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The Characterization of Hotspots on Photovoltaic Modules and Its Analysis Through Matlab

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***Abstract*—In commercial Photovoltaic (PV) deployment, solar modules are connected in series with the bypass diodes across each module to reduce the effect of shading on PV modules. Shading results in the creation of localized heating called hotspots it affects both short-term in form of power output reduction and long-term performance as the reliability of PV system, but still, there is no standard procedure to tell whether a PV module or a PV string has hotspots or not. We like to focus on the above issue where we have effectively analyzed thermal, visual and electrical data Of PV modules of Silicon technology namely Mono-crystalline and Poly-crystalline PERC and PERC plus to formed a standardized real-time procedure to tell whether a PV module has hotpot defects or not. The results can be extended to the big running power plant also. A MATLAB based code is developed to convert the thermal IR image effectively to detect the location of the hotspots by giving the exact temperature and the image pixels value to the information data. Our main focus is on mono-crystalline and poly-crystalline PV modules as it is easily viable for the consumers.**

***Index Terms*—Hotspots, mono-crystalline, poly-crystalline, IR Thermography, MATLAB code**

1 INTRODUCTION:

Analyzing and detection techniques are available in the marketing and also the quality analysis procedures but it is difficult to detect the degraded PV modules or module in the high generation power plant. Even, in the string it difficult to find the fault and detect the main cusses but with over experiment and methods, we made it easy and simple to analyze the problem and find the exact module and the hotspot[1][2]. We did it through imaging processing technique and by MATLAB. There are two different types of infrared or IR thermography cameras, one cooled and other warm detectors[3]. The sensors of cooled thermography cameras are made from narrow band gap semiconductors with high spectral response and while having very high sensitivity, are not commonly used in PV applications due to the cost and complexity of the associated cooling system. The most commonly used thermography cameras are those based on warm sensors that can work at ambient temperatures[4].

1.1 Major Factors affecting the Performance of PV module

1. Temperature:

The output of PV module depends on the temperature at which the solar cell works.

One of the important things is that module temperature is higher than the ambient temperature. The increase in temperature is due to glass cover which traps the heat in the form of infrared radiation. Increase in the temperature means reduction in the band gap of PV cell in a module. Therefore, increase in the short circuit current (I_{sc}) but decrease in the open circuit voltage (V_{oc}). Decrease in V_{oc} is more important than the increase in I_{sc} and this is main reason overall decrease in power output[5].

2. Solar Irradiation:

The output of the PV module strongly depends on the solar irradiation striking the cells. Increase in the power output is linearly depends on the increase in incident solar radiation. With the increase in the solar radiation number of photons increased which is sustains to move the electrons from move balance band to conduction band into the production of more current[5][6].

1.2 Defects Related to Solar Photovoltaic (PV)

It appears when, due to some anomaly, the short circuit current of the affected cell becomes lower than the operating current of the whole and giving rise to reverse biasing, thus dissipating the power generated by other cells as heat[7]. A shaded cell in a module can be distinguished between two types, according to its reverse bias behavior: current-limited or voltage-limited. The current-limited cells are the less critical[8]. There are number of factors that affect PV module which shows their symptoms after a certain span of time and these are not detected during the time of installation; most degrading ones are:

1. Micro-cracks
2. Potential Induced Degradation (PID)
3. Hotspots
4. Snail track
5. Internal corrosion

This paper focus on the mechanism to detect early symptoms of hotspots in a PV module or a string, so that the module can be removed and there is big damage on the entire generation. Hotspots are the areas of elevated temperature affecting only part of the solar module. The localized hotspot decreases its efficiency, which results in lower power output and acceleration of materials degradation in the affected area. Hotspots are rarely stable and usually intensify until total failure of module performance in the terms of electricity generation or safety.

1.3 Main causes of Hotspots

There are multiple causes of hotspots and are functional or operational[8]. The functional reasons can be divided into two areas

1. Cell mismatch which occurs when cells of different current production are connected in series.
2. Cell damage which occurs during the production process because the cell is subjected to many pressures and stress during lamination, handling and transportation.

The operational reasons for hotspots are related to the solar park design and operation, and are as follows

1. shading
2. Rooftop condition
3. soiling

In order to improve the accuracy of the model, use of IEC 60891 and 61215 standard procedure to determine the temperature coefficients of the module is employed[9]. Furthermore, the performance of the PV module is tested against the set of operating condition and compared to the actual experiment values obtained using outdoor and indoor tests in order to validate the accuracy of the proposed design technique.

