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Nikolaj VIŠNIAKOV
Artūras KILIKEVIČIUS
Jurij NOVICKIJ
Audrius GRAINYS
Vitalij NOVICKIJ

LOW-COST EXPERIMENTAL FACILITY FOR EVALUATION OF THE EFFECT OF DYNAMIC MECHANICAL LOADS ON PHOTOVOLTAIC MODULES

TANIE URZĄDZENIE DOŚWIADCZALNE DO OCENY WPŁYWU DYNAMICZNYCH OBCIĄŻEŃ MECHANICZNYCH NA MODUŁY FOTOWOLTAICZNE

The efficiency of modern photovoltaic systems is strongly reduced when the crystalline structure of the solar cells is being damaged due to extensive mechanical stress caused by climatic factors such as heavy wind or snow. This work is focused on the investigation of the cyclic dynamic mechanical loads required to alter the efficiency of typical solar panels in order to simulate various weather conditions and investigate the reliability of the solar panels when they are subjected to stress. Experimental setup is described in the study. During experiments the solar panels have been treated up to 40 Hz vibrations with the maximum magnitude of the shift of the solar panel in the range of 0.3 mm. Simulation model of the characteristic frequencies during vibrations is also presented in this work. The experimental vibration spectrum has also been determined. The acquired experimental data showed appearance of micro fractures in the crystalline structure of the photovoltaic modules and allowed estimation of the average reliability of a typical modern photovoltaic module in harsh weather conditions. The setup could be successfully applied for express testing of solar panels and investigation of the susceptibility of photovoltaic modules to mechanical stress.

Keywords: *solar cells, degradation, measurement of mechanical stress, reliability, climatic stress simulation.*

Sprawność współczesnych instalacji fotowoltaicznych drastycznie spada, kiedy struktura krystaliczna ogniw słonecznych ulega uszkodzeniu z powodu dużych naprężeń mechanicznych powodowanych przez czynniki klimatyczne, takie jak silny wiatr lub śnieg. Niniejsza praca skupia się na badaniu cyklicznych dynamicznych obciążeń mechanicznych niezbędnych do obniżenia sprawności typowych paneli słonecznych w celu symulacji różnych warunków pogodowych oraz badania niezawodności paneli słonecznych poddanych oddziaływaniu czynników zewnętrznych. W publikacji opisano układ doświadczalny. W ramach doświadczeń, panele słoneczne zostały poddane drganiom do 40 Hz przy maksymalnej wielkości przesunięcia panelu słonecznego w zakresie do 0,3 mm. W pracy omówiono także model symulacyjny częstotliwości charakterystycznych w czasie drgań. Określono widmo drgań doświadczalnych. Uzyskane dane doświadczalne wykazały pojawienie się mikropęknięć w strukturze krystalicznej modułów fotowoltaicznych i pozwoliły na oszacowanie średniej niezawodności typowego współczesnego modułu fotowoltaicznego w trudnych warunkach pogodowych. Układ może być z powodzeniem wykorzystywany dla potrzeb doraźnego testowania paneli słonecznych oraz badania podatności modułów fotowoltaicznych na naprężenia mechaniczne.

Słowa kluczowe: *ogniwa słoneczne, degradacja, pomiar naprężenia mechanicznego, niezawodność, symulacja oddziaływania czynników klimatycznych.*

