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DIAGNOSTICS OF POTENTIAL INDUCED DEGRADATION IN PHOTOVOLTAICS

Vladimír Šály*, Michal Váry*, Viktor Schlosser**, Juraj Packa*, Milan Perný*, Eduard Firický*,
Ondrej Kulich* and Vladimír Ďurman*
*Slovak University of Technology, FEI, Ilkovičova 3, SK-81219 Bratislava, Slovak Republic
** University of Vienna, Faculty of Physics, Strudlhofgasse 4, A-1090 Vienna, Austria

Abstract

The aim of this paper is the investigation of electrical and mechanical properties of solar cells assembled into modules, before and after accelerated ageing. It was shown that impedance spectroscopy measurement and characterization is an important tool to reveal the degradation due to high voltage stress and increased temperature stress. The mechanical parameters were derived from natural vibration measurements. Important differences between the results of measurements were found before and after stressing the modules.

Key words: *Solar cells and modules, Accelerated ageing, High voltage stress, Impedance spectroscopy*

1. INTRODUCTION

Photovoltaic generator converts solar radiation into electricity directly using single solar cells interconnected together within photovoltaic module into bigger and compact assignment. Photovoltaic cell and module are dc electric sources active during the time period when light, coming from sun or other light radiation source, is available. Common PV module represents dc electric source producing electric power usually at tens of volts and units of amperes which results into power ranging up to 200 – 300 W. The power depends on the amount of single cells connected together in module.

Compact photovoltaic module is layered structure where interconnected and encapsulated solar cells are embedded between substrate and superstrate (back and front sheets), glass or plastic sheets, in order to create compact and sealed unit, ease to handle and protected against environmental detrimental influences. Usual alignment from top to bottom in flat plate sandwich module structure is:

- Transparent covering glassy or plastic sheet
- Solar cells strings encapsulated between two sheets of encapsulant foil – mostly commercially available modules use EVA (ethylene vinyl acetate) foil as an encapsulant
- Bottom supporting glassy or plastic sheet

Schematic figuration is in Fig. 1. Commercially available photovoltaic modules are with or without metallic frame. Metallic frame helps to support the module while on the other hand, in the case of module without frame, the cost of metallic part is avoided. Photovoltaic modules installed in photovoltaic generator in outer environment are intended to operate reliable for more than twenty years without any considerable decrease of conversion efficiency.

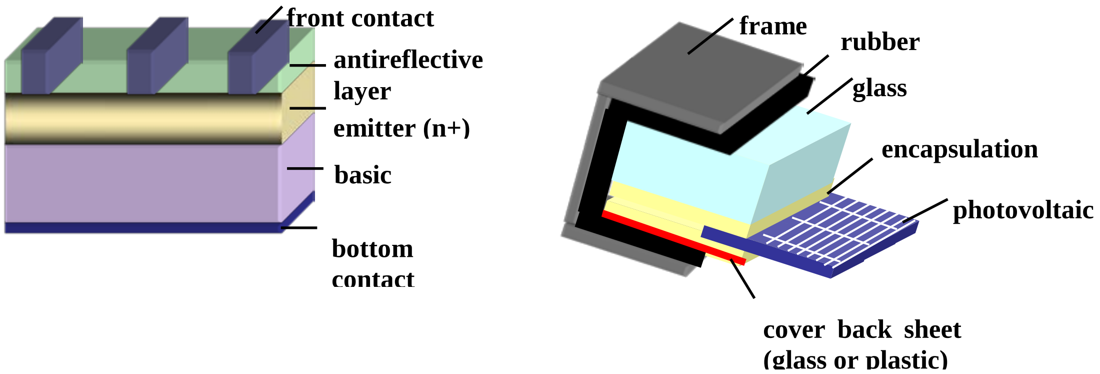

Fig. 1 Photovoltaic cell and module arrangement

The solar photovoltaic modules that are available on the market are rated with their peak power W_p. This value is important for the installers but the power is generated at standard test conditions only, usually 1000 Wm^{-2}. The illumination light is characterized by standard spectra, eg AM1 or 1.5. General labelled information include parameters as

- open circuit voltage V_{oc}
- short circuit current I_{sc}
- maximum power voltage V_{max}
- maximum power current I_{max}
- maximum power rating P_{max}.