Various parameters of the modules were analyzed like open circuit voltage(V_{oc}), Short circuit current(I_{sc}), Maximum power(P_{max}), maximum voltage(V_{max}), maximum current(I_{sc}) and Fill-Factor(FF) which will helped us to shape our final result that is V_{oc} and P_{max} of a hotspot PV module is always less than a good module[10].

2 EXPERIMENT

This paper minimizes the electrical engineering problems that are huge problems for human intervention and are generally seen at the site of solar power plant. This is due to lack of technologies to effectively determine a different kind of defect observed on solar power plants[11]. Solving these problems, we would require a pre-requisite Knowledge of electrical parameters and the practical application of the theory.

We study the terminology related to solar PV cell of the electrical and the thermal characteristics of PV modules. The solar cell parameters such as I-V curves, efficiency, short circuit current (I_{sc}), open circuit voltage (V_{oc}), Fill factor (FF), maximum power (P_{max}), temperature coefficient[12].

The process of creation of hotspots and its impact on the PV module and on the entire string and the relationship between open circuit voltage (V_{oc}) and maximum power (P_{max}) generated in both PV modules with hotspots and without hotspots.

We did the entire experiment with the help the FLIR thermal camera solmeteric. The images are analysed with help of matlab coding to improve the supervision and human machine interface. We convert the thermal image to grey scale image with coding and as we know grey scale images easily detect the hotspots with help of histogram[13].

3 DISCUSSION

Thermal analysis of PV module gives us the data about the temperature distribution of the entire module, which makes it easy to understand the thermal behaviour of a module in that particular surrounding. It’s allowed us to easily detect the defects such as hotspots, burning and cracks in a PV module which are not the evident in visual inspection.

We did the experiment with the help of the IR thermal camera by taking images at same intensity but at

different temperature of two different PV modules one with hotspots and other without hotspots and saw wide variation in the minimum, maximum and mean temperature[14].
Then we created a MATLAB code where we upload the thermal image and it gives us the corresponding grey scale and temperature image which allows us detect the temperature distribution at each pixel of the image and shows the exact location of the hotspot, the code also calculate the display the maximum, minimum and the mean temperature of the image and plots the histogram relating the frequency and the temperature[15].

3.1 Analysis of both PV modules results
Based on the work of R.Moreton at.el., in "Dealing in practices with Hotspots" it was observed that if the irradiance level more than 700W/m^2 than the following results are applicable to the PV module[16][17].

$$\nabla T_{sh} = \text{Max Temperature} - \text{Mean Temperature}$$

Where ∇T_{sh} is effective Temperature
For every PV module which is having a hotspot, having the following results:

1. If $\nabla T_{sh} < 10^oC$ consider the module non defective, except in the case that one or more bypass diodes are defective.
2. If $\nabla T_{sh} > 20^oC$ consider the module defective.
3. If $20^oC < \nabla T_{sh} < 10^oC$, consider all the PV modules with an effective power loss (measured as a decrease in the operating voltage in relation to a non-defective PV module of the same string) that exceeds the allowable peak power losses fixed at standard warranties defective.

Here, the first module $\nabla T_{sh} = 12.8^oC$ and second module $\nabla T_{sh} = 5.7^oC$ thus we said that first module is having a localized hotspots and must have an effective power loss and second module is non-defective and in good condition.
We may increase the accuracy of our results by normalized the thermal image

3.2 Normalized of IR image
The irradiance and Temperature are constantly changing the real-life scenario, thus the thermal image that we are capturing would also get affected and hence it's accuracy decrease for our final results. To get rid of this practical issue we change the parameters to standard test conditions (STC), which takes 25^oC and 1000W/m^2 irradiance in consideration.
The normalized temperature in degree Celsius of each PV module was calculated using the following equation[18].

$$T_{Translated} = \frac{25^oC + (T_{measured} - T_{ambient}) * 100}{Irradiance}$$

Were,
$T_{Translated}$ = Translated temperature of PV module under reference condition
$T_{measured}$ = Measured temperature of PV module (obtain from IR image)
$T_{ambient}$ = Ambient temperature at the site and surrounding.

