DYNAMIC MECHANICAL LOAD TESTS ON CRYSTALLINE SILICON MODULES

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ABSTRACT: The mechanical load test in the actual standard for photovoltaic module product qualification is simulating the combined wind and snow load by the means of a static load. Critical issues are the size, thickness and treatment of the module front glass, the stability of the framing and mounting scheme and the mechanical reliability of the solder joints. For crystalline silicon modules, micro cracks offer an additional risk. But operating conditions in the field and conditions during handling and transportation are not necessarily static. In this work we compare the effects of dynamic and static load tests and investigate their interaction with climatic stress tests. Different test combinations and sequences are evaluated with respect to electrical power losses and to possible changes that can be observed via electro-luminescence. The aim is to prove or improve the existing reliability tests towards a more complete simulation of real operating conditions and to broaden the portfolio of very fast reliability tests beyond the existing standards. Various test sequences are probed on identical commercial modules and the results are compared to the statistical test data from the laboratory's database.

Keywords: Dynamic mechanical load, crystalline silicon modules, reliability

1 INTRODUCTION

Along with increasing competiveness in order to meet dropping grid-feed tariffs for photovoltaic systems, performances issues and in particular reliability requirements for photovoltaic modules are becoming more important. New tests beyond existing standards with short response times for benchmarking and quality control are requested by the customers more frequently.

In the existing procedure for design approval of PV modules, each new type of module has to undergo a series of climatic, electric and mechanical stresses, which are determined in the well established and accepted standards IEC 61215 and IEC 61646 [1] [2].

The static mechanical load test (SML) in these standards is probing the reliability of the module type with respect to wind and snow loads. It consists of three 2 h cycles with a static load of 2,400 Pa to the back and then to the front. A load of 5,400 Pa to the front at the end of the last cycle is an option for the heavy load test case. The older American standard IEEE 1262 proposes an additional dynamic mechanical load test (DML) [3] with 10,000 cycles at 1440 Pa and at least 3s per cycle. This test is not in use at the time being, but BP Solar reported power losses up to 20% after combining this test with climate chamber tests on intentionally damaged modules with micro cracks [4].

For the qualification of building integrated photovoltaic (BIPV) the dynamic mechanical load is under consideration as an additional test for a separate BIPV standard, together with fire, arcing and water tightness tests [5].

In the case of field or roof top applications, the annual degradation rate of crystalline modules is generally assumed to be in the order of -0.4 %/a, which is attributed to a decrease in the light transmission of the encapsulant and/or corrosion of the interconnections between the cells. The latter is normally addressed to long-term corrosion at the soldered contacts. Recently, ECN reported a corrosion of the Al/Ag-Overlap of the screen printed back contact on their metal wrap through cells after an extended damp heat (DH) test of 2,000 h at 85°C and 85% relative humidity [6].

During his life cycle, the module experiences mechanical stress from transportation in terms of shocks and vibrations [7]. After installation, the modules are exposed to static loads such as snow and to dynamic loads given by wind [8].

PI Berlin is testing in accordance to IEC 61215 and IEC 61646 as a so-called CB-Testing Lab (CBTL), within the certification body (CB) scheme of the IEC. The test results are collected in an internal database. Anonymous test data have been used for this study. In this paper, the results of standard SML vs. DML has been investigated in regards to:

1. How does the number of micro cracks correlate with the power losses after static and dynamic load tests and
2. How a subsequent damp heat (DH) exposure is influencing that correlation mentioned above?

2 EXPERIMENTAL SETUP

The module tests described in this study have been carried at the mechanical load test set-up of PI-Berlin which consists of 16 pneumatic cylinders, each of them equipped with four vacuum cups, as shown in Fig. 1. Load and cycle times can be varied via software.

Figure 1: Mechanical load set-up at PI Berlin.

The modules used in the following test sequences are commercially available of 1,595 mm x 792 mm in size and consist of 72 single-crystalline cells of 5'' (127 mm) in size and are equipped with two bus bars.

All tests have been performed at PI-Berlin according to the test procedures as given in Table I. For this paper the DML was adjusted to the existing standard IEEE 1262, i.e. the cycle time was set to 3 seconds and the maximum force to 1,440 Pa.

Table I: Test scheme for 15 full-size single-crystalline PV modules including static mechanical load tests (SML), dynamic mechanical load tests (DML) and 672 hours of damp heat (DH) treatment.

Module	SML	DML	DH672
SML1	X	-	X
SML2	X	-	X
SML3	X	-	-
SML4	X	-	-
SML5	X	-	-
DML1	-	X	X
DML2	-	X	X
DML3	-	X	-
DML4	-	X	-
DML5	-	X	-
DH1	-	-	X
DH2	-	-	X
DH3	-	-	X
DH4	-	-	X
Reference	-	-	-

Before and after each test of Table I, electrical power putput at STC has been measured, also insulation tests (dry and wet) and electro-luminescencehas been caried out. Electroluminescence analysis is a uselful tool to detect micro cracks and other defects in PV modules. Because of its unique spatial information, PI-Berlin is using this method sucessfully since 2007 for fast module characterisation and as a tool for failure analysis [9].