During operation the module undergo degradation due to environmental influences, as increased temperature, humidity, hailing and lightning effects. The impact of the above mentioned quantities results in decrease of conversion efficiency. The influences of electrical nature, like overvoltage, biasing or high voltage stress, can have also deteriorating effect. Their origin can be natural, as in the case of atmospheric electricity, or artificial, coming eg from electric grid. Sometimes it comes out from the photovoltaic system itself, like in the case of dc potential generation when a great number of single cells is connected together in series. This is the potential between electrified cells and grounded frame.

In order to reasonable control the power output of PV system, the degradation and its influence must by clearly recognized during the operation.

When we have a great number of solar cells connected into series, high voltage appears between the first cell metallization and the module or system frame. In such a case it is generally known that at sharp edges and corners the local maximum of the electric field occurs and leakage currents flow from the module cells through encapsulant – module insulation into the frame. The degradation and power loss which results from the stress exerted by system voltage bias and high voltage in the fielded arrays have been observed in PV modules. An electric breakdown of the cell encapsulant stressed by great electric field can be also expected (Mon, G.R. et al., 1984).

When the module dimension increases, some critical aspects must be taken into account (Šály, V. et al., 1995), like changes of the solar cells metallization and their electrical parameters under a high voltage stress (HVS) or changes of electrical, mechanical and optical properties of an encapsulant under various influences.

HVS is related to phenomenon – Potential-Induced Degradation (PID) which is still attracting attention. In this field, a powerful diagnostics technique is of great importance. Potential induced degradation process undergoes both, solar cells and modules encapsulation. The effect of HVS depends on the leakage current between solar cells and ground and affects the long term stability. Possible leakage current paths are discussed eg in (Pingel, S. et al., 2010). Long-time known process has got interest with rapid growth in photovoltaic plant deployment. On the other hand, increased production volume has brought price reduction but it is occasionally accompanied with quality reduction of modules (http://solarenergy.advanced-energy.com/upload/File/White_Papers/ENG-PID-270-01%20web.pdf).

2. PHOTOVOLTAIC MODULE DEGRADATION

Degradation of photovoltaic modules worsens the performance. It is reflected mainly in decreased efficiency. PID is an undesirable property which can appear and influence some solar module performance. The process is ascribed to the influence of voltage, heat and humidity. The effect does not occur on all photovoltaic systems. During the operation of photovoltaic plant, the day and night conditions alternate which result in cycling influence of voltage bias of cell strings and regeneration process in the night (Koch, S. et al., 2013)

Both, solar cells themselves and encapsulation material of the photovoltaic modules, during the real life time, undergo the degradation process. To exclude a lot of connections, large modules with a higher output voltage and power are interesting when the high power source is requested. When the module dimension increases, some critical aspects must be taken into account (Šály, V. et al., 1995). Among them:

- changes of solar cells metallization and electrical parameters change of the single cell and modules under a high voltage stress (HVS),

- encapsulation material, its electrical, mechanical and optical properties under various temperature, radiance and weather influence.

As a particular module degradation mechanism, the electrochemical corrosion of the cells metallization gives rise to the encapsulant deterioration, especially its electrical stability. The voltage between two electrified cells or between cell and grounded metallic frame can result in dissolution of the cell metallization into surrounding encapsulant, which becomes unable to prevent formation of an electrical breakdown. The humidity is very effective to expedite this process. In order to avoid the failure of the electrical equipment and in order to estimate the real life time, the accelerated ageing tests are often done under the extremely conditions (elevated temperature, electric field, UV radiation).

