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# Renovation and Performance Study of SPV Power Plant

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***Abstract***- The performance of a photovoltaic array implemented in the Block A Rooftop Solar Plant at National Institute of Solar Energy (NISE) which installed last 20 years ago is analyzed. This plant consists of 80 monocrystalline PV modules with a MPP power of 35 W under STC. This plant is divided into 4 parallel strings with each of 20 modules connected in series as string. The mismatch losses on different array configurations are analyzed firstly using measured IV characteristics for each module using a solar analyzer device, and secondly using MATLAB SIMULINK model. Infrared (IR) thermography testing is used for hot-spot [detection], cell line checking is used for interconnect integrity and electroluminescence (EL) testing is used for [detecting] degradation of some modules.

***Index Terms***- PV module, Mismatch, MATLAB SIMULINK, NISE

## I. INTRODUCTION

Mismatch losses (MML) are a very serious problem in photovoltaic modules and arrays because it causes the lower output power so the system efficiency and performance become lower. In photovoltaic module the mismatch losses occur when the configuration and parameters of one solar cell are different from the other cells. The impact of power loss due to mismatch depends on circuit configuration, operating point and parameter which are different from the remaining of the solar cells. There are two mismatch losses occur through series that are open circuit voltage and short circuit current. The mismatch effect occurs in short circuit current of series connected cells are relatively minor as compare to open circuit voltage [1]. The mismatch is related to the power losses of a solar cell, module, or plant operating under adverse conditions.

Different configurations of PV system modules connections are Total Cross-Tied (TCT), Series-Parallel (SP), Honey Comb (HB) and Bridge-Linked (BL). In TCT configuration, the row PV modules are firstly connected in parallel, and then connected in series forming the PV array. In SP configuration, to get PV strings, the modules are connected in series, and then these strings groups are connected in form of parallel forming the PV array. In the traditional TCT and SP configurations the interconnection operation of the PV modules normally is fixed [5]. The array configuration of SP and TCT are shown in Figure 1. Series parallel and total cross tied configurations are investigated. Differences in simulated and measured module, string and array parameters are compared. The physical degradation of the PV modules is investigated using infrared thermography to detect hot spots; electroluminescence to detect micro-cracks, and interconnect integrity is checked using cell line checking. Measured and simulated mismatch losses for SP and TCT configuration are presented.

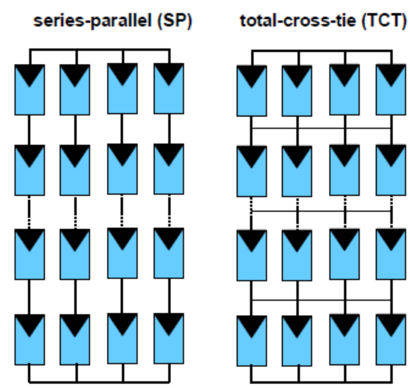


Figure 1: SP and TCT array configurations [5]

## II. ANALYSIS OF ROOFTOP SOLAR PLANT

### *A. Analysis of using AMPROBE Solar Analyzer*

The performance of PV modules was measured with AMPROBE Solar Analyzer, Solar-4000 measurement equipment. The characteristic curve measured by the SOLAR-4000 will be extrapolated to standard test conditions by using of the measured values of the sensor and then displayed.


Figure 2: AMPROBE Solar Analyzer [7]

In addition, the manufacturer's STC ideal characteristic curve can be displayed as well using the integrated module database. The wireless sensor measures the cell temperature without direct contact, as well as the inclination angle and the irradiation in the solar module level. The measurement values are transmitted directly to the main device by radio signal. To measure the irradiation, the device switches the reference cell automatically from a monocrystalline to a polycrystalline cell. This equipment generates the curves corresponding to standard conditions of measurement STC (irradiance of 1000 W/m$^2$ and temperature of 25ºC) in order to compare that results with other ones.

