length-side of the modules.

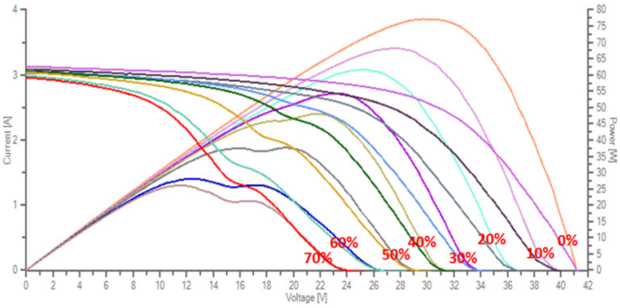

Fig. 4 I-V & P-V curves of a-Si PV Modules shading along length

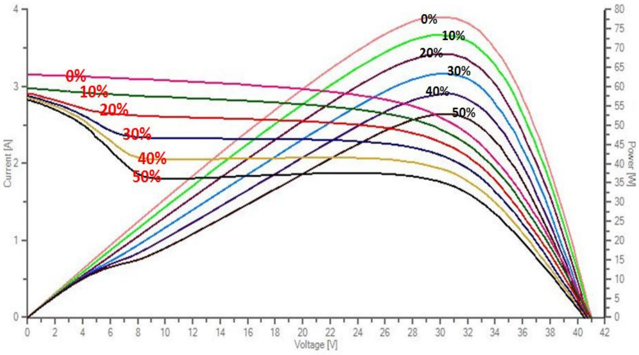

Fig. 5 I-V & P-V curves of a-Si PV Modules shading along width

B. *Operation of mc-Si PV Modules with/without Bypass Diodes under Shading*

For the PV module equipped with bypass diodes, the bypass diodes may malfunction due to the lightning transient inrush and overheat operation. The damage of bypass diode may affect the power generation of the PV string to which the module is connected. The mc-Si PV modules with and without bypass diodes were selected to explore the impacts of faulty bypass diode on the performance of PV module under shading.

Figs. 6 and 7 show I-V and P-V curves of two mc-Si PV modules, one with bypass diodes and another without. It can be seen in Fig. 6 that the 'indents' appear in the I-V and P-V curves of the PV module with bypass diodes under 10%, 20% and 60%, resulting from conduction of bypass diodes. When PV cells of the module are shaded, the bypass diode connected to the cell string conducts to bypass load current to other unshaded cells string, which helps to avoid drastic drop in its power output.

As indicated in Fig. 6, when less than 50% of PV module area like 10% and 20% was covered by the shade along its length-side, only part of the first column cells on the left-hand side of the module shown in Fig. 3 was shaded and the unshaded part of those cells still converted solar energy to electricity at lower current due to conduction of bypass diode. On shading the PV module by 50%, it is found that when the whole string of 18 cells was bypassed by the bypass diode, resulting in the operation of another half module. With the increasing of partial shadow beyond 50% like 60% in the diagram, the rest 18 cells of the same module was covered by the shadow father reducing the power output.

Fig. 7 presents the similar I-V and P-V curves resulting from testing on mc-Si PV module without bypass diodes. Comparing the results with those in Fig. 6, it is apparent that the power output of mc-Si PV module without bypass diodes dropped dramatically with the increase of shading area on it.

It is observed that without bypass diode, every increase in excessive shading will cause a rapid decrease to the total energy yield of the module unless it has some special structure. It is also important to know the internal structure of the cell and the position of the bypass diode. Placement of the solar modules is most crucial. If the shading blocks out the parallel connected cells, current will still be able to transfer to other working area. However, if the series side is blocked, it will drag down the whole performance, due to mismatched cells.

