

FIRST RESULTS – CORRELATION BETWEEN IR IMAGES AND ELECTRICAL BEHAVIOR AND ENERGY YIELD OF PV MODULES

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ABSTRACT: This paper gives an overview about the first results regarding the correlation between IR images of defective PV modules in the field and the corresponding electrical behavior. While electrical measurements of PV generators in operating PV plants are often very extensive, IR imaging gives a fast and effective method to find defects in PV modules. Daily profiles with one minute I-V curve measurements of different PV modules with thermal phenomena were done under outdoor conditions. Additionally continuous IR imaging and meteorological data sampling was realized.

Keywords: IR imaging, Energy performance, Qualification and testing, Thermal phenomena, Field measurement

1 INTRODUCTION

Actual monitoring systems are not able to detect all defects in PV modules causing a substantial impact on the electrical behavior and the resulting energy yield. Furthermore many of these defects cannot be visually discovered, so a possible power loss is not cognizable without an extensive electrical measurement effort.

In this case, field IR imaging of PV modules provides a comfortable way to identify different thermal effects on PV modules. However, these effects are difficult to interpret without more background information regarding the interconnection between thermal anomalies and electrical operation behavior. By analyzing the IR images, the following topics are of interest:

- Impact to electrical behavior of the PV module(s) / Strings
- Impact to energy yield
- Long term behavior of thermal effects
- Impact to the lifetime of PV modules

In former publications different thermal effects are described in detail [1] but only few detailed measurements were done to analyze the electrical operation behavior of the conspicuous PV modules. To get more information daily profiles with one minute I-V curve measurements of different PV modules with thermal phenomena were now done under outdoor conditions. Additionally continuous IR imaging and meteorological data sampling was realized.

2 THERMAL EFFECTS OF PV MODULES

At first an overview of the different thermal effects which are detectable by field IR imaging is shown. All analyzed modules are taken from existing PV plants in Germany. The following figures show some demonstrative IR images of PV modules with thermal anomalies which often found in analyzed PV plants.

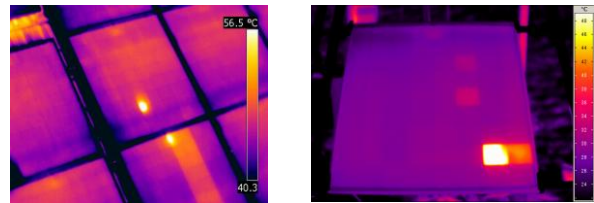


Figure 1: PV module with hot spot (left) / heated cell (right)

The left image in figure 1 shows a PV module under operating conditions with a hot spot. The increase of temperature compared to the rest of the module is about 40 K and the absolute temperature is more than 90°C. This can lead to an irreversible damage of the PV module [2]. The power loss due to a local hot spot achieves in this case up to 10 percent caused by a defect soldering joint, which causes a higher series resistance.

In the right image of figure 1 a hot cell is shown. The temperature difference between the hot cell and the average temperature of the module amounts 13 K. Generally the reason for this effect can be a defect cell and / or mismatch effects [3] or local staining.

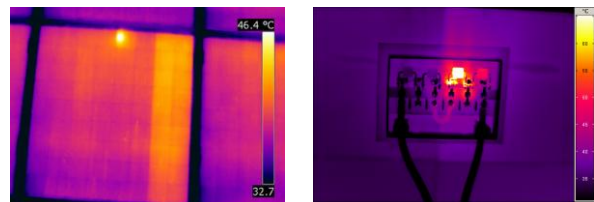


Figure 2: PV module with an open loop cell array (left) and corresponding overheated bypass diode (right).

In Figure 2 an open loop cell array (left) with a corresponding overheated bypass diode is shown.

The temperature difference between the hot cell array and the normal cell arrays is 2 K, and the cell array produces no output power. The reason for that is a soldering joint problem in the heated cell array.

Another possibility for this IR image could be a defect bypass diode (shown in figure 2, right image). In both cases the cell array is slightly warmer than the rest of the PV module, because the absorbed solar power is only converted into heat, and the bypass diode heats up.

Therefore the interpretation of thermal effects shown in figure 1 and 2 can be difficult because there are several different electrical failures, which can cause a thermal phenomenon. Figure 3 and 4 give an overview about thermal effects, in relation to the IR images and some of their possible reasons.

