IN-FIELD EIGEN OSCILLATION-MEASUREMENT FOR DETECTION OF UV-INDUCED EVA-DEGRADATION

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ABSTRACT: Photovoltaic-modules are exposed to static mechanical loads, such as snow and wind loads during conventional use. Wind also triggers oscillations. It is obvious that the dynamic loads are more likely to cause well known fatigue of materials even with little amplitudes, especially of brittle behaving PV-cells and ductile copper connecting wires.
The dynamic behavior of PV-modules depending on the UV-induced aging of the ethylene vinyl acetate encapsulation is analyzed in outdoor strain-measurements. A detailed numeric model of a PV-module was created and mechanical loads for measurements in inaccessible regions in the laminate were calculated. The dependence from aging condition of encapsulation polymer shown in outdoor-results could be reproduced in the model.

Keywords: dynamic mechanical loads, FEM-simulation, outdoor tests

1 INTRODUCTION

PV-modules are sold all over the world and are installed at different sites and facilities under a variety of climatic conditions. All of these climates have one apparent thing in common: modules are exposed to UV-radiation. Today modules are certificated by standard tests according to IEC 61215 [1] and IEC 61646 [2] to qualificate them for application. These tests are merely a certification, not a prognosis for module-lifetime; it is not suitable to picture aging effects of modules in field. Even natural loading scenarios as almost omnipresent wind load and especially its dynamic is not addressed in the tests. Neither the complex influence of dynamic loads on the components in the laminate of PV-modules nor the influence of e.g. the aging on the modules dynamic is considered. There is no standard for testing the consequences of UV-aging of polymers in the laminate on stress based defects of components caused by oscillation effects; even though UV-aging tests exist.

In the context of the work that forms the basis of this article, the oscillation behavior of PV-modules was investigated. The aging effect of PV-modules on its oscillation behavior was therefor observed in field as well as numerically calculated; in particular the aging effect of the polymeric encapsulation was observed. Moreover the effect of EVA aging and dynamic behavior on the mechanical stresses in the laminate was calculated.

2 FREEWEATHERING: MEASUREMENT OF DYNAMIC BEHAVIOR OF PV-MODULES

PV-modules in the field are exposed to static loads, such as snow and wind loads and also to dynamic loads caused by squalls and wind. To quantify the result of these acting loads in field, gains at the module have to be measured and be correlated with weather conditions at the moment of appearance.

2.1 Experimental setup

For the experiments a glass-foil-PV-module with the size of 1620 x 810 mm² (6 x 12 Si-cells) was equipped with six two-wire strain gauges (0°/45°/90°, type KFG-2-120-D17-11l1M2S), which were fixed at the top of front glass with special glue as shown in Figure 1. The strain gauges are protected by PU-finish and different layers of polymeric cover from atmospheric exposure [3]. Strain gauges were electrical connected. Data were collected and handled by a data acquisition system based on a common computer and a CANHEAD® direct by Hottinger Baldwin Messtechnik GmbH. With this setup, a 150 Hz data acquisition is possible. Data transfer to Germany is assured by UMTS communication.

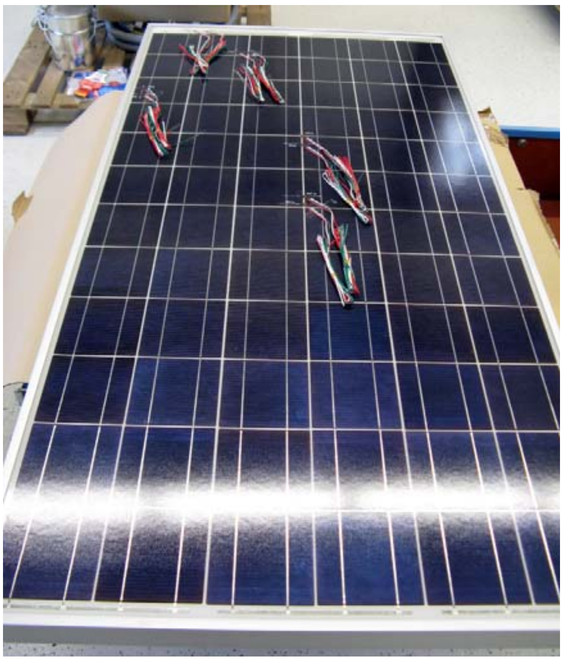

Figure 1: strain gauges equipped PV-module

The data acquisition system and the PV-module, which is prepared in the described way was shipped to Grand Canary. The module was mounted on an aluminum-rack by the specifications of the manufacturer at a typical slope facing the sun. Adding the strains the modules temperature was measured by PT100 temperature sensor, mounted at the polymeric back sheet at the backside of the module.