3.3 I-V Analysis of Hotspots on a PV module
I-V analysis of a PV module is done by solmeteric which gives the real time data of the current and the voltage data of the PV module, other parameters like fill factor (FF), maximum power (P_{max}), short circuit current (I_{sc}), open circuit voltage (V_{oc}) and title angle. The electrical I-V data related with thermal data of the module provide the exact value and details about the current condition of the module and will be accurate to the exact position of the defects and hotspots of the PV modules.

3.4 Translation Procedure IEC 60891 procedure
The IEC 60891 standard defines three procedures for correcting measured I-V characteristics to other condition of temperature and irradiance, as well as the procedures used to determine factors relevant for these corrections, in this we used the procedure one (1). This method is applicable to any PV module technology type, provided the device performance is liner with temperature and irradiance over the range of interest[19].
This method originates from the work of Sandstrom at Jet propulsion Lab in 1967. The measured I-V characteristics are translated to an alternative temperature and irradiance by applying equation (1) and (2)[14].

$$I_2 = I_1 + I_{SC}\left(\frac{G_1}{G_2} - 1\right) + \alpha(T_2 - T_1) \quad (1)$$

$$V_2 = V_1 - R_S(I_2 - I_1) - kI_2(T_2 - T_1) + \beta(T_2 - T_1) \quad (2)$$

Where:

I_1 And V_1 are co-ordinates points on the measured I-V curve, I_2 and V_2 are co-ordinates of the corresponding points on the corrected curve.

Table 1

Module No.	V_{OC}	I_{SC}	P_{max}	V_{max}	I_{max}	FF
1	61.2523	6.573419	304.1174	51.25535	5.933378	0.755314
2	56.41006	6.484638	274.1071	47.15266	5.898015	0.760273
3	60.72345	6.485869	303.103	51.29667	5.908824	0.770903
4	60.72345	6.499923	301.5719	50.79048	2.778421	0.764058
5	61.28457	6.555439	302.676	49.72585	6.086895	0.753399
6	60.97549	6.568308	304.0594	50.22187	6.054323	0.759189

G_1 is the irradiance measured with the reference temperature; G_2 is the irradiance at the standard irradiance. T_1 is the measured temperature of the test device, T_2 is the standard temperature. I_{SC} is the measured short circuit current and voltage temperature coefficient of the test device at G_1 and T_1, α and β are the current coefficient of the test device in the standard or target irradiance for correction within the temperature range of interest; R_s is the internal resistance of the device and K is a curve correction factor[20].

4 RESULTS

Here are some results of latest technologies of the PV modules and their time degradation with environment. These are data of the running power plant PV modules and the fresh PV modules; we had taken random survey of six PV modules of each technology and show the results through their I-V characteristics and thermal characteristics. This clearly shows on the graph that how the hotspots generally occur on the degraded PV modules and affect the whole string.

Relation Between thermal and I-V data of the PV module

1. Mono-crystalline Sunpower

Specification:

PV Module no	P_{max}	V_{mp}	I_{mp}	V_{oc}	I_{sc}
SPR-E20-327-COM	327W	54.7	5.98A	64.9	6.46A

I-V characteristics

Module specific parameters

Table 2

Module no.	I_{sc}	P_{max}	V_{max}	I_{max}
1	5.6832	230.3619	45.77067	5.032959
2	4.8591	210.3152	46.74249	4.499444
3	5.0056	211.8269	45.67288	4.637914
4	5.1386	216.6833	45.30762	4.780456
5	5.2737	217.7619	45.55254	4.780456
6	5.50235	222.9026	44.75943	4.980015

Thermal characteristics:

Table 3

Module No.	Solemeteric Temperature	Maximum Temperature	Minimum Temperature	Mean Temperature	Max-Mean Temperature
1	63.224	62	43.7	54.3	7.7
2	53.712	66.1	43.5	54.9	11.2
3	57.481	72.3	43.3	55.2	17.1
4	55.7735	72.1	44.3	53.9	18.2
5	55.676	65.4	43.5	55.5	9.9
6	64.5482	67.3	43.8	54.8	12.5

Graphs Plot

We had analysis the six different PV modules with defective and good one and justify that how degraded PV modules effect the power performance of the plant. There IV characteristics and temperature characteristics show us a clear view about the hotspots generated modules and the good modules. These hotspots create excessive heating and the thermal temperature difference compared with good cells can be higher than 50°C.