High voltage can lead to module degradation by multiple mechanisms. The voltage bias degradation is linked to the leakage current (Fig. 2). Electric charge is flowing from silicon active layer (in the case of silicon solar cells) through the encapsulant and glass to the grounded module frame or to the supporting grounded construction structure. On the other hand moving electric charge can accumulate in specific location within PV module. This effect results in persistent polarization (Hacke, P. et al., 2011).

The encapsulant in PV module is the dielectric in capacitor of a low capacitance value and non-defined geometry. Its electrodes are either metallic frame or metallic electrodes of the contact grid. Measurement capacitor, made of conductive foils and encapsulant as dielectric, can be included into module structure in order to perform experimental electric measurements.

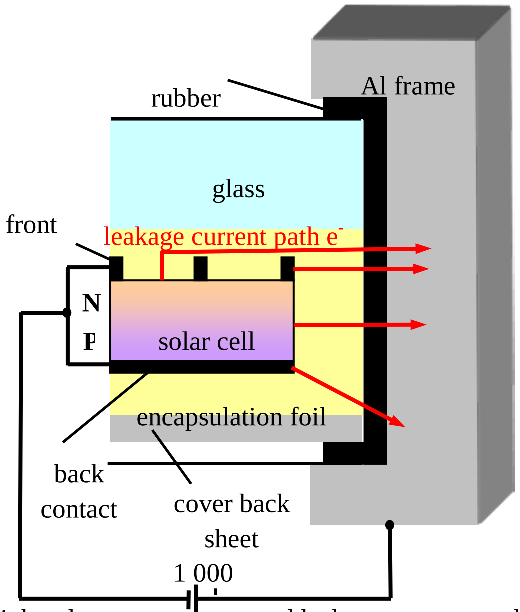

Fig. 2 High voltage stress setup and leakage currents paths

Under the dc conditions capacitor is loaded and characterized by time constant τ corresponding to equivalent circuit. The dc resistance is measured at voltage at least 500 V and 50 MΩ is accepted according standards issued by International Electrotechnical Commision. It should be remarked that the value of insulation resistance is a matter of used material on one hand and the matter of geometry on the other hand.

Currents through the insulator or resistance measured at dc voltage are time dependent quantities. Under the influence of electric potential on grounded PV module structure also ionic current leaks which can result in degradation.

3. FACTORS WHICH CAUSE POTENTIAL INDUCED DEGRADATION

Currents of the mobile ions within the module structure can result in PID. The conductive paths are through semiconductor material of solar cells, encapsulant plastic foil, glass or plastic supporting and covering sheets and metallic mounting frame or structure. The mobility of ions is related to temperature and humidity as it is generally common in electrical insulating material. The environmental factors interact with the factors resulting from photovoltaic system operation which involve system itself, the properties and behaviour of module and the cells. Environment is the matter of installation but system, modules and cells are the matter of choice and can by controlled.

Environment Among most effective environmental influences one has to take into account the humidity which effects photovoltaic module in interoperation with temperature variations from freeze to hot. These factors have been found to be effective in PID process. The reliability of the modules is commonly estimated according international standards as eg IEC 61215 Crystalline silicon terrestrial photovoltaic (PV) modules – design qualification and type approval. More about testing and accelerated ageing see (Osterwald, C.R.T. and McMahon, J., 2009). During operation of photovoltaic plant high voltage stress, effective in PID process, appears periodically as day and night, low and high temperature periods repeat, and following, degradation due to PID and regeneration of the modules reducing PID appear. Finally, a clear correlation can be observed between PID and weather conditions.

Photovoltaic system the voltage potential which stresses the module, depends on the position of the module in the photovoltaic array and also on the grounding topology. String potential regarding the grounding scheme is shown in Fig. 3 (Pingel, S. et al., 2010).