2.2 Frequency analysis of strain data and shifts in dynamic behavior

The recording of strains at the tempered glass-pane front side with a measurement rate of 100 Hz indicates explicit dynamic behavior of the module. This is well known from mensuration in laboratory with different types of PV-modules [4]. For a more precisely identification of dynamic behavior a Fourier transformation with the 100 Hz-data was executed [5] over a period of one hour. The transformed data showed some clear peaks at 11.8 Hz and at 20.4 Hz respectively 21.8 Hz (see Figure 2), which can be treated as resonances.

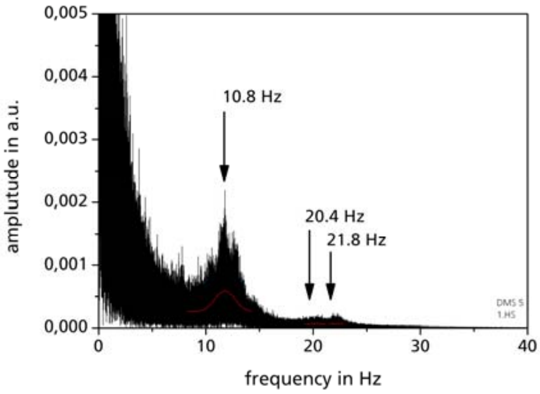

Figure 2: Fourier transformation of strain data for frequency analysis (6^{th} May 2012, 10:44 am – 11:44 am, DMS 5)

2.3 Materials specific values of polymeric encapsulation EVA

Having regard to its mechanical nature, the aging behavior of the polymeric encapsulation – in this case ethylene vinyl acetate (EVA) – is to be investigated. Two test samples (one tempered glass-pane, EVA, Si-cells and polymeric back-sheet with the size of 550 x 200 mm²) were produced in an industrial lamination process. Sample one was UV-weathered with overall 105 kWh, what is assimilable to 1.5 years in Cologne, Germany. Interim, sample two was stored at a dark, cool and dry place.

After UV weathering of sample one, both laminates were cut and micro sections were prepared. The elastic modulus of EVA in sample one was measured by nanoindentation with a Fisherscope NT1100 by Helmut Fischer GmbH. The elastic modulus was compared with elastic modulus of EVA in sample two, which was acquired in the same way. The results showed even after the short exposition of UV a clear embrittlement of the polymer. This becomes apparent by an increase of elastic module of the EVA in the UV-exposed sample in comparison to the comparator laminate. The increase of elastic module caused by UV-exposition is within the range of 60 %.

2.4 Shifting of intraday oscillation behavior

Due to the increase of elastic modulus of the polymeric encapsulation EVA, a measurable influence on oscillation behavior of the module is expected. We want to measure the resulting effect of embrittlement of EVA in consequence of in field UV exposition. Therefor the location of the first peak in Fourier spectrum (during the further named as zero order Eigen oscillation) is traced for a period of a few hours to a day. This showed an interim shift of frequency, which converges to a sinus, as shown in Figure 3 (underpart). Causal for this behavior is not the caused by an aging effect and an embrittlement of the encapsulation polymer. This process is an effect with a shorter time constant. It is rather an effect caused by a highly temperature depending elastic modulus of EVA. The temperature dependence of the elastic modulus of the polymer causes a change in the stiffness of the whole module. This leads to a measurable change in the oscillation behavior and in this way to a shift of Eigen frequency.

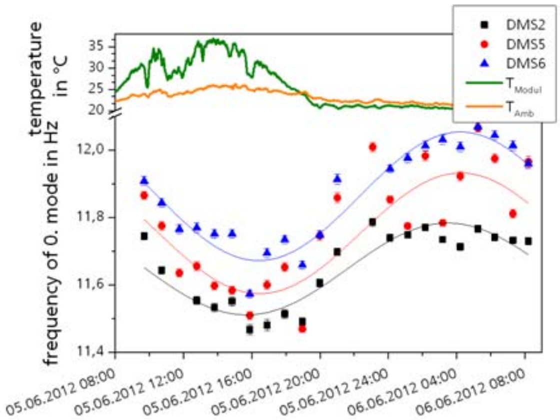

Figure 3: Interim shift of frequency of zero order Eigen mode compared to back side measured module temperature T_{mod} [6]

2.5 Shifting of oscillation behavior caused by aging effects

Our goal was to measure the UV-aging effect in field; we had to separate the expected shift of frequency over time caused by embrittlement of the encapsulation polymer EVA from the temperature induced effect. Therefor data were filtered by temperature. Only strain data grabbed within a module temperature range $\Delta T_{mod} = \pm 2.5$ K (between 22.5 °C and 27.5 °C) were used.