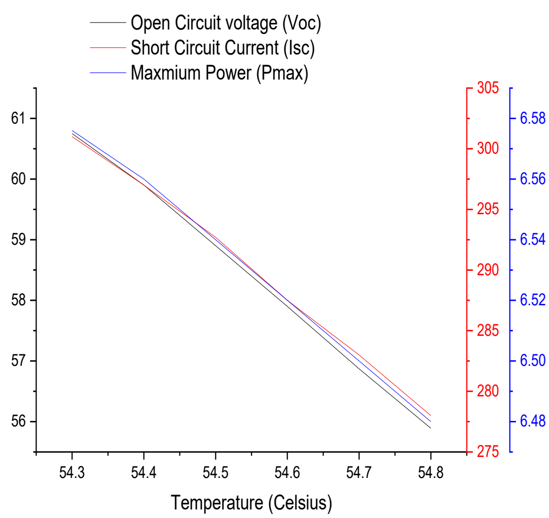

Figure 1 Parameters of Mono-crystalline PV module at different temperature

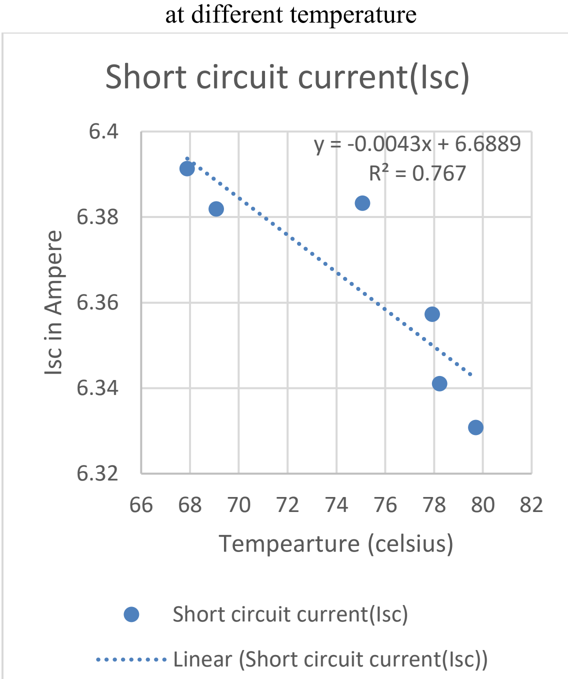

Figure 2 Relation between I_{sc} and Temperature of a Mono-crystalline PV module

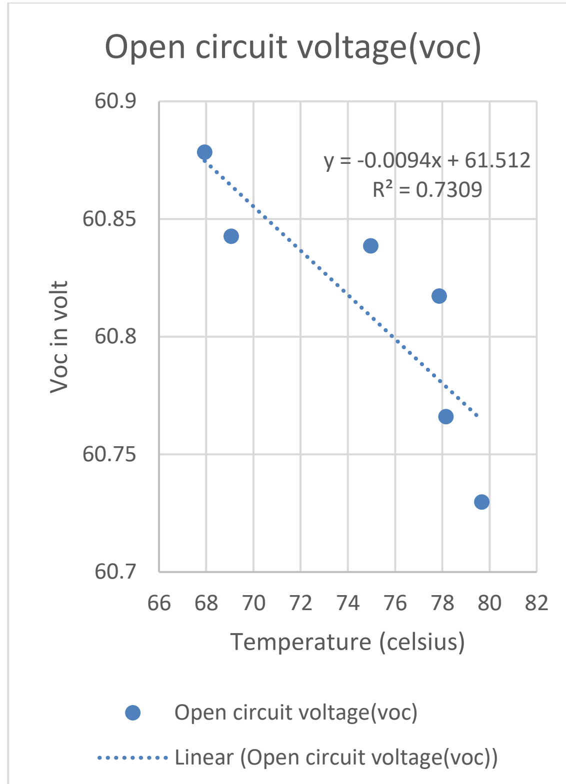

Figure 3 Relation of V_{oc} and Temperature of a PV mono-crystalline module

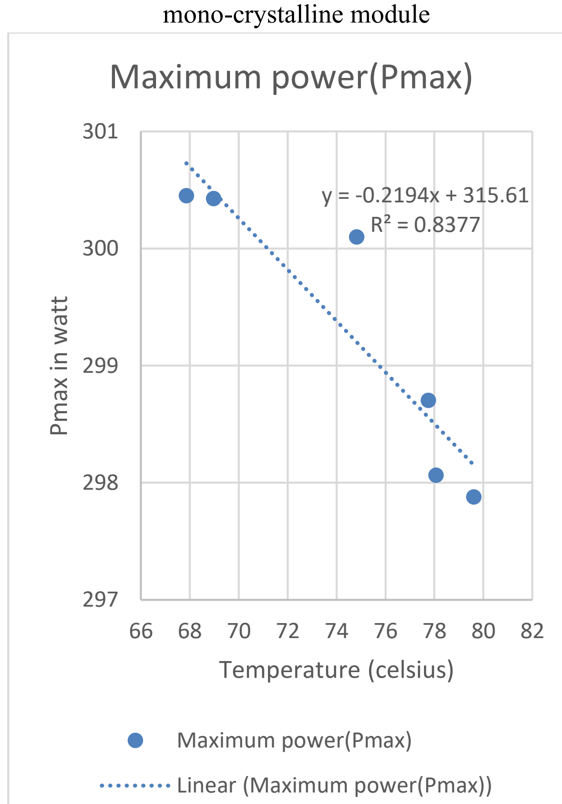

Figure 4 Relation of P_{max} and Temperature of a Mono-crystalline module

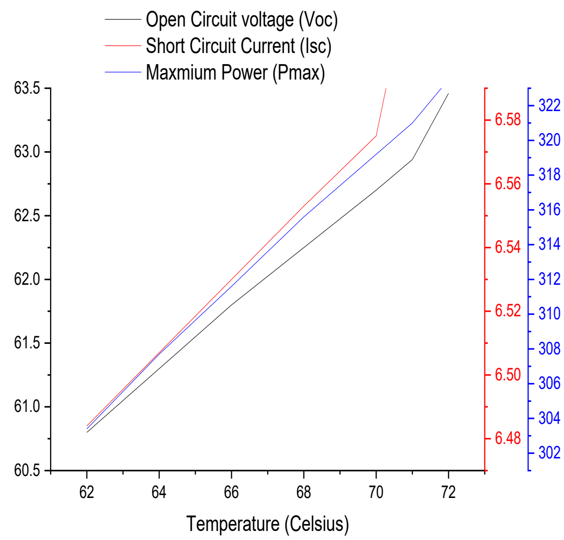

Figure 5 Parameters of mono-crystalline PV module at hotspots temperature

1. Multi-crystalline/Polycrystalline

We had analysis the six different PV modules with defective and good one and justify that how degraded PV modules effect the power performance of the plant. There IV characteristics and temperature characteristics show us a clear view about the hotspots generated modules and the good modules. These hotspots create excessive heating and the thermal temperature difference compared with good cells can be higher than 50°C