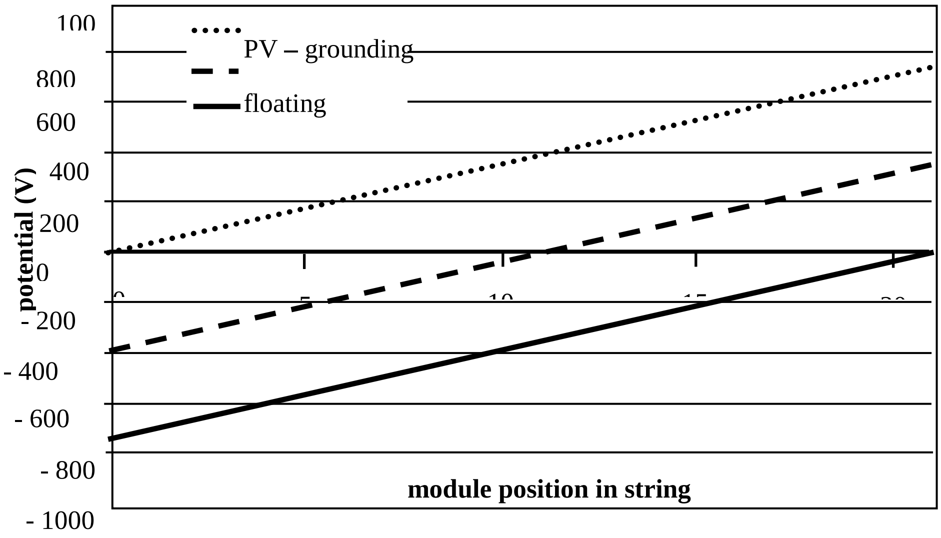

Fig. 3 PV array string potential according the grounding scheme PV+/floating/PV

PID is most often associated with a negative voltage potential to ground, nevertheless, the positive potential to ground and its effectivity in PID process was described in (Swanson, R. et al., 2005). As array voltage increases, mainly by means of system cost reduction in large photovoltaic plants, resistance to PID will become increasingly critical. Photovoltaic industry is considered plants up to 2000 V.

Module structure Semiconductors, glass and organic plastic materials create a compact structure in which solar cells are effectively protected. Module is a basic electric element of photovoltaic system. Front covering glass contains sodium which is considered as one of factors resulting in PID. It was understood that sodium but also aluminium, magnesium, and calcium presented in smaller concentration in soda-lime glass might be effective species. This finding also does not yet reveal if the chemical nature of the unknown species is important or if it just acts as a carrier for charge and current (Schütze, M. et al., 2014).

Ethylene vinyl acetate (EVA) is the most common encapsulating material for crystalline silicon modules. EVA still commands the vast majority of solar module encapsulation today: it has a proven track record and is a low-cost option. Additive materials to improve EVA's crosslinking and adhesion properties can generate "free radicals" which contribute to physical deterioration and degradation of properties, starting with yellowing or discolouration. Among these is generation of acetic acid.

Except of EVA, ionomer materials have been employed as encapsulants in niche applications for several years. Among the key performance benefit is minimising potential induced degradation, a well-known cause of solar panel failure.

Commercialising of polyolefin-based encapsulant film began in late 2010. Polyolefin-based encapsulant offers the best volume resistivity – significantly better than ionomers, and up to 1000 times better than EVA. Higher volume resistivity means lower leakage current and longer-term performance (Montgomery, J., 2014).

Silicon dioxide deposited on the glass sheet can act as diffusion barrier for sodium between glass and encapsulant, thus preventing but not eliminating PID.

Solar cells are covered by the antireflective coating (ARC) at the top of the cell which is integral part of photovoltaic cells and increases the cell efficiency. It is another prerequisite for the PID process (Pingel, S. et al., 2010). Also the wafer material has been identified to be another crucial factor regarding PID. The most significant parameter in this respect is the base resistivity (Berghold, J. et al., 2014).