3 DYNAMIC AND STATIC LOAD TESTS

BP Solar reported strong power losses after dynamic load tests combined with climatic stress at modules with micro cracks, but did not sense this for the static load tests [4].

Fracture mechanics of silicon shows that the propagation of micro cracks or/and cell breakage is depending on the maximum bending radius of the module and not the number of cycles [10] . The dynamic load test (DML) is running with only half the pressure, but for 10,000 cycles - compared to three cycles at the static load test.

Figure 2 shows the amount of all micro cracks, broken cells and contact problems counted of every single module before and after mechanical stress and also compares static (SML) with dynamic load (DML) tests. While micro-cracks and broken cells are visible via dark lines or show completely inactive areas bordering the cell edges, solder problems can be identified from asymmetric luminescence intensities at each half of a cell, i.e. differently at the two bus bars.

The modules DML1, DML3 and DML4 failed completely after DML. No power and no electroluminescence image could be detected, apparently due to a complete interruption of the electrical circuit and most likely from loose solder joints to the bussing ribbons or parallel solder joint problems on both bus bars. The latter is supported by the significant lager number of contact problems for the dynamic load test modules detected by electroluminescence.

For failure analysis the strings were measured separately at module DML3, which revealed one defect string. The average power loss of the remaining strings was -4.2% for this module (not listed in Table II)

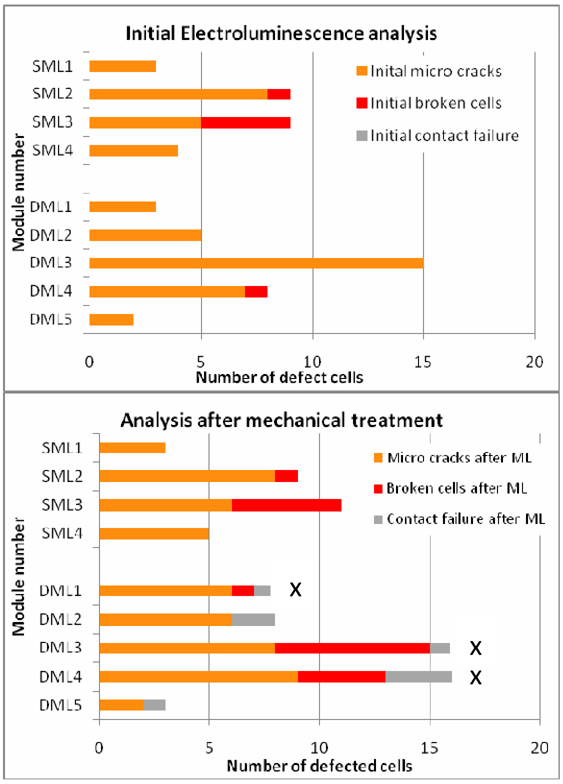


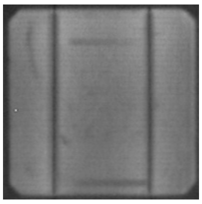
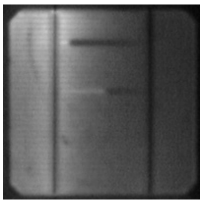
Figure 2: Micro cracks, broken cells and contact problems before and after mechanical load tests, detected via electroluminescence. X indicates those modules that showed a total power loss after mechanical load.

Table II: Module power losses after static mechanical load (SML) and dynamic mechanical load (DML).

Module	Before ML	After ML	Power change
SML1	154.1	150.5	-2.4%
SML2	154.1	151.1	-2.0%
SML3	153.8	150.7	-2.1%
SML4	153.1	151.5	-1.0%
DML1	152.9	failure	-
DML2	149.6	148.6	-0.7%
DML3	153.3	failure	-
DML4	152.1	failure	-
DML5	151.9	150.6	-0.8%

Apart from the breakdown of the three dynamic load modules, Table II shows power drops for all remaining modules as well. The power losses are slightly higher for the static load modules than for the "surviving" dynamic load modules. The "surviving" modules are among those modules, which show no increase in the number of broken cells. But contacts problems were detected at these "surviving" dynamic load modules as for all dynamic load modules. No contact problems were observed for the static load modules.

Table III: Electroluminescence pictures before (left) and after (right) dynamic mechanical load. While micro cracks and broken cells are visible through dark lines or complete inactive areas bordering to the cell edges, solder problems can be concluded from asymmetric luminescence intensities for both cell halves, i.e. differently for the two bus bars as shown on the right picture.

	Before	After dynamic load test
Cell#1		

The dynamic load test is able to sense contact problems from bad soldering much better than the static load test. As long as only one bus bar is involved, one observes just slight power losses, due to the redundancy of bus bar still in operation. If both bus bars are involved, the module fails completely. The high number of cycles in the dynamic load is likely to be responsible for weakening the solder joints or the copper ribbons themselves. Both materials show plastic deformations beyond the elastic regime and are not brittle such as crystalline silicon, which will not deform but break under tensile stress.