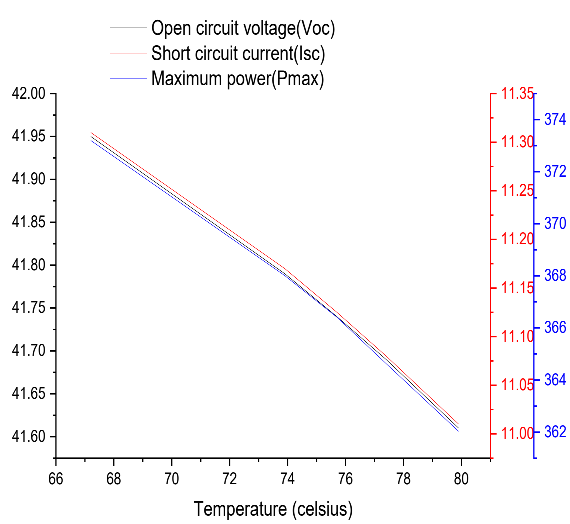

Figure 6 Parameters of Multi-crystalline module at different temperature

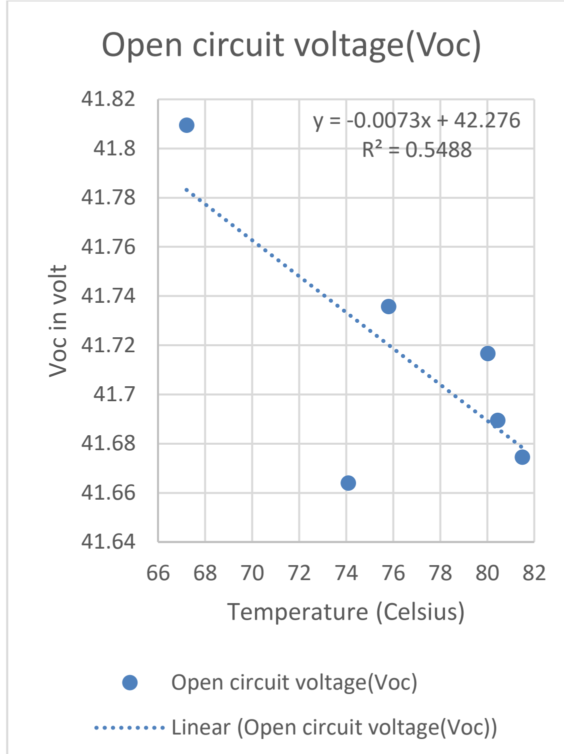

Figure 7 Relation of V_{oc} and Temperature of a Multi-crystalline module

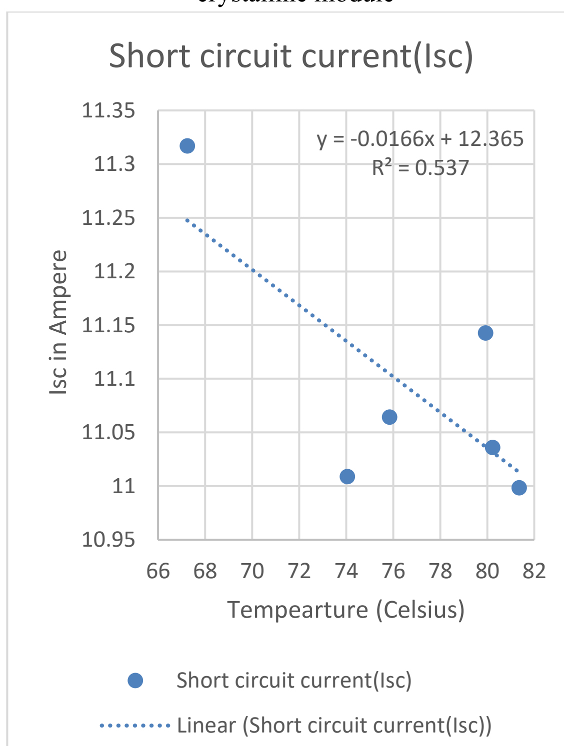

Figure 8 Relation of I_{cs} and Temperature of a Multi-crystalline module

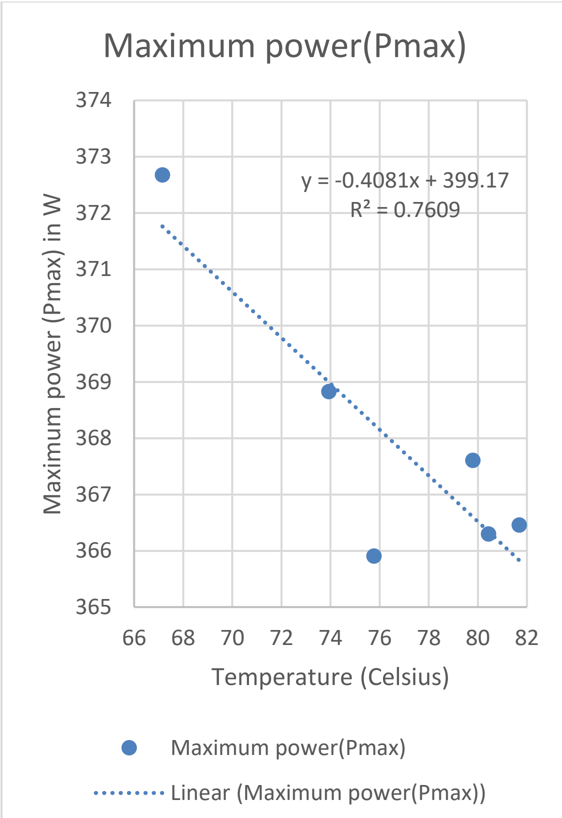

Figure 9 Relation of P_{max} and Temperature of a multi-crystalline module

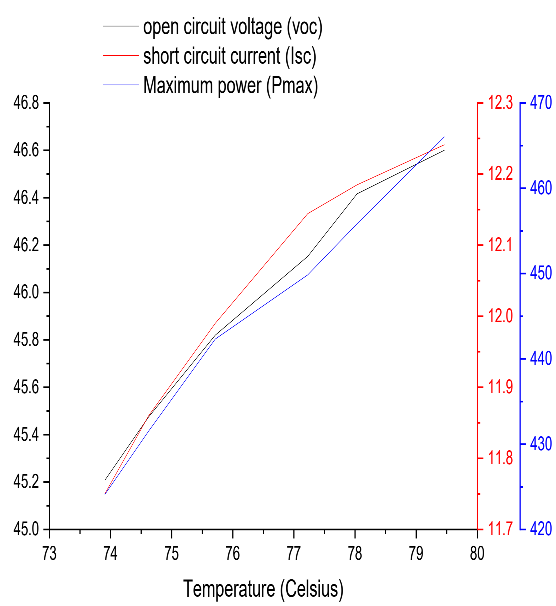

Figure 10 Parameters of Multi-crystalline module at different hotspots Temperature

4.1 Analysis of the results

a. At the temperature measured by solmeteric PV analyser the P_{max}, V_{oc} and I_{sc} of the good PV modules (PV modules without hotspots) are always higher than that of the PV modules with hotspots and the parameters P_{max}, V_{oc}, and I_{sc} of the PV modules decrease with respect to temperature. When heating occur then large number of PV cells cause a large reverse bias across the shaded cell, leading to the large dissipation of power in the poor cells because of this the P_{max}, V_{oc}, and I_{sc} the hotspots PV modules also decrease.

