46. Mechanical Testing and Failure Analysis of Photovoltaic Modules

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Abstract

Fossil fuels are rapidly depleting, shifting the energy paradigm to renewable energy. Among the renewable energy technologies, photovoltaic (PV) technology is an emerging area of interest. PV technology has shown that it can generate electricity for a wide range of applications, scales, climates and geographic locations. Mechanical integrity, among other factors, plays an important role in maintaining the efficiency of photovoltaic modules. Depending on the level of compromise on the mechanical integrity, the output power can be reduced substantially. Mechanical stresses are generated in PV modules right from the processing and fabrication such as during soldering, lamination and framing processes. In addition, transportation loadings and difference in service loads serve as mechanical loads to the modules. PV modules can be modelled for in-service mechanical loadings to predict the reliability of modules and consequently predict the output power levels. Extensive qualification tests are also developed to provide an estimate about the module's lifetime and the extent of degradation under simulated real field conditions.

This study presents detailed analysis and experimentation to test the effect of wind loads on the mechanical integrity of PV module in accordance with the international standards (IEC 61215 and ASTM E1830-15). A mechanical test rig was indigenously designed and fabricated for mechanical load testing of PV modules. Mechanical load tests were performed on the commercially available PV modules, preceded and followed by electroluminescence and electrical efficiency tests. Four samples of 60W PV modules were subjected to the above mentioned tests. It was observed that winds load has the potential to degrade the peak power output of PV modules by 2%. In addition, the average decrease in fill factor of 0.20% is another indication of decrease in the output power.

Keywords: *Renewable Energy; Solar Cells; Photovoltaic Modules; Mechanical Intergrity; Power Output*

1. Introduction

Photovoltaic modules (PV) are widely used for converting the abundantly available solar energy into the electrical energy. Efficient PV modules can ensure maximum advantage of exploitation of solar energy. Efficiency of the PV modules, in addition to the type of the cell, depends upon the cell design and the mechanical integrity of the module. The mechanical integrity is a key factor in maintaining the power output and ultimately the efficiency of the modules and is dependent on different design parameters like geometry and dimensions of solar cells, orientation of bus bars, type of soldering material, type of adhesive used and the curing temperature of the module. Optimization in processing to improve mechanical integrity can be achieved by having alternative soldering techniques, changing the orientation and amount of bus bars [1-4].

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The output power of the modules is reduced if the mechanical integrity is compromised. For example, if there are cracks in the cells it would provide resistance to the flow of the charges and if the parts of the cells are electrically isolated, the active cell area will be decreased, greatly reducing the output power. Moreover, this separation produces a difference in overall current which results in reverse bias operation and potential of hotspot risks. Therefore, mechanical stability influence both the power output as well as module's reliability. According to the crack statistics of the PV modules that are subject to mechanical loadings, it is concluded that the cracks that are parallel to the bus bars are very critical when it comes to the cell separation [2, 5, 6].

Stresses are generated in the PV modules from the very start; during doping and other manufacturing processes. The transportation loadings and in-service loads like; static and dynamic wind loads, snow loads, dust loads, hails, rain and other ambient loadings also introduces mechanical stresses in the module. These loads can be simulated on the module using different techniques to predict their reliability. The in-service loads cause the micro cracks generated in cell processing to get propagated. All these factors serve to degrade the PV modules and decrease its output power [7-9].

In this research, the effect of the wind load on the modules was studied by simulating the forces that are applied on the module by the wind. To simulate the wind load on the modules, a test setup was designed and fabricated and testing was performed on the PV modules using the international standards (ASTM E1830-15 and IEC-61215). The mechanical testing was preceded and followed by electroluminescence (EL) and flash tests.

2. Materials and Methods

2.1. Photovoltaic Modules Specifications

Four commercially available PV modules, each of 60W rated power, were selected for research. These modules were obtained from the same local supplier and were of the same manufacturer (German Cells, PRC). The rated specifications of the modules are listed in Table 1.