The static load test is potentially more critical for crystalline silicon cells with micro cracks, because of the higher load of 2,400 Pa compared to 1,440 Pa, which results in a higher tensile stress on the silicon cell [10].

4 DAMP HEAT TREATMENT

A recent report from ECN demonstrates corrosion effects after damp on ECN's MWT-cells [5]. In that study, the Al-Ag overlap is corroding due to humidity and acetic acid generated by EVA. The Al-Ag overlap is also part of a standard crystalline cell, what would mean, that standard crystalline modules eventually could be affected as well.

Eight modules were exposed to 672 hours 85°C/ 85% r.h., four modules with and four modules without pre-treatment by static and dynamic mechanical load. The power output was monitored on a weekly basis. We did not observe any corrosion in the EL pictures or any evidence for degradation in all modules' power output. Micrographs from bare cells after dynamic load cycles and damp heat show no visible corrosion effect either. We observed an increase of 2.3% and 1.7% for the modules with and without mechanical pre-treatment, respectively. This increase is mainly driven by an increase of the fill factor *FF*. This effect cannot be attributed to this study - it is typically observed during all IEC product qualifications after damp heat treatment. Generally sample modules, which are tested in the damp heat chamber according to the IEC standard, show a higher power output P_{max} deriving from an increase in open circuit voltage V_{oc} and short circuit current I_{sc}.

Table IV: Averaged changes of electrical parameters for 15 single-crystalline modules after mechanical load test (ML) with a subsequent damp heat treatment of 672 h, the same damp heat exposure only, and data from PI Berlin after 1,000 h of IEC damp heat treatment (also for single crystalline modules).

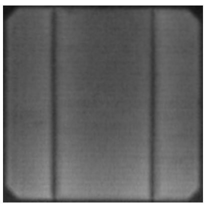
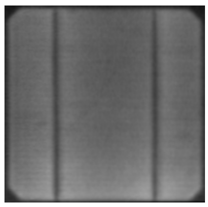
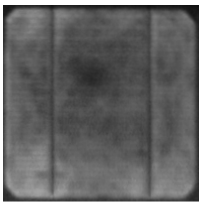
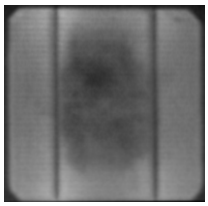
	ML and damp heat (672 h)	Damp heat only (672 h)	Damp heat only PI's IEC data (1000 h)
ΔP_{max}	2.3%	1.7%	1.1%
ΔI_{sc}	0.6%	0.1%	0.7%
ΔV_{oc}	0.5%	0.3%	0.5%
ΔFF	0.9%	1.2%	-0.04%

A similar effect is described in [11] by a passivation of bare cells under high pressure hot water vapor at temperatures of 300°C and pressures of 1.5 MPa, which is explained therein from the terminating of the silicon dangling bonds by activated oxygen.

The authors reported an increase in diffusion length and surface recombination velocity for the microwave photoconductance decay (µ-PCD), an increase in *FF*, I_{sc} and V_{oc} at the sun simulator and an increased electro-luminescence emission after the hot vapour treatment.

We observe the same effect in the damp heat chamber already at 85°C and at atmospheric pressure. The EL images in Table IV show the comparison of two cells before and after 672 hours of damp heat exposure. Dark areas on the cell are an indicator for poor electronic micro parameters, i.e., low diffusion lengths and high surface recombination rates. After the damp heat exposure, those areas become brighter and more homogenous for the modules under test, see Table IV.

Table V: EL-images of single-crystalline silicon cells from the same module before (upper image) and after (lower image) 672 hours of damp heat treatment.

	Before	After damp heat exposure
Cell#1		
Cell#2		

Moreover, Table IV is demonstrating as well that the passivation effect deriving from the damp heat treatment is not affecting all cells at the same level. The electrical mismatch between the cells in the same module will increase from this cell dependent passivation effect. This results in a fill factor increase as known for non-uniform irradiation over the module area in sun simulators [12]. The more inhomogenous the cells in the initial state, the more pronounced is the fill factor increase as for the 15 modules under test compared to the PI Berlin database's average, see Table III.

5 CONCLUSIONS

Dynamical mechanical load tests affect the mechanical robustness of the solder contacts in photovoltaic modules. We sensed a high failure rate at the electrical circuit with complete breakdown of the module power, but not with static load on the same group of mono crystalline test modules. We believe that this rate is highly dependent on the module manufacturer's soldering process.

Static mechanical load tests increase the number of micro cracks and broken cells more efficient as detected by electroluminescence. This is due to the higher pressure laid down in the standards for the static mechanical load test. Power losses are slightly higher in the range of -2% for the static load test

There was no indication for a corrosion effect as reported for MWT cells at the Ag/Al-overlap on the backside after 672 h damp heat with and without mechanical load pre-treatment. The damp heat exposure will be continued.

The passivation effect from damp heat treatment results in an power increase of +2% in average on single crystalline silicon modules. This in accordance with data from our data base on single crystalline modules in the IEC certification test procedure with an average increase of +1%. This interesting effect will be investigated in further studies.

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