Typical result of PID is the decrease of shunt resistance R_{sh} which reduce the maximum obtained power. This is depicted on the current-voltage characteristic in Fig. 4.

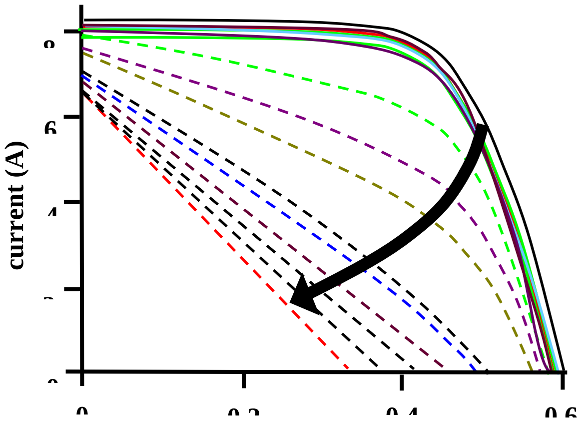

Fig. 4 PID affected module according (Schütze 14). The evolution of PID results in decreasing fill factor, open circuit voltage and short circuit current.

4. PHOTOVOLTAIC MODULE AS AN INSULATION SYSTEM

As to the electric insulation, the present photovoltaic modules can easily withstand voltages up to 5 000 V and this limit can be even increased in excess of 10 000 V with simple and inexpensive improvements. The experience gained up to date with solar PV modules already in service is in favour of the supposed good reliability even when they were connected in series of hundred and more. The other point that must be investigated is the general behaviour and long term performance of the solar cells when they have to operate under high voltages (Redi, P., 1991).

For the estimation of experimental or commercial PV module electric parameters both, dc and ac measurements can be performed. Insulation resistance, charging/polarisation current (dc current at applied voltage bias) and chosen dielectric quantities are measured either on solar cells themselves or on encapsulant within the interval of temperatures.

The current in the body of the insulation or in semiconductor solar cell structure is the sum of three components:

- capacitance charging current,
- absorption current,
- leakage or conduction current.

Leakage current is independent on the time of applied voltage in comparison with capacitance and absorption currents. The absorption current in a layered insulating structure is the sum of charging current of the capacitor, the polarization current, space charge current and conduction current. Slow dielectric interfacial polarization within layered insulating system appears to be quite effective.

Quantities like complex impedance/admittance, permittivity or loss factor are usually investigated in order to characterize measured system and its behaviour (Ďuriš, T. et al., 2010). Typical dependence of loss factor obtained on the capacitor created by cell metallization and outer electrode is shown in Fig. 5. Low frequency polarization process related to interfacial phenomenon is markedly distinguished.

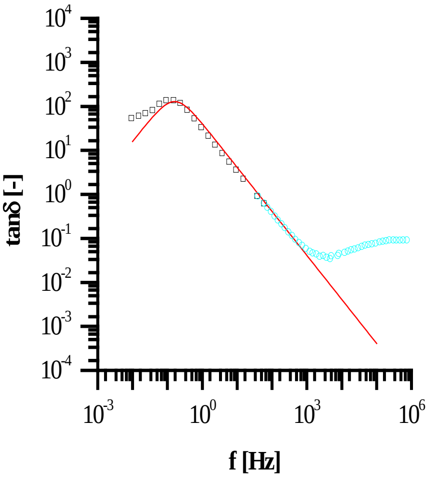

Fig. 5 Plot of tanδ versus frequency – verification of interfacial polarization. The data within 10^{-2} Hz up to 50 Hz were captured by very low frequency measurement method while data at frequency higher then 50 Hz were measured using HIOKI Z tester. The measurements were carried out after the accelerated ageing test at elevated temperature 70 °C.