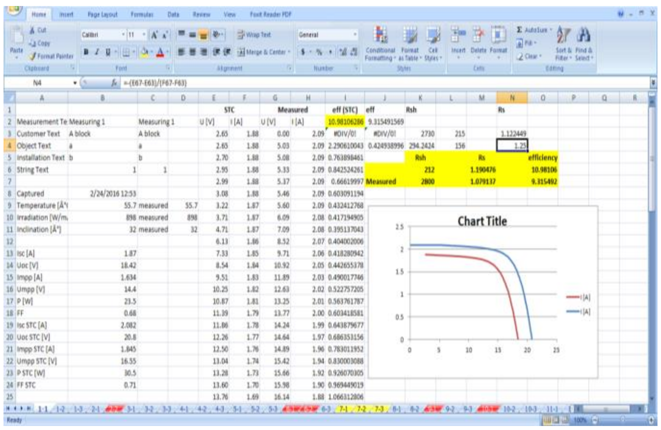

Figure 3: Extract measured data in Excel

Every module was measured independently and then the whole system was measured, getting I-V and power curves with $V_{oc}$, $I_{sc}$, $V_{mp}$, $I_{mp}$, $P_m$, Fill Factor, Irradiance, and Module temperature, respectively. Figure 3 shows the measurement data of one module with AMPROBE solar analyzer and data extract in Excel.

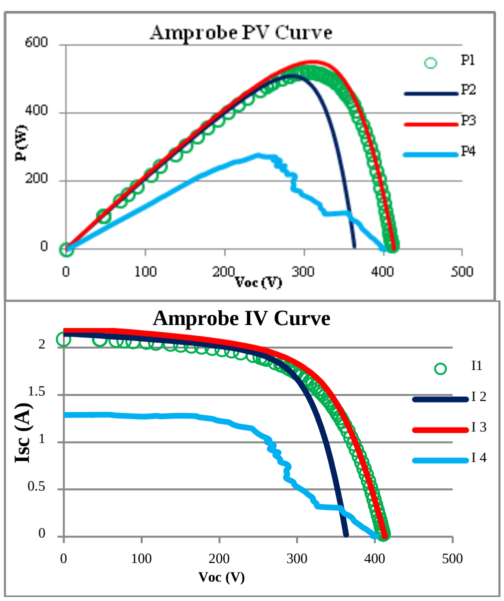

Figure 4: IV curve by Amprobe measurement

For the past 20 years each module has similar rated power with 35W for 80 modules. For the current retested measuring the average maximum power is around 30W, their maximum voltage ranges from 18.5 V to 21.42 V whereas current varies between 1.35 A and 2.5A. Figure 4 shows the IV characteristics curve for each string by measuring AMPROBE solar analyzer.From these measuring; efficiency, series resistance $R_s$ and shunt resistance $R_{sh}$ of each module were calculated. The efficiency is calculated by

$$\eta = \frac{I_{max} \times V_{max}}{\text{Incident solar radiation} \times \text{Area of solar cell}}$$

$$= \frac{V_{oc} \times I_{sc} \times FF}{G \times A} \qquad \text{Eq (1)}$$

By calculation which module is still best, good or low efficiency can be found. Figure 5 shows the total modules efficiency. From analyzing, the highest efficiency is 12.86 and the lowest efficiency is 4.0.

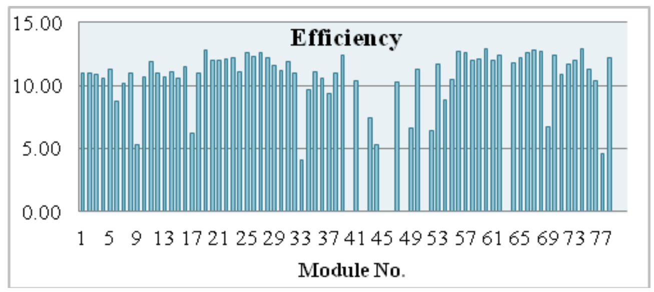

Figure 5: Total module efficiency of each module

*B. Analysis of MATLAB SIMULINK Model*

MATLAB SIMULINK model is used to compare the result of simulation and actual measurement data. Each string consists of 20 modules with series connection and 4 strings are connected to parallel connection. The results are shown with IV, PV curves and workspace. Figure 6 shows the MATLAB SIMULINK model for 80 modules simulation.

