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Study and performance of photovoltaic (PV) modules under partially shaded condition

[1]Anbu Pandian, [2]Kamal Bansal, [3]D. John Thiruvadigal, [4]S.Sakthivel

[1,2]University of Petroleum and Energy Studies, India.
[3]Department of Physics and Nanotechnology SRM University, Kattankulathur Campus, Tamilnadu, India.
[4]Technology Group, TATA Consulting Engineers Limited, India.

Address For Correspondence:
Anbu Pandian, University of Petroleum and Energy Studies, India.
E-mail: anbuvendan.d.pandian@gmail.com phone: +91-44-26545919

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ABSTRACT

When the photovoltaic (PV) cell surfaces are partially shaded due to dust or shadow; it causes improper illumination distribution results in loss of power and temperature rise over the PV system. The shaded PV cell is reverse biased and its short circuit current (I_{sc}) is reduced below the module operating current, then it will not produce energy but creating hot-spot over the surfaces. The magnitude of power output loss and temperature rise is a complex study with multiple variables such as cell properties, shade percentage over the cell area, number of cells connected in series, opacity of the shade, irradiance at site, weather conditions and the breakdown voltage on the faulty cell. The aim of present work is to investigate the empirical test of partial shade on mono crystalline and poly crystalline solar photovoltaic (PV) modules with bypass diode (BD) and without bypass diode for a comprehensive analysis on loss of power output and temperature rise. Comprehensive analysis of performance of PV system is characterised through I-V, P-V curves and temperature rise plots in normal and partial shade conditions. It is inferred that the output power loss is greater than proportional to the amount of shade on the PV module. The PV system suffers considerable energy loss due to partial shading and it leads to increase the cell surface temperature and magnitude of rise in temperature has different set of influencing variables. . The result of experimental data showed that the power output loss and temperature rise on cell surface are at significant level and it is a fire hazard in a hydrocarbon / coal field applications.

INTRODUCTION

Many factors such as partial shading, humidity, dust, bird droppings, air velocity are strongly influences the photovoltaic cell performance(Vivek*et al*. (2015)). Especially, the study on effect of particle shading due to dust particles has been great interest as the tropical regions such as the Indian subcontinent, the Middle-East, Saharan Africa and the south-western United States and Southeast Asia are particularly vulnerable to the accumulation of dust on PV installations (Abhishek *et al*. (2014)). Due to the partial shading, hot-spots generated on the photovoltaic cell surface and the magnitude of temperature rise at the hot-spot depends on many factors (Stefan *et al*. (2010)) such as cell properties, leakage current during shade, type of shade, opacity of the shade, wind velocity, weather conditions, cell operating temperature and bypass diode function. The hot-spot heating occurs due to shading by dust deposition, trees or building shades, passing cloud, strict opaque object and atmosphere fluctuation. Numerous experimental and theoretical research studies (Deline*et al*. (2013);Huiying Zheng *et al*. (2014);KashifIshaque*et al*. (2011); Pieter &Doutreloigne (2014)) on the effect on partial shading on the solar system were reported in the literature. Particularly, dust accumulation over the surface of PV modules creates