Table 1. Rated Specifications of the PV modules

S. No.	Parameter	Value
1	Maximum power at STC	60 W
2	Output tolerance	±3%
3	Current at Pmax, Ipmax	3.37 A
4	Voltage at Pmax, Vpmax	17.8 V
5	Short circuit current, ISC	4.04 A
6	Open circuit voltage, VOC	21.6 V
7	Nominal operating cell temperature	450C
8	Dimension	750 x 535 x 20 (mm)
9	Maximum series fuse rating	12 A

2.2. Fabrication of the Test Setup

A mechanical test setup was indigenously designed and fabricated for the mechanical testing of the PV modules according to the international standards (ASTM E1830-15 and IEC-61215) [10] and [11]. Fig. 1 shows the test setup which consists of main frame, mountings and load application mechanism. The main frame provides structural support to the other parts of the test setup. It is designed to take up the load of 5400 Pa, with a factor of safety of 3. The test setup can be used to test a module having the dimension upto 3x3 ft. Mountings are required to firmly fix the module in the main frame. The dimensions of the mounting are taken according to those used commonly for mounting of the PV modules in practice. The material of mounting is mild steel and the cross section is C. Sand bag was used to apply the load on the modules, fine aggregate sand was used for this purpose. It was a rectangular bag having the dimensions equal to the size of the module. The depth of the bag was calculated using the density of the sand. Hooks and ropes were used to connect this bag with the main frame and to lift up the load.

2.3. Characterization

The characterization tests, that is, electroluminescence imaging and solar flash testing (electrical efficiency test) were carried out on the modules before and after the mechanical testing. These tests were performed in Pakistan Council of Renewable Energy Technologies (PCRET) laboratories, Islamabad, Pakistan. The steps followed are shown in the Fig. 2.

Fig. 1. Test setup used for mechanical testing

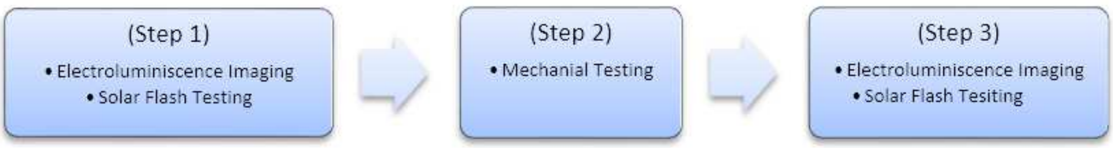

Fig. 2. Steps to characterize the mechanical integrity of photovoltaic modules

2.3.1. Electroluminescence Testing

Electroluminescence tests were performed on Electroluminescence Tester (Wuhan Gobo Photovoltaics, PRC). In this technique, the PV module was forward biased which favored the radiative recombination in the Silicon cells. The light emitted was in Infra-Red region and the image was detected using an Infra-Red CCD Camera. The cracks and other defects were visible in the electroluminescence image because the input current was unable to reach the defected regions to cause luminescence. These areas appeared dark in the image.

2.3.2. Solar Flash Testing

Solar flash testing (electrical efficiency test) on the modules was performed to measure the parameters like series resistance, fill factor, peak output power, short circuit current, open circuit voltage and efficiency. The equipment used was Sun Simulator Tester, manufactured by Wuhan Gobo Photovoltaics, PRC. In this test the module was exposed for a very small period of time to a bright flash of light of 1000 W/m^2 using a xenon filled arc lamp. The test was performed at standard test conditions (STC), which consist of; Irradiance 1000 ± 50 W/m^2, Cell temperature 25°C, Spectral distribution of irradiance AM1.5 [12].

2.3.3. Mechanical Testing

The mechanical testing was performed according to the standard ASTM E1830-15 using the fabricated test bench [10]. The mechanical testing consisted of three cycles of 2400 pa pressure simulating wind load. Each cycle was of two hours, in which force was applied on the front side of the module for one hour and then on the back side of the module for one hour. Application of mechanical load on the module was gradual. Sand was uniformly distributed in the bag, so it applied a uniform load on the module.

3. Results

Figs 3 and 4 show the results obtained by the electroluminescence imaging of two selected modules (module # 1 and 2). The pre-mechanical testing results are those which are taken before the application of mechanical load while the post-mechanical testing results are those which are taken after the mechanical testing was performed. Module # 1 had a greater number of defects prior to the mechanical testing and the highest increase in defect concentration after the application of the mechanical load. The module # 2 had fewer defects prior to the mechanical testing and the defect concentration did not increase much after the mechanical testing.