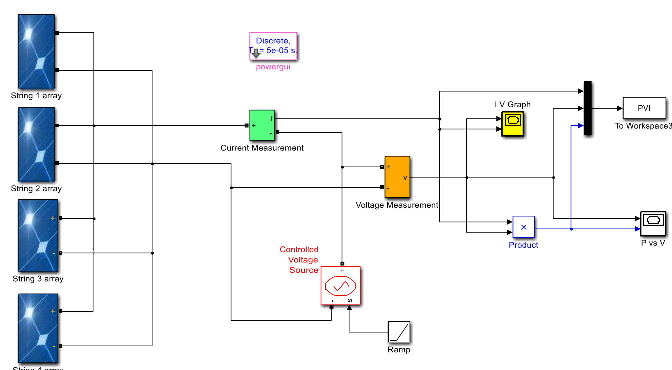

Figure 6: SIMULINK Model for 20 modules x 4 strings

*C. Comparison of Actual and Simulation Measurements*

Figure 7 shows the comparison of the actual measurement and simulation result of each string. In comparison of $P_{mp}$, string 1, 2 and 3 are not too much error but string 4 is a big error. And then, the comparison of $I_{sc}$, $I_{mp}$, $R_s$ and $R_{sh}$ of string 4 are also problems.

As in string 4, some module efficiencies are very low. String 1, 2, 3 and 4 are series connection of 20 modules. So the mismatch losses are mainly related with series PV modules connection. In total string, four strings are connected in parallel so the mismatch losses are less than series connection. Table 1 and 2 show the difference of simulation and actual measurement for 20 modules of string 1 and total four strings.

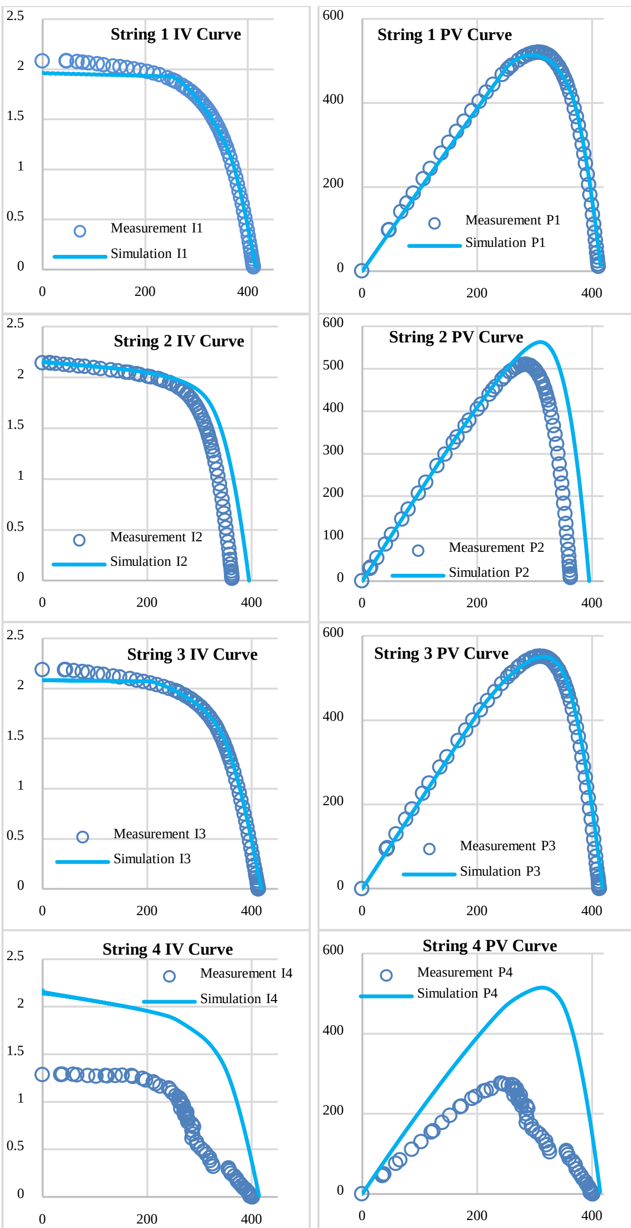


Figure 7: Comparison of actual and simulation result

**Table 1: String 1 compared result**

| String 1 | Amprobe Measure-ment | Simulation | Difference | % error |
|---|---|---|---|---|
| $I_{sc}$ | 2.09 | 1.97 | -0.12 | -6.09 |
| $V_{oc}$ | 411.76 | 415.00 | +3.24 | +0.78 |
| $I_{mp}$ | 1.70 | 1.74 | +0.04 | +2.30 |
| $V_{mp}$ | 306.40 | 295 | -11.40 | -3.86 |
| $P_{mp}$ | 520.88 | 514.17 | -6.71 | -1.31 |
| $R_s$ | 32.42 | 40.90 | +8.48 | +20.73 |
| $R_{sh}$ | 4749.1 | 3051.28 | +1697.82 | -55.64 |