5. MECHANICAL DAMAGE

Mechanical damage is frequently monitored by vibration studies. Experimental modal analysis where a structure is excited by external forces such as an impact hammer or shaker and its frequency response is evaluated and used in many disciplines (geophysics, material science, architecture and engineering). In photovoltaic research it was successfully applied to image stress inhomogeneities (Best, S.R. et al., 2006) and cracks in silicon wafers (Belyev, A. et al., 2006). Resonant frequency, mode shapes and damping of a structure are derived from a modal test system which uses one excitation point on the structure and records the response at many other points thus generating a signal pattern which allows to do some kind of surface imaging.

6. EXPERIMENTAL RESULTS AND DISCUSSION

6.1 Electric performance

The mini-modules assessed in our work were created from a series connection of three high efficiency c-Si solar cells with a cell area 0.6 x 0.6 cm. Module were produced by IXYS Corporation. The modules under test were type KXOB22-04X3-ND from the IXOLAR Palette. They were specified to output an electrical power of 1.5x13.38 mW under STC (www.digikey.com/product-highlights/us/en/ixys-ixolar-solarbit/823).

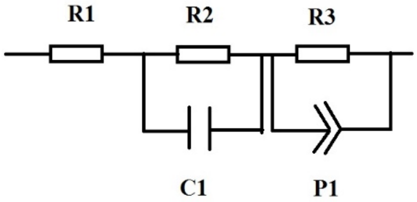

Fig.6 Equivalent circuit used for experimental impedance spectroscopy data evaluation.

Experimental mini-modules were stressed under 1000 V dc (short circuited top and bottom electrodes against grounded auxiliary electrode) and at temperature 80 °C for 48 hours. The influence of PID was evaluated by impedance measurements and the difference in the state before and after the degradation determined. The electric behaviour of the module is interpreted using equivalent circuit (Fig. 6) proposed in accordance with complex impedance frequency dependencies through standard simulation techniques. Constant phase element P1 was included for the best fitting and current transport processes estimation. Complex impedance, real and imaginary parts, was measured under bias 1347 mV and the results are presented in Fig. 7. The values of equivalent circuit elements are presented in Tab. I.

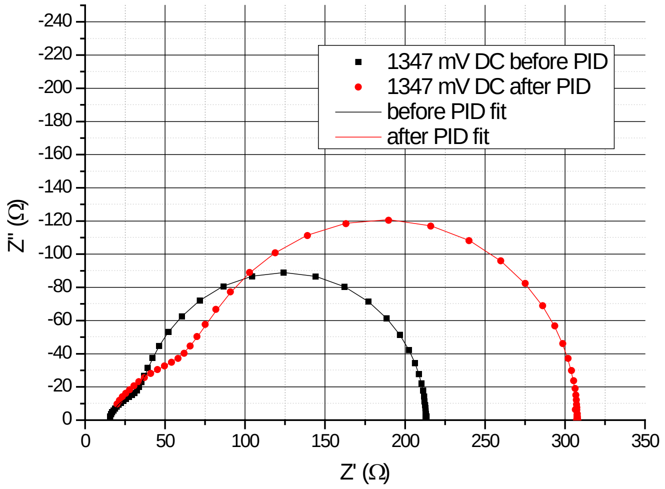

Fig.7 Comparison of Nyquist characteristics for sample module before and after PID treatment, measured at 1347 mV dc.

Tab.I Equivalent circuit elements for sample before and after PID treatment at 1347 mV DC.

	C1 [F]	R1 [Ω]	R2 [Ω]	R3 [Ω]	P1 [F.s$^{(n-1)}$]	n [-]
Before PID	2.877E-07	15.430	175.97	21.701	5.0839E-07	0.84861
After PID	1.3574E-07	15.742	233.16	58.873	3.8374E-07	0.78903