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significant impact such as (a) reducing the energy input to the cell; (b) increasing energy losses in the shaded cells, and (c) reverse bias in the cell due to reduced illumination. The PV cell without shading is forward biased during the sunny day time and the electrical output of the same is characterized by I-V and P-V curves. Other hand, when the solar PV cell is under shadow condition, the reverse bias occurred and it prevents excitation of a PV cell that can be verified through dark characteristics. The partial shade over the surface of the PV cell is classified as high shunt or low shunt types based on the percentage of the shade over the PV surface (BS EN 61215, 2005(8)). The PV cell is referred as 'voltage limited' (Type-A) with high shunt resistance when the small area of the cell is shaded causing reverse performance while the same is referred as 'current-limited' (Type-B) with low shunt resistance when the large area of the cell is shaded leaves only small area for exposure to illumination. In latter, the current mismatch between adjacent cells causing the reverse performance. Theoretically, Type-A shade has slow and uniform temperature rise over the large un-shaded portion of the cell thereby limited chance of damaging the cell. On the other hand Type-B shade has rapid temperature rise over small area of un-shaded portion causing hot-spot and damage to the cell. The commercial PV modules are included with bypass diodes and it prevents the creation of hot-spot and overheating (Murtaza*et al*.(2014);Huiying Zheng *et al*. (2014)). Normal design in commercial PV modules consider to add a by-pass diode for a set of 15 ~ 18 PV cells. However, due to the mismatch in characteristics between the PV cells and by-pass diode, the prevention of hot-spot is not ensured in total especially in the event of diode failure. The effect of shaded PV module on power output of typical PV installations is a nonlinear function in that a small amount of shade on a portion of the array can cause a large reduction in output power (Deline 2009).When a single cell in a string on PV module gets shaded, the whole string output is lost and also the bypass diode switched on to prevent the module heating. The energy output from the PV module would become zero when the two cells are shaded in a 36 cell module with two strings of 18 cells each; this results in drastic reduction in the performance of the array. PV cell area shade percentage plays a vital role in energy reduction level and decides the bypass diodes activation. According to Deline (2009) the spatial extent of shade percentage and the output reduction can be derived through shade impact factor (SIF). Accordingly the shade impact program has to be defined with variable cell shade percentage and change in shade media in order to thoroughly understand the shade impact on the power output. However, there is limited focus on both energy loss and the hot-spot creation due to partial shading of the solar panel and its level of temperature rise is an issue that has not been dealt with comprehensively as it is complex and difficult to predict. In the present work, the focus is mainly on formulation of empirical test to study the impact of partial shade especially by shadow and dust particles on mono crystalline and poly crystalline solar photovoltaic (PV) modules both with and without presence of bypass diode (BD). The performance of PV system is characterized through I –V, P-V curves and temperature rise plots on cell for both normal and partial shade conditions.

II. Experimental Setup:

Experiments test were conducted in a test laboratory installed with poly crystalline PV module (100 W_p), poly crystalline PV module (230W_p) and mono crystalline PV module (250Wp). The poly crystalline PV module with 100 W_p is a 36 PV cells in two strings of 18 cells each with a removable bypass diode. Similarly, a poly crystalline PV module with 230 W_p is PV cells in three strings of 24 cells each with a soldered bypass diode while mono crystalline PV module with 250W_p is PV cells in three strings of 20 cells each with a removable bypass diode. Fig. 1 indicates the PV modules with components subjected for experiment test and the specifications data of PV modules are in Table-1. The experiments were conducted on roof top in the building without any pole shade. PV modules are installed in a steel structure with manual adjustment for inclination adjustments so as to track the sun.The hot-spot is simulated through two different types of shading medium such as opaque black masking tape and sand dust. Digital volt and Ampere meters were used for the measurements of voltage and current on the series / parallel circuits. Lamps with 12~24 DC V, 50 ~ 150 watts were used as load.PV modules cells are numbered based on its location on the matrix viz. cell (1, 1) at the left side top of the module and to cell (4, 9) at the right side bottom of the module in poly crystalline PV module (100 W_p). Similarly for poly crystalline PV module (230W_p) numbered as cell (1, 1)&(6, 12) and also for mono crystalline PV module (250Wp) it is numbered as cell (1, 1)&(6, 10) based on its location on the matrix. K-Type skin thermocouples with a multipoint temperature scanner were used to measure the front & rear surface temperature of the PV cells. IR thermo laser gun with variable emissivity was used for non-contact temperature measurement. The experiments were carried out for varying irradiance intensity from 800-1000 W/m^2. Other independent variables such as wind direction (SW ~ NW), wind velocity (9~18 km/hr), module tilt (40^o~60^o) and ambient temperature 31 ~ 41 º C were reordered. Site irradiance was measured through pyranometer and the maximum value of 1030 W/m^2 at zenith was recorded during the test.

III. Test & Methodology:

Hot-spot test procedure was based on ASTM-2481-08. The PV modules were exposed to sunlight with an irradiance intensity level of 800 ~ 1000 W/m^2 and the module temperature was stabilised within 60 ºC. Firstly, each module was tested with no cell shaded condition to verify its healthiness and characterized through I-V & P-V curves as illustrated in Figs. 2, 4 & 6. Then, the PV cell shade simulated by opaque black masking tape and sandy dust as shading media was tested for different percentage of cell shaded. One cell on each module on a specific substring was shaded in this experiment, so that the module voltage drop was observed. Also the test include two cell shade on a module but on different substrings, therefore module voltage drop up to 1/2 ~ 1/3 once the bypass diode was forward biased. The cells are shaded with masking tape and sand dust from 20 % ~ 99 % of the area of the cell. The effects on voltage and current and, temperature rise on substrate and superstrate of the PV was noted. The surface temperature of front (XY-1) and rear (XY-2) surface of PV module was measured by using thermocouples and IR thermo gun was used to measure both side surface temperatures (X1). The voltage (V) and current (A) of the moduleare recorded for data analysis cum interpretation. Additionally the substring voltage of the module was also recorded for verification of its behaviour during bypass diode switch on functions.