**Table 2: Total compared results (%)**

| | String 1 (%) | String 2 (%) | String 3(%) | String 4(%) | Total String (%) |
|---|---|---|---|---|---|
| $I_{sc}$ | -6.09 | +0.46 | -4.78 | +40.55 | -2.61 |
| $V_{oc}$ | +0.78 | +7.87 | +1.87 | +4.74 | -0.22 |
| $I_{mp}$ | +2.30 | +1.43 | -2.55 | +30.10 | -3.07 |
| $V_{mp}$ | -3.86 | +7.81 | +2.06 | +22.91 | +6.01 |
| $R_s$ | +20.73 | +17.66 | +8.31 | -414.75 | -1.50 |
| $R_{sh}$ | -35.75 | -41.38 | +34.91 | -368.54 | -33.61 |
| $P_{mp}$ | -1.31 | +9.13 | -0.43 | +46.11 | +3.13 |

*D. Analysis of using Cell Line checker*

In this analysis, to check the cell interconnection of the module cell line checker is used. "Cell Line Checker" is a tool based on non-contact method to identify and locate electrical failures in PV modules and systems. When a bad electrical connection is detected, the beeping sound stops and LEDs cease to flash. This corresponds to the location of failure. Figure 8 shows the checking of PV module by using cell line checker.

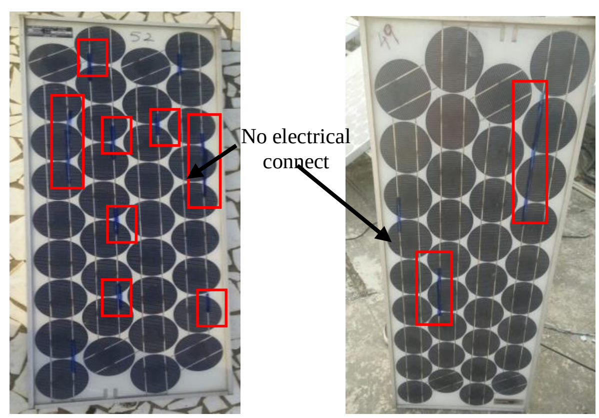


Figure 8: Cell line checking of PV module

*E. Analysis of using EL and IR*

To find the defects of PV modules, Infrared (IR) Thermography and Electroluminescence (EL) testing are used. EL imaging is very effective in detecting defects in module such as cracks, broken fingers and broken cell. EL is also a useful tool in identifying damaged or cracked cells which are responsible for cell mismatch in a module. So, some modules are measured in EL testing lab at NISE. Figure 9 shows EL image for some modules testing.

Figure 10 shows a typical IR image and its temperature histogram. Modules were also characterized using infra-red (IR) thermography, which shows the temperature distribution over the module, and is particularly useful for identifying hot spots in the module, which can cause significant long-term degradation.