6.2 Vibrational resonances

The analysis of vibrations is a widespread instrument of failure diagnostics in the industry (Piersol, A.G. and Paez, T.L. ed., 2010). In many cases the degradation of complex systems can be easily derived from deviations in the acoustic signal without the necessity to identify a particular source of failure (Braun, S.J., 1986). We applied this method to the investigated minimodules before and after stress. The experiments were carried out with a similar set up which was previously used to analyze silicon wafer for the solar industry (Mitterhofer, S. et al., 2014). The original data evaluation was based on the Kirchhoff Plate equations (Kirchhoff, G.R., 1850). This assumption however, is justified solely for an ideally homogenous, thin rectangular plate. In this case the natural modes can be calculated from the Kirchhoff Plates equations (Ventsel, E. and Krauthammer, T., 2001) where the solution is based on the plate's elasticity and geometry. These conditions are quite well fulfilled in the case of large (156 mm x 156 mm) square shaped c-Si wafers. In the case of the modules the situation is complicated due to the fact that (i) it is a compound system and (ii) the thickness of ~2 mm can no longer be considered to be much smaller than the length (22 mm) or the width (7 mm). The fact that neither the individual materials nor their mass fractions are known makes the search for natural resonances even more challenging. The total mass of the investigated modules as determined from weighting varies between 476.1 mg and 514.2 mg.

A continuous sine wave excitation at one end of the modules was made in the frequency range of 250 Hz to 10 kHz. The wavelength increment was kept invariant at 1 Hz. At the opposite end of the module the magnitude and phase of the transmitted oscillations was received by a microphone. The signal was recorded by a Lock In amplifier (model Stanford Research 850) as a function of the excitation frequency. Only the first harmonics were investigated. In Fig. 8 four maxima in magnitude due to resonant excitation are indicated by arrows. The occurrence of a peak in the magnitude was always accompanied by a change of the phase. Since simple plate theory predicts that vibrational resonances shift linearly towards higher frequencies with the increasing mass of the homogeneous rectangular plate, the correlation of our experimentally observed maxima with the module's mass was examined. However no linear dependency was found.

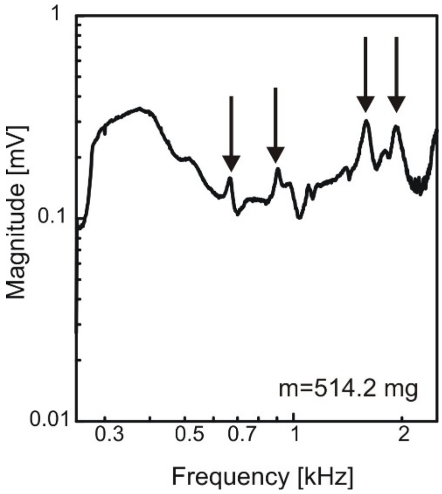

Fig. 8 Recorded vibration spectrum of one mini-module before ageing.

The vibration resonances were examined before and after stressing the modules. Differences in the position of the maxima on the frequency scale as well as changes in shape and heights were observed. So far the results indicate that the proposed method is sufficiently sensitive to changes in the modules mechanical properties caused by forced ageing. A better understanding of the ageing mechanism and how it affects the natural resonances still has to be elaborated in further experiments.

7. CONCLUSION

The aim of this paper was to present some circumstances of solar module performance in photovoltaic system. The various aspects of degradation processes were taken into account and finally the results of high voltage stress experiment presented and discussed.

Vibration analysis was shown to be the sensitive technique able to display very fine changes in the modules mechanical properties.

Complex impedance technique has found application in electrochemistry and it is also capable and giving relevant results in estimation of PV module behaviour, either the solar cells themselves or total module layered structure which includes semiconductor, insulator and metallic parts. The degradation due to high voltage stress was clearly distinguished using complex impedance measurements and the elements of equivalent circuit calculated using simulation technique.

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REFERENCES

BELYAEV, A., POLUPAN, O, DALLAS, W, OSTAPENKO, S., HESS, D., WOHLGEMUTH, J. (2006) *Crack detection and analyses using resonance ultrasonic vibrations in full-size crystalline silicon wafers.* Appl. Phys. Lett. 88, 2006, 111907.