RESULTS AND DISCUSSION

Performance of the PV modules can be verified thorough the IV & PV curves as shown in Figs 2, 4 & 6 for poly crystalline PV module of 100Wp & 230 W_p and Mono crystalline PV module of 250 W_p respectively. It is inferred that all the PV modules are healthy and IV& PV curve performance are as per the design specifications. Factors affecting the magnitude of power output loss due to shading can be categorised as directly proportional variables such as type of PV material (viz. Group-IV, III/VI, II/V), band gap voltage of the cell material, irradiance, cell area shade percentage, opacity of the shade material, series resistance and inversely proportional variables such as irradiance, ambient temperature, wind direction cum velocity, ventilation of the module rear surface, superstrate and substrate material, air mass and shunt resistance.The overheating on the surface temperature of the PV cells due to partial shade is plotted with respect to load andshown in Fig. 3, 5 and 7. Hot-spot creation and its temperature rise is strongly influenced by various variables such as cell material, short circuit current of cell, diode breakdown voltage, number of cells connected in series, shade percentage over the cell area, opacity of the shade, type of shade A or B, irradiance, series resistance and ambient temperature and air mass. The reverse bias characteristic of the PV module during shade operation is verified and the dark current analysis is performed for the same. It is verified that magnitude of temperature rise over the hot-spot point is inversely proportional to the hot-spot area (higher shade percentage) and directly proportional to the leakage current. Variability of the module output voltage and hot-spot surface temperature from the normal operation to the partial shade operation in different loads is of great interest in this work. The IV & PV performance curves in normal mode and shade operation depicts the variability of the power output loss. Similarly temperature versus the load plot gives the variability of the hot-spot temperature also.

4.1. Result of poly silicon 100 Wp / 12 V module:

The I-V (Current- Voltage) and P-V (Power output *vs* Voltage) curves for polysilicon with 100Wp are shown in Figs 2 (a) & (b) and it shows the variability of the module output voltage, current and power output at normal and shaded mode. Single cell is shaded in each test either on string 1 or 2. From Figure 2 (a), it is observed that the performance of PV system is better for normal mode as the current is significantly reduced for the same given voltage with shading. Similarly, the power output is also lower for PV cell with shaded mode compared to that of normal mode. The lowest performance is observed for the cell of (9, 3) (i.e. cell matrix location) which is shaded about 70 % with black masking tape material with bypass diode turned ON as seen in the I-V curve. Similarly, other cell locations (5, 2 & 5, 3) which are shaded with black masking tape material at different percentage level showed the reduced performance when compared with normal mode. Fialho*et al*(2014)also confirmed that partial shading on PV system is reducing the output performance through simulation result. Actually, bypass diode were not turned ON during lower cell area shade test. However, increasing the shade percentage leads to the bypass diode switch ON (forward bias) function. The shade string output voltage reached to negative, when the bypass diode switch ON, giving a consistent loss of power output.Also, it is inferred that power output is reduced with all percentage of shaded condition compared to that of normal condition (no cell shaded). The shaded PV cell is reverse biased and its operating current exceeds the short circuit current (I_{sc}), then shaded cell will not generate any energy instead of creating hot-spot over the cell surfaces. It causes to increase energy and thermal conversion loss due to the shading. These solar cells are connected in a series array and forced to carry the same current even though a few cells under shade produce less photon current as seen in Fig 2 (b). These shaded cells are not only reducing the power and also create a hot-spot or overheating of shaded cell on PV module. The hot-spot on PV system is leading severe damage of whole PV system and causes fire hazard in the application area.The cell surface temperature was noted for poly silicon 100 W_p with and without presence of bypass diode condition. Figs 3 (a) & (b) show the hot-spot temperature on the rear and front side of PV cell under partial shade condition. It is observed that the surface temperature of XY-2 (rear side) is higher than X1 (rear side) with and without presence of bypass diode condition. The surface temperature of cell matrix location (9, 2) was about 347 ºC at bypass diode OFF condition. The cell location (9, 3) was shaded by black masking tape and its surface temperature is about 308 ºC at XY-2 (rear) without presence of bypass diode condition. It is inferred that the surface temperature rise is far less than the rear surface temperature due to presence of glass superstrate. In addition, the cell damage was also observed at the cell junction with discoloration of cell due to hot-spot creation by particle effect. This results show that the magnitude of power output loss and temperature rise on cell surface at significant level and it can become a fire hazard in hydrocarbon and coal industrial areas.