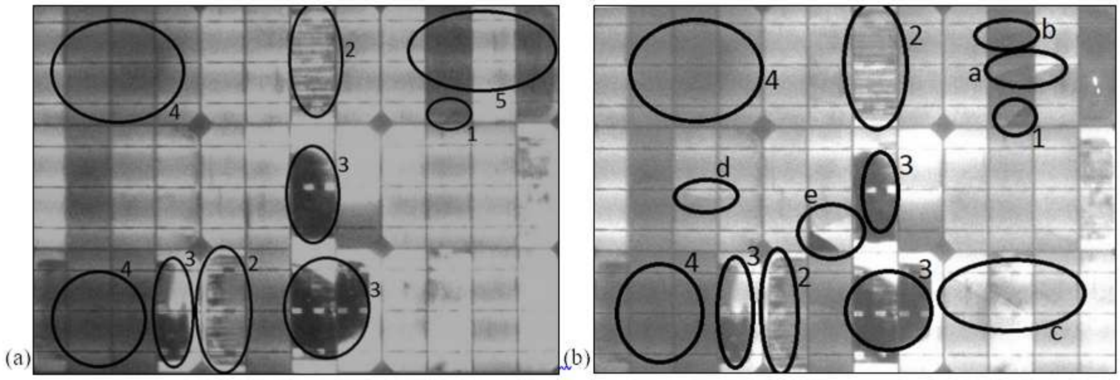

Fig. 3. Electroluminescence image of module # 1 (a) Pre-Testing and (b) Post-Testing.

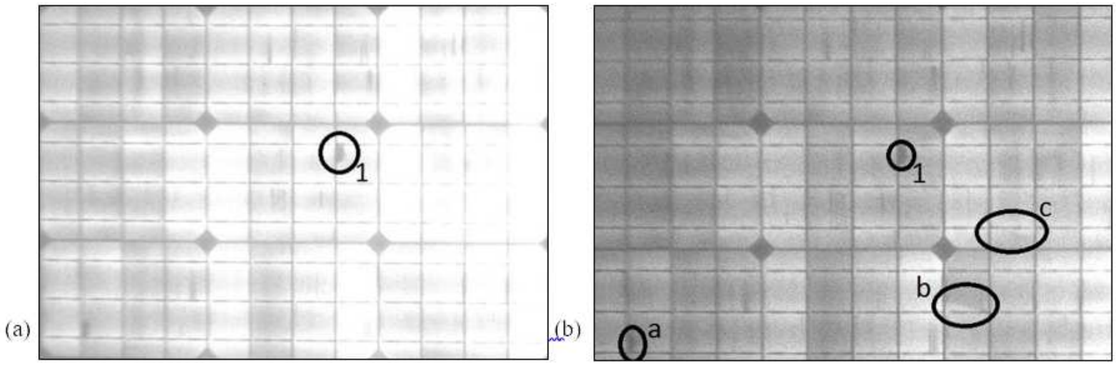

Fig. 4. EL image of Module no. 2 (a) Pre-Testing and (b) Post-Testing.

Four different types of defects were visible in the module # 1 (Fig. 1a); these defects are due to the manufacturing flaws and transportation loadings. A small crack is visible in region '1'. Tire like patterns are visible in region '2', which are due to the mechanical degradation of the cells. Region '3' is completely dark region which shows the areas of the cell which are electrically isolated. Regions '4' & '5' are the shaded region which are present due to improper doping of the cells. Comparing this to the post testing electroluminescence image of module # 1 (Fig. 1b), a number of cracks are visible (a – e). These cracks are generally diagonal to the bus bars. The defected regions are encircled and named as lower case letters. A slight difference in the colour is observed in the regions where cracks are present. One of the cracks, observed in the region 'e' propagates and overlaps the bus bar and a darker region is present near it.

Fig. 2 shows the electroluminescence image of the module # 2. There are no defects in this module prior to the mechanical testing, shown in Fig. 2a. Comparing this to the electroluminescence image after the mechanical testing (Fig. 2b), it can be seen that there are a very few cracks in the module # 2. These cracks run diagonally to the bus bars but none of them overlaps the bus bar.

The representative results of the solar flash testing of module # 1 is given Table 2. These results are similar to those reported earlier.