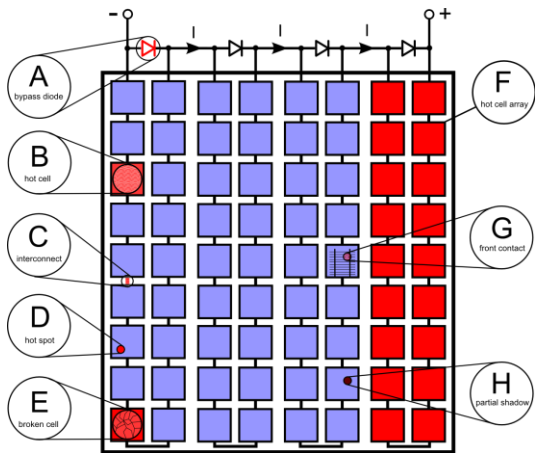


Figure 3: Overview about electrical failures which can cause noticeable thermal effects

In figure 3 these reasons are shown exemplarily on a schematic PV module. The thermal effects of broken cells are not yet verified, also effects without impact to the electrical behavior of the PV module are not considered in figure 4 (for example delaminating). Some effects are interconnected to each other, for example a hot cell array can be caused by an interconnection failure or a bypass diode defect as described above.

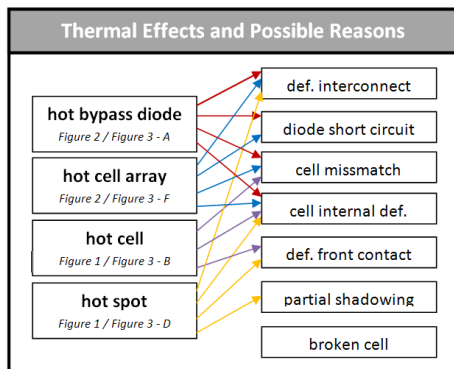


Figure 4: Relation between thermal abnormalities and possible electrical reasons

To study these relations in detail, a specific test environment, shown in figure 5 has been installed which is described below.

3 TEST ENVIRONMENT

All measurements were realized on an Outdoor Test Stand (figure 5), located in Bavaria, Germany. In the past many measurements of PV plants were made and modules with thermal anomalies were removed for a detailed examination. One representative PV module without thermal or electrical phenomena with average output power was additionally used as reference for every measurement.

Technical equipment:

- Weather station with mono- and polycrystalline calibrated solar cells, pyranometer, air temperature sensor, wind speed- and direction sensor with a sampling rate of one second
- Free programmable high accuracy Electronic Load samples every 1 minute one complete I-V curve of the complete module, all cell arrays and one reference module
- High resolution IR camera takes every minute one image



Figure 5: Outdoor Test Stand, BEC-Engineering GmbH

An electrical cabinet was used to successively switch a maximum of eight channels to the Electronic Load. In a one minute measurement cycle, the first channels were used to measure the I-V curves of the cell arrays, and the next channels were used for the entire module and a reference module. Between each measurement cycle, the module was held in MPP to simulate standard operating and thermal conditions. Metrological data like global irradiation on a tilted plane and ambient temperature were measured with a one second time resolution. Additionally one IR picture was taken every minute. All measurement values were automatically saved in a log file for a later analysis.

4 FIRST EXEMPLARY MEASUREMENT RESULTS

4.1 PV module with one single heated solar cell

A PV module with one particular heated solar cell was detected in a PV plant using IR imaging (figure 6). This module was analyzed more in detail. It consists of four cell arrays, each with 18 cells in series and one bypass diode per cell array in parallel. This gives in sum 72 cells in series. The I-V curves of all 4 cell arrays, the entire module and one reference module were measured. Figure 7 shows the results for one measurement cycle. All cell array I-V curves, mathematically added, give as expected the measured I-V curve of the complete module.

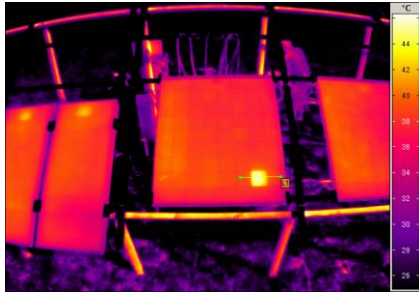


Figure 6: PV module with one single heated cell

The temperature difference along the considered line L1 has a maximum delta of about 9 K ($G_{\text{mod}} = 622 \text{ W/m}^2$, $T_{\text{amb}} = 24.3 \text{ }^\circ\text{C}$). The measured I-V curves show a significant power loss at the fourth cell array where the heated solar cell is located (figure 6).

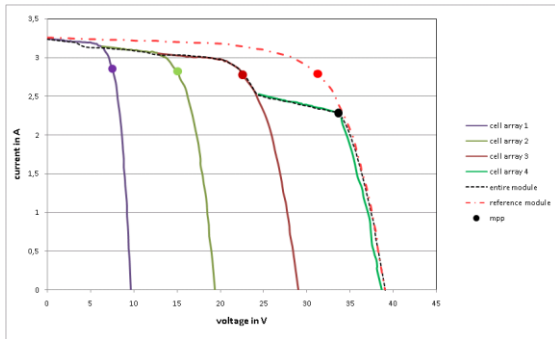


Figure 7: I-V curve of one PV module and its four separate cell arrays.