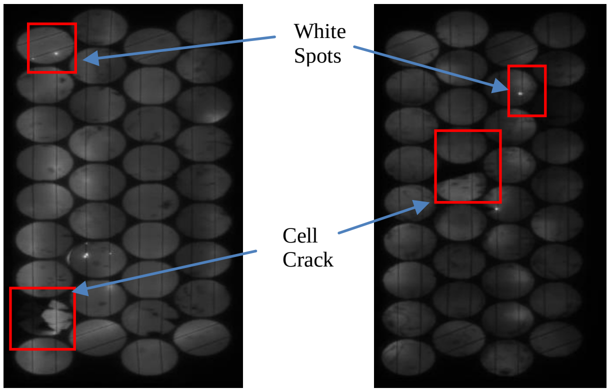


Figure 9: EL images for some modules

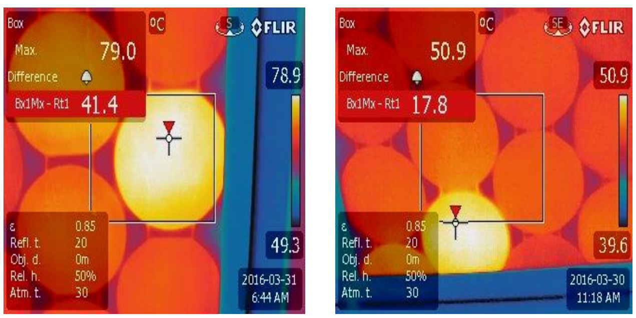


Figure 10: IR images testing

*F. New Installation 18x4 strings*

After checking with EL, IR and cell line checker, 8 modules have many defects. So these 8 modules are removed. And then the remaining modules are rearranged by current and new installation is step up and analyzed again. This new plant has 72 modules, 18 modules connect series per string and parallel these 4 strings. In this analysis, two interconnections of PV array configuration: serial-parallel (SP) and total-crossed tied (TCT) are modified. In Figure 11, SP connection are set up and compared with actual measurement and simulation results of each string. Table 3 shows the result data.

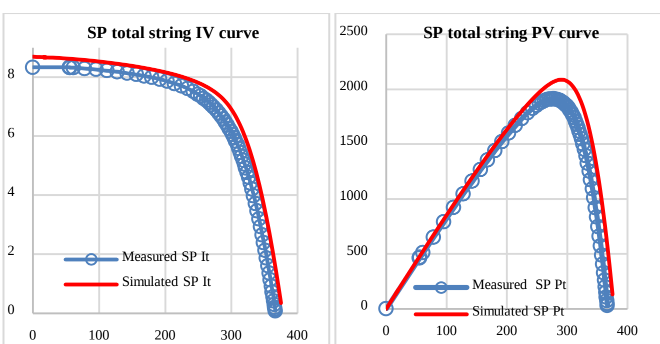


Figure 11: Comparison of SP configuration

Figure 12 shows the TCT connections results. From Table 4, the maximum peak power is 5.02% increased in TCT versus SP configurations. So the mismatch losses are reduced in TCT than SP configuration.

**Table 3: Amprobe and simulation measurements data for SP Configuration**

| | $I_{sc}$ (%) | $V_{oc}$ (%) | $I_{mp}$ (%) | $V_{mp}$ (%) | $P_{mp}$ (%) | $R_s$ (%) | $R_{sh}$ (%) |
|---|---|---|---|---|---|---|---|
| string 1 | 3.77 | 0.76 | 3.06 | 1.68 | 4.82 | -11.14 | -76.01 |
| string 2 | 2.68 | 1.43 | 6.53 | 1.08 | 7.26 | 0.13 | 55.28 |
| string 3 | 4.23 | 0.86 | 3.31 | 0.38 | 3.67 | 12.91 | -8.20 |
| string 4 | 5.67 | 0.65 | 2.84 | 1.59 | 4.09 | 37.99 | -71.99 |
| Total | 3.68 | 1.97 | 4.31 | 4.24 | 8.31 | 13.69 | -11.54 |