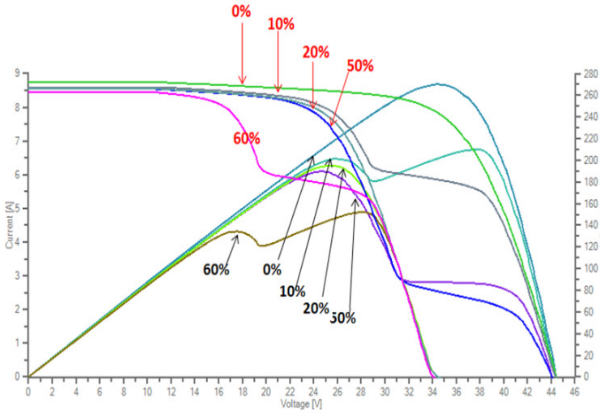

Fig. 6 I-V and P-V curves of mc-Si PV module with bypass diodes (shading along the length)

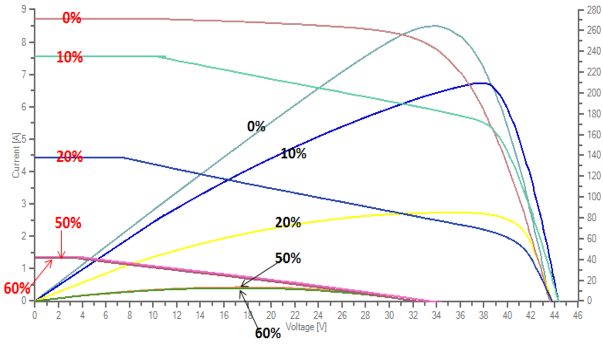

Fig. 7 I-V and P-V curves of mc-Si PV module with bypass diodes (shading along the width)

V. ANALYSES ON THE TESTING RESULTS

As all the modules have different power ratings and inputs, it is difficult to compare the performances of selected PV modules directly using the experimental results on site. In this paper, the ratios of the measured output powers of each PV module to its rated power were used to evaluate module performances under various testing conditions.

To compare the performances of different types of PV modules shaded along the length-side, the curves of power percentage drop vs. shaded area are plotted and presented in Fig. 8. It indicates that shading on a PV module may cease power output of a module under different area depending on what PV technology is used in the module. The experimental results in Fig. 8 reveal that a-Si module sustains higher amount of shading, followed by CdTe module, mc-Si module with bypass diode, CIGS module and mc-Si module without bypass diode. The a-Si module proves to be the best out of the 4 modules, maintaining its power output till 70% of shaded area. CdTe and mc-Si with bypass diode remain their power output until 60% of shading area but the mc-Si module possesses uneven decrease when its shaded area is bigger than 12% of module area. CIGS stops its output when 30% of its area is shaded, while mc-Si module without bypass diode terminates its output under 10% of shaded panel area.

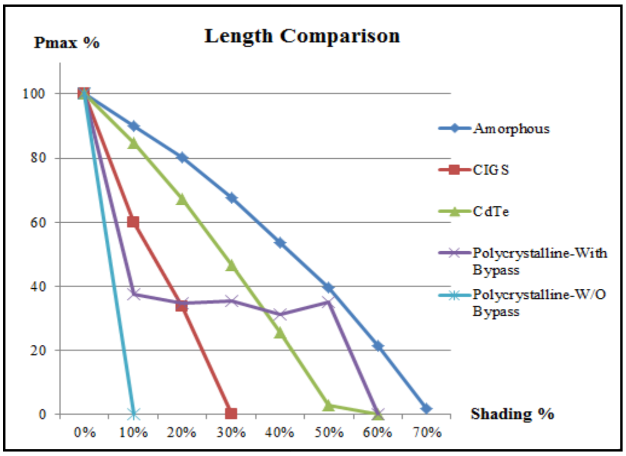

Fig. 8 Comparison of power reduction due to length-side shading

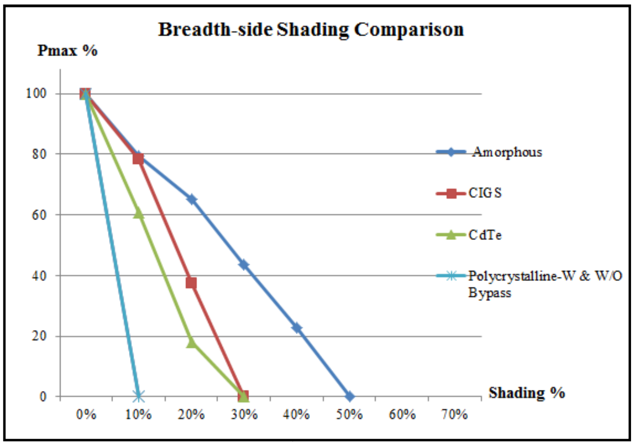

Fig. 9 Comparison of power reduction due to breadth-side shading

The performance tests were also performed when different PV modules were shaded along their breadth-sides as depicted in Fig. 9. The experimental results display that the a-Si PV module still keeps the highest tolerance to the shadow up to 50%, followed by CdTe and CIGS modules till 30% of shading panel area, and mc-Si modules with and without bypass of 10%.The results stem from the different internal structure of the cells and connection of bypass diodes.