4.2. Result of poly silicon 230 W_p:

The I-V and P-V curves for poly silicon with 230 W_p are shown in Figs 4 (a) & (b) and it shows the variability of the module output voltage, current and power at normal and shaded mode. Single or dual cell is shaded in each test either on string 1 or 2 or 3. From Figure 4 (a), it is illustrated that the performance of PV system is better for normal mode as the current is significantly reduced for the same given voltage with shading. The performance of poly silicon of 230 W_p module was studied with and without shading condition as shown in Fig 4 **(a**). The cell matrix locations (2, 6) & (3, 2) were shaded by sand dust material at 75 percentage level showed the reduced performance of I-V when bypass diode turned ON.

Similarly, other cell locations (1, 4 & 1, 6) were shaded by sand dust material at 90 percentage level. It is inferred that the overall power is reduced with all percentage of shaded condition compared to that of normal condition (no cell shaded).

The output power loss is occurred from shaded cell and also mismatch of current within a PV string and mismatch of voltage between parallel strings of 1 & 3. It also inferred that one third of the output power is lost even a single cell in a string is shaded and bypass diode turned ON as shown in Fig 4 (b). The cell surface temperature was noted for poly silicon 230 W_p with and without presence of bypass diode condition. Figs 5 (a) & (b) depicted that hot-spot temperature on the rear and front side of PV cell under partial shaded condition. It is observed that the surface temperature of XY-2 (rear side) is higher than X1 (rear side) with and without presence of bypass diode condition. There is no significant surface temperature rise on partial shaded stings cell locations (8, 3 & 1, 6) due to presence of bypass diode and which was also switched ON condition. The surface temperature of cell matrix locations (5, 4) and (7, 6) was rise about 168 ºC and 154 ºC respectively in bypass diode turned OFF.

4.3. Result of mono silicon 250 W_p:

The I-V and P-V curves for mano silicon with 250 W_p are shown in Figs 6 (a) & (b) and it shows the variability of the module output voltage, current and power at normal and shaded mode. Single cell is shaded in each test either on one string. From Figure 6 (a), it is illustrated that the performance of PV system is better for normal mode as the current is significantly reduced for the same given voltage with shading. The performance of mono silicon of 250 W_p system was studied with and without presence of shading condition as shown in Fig 6 (a). The cell matrix location (9, 2) which are shaded by sand dust material at 70 percentage level and it showed that the reduced performance of I-V when bypass diode turned ON. Similarly, other cell location (5, 6) is shaded with black masking material at 80 percentage level. It is inferred that the overall power is reduced with all percentage of shaded condition compared to that of normal condition (no cell shaded). The cell surface temperature was noted for mono silicon 250 W_p with and without presence of bypass diode condition. Figs 7 (a) & (b) shown that hot-spot temperature on the rear and front side of PV cell under partial shade condition. Figs 7 (a) & (b) depicted that hot-spot temperature on the rear and front side of PV cell under partial shaded condition. It is observed that the surface temperature of XY-2 (rear side) is higher than X1 (rear side) with and without presence of bypass diode condition. There is no significant surface temperature rise on partial shaded stings cell location (3, 5 & 5, 6 & 6, 5) due to presence of bypass diode and which is also switched ON condition. When without presence of bypass diode, the surface temperature of cell matrix locations (9, 2) and (7, 6) were rise about 135 ºC on rear side and 58 ºC on front side respectively. In addition, the rear side of surface temperature is rising higher than front side due to presence of glass surface in front side. However, the formation of hot-spot and discoloration is seen both front and rear of cell.