While the first three cell arrays show only very little deviation among each other, the fourth cell array has a clear decrease of the MPP current. The reference module, which has a common I-V curve, is also drawn in figure 7. Table 1 shows the significant electrical values.

Table 1: Comparison of Significant Electrical Values in Module 1						
	average of cell array 1-3	cell array 4	Δ_1	reference module	entire module	Δ_2
Isc in A	3.1	2.5	-19.9%	3.3	3.2	-0.8%
Voc in V	9.7	9.6	-0.6%	39.0	39.1	0.2%
Impp in A	2.8	2.3	-19.6%	2.8	2.3	-18.2%
Vmpp in V	7.5	8.0	6.0%	31.3	33.7	7.6%
Pmpp in W	21.2	18.1	-14.8%	87.3	76.9	-12.0%
fill factor	0.7	0.75	7.0%	0.69	0.61	-11.5%

Comparing the four cell arrays among each other, it is obvious that cell array four has a large impact on the MPP current of the entire module, which of course also affects the resulting MPP power. The effect on a complete module string in operation conditions and the resulting power loss will be analyzed in the future. The same module was measured over a longer period on a sunny day with only few clouds, to determine a possible correlation between temperature differences, power loss and irradiation values. The temperature is measured between the heated cell and the average temperature of the module. Figure 8 shows a selected profile of 1.5 hours. The spontaneous steps in the characteristic at a time of 09:14 and 09:56 could not be explained. Neither the irradiation nor the ambient temperature give an indication of an influence on the measured values. However, it appears that the temperature difference is still correlated to the power difference between the concerning cell arrays.



Figure 8: Exemplary temporal course of temperature and power difference comparing normal cell strings to those with thermal anomalies

Figure 9 shows the MPP power differences between the cell array with the heated cell and the average power of the other three cell arrays sorted by irradiation classes. The data points are based on the same series of measurements as in figure 8.

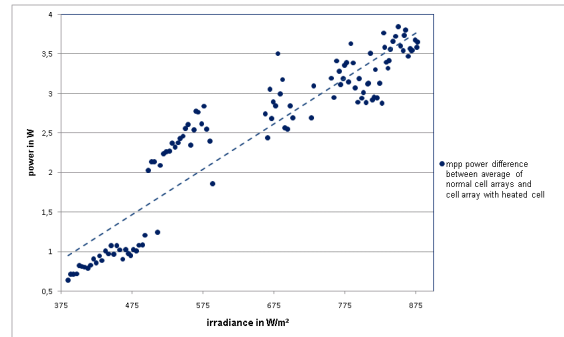


Figure 9: MPP power deviation between normal cell strings to those with thermal anomalies in relation to the irradiance

Obviously there is an approximately linear behavior: the power loss increases with rising irradiation values.

4.2 Multiple heated solar cells

A PV module with multiple heated solar cells has been examined. Like the module before, this module consists of four cell arrays, each with one bypass diode in parallel. Figure 10 shows the considered module in operating conditions ($G_{\text{mod}} = 817 \text{ W/m}^2$ in tilted plane and $T_{\text{amb}} = 19.3 \text{ }^\circ\text{C}$).

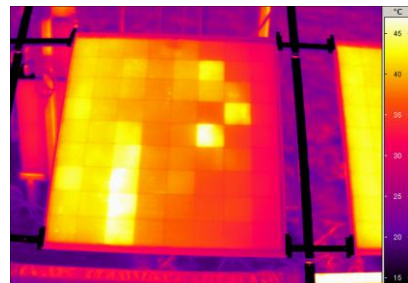


Figure 10: PV module with multiple heated cells

There are several heated areas in this module. Each single cell array contains at least one cell that has a higher temperature than the average temperature of the module. The second cell array has at least four hot cells (cell array 2: $T_{\text{max}} = 49.6 \text{ }^\circ\text{C}$, $T_{\text{avg}} = 40.4 \text{ }^\circ\text{C}$).

In cell array one (cell array 1: $T_{\max} = 47.5$ K, $T_{\text{avg}} = 41.4$ °C) the entire cell array is warmer than the total average temperature (entire module: $T_{\text{avg}} = 38.3$ °C). The I-V curves of this module are shown in figure 11.