BERGHOLD, J. et al. (1995) *Potential Induced Degradation of solar cells and panels* (www.solon.com/.../solon-fronius-valencia-PID.pdf)

BEST, S. R., HESS, D. P., A. BELYAEV, A., OSTAPENKO, S., KALEJS, J. P. (2006) *Audible vibration diagnostics of thermo-elastic residual stress in multi-crystalline silicon wafers*. Applied Acoustics 67, 2006, 541–549.

BRAUN, S.J. (1986) *Mechanical Signature Analysis*, Academic Press, London, 1986.

ĎURIŠ, T., ŠÁLY, V., ĎURMAN, V., PERNÝ, M., KUSKO, M., BAŘINKA, R. (2010) *Assesment of PV module encapsulant as an insulation system.* Proc. 25 PVSEC, Valencia 2010, paper 4AV.3.31.

HACKE, P. et al. (2011) *System voltage potential-induced degradation mechanisms in PV modules and methods for test*. In: Conference Paper NREL/CP-5200-50716, July 2011.

KIRCHHOFF, G.R. (1850) *Über das Gleichgewicht und die Bewegung einer elastischen Scheibe*, J. Für die Reine und Angewandte Mathematik, 40, 1850, pp. 51 – 88.

KOCH, S. et al. (2013) *Work towards simulation model for potential induced degradation effect on crystalline silicon cells*. 28th European Photovoltaic Solar Energy Conference and Exhibition EPSEC, Paris 2013, p. 1665.

MITTERHOFER, S., PÜHRINGER, J. D. AND SCHLOSSER, V. (2014) *An acoustic set up for the vibration analysis of silicon wafers*, Proceedings of the IECON 2013 - 39th Annual Conference of the IEEE, 2014, p.8068 – 8073, doi:10.1109/IECON.2013.6700482.

MON, G.R., OREHOTSKY, J., ROSS, G.R. & WHITLA, G. (1984) *Predicting electrochemical breakdown in terrestrial photovoltaic modules.* In. Proc. 17th IEEE Photovoltaic Specialists Conference, May 1-4, Kissimmee, 1984, USA 682.

MONTGOMERY, J. (2014) *New PV module encapsulation materials led by new cell types*. Renewable Energy World.com, March 19, 2014.

OSTERWALD, C. R. T. , MCMAHON, J. (2009) *History of accelerated and qualification testing of terrestrial photovoltaic modules: A literature review.* Prog. Photovolt. Res. Appl. 17 (2009) 11.

PINGEL, S. et al. (2010) *Potential induced degradation of solar cells and panels.* In. Proc.: Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE, (http://ieeexplore.ieee.org/).

[1] PIERSOL, A.G. AND PAEZ T. L. (editors) (2010) *Harris‘ Shock and Vibration Handbook*, McGraw-Hill, 6th edition, 2010.

REDI, P. (1991) *Considerations about the design of PV modules for central power plants.* In Proc. 10th European Photovoltaic Solar Energy Conference, April 8-12, Lisbon, Portugal, 1991, 959.

SCHÜTZE, M., et al. (2014) *Laboratory study of potential-induced degradation mechanism in PV Modules* (http://www.q-cells.com/uploads/tx_abdownloads/files/Manuscript_Schuetze_et_al_37PVSC_final.pdf) March 2014.

SWANSON, R. et al. (2005) The surface polarization effect in high-efficiency silicon solar cells, Sun Power Corporation 2005 (www.solarweb.net/forosolar/) (March 2014).

ŠÁLY, V., RUŽINSKÝ, M. & REDI, P. (1995) *Photovoltaic panel design and related problems*. J. Electrical Engineering, 45, 1995, 384.

VENTSEL, E. AND KRAUTHAMMER, T. (2001) *Thin Plates and Shells: Theory, Analysis, and Applications*, Marcel Dekker, Inc., New York, New York, 2001.