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Table 1: Specifications for studied PV Modules

Specification	PV Module (100 W_p)- Poly	PV Module (230 W_p)- Poly	PV Module (250 W_p)- Mono
Voltage @ Max.Power (V_{mp}), V	17.5	35.4	30.06
Current @ Max.Power (I_{mp}), A	5.71	6.49	8.32
Open Circuit Voltage (V_{oc}), V	21.5	43.97	36.78
Short Circuit Current (I_{sc}), A	6.28	7.14	8.75
Number of PV Cells	36	72	60

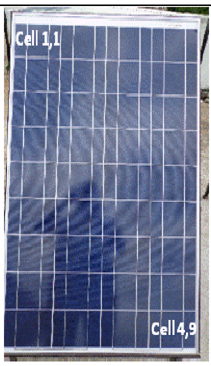
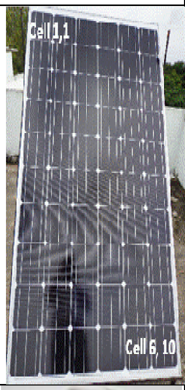
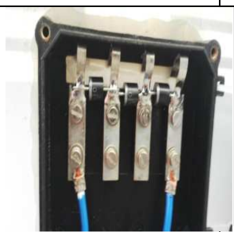
	Poly crystalline (100Wp)	Poly crystalline (230Wp)	Mono crystalline (250Wp)	Three different PV module
Modules				
By Pass Diode Configuration				
	Two Strings of 18 Cells in the module with two removable bypass diodes	Three Strings of 24 Cells in the module with three removable bypass diodes	Three Strings of 20 Cells in the module with three soldered bypass diodes	Cells shaded by sand dust

Fig.1:PV Modules on the experimental Laboratory

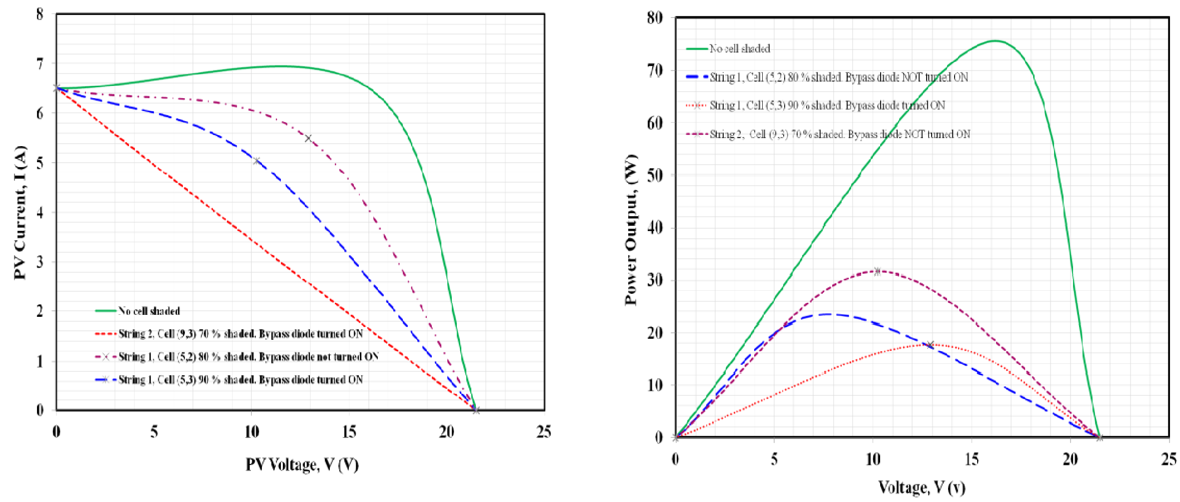


Fig.2:(a) I-V curve for poly silicon 100 Wp, (b) P-V curve for poly silicon 100 Wp