VI. CONCLUSION

Partial shading in solar modules posts a great problem in creating failure in local overheating of shaded area and causes malfunction to the entire string of module. This paper presents the experiments on 4 different types of PV modules under the partial shading and the analytic results on their performance when various partial shades were applied to the module along its length-side and breath-side. The study concludes that with increase of partial shade on a PV module, power output decreases depending on the use of PV material, the structure of PV module and connection of bypass diodes. In general, the shade on a module along breadth-side causes higher power drop than the shade on the module along its length-side. The results also show that thin-film PV modules are more tolerant to the partial shade than mc-Si module. Under the partial shade, a-Si PV module performed best, followed by CdTe module, mc-Si module with bypass diode, CIGS module and mc-Si module without bypass diode.

To explore the impact of bypass diodes on the power production of PV modules, mc-Si PV modules with and without bypass diodes were selected to undergo the shading tests. A PV module with malfunction of its bypass diode will dramatically reduce the energy yield of PV string to which the shaded module is connected.

By installing the modules in locations without any obstruction will be preferable, but in urban areas like Singapore will be virtually impossible. Thus, if the shade is not avoidable it is advisable to install PV modules in such a way that the modules are shaded along their length-side instead of their breath-side to minimize effect of partial shading on performance of PV system

ACKNOWLEDGMENT

The authors are thankful to Singapore Polytechnic and Panasonic Eco Solution Asia Pacific which provided project funding, the experimental facilities for the whole experiment and strong support to the project.

REFERENCES

[1] E. Suryanto Hasyim, S.R., Wenham and M.A. Green, "Shadow toterance of modules incorporationg integral bypass diode solar cells", Solar Cells, Vol. 19, March 19, 1986, pp109-112.

[2] B Any, J., Appelbaum, J., "The effect of shading on the designof a field of solar collectors", Solar Cells 20, 1987, pp201–228.

[3] Appelbaum, J., Bany, J., "Shadow effect of adjacent solarcollectors in large scale systems", Solar Energy 23, 1979, 497–507.

[4] A Bete, A., Barbisio, E., Cane, F., "A study of shading effects in photovoltaic generators". Proceedings of the 9th EC PVSolar Energy Conference, Freiburg, 1989, pp. 240–244.

[5] A Lonso, M.C., Arribas, L.M., Chenlo, F., Cruz, I., "Shading effect on a roof integrated grid-connected PV plant". Proceedings of the 14th EC PV Solar Energy Conference, Barcelona,1997, pp. 1891–1894.

[6] Ramaprabha Ramabadran , Rajiv Gandhi Salai and Rajiv Gandhi Salai, "Effect of Shading on Series and Parallel Connected Solar PV Modules", Modern applied Science, Vol. 3, No. 10, Oct. 2009, pp32-41.

[7] S. Silvestre,and A. Chouder, "Effects of Shadowing onPhotovoltaic Module Performance", Prog. Photovolt: Res. Appl. 2008, Vol. 16, pp141–149

[8] A lonso, M.C., Herrmann, W., German, R., Boehmer, W., Wammodulebach, K., "Outdoor hot-spot investigation in crystalline silicon solar modules". Proceedings of the 17th EC PV SolarEnergy Conference, Munich, 2001, pp. 638–641.

[9] D Anner, M., Bu¨cher, K., "Reverse characteristics of commercial silicon solar cells—impact on hot spot temperatures andmodule integrity". Proceedings of the 26th IEEE PhotovoltaicSpecialists Conference, Anaheim, CA, 1997,pp. 1137–1140.

[10] H ermann, W., Wiesner, W., Vaassen, W., "Hot spot investigations on PV modules—new concepts for a test standard andconsequences for module design with respect to bypass diodes". Proceedings of the 26th IEEE Photovoltaic SpecialistsConference, Anaheim, CA, 1997, pp. 1129–1132.