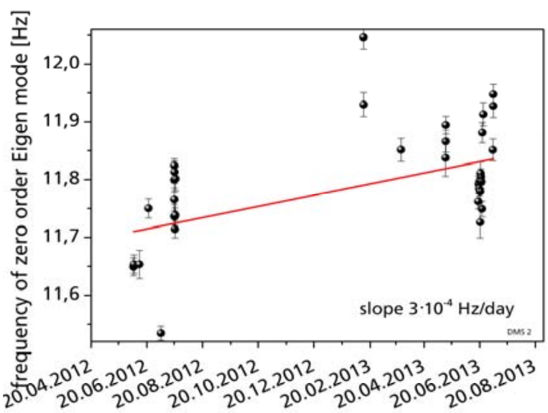

Figure 4: Frequency trend of zero order Eigen mode at constant module temperature T_{mod} over a period of more than one year

Over a period of more than one year the frequency of zero order Eigen mode was traced[1]. It was plotted against time as shown in

Figure **4**. In this graphic an increase of the measured Eigen frequency of $(3.1 \cdot 10^{-4} \pm 0.8 \cdot 10^{-4})$ Hz/day over time caused by aging of the en-capsulation polymer can be found. For more precise evidence a longer period of several years has to be considered.

3 NUMERIC CALCULATION: DYNAMIC BEHAVIOR OF PV-MODULES AND ITS INFLUENCE ON MODULE COMPONENTS

3.1 Layout of FEM model

Beside the infield measurement of strains a fully 3D-FEM model of a PV-module was developed in analogy to the one in field. In the FEM model the layer buildup, the aluminum frame and its bonding as well as the mounting at the aluminum rack was considered. Additional a sub model was created which considered further details as Cu-interconnections and its soldering. Details of the model are shown in the sketch in Figure 5. Previously determined specific values of all in the laminate used materials and components were implemented in the FEM model. The model was verified by comparative analysis with test samples.

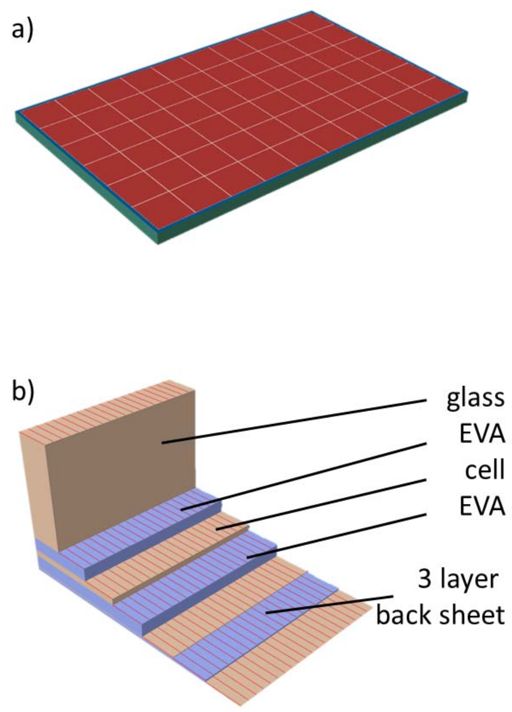

Figure 5: Sketch of FEM-models layout
a) global model of PV-module
b) detailed layer setup of modules laminate

[1] The gap in autumn and winter (between august 2012 and February 2013) is caused by lower wind speed [6] averages in this period. This leads to less prominent Eigen frequency peaks.

The oscillation behavior of the module was calculated using the detailed FEM-model of that PV-module. The calculation results are in good agreement with the frequencies obtained of the infield measurement of zero order and first order Eigen mode as shown in table I.