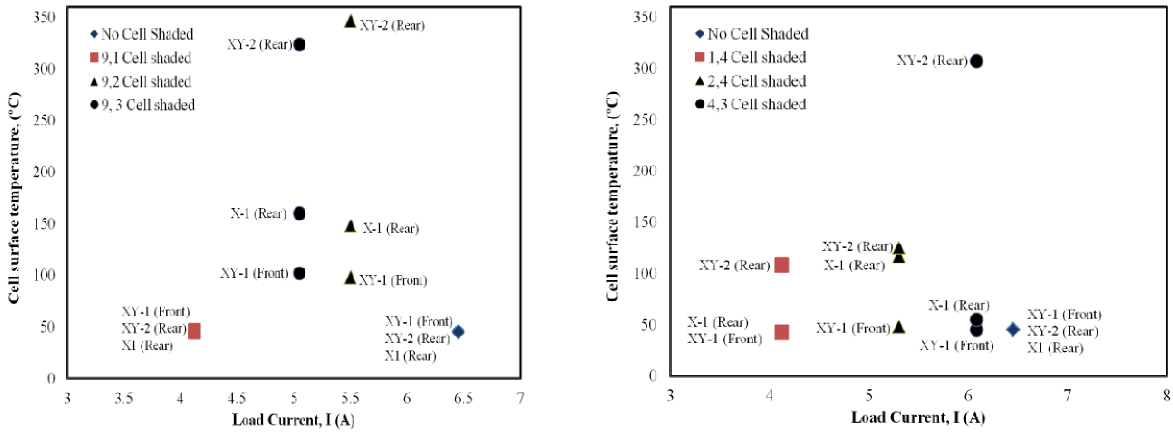


Fig.3: Effect of surface temperature of poly silicon 100 Wp module (a) With bypass diode (b) Without bypass diode

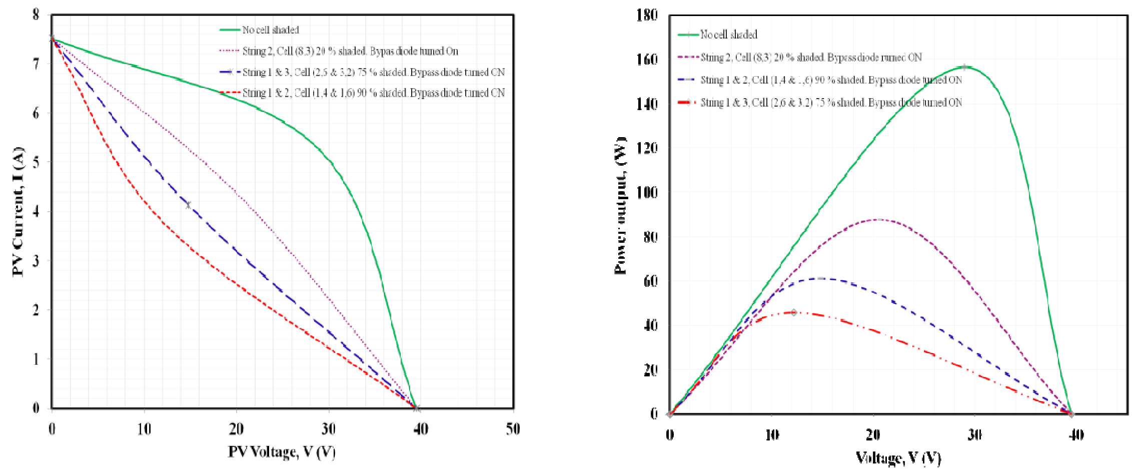


Fig.4: Poly silicon characteristic of 230 Wp (a) I-V& (b) P-V-curve

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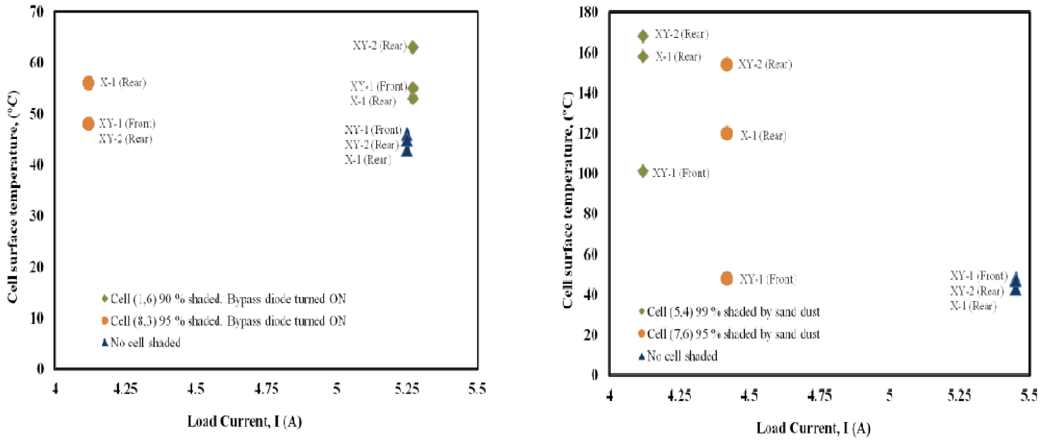