b. We observed the PV module by taking the maximum Cell temperature or the hotspot temperature as the entire module temperature, P_{max}, V_{oc}, and I_{sc} increases with the respect of the temperature at standard Test Condition (STC). The difference of the hotspot temperature to STC is always greater than that of the Solmeteric temperature at the same intensity. Thus, the hotspot PV module has higher P_{max}, V_{oc}, and I_{sc} than the good PV modules.

c. The graphs of mono-crystalline PERC are lesser stepper which indicates an incremental change in temperature has huge impact on P_{max}, V_{oc}, and I_{sc} of the PV module.

d. The graphs of multi-crystalline are very steep which means that an incremental change in temperature has a huge impact on P_{max}, V_{oc}, and I_{sc} of the PV module.

4.2 MATLAB coding

```
hp1.Position= [0.45,0.03,0.25,0.05];
subplot (2,2,4);
histogram (thermalImage, 'Normalization','probability');
grid on;
caption = sprintf('Histogram of Thermal Image');
title (caption, 'FontSize', fontSize, 'Interpreter', 'None');
xlabel('Temperature', 'FontSize', fontSize, 'Interpreter', 'None');
ylabel('Frequency', 'FontSize', fontSize, 'Interpreter', 'None');
A=thermalImage;
M1=max(A);
Max=max(M1);
M2=min(A);
Min=min(M2);
```