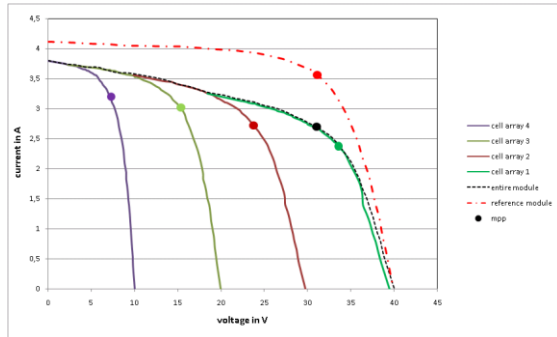


Figure 11: I-V curve of one PV module and its four separate cell arrays

Obviously, the four cell arrays show a clear inconsistency. The power difference between the hottest and the least hot cell array amounts 18.3% (table 2: Δ_1). The relevant electric and thermal values are listed in table 2:

cell array	4	3	2	1	Δ_1
Isc in A	3.8	3.7	3.6	3.3	-14.4%
Voc in V	10.0	9.9	9.8	9.7	-3.0%
Impp in A	3.2	3.0	2.7	2.4	-25.8%
Vmpp in V	7.3	7.5	7.5	8.0	10.1%
Pmpp in W	23.2	22.7	20.1	19.0	-18.3%
T_{avg} in °C	33.6	37.9	40.4	41.4	23.2%
fill factor	0.61	0.61	0.59	0.60	-1.6%

Comparing the average temperature of each cell array with each other, the power output seems to correspond with the average temperature. The correlation between the average temperature of the cell arrays and the comparable power loss will be verified in future measurements. The long term behavior of the temperature and power difference between cell array one and four is shown in figure 12

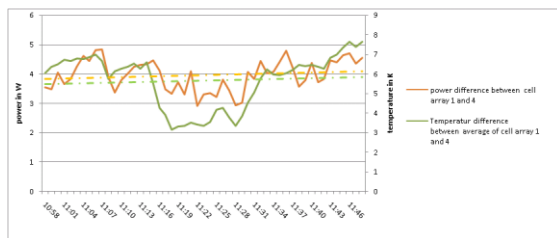


Figure 12: Exemplary temporal course comparing the average temperature and the power difference between the two cell strings with the largest deviance

Even though the measurement offers inconsistencies regarding the irradiance and resulting power differences, a correlation between temperature and power difference can be seen.

4.3 Another PV module with one single heated solar cell

Another module with one single heated cell (figure 13) has been measured. Like the modules before, it consists of four cell arrays, and one bypass diode parallel.

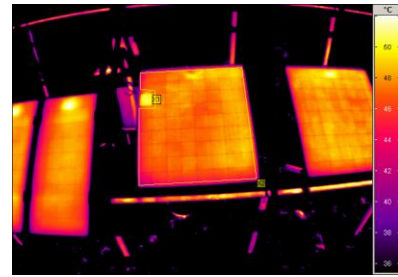


Figure 13: PV module with one single heated cell

The temperature delta between the heated cell in cell array 1 and the average of the module area amounts only 2.0 K, but the measured I-V curve (figure 14) shows a noticeable power loss compared to the reference module.

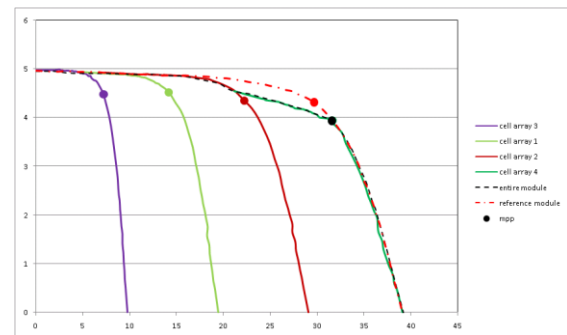


Figure 14: I-V curve of the measured PV module and its four separate cell arrays.

The related electrical values are shown in table 3:

	average of cell array 1-3	cell array 4	Δ_1	reference module	entire module	Δ_2
Isc in A	4.9	4.5	-8.1%	5.0	4.9	-0.3%
Voc in V	9.7	10.0	2.7%	39.1	39.2	0.3%
Impp in A	4.5	3.9	-11.4%	4.3	3.9	-8.8%
Vmpp in V	7.2	7.3	1.3%	29.7	31.6	6.5%
Pmpp in W	32.1	28.7	-10.7%	128.1	124.5	-2.8%
fill factor	0.67	0.63	-5.0%	0.66	0.64	-2.8%

Even a temperature delta of few degrees can show a clear impact to the electrical behavior of the PV module.

5 CONCLUSION

Some exemplary measurement results of analyzed PV plants with single and multiple hot cells are shown. One main result is a direct relation between the power- and the thermal differences. An impact to the energy yield seems obvious but further evaluations are necessary to quantify the effective loss in kWh / kWp per year. The topic will be observed with more detailed long term analyzes and measurements of single cells (disassembling of PV modules). With these results simulations will be done with INSEL to verify the thesis and get more information regarding the impact to the energy yield.

6 REFERENCES

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