Fig.5: Effect of surface temperature of poly silicon 230 Wp module (a) With bypass diode & (b) Without bypass diode

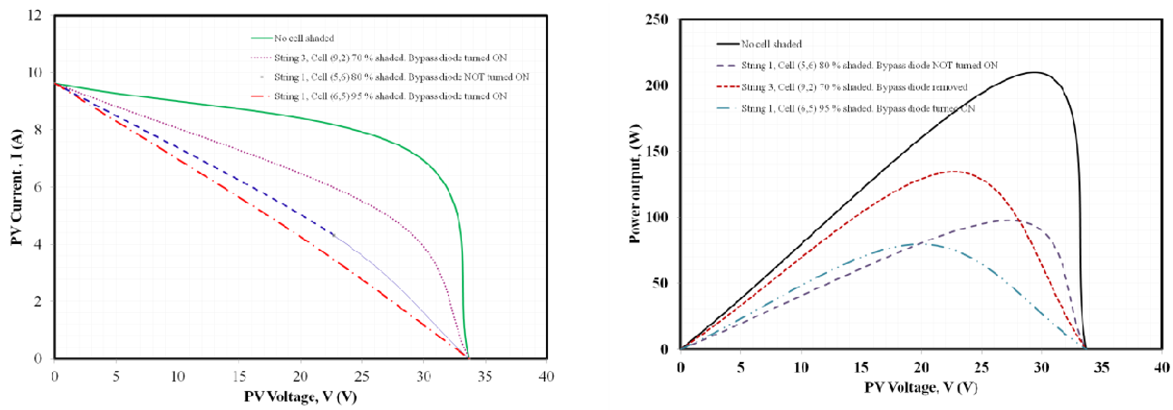

Fig.6: Mono silicon characteristic of 250 Wp(a) I-V& (b) P-V-curve

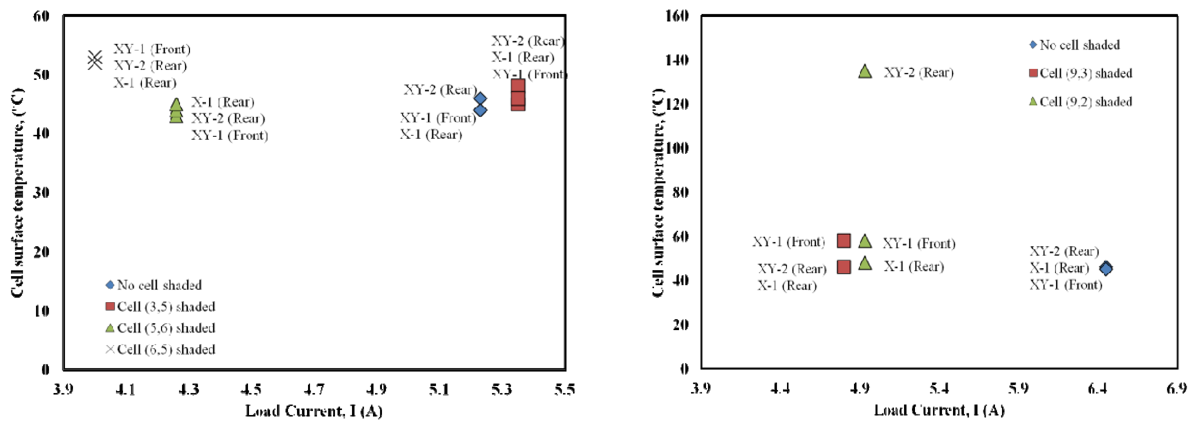

Fig.7: Effect of surface temperature of mono silicon 250 Wp module (a) With bypass diode & (b) Without bypass diode

Conclusion:

The influences of partial shading on performance PV system with and without both bypass diode conditions were studied comprehensively. The partial shading on a solar PV module is one of the main causes for reduced overall performance and overheating the surface of cell of module. The results of module power output are non-linear with respect to the PV cell shade percentage. However the bypass diode activation removes the whole substring output and it is consistent. Also creation of hot-spot and magnitude of temperature rise at the hot-spot point is also non-linear function with spatial distribution of recorded data. Further research can proceed with modelling of the partial shade phenomena focusing on the predictability of the power loss and hot-spot behaviours.

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