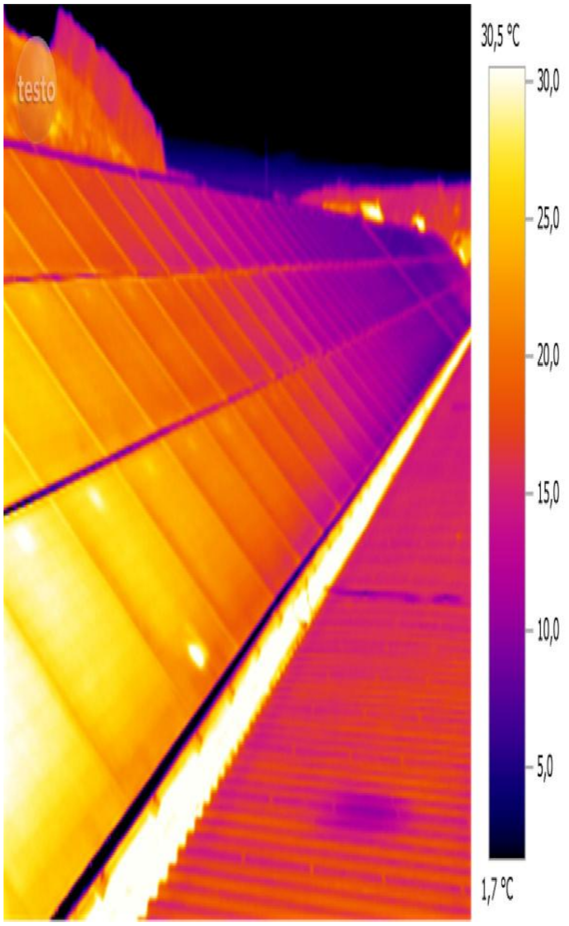

Figure 11 the Thermal image 100KW Power plant at NISE.

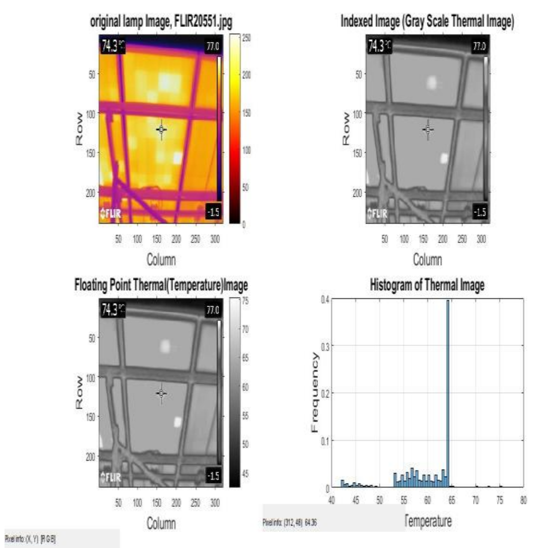

Figure 12 image processing code for converting thermal image into gray scale with histogram.

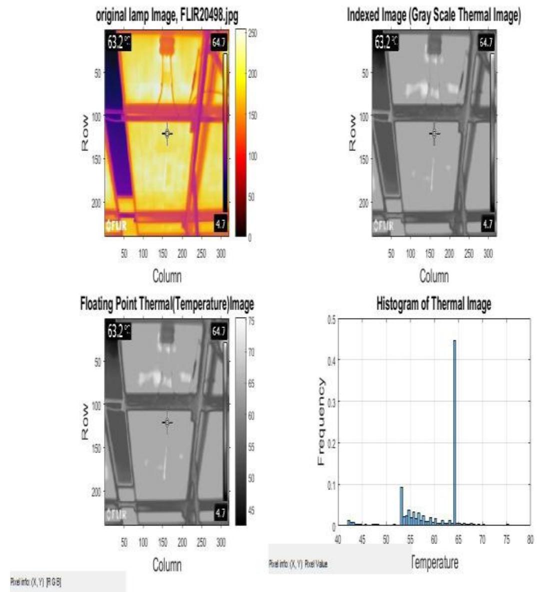

Figure 13 image processing code for converting thermal image into gray scale with histogram

The image processing coding in MATLAB concludes us a clear view about our work and the help us to extract us the exact hotspots of each individual PV module. The coding basically deals with the mean temperature and also the ambient temperature and the behavior of the hotspots range within it. We plotted the histogram which gives a clear view about the frequency and the temperature distribution the any PV modules. Gray scale image always shows a clear and particular pixel of the image like the hotspots. This paper provides a quantification view of the hotspots and their effects on the PV modules and PV modules plant.

5 CONCLUSION

The open circuit voltage (V_{oc}), short circuit current (I_{sc}) and maximum power (P_{max}) always less for a hotspots PV module when compared with good PV modules (modules without hotspots). P_{max}, V_{oc}, and I_{sc} decreases with the increases in measured temperature. And always increases with increase in hotspot or the maximum temperature of PV modules. Reliability and lifetime studies for different technology PV modules has been changed unsound as quite daydream and probe has brought out many results that extend some knowledge on common degradation technique and their remedies. In our design and analysis, we have concluded that indignity in tropical climate occurs primarily due to heat and moisture progress that boot case for delamination and electrochemical degradation of contacts of PV cells of different modules. We conclude that our experiment could easily detect the shunts on large and mass scale.

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