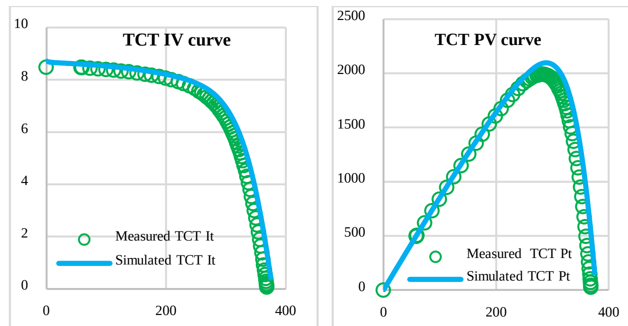


Figure 12: TCT configuration IV and PV curves

**Table 4: Comparison of SP and TCT Configurations**

| | Amprobe Measure-ment (V) | | Simulation (V) | | Difference (V) | | % error | |
|---|---|---|---|---|---|---|---|---|
| | **SP** | **TCT** | **SP** | **TCT** | **SP** | **TCT** | **SP** | **TCT** |
| $I_{sc}$ | 8.38 | 8.45 | 8.7 | 8.71 | 0.32 | 0.26 | 3.68 | 2.99 |
| $V_{oc}$ | 367.62 | 369.01 | 375 | 375 | 7.38 | 5.99 | 1.97 | 1.6 |
| $I_{mp}$ | 6.89 | 7.02 | 7.2 | 7.23 | 0.31 | 0.21 | 4.31 | 2.9 |
| $V_{mp}$ | 277.7 | 283.7 | 290 | 290 | 12.3 | 6.3 | 4.24 | 2.17 |
| $R_s$ | 7.19 | 6.83 | 8.33 | 8.52 | 1.14 | 1.69 | 13.69 | 19.84 |
| $R_{sh}$ | 514.55 | 546.01 | 461.3 | 514.01 | -53.25 | -31.99 | -11.54 | -6.22 |
| $P_{mp}$ | 1913.4 | 1991.6 | 2086.7 | 2096.9 | 173.3 | 105.3 | 8.3 | 5.02 |

## III. DISCUSSION

When average maximum power of 30W PV modules are used to get the maximum power 2.4 kW for 20 x 4 array and 2.16 kW for 18 x 4 array at STC condition. This analysis is based on 20 years used PV modules. Mismatch losses of the array are then calculated by equation (2).

**Table 5: Mismatch losses of the array**

| | **20x4 SP** | **18x 4 SP** | **18x 4 TCT** |
|---|---|---|---|
| Amprobe measurement MML (%) | 13.94 | 11.41 | 7.8 |
| Simulation MML (%) | 11.15 | 3.39 | 2.92 |

Table 5 shows the MML for each configuration. Measured mismatch losses are reduced from 11.41% in series-parallel configuration to 7.8% in total cross tied. By this result, reinstallation of TCT configuration is better performance.

$$MML=1-\frac{P_{max\text{-}array}}{\sum_{i=1}^{M\text{-}N} P_{maxi}} \qquad \text{Eq (2)}$$

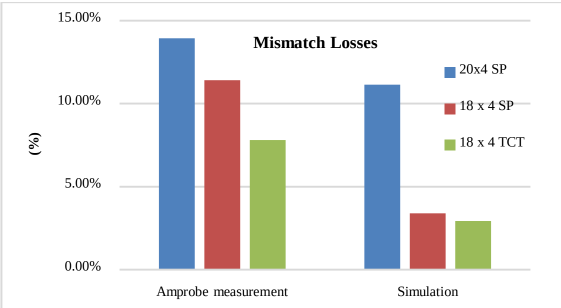


Figure 13: Mismatch losses for old and new installations

**Table 6: Comparison of module parameters over 20 years and Current value at STC**

| Parameter | New value | Average Current value | % Change | Degradation rate (%/year) |
|---|---|---|---|---|
| $P_{max}$ (W) | 35 | 30 | -14.29 | -0.71 |
| $V_{oc}$ (V) | 21.6 | 20.7 | -4.17 | -0.42 |
| $I_{sc}$ (A) | 2.4 | 2.17 | -10.6 | -0.53 |
| $V_{mp}$ (V) | 16.4 | 15.7 | -4.27 | -0.21 |
| $I_{mp}$ (A) | 2.1 | 1.9 | -9.52 | -0.48 |

## IV. CONCLUSIONS

In this analysis, Amprobe solar analyzer and MATLAB SIMULINK model are used to measure 35 W 20x4 strings rooftop solar plant. Variation of IV characteristics of PV modules can lead to significant power loss. By changing PV array configuration, mismatch losses must be reduced from 11.41% to 7.8% by changing the configuration from serial-parallel to total cross tied. Even though there was little change in the average value of $V_{oc}$, the short circuit current ($I_{sc}$) has on average decreased 9.58% leading to an average 14.29% decrease in $P_{max}$. "The reduction in $P_{max}$ is primarily due to decrease in current outputs by the lower values of $I_{sc}$ and $I_{mp}$", as higher currents from certain modules in the string will dissipate their power to the modules 80utputting slightly lower current, as only one current can flow in a series string. The drop in current production by the modules can be attributed in part to the visually observable physical defects including EVA browning, delaminating at the cell/ EVA interface and the occurrence of localized hot spots.

Mismatch losses are reduced in TCT configuration but method involves greater cost and greater complexity. Infrared (IR) thermography testing is useful for identifying hot spot of the modules, which cause significant long term degradation. EL testing images detect micro-cracks of the modules. That causes power degradation.

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