Table I: Comparison between calculated and measured frequencies of zero and first orders Eigen modes

	zero order	first order
Calculation	11.7 Hz	27 Hz
Measurement	11.8 ± 0.1 Hz	21 ± 1 Hz

3.2 Shifting of oscillation behavior caused shifts in elastic modulus of encapsulation polymer due to aging

Eigen frequencies were calculated based upon material specific values of freshly cross-linked EVA utilizing the above specified FEM-model. The same calculation with specific values of UV aged EVA was proceeded in comparison. Therefore the elastic modulus of EVA was varied from 0.8 times of the elastic modulus of 'new' EVA up to 1.8 times and the zero order Eigen frequency of the PV-module calculated. The calculation showed shifts of frequencies for UV aged EVA, which is shown in Figure 6. The shifts are in the same range as they are in the infield tests shown in

Figure **4**.

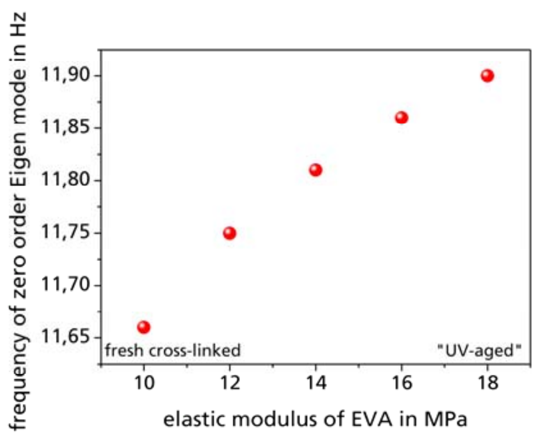

Figure 6: Numerical calculated context between elastic modulus of encapsulation polymer (EVA) and the resulting zero order Eigen frequency of PV-module

3.3 Influences of polymer aging effects on components in the module

It is now possible to calculate resulting strains and mechanical stresses in areas which are inaccessible for measurements or in components in the laminate, using the FEM model and experimental based data from infield measurements. Therefore, measurements of apparent amplitudes during oscillation were used [7]. Notably the copper interconnectors between Si-cells are exposed to mechanical stress at the maximal detected amplitude of 14 mm while zero order Eigen mode. Especially the region of the interconnectors crank is exposed to an exaggeration of mechanical stress, which is pictured in Figure 1. Likewise dynamic loading causes stresses in interfacial regions between different layers of front glass, encapsulation, Si-cells and back sheet. This can lead to delamination. It could be demonstrated that embrittlement of the encapsulation polymer leads to an explicit increase of mechanical stress in the crank region of cells interconnection thereby to an increase of failure probability during oscillation of the module [8].

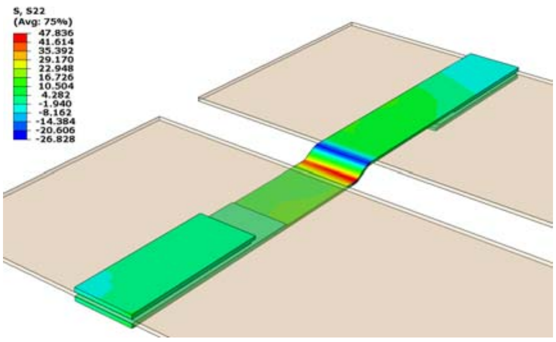

Figure 7: Calculated mechanical stresses in Cu-interconnector during maximal deflection of 14 mm during zero order Eigen mode of module

4 CONCLUSION

Using strain measurements with data rates up to 100 Hz it was possible to proof Eigen oscillations of PV-modules infield induced by wind. Additionally the influence of temperature - that leads to a shift of the elastic modulus of EVA - on the oscillation behavior is shown. It was possible to separate temperature effects of EVA-stiffness from UV-aging effects causing embrittlement by filtering data regarding constant module temperature T_{mod}. The increase of elastic modulus of EVA as a result of UV-aging could be demonstrated infield for a period of more than one year. An increase of frequency of zero order Eigen mode could be recorded. It was determined to $(3.1 \cdot 10^{-4} \pm 0.8 \cdot 10^{-4})$ Hz/day. For more precise evidence a longer period of several years has to be considered.

A numerical calculation with detailed FEM model was able to reproduce the measured effects. It is possible to calculate effects of aging and the resulting effects on stresses even in regions which are inaccessible for measurements or in components in the laminate of PV-modules. Calculations show maxima of mechanical stresses at the crank of Cu-interconnectors. Over that it is possible to calculate the aging condition respectively the elastic modulus of EVA using oscillation data from infield measurements.

Calculations have shown that in the experiments measured UV-caused aging leads to increase of mechanical stress in components in the laminate of the module.

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