Table 2. Representative results of solar flash testing (module # 1)

S. No.	Parameter	Pre-Testing	Post-Testing
1	Isc (A)	3.23	3.16
2	Voc (V)	21.06	21.05
3	Pm (W)	49.58	48.47
4	Ipm (A)	2.88	2.82
5	Vpm (V)	17.24	17.18
6	Efficiency	12.24%	11.97%
7	Fill Factor (%)	72.87%	72.77%
8	Rs (mOhms)	788.42	826.93
9	Irradiance (W/m2)	986.36	995.77
10	Temperature (°C)	27	28.4

The changes in the four important electrical parameters; series resistance, fill factor, peak output power and electrical efficiency were analyzed. Table 3 shows the changes in these four parameters for the four different modules. The results show that the change is significantly different for different modules. The maximum rise in the series resistance was observed in module # 1 (4.88%) and minimum rise was observed in module # 4 (2.73%). Maximum drop in the fill factor was observed in module # 2 (0.41%) while the fill factor of the module # 4 remained the same before and after mechanical testing. Module # 1 had the highest drop in the peak output power and efficiency, while module # 2 and 4 did not show any change in the peak output power and efficiency.

Table 3. Results of the parameters to be analyzed

S. No.	% increase in series resistance	% drop in fill factor	% drop in peak output power	% drop in efficiency
Module # 1	4.88	0.1	2.23	0.27
Module # 2	2.83	0.41	-	-
Module # 3	2.92	0.17	0.66	0.09
Module # 4	2.73	-	-	-

4. Discussion

The electroluminescence test results show that several defects are present in the modules even before the application of mechanical load. The completely dark regions show the areas of the cell which are electrically isolated. This isolation is due to the fact that cracks in these regions run diagonally to the bus bars, overlapping them and causing the de-metallization of the cells. The results also show that these defects are enhanced after the load is applied on the module (Figs 1 and 2). The slight difference in the colour (in the regions named by lowercase letters) is due to the presence of the crack in that region, which provides resistance to the flow of the current and thus a difference in the glow during the electroluminescence test. These cracks give the account of the effect on the module due to the simulated wind load in the mechanical testing. The cracks cause hindrance to the flow of electrical charges and thus result in a decrease in the output power of the module. The crack observed in the region 'e' propagates and overlaps the bus bar and thus is more severe as compared to others which do not cross the bus bars (Fig. 1b). It can be concluded that this crack caused the electrical isolation of this part of the cell as it caused damage to the bus bar.

The average series resistance of four modules before mechanical testing was 734 mΩ which rose to 759 mΩ after mechanical loading of 2400Pa. Table 3 gives the percent increase in the series resistance of the modules. This increase in the series resistance is because of the mechanical degradation of the cells. Fill factor is an indirect measure of the percent effective area of PV modules. The impact of increased series resistance is to reduce the fill factor. As observed from the Table 3 the fill factors of the modules were decreased in three of the four modules tested while no drop was observed in module # 4. This decrease in the fill factor is because of the increase in the series resistance which in turn is due to the emergence of cracks.

Table 3 shows that there was a drop in the peak output power of the module # 1 and module # 3. The percent drop in power in module # 1 was the highest (2.23%). This is attributed to the greater number of cracks produced in the module because of the application of the load and also because of the electrical isolation of the cell in this module. A drop in power is also observed in module # 3 which is lesser then that of module # 1, which is due to the lesser number of cracks produced in it. The reason that the power of the module # 2 and module # 4 remain the same is that these modules were not affected significantly by the mechanical loadings applied on them. Although some cracks were observed in them due to which a slight increase in the series resistance was observed but these cracks were not significant to drop the output power of these modules.

The light to electricity conversion efficiencies of the PV modules before mechanical testing were in the range of 11.5- 14.3%. Similar to the case of peak output power, a drop in the efficiencies of the module # 1 and 3 was observed which is attributed to the cracks generated in them. While the efficiency of the module # 2 and module # 4 was not affected by the application of the load.

5. Conclusions

In this study the mechanical degradation caused by wind load was characterized. It shows that beside propagating existing cracks, the loads also induce new cracks in the PV modules. Major number of these cracks are diagonal to the cell geometry. After the mechanical testing, degradation was observed in the modules, which led to the loss in the output power and drop in the efficiency of the modules. Maximum drop in the peak output power was 2.23% and while the average power drop was 0.72%. The maximum drop in the fill factor was 0.41% while the average drop was 0.17%. The maximum drop in the efficiency was 0.27%. This shows that mechanical integrity plays an important role in the performance of PV modules.

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