1. Introduction

Renewable energy sources are attracting more and more investors each year, which increases the share of renewable electricity generation [1]. Different dotation programs in the European Union exist to stimulate the popularity of solar and wind power. While many renewable energy sources are large scale implemented by corporations or government due to high cost of installation, solar energy is available for private users and relatively the cost of solar panels is low, which stimulated the mass production and popularity of the technology [2, 10]. However, reliability is a crucial parameter of photovoltaic systems and there are a number of standards covering the maximum allowed performance reductions influenced by stress in harsh weather conditions because dependent on the annual weather conditions the solar panel performance may be significantly reduced. Such weather factors as heavy wind bursts, snow, temperature fluctuations are important in prediction the efficiency of a specific solar module and the durability of the solar system must be taken into account [5, 11]. As a rule during heavy mechanical loads the crystalline structure of the photovoltaic modules is damaged and the micro fractures appear [4], which negatively affect the conversion effectiveness of the energy of light into electricity and stimulates further degradation of the module [9]. In order to minimize such loses in efficiency, enforcements in the frame structure of the photovoltaic system could be made dependent on the specific weather conditions it is being installed in. However, preliminary analysis and simulation of the weather conditions and possible stress are required [8]. Therefore, in order to meet the standards and estimate the degradation ratio the accurate prediction and accumulation of the statistical data of the solar cell performance in harsh weather conditions and under heavy dynamic mechanical loads. The area of research is new and still lacks accurate statistical and experimental data of mechanical stress influence on the appearance of micro cracks in the photovoltaic modules [6, 7]. The standards still do not include mechanical stress information on the photovoltaic modules. Therefore, in this work a computer controlled vibrational stand and an array of 3-axis acceleration evaluating sensors has been applied in order to investigate the influence of dynamic mechanical loads on the crystalline structure of a solar cell and propose a measurement setup for the testing of the solar modules.

2. Theoretical approximation and FEM analysis

The behavior of any subject interacting with dynamic forces can be specified by the dynamic equilibrium equation [12]:

$$[\mathrm{M}]\{\ddot{\mathrm{U}}\}+[\mathrm{S}]\{\dot{\mathrm{U}}\}+[\mathrm{K}]\{\mathrm{U}\}=\{\mathrm{F}\} \quad (1)$$

where [M], [S], [K] are the mass, suppression and stiffness matrices, respectively; {F} is the outer mechanical stress vector; $\{\ddot{\mathrm{U}}\}=\left\{\frac{d^2\mathrm{U}}{d^2t}\right\}$,

$\{\dot{\mathrm{U}}\}=\left\{\frac{d\mathrm{U}}{dt}\right\}$, {U} are the accelerations, velocities and displacement, respectively. For the quasi-static process when there is no forced deformation, the equation is further simplified to:

$$[\mathrm{M}]\{\ddot{\mathrm{U}}\}+[\mathrm{K}]\{\mathrm{U}\}=\{0\} \quad (2)$$

The non-zero periodic solutions will take form of:

$$\{\mathrm{U}\}=\left\{\hat{\mathrm{U}}\right\}\cos\omega t \quad (3)$$

After differentiation the equilibrium equation is expressed as:

$$\left([\mathrm{K}]-\omega^2[\mathrm{M}]\right)\left\{\hat{\mathrm{U}}\right\}=\{0\} \quad (4)$$

Any mechanical system could be characterized by the number of natural modes and characteristic frequencies. Any vibration can be evaluated as a superposition of the natural modes in a form of:

$$\{\mathrm{U}(t)\}=\sum_{i=1}^{n}(a_i\cos\omega_i t+b_i\sin\omega_i t)\{\hat{\mathrm{U}}^{(i)}\} \quad (5)$$

where a_i, b_i, n – are the constants based on initial conditions. The solution could estimated analytically.

However, if the geometrical parameters and mechanical conditions of the system are known it is convenient to use the finite element method (FEM) analysis. The differentiation of the model could be performed allowing approximation of the physical processes happening during mechanical stress and the changes in geometrical features of the solid structure under investigation. If the solution is a vector function *f(x)*and the whole model is differentiated into finite elements, for the element *e* the function could be expressed as:

$$\mathrm{f}^e(x)=\mathrm{U}^e\left[\mathrm{E}^e(x)\right] \quad (6)$$

where $\left[\mathrm{E}^e(x)\right]$ is the finite elements matrix, U^e is the vector of element values at boundary conditions.

In order to simulate a more accurate response of the solar panel and determine the possible resonant frequencies a finite element method (FEM) analysis has been performed in SolidWorks software package environment. The parameters selected for simulation are as follows: composite material – Tedlar (PVF), tensile strength 55 MPa, tensile modulus – 2.103 Gpa, mass density –1370 kg/m3, possion ratio – 0.4. The modeling has been performed in 0 – 30 Hz frequency range with vibration amplitude up to 0.3 mm. During simulation four characteristic frequencies and corresponding displacement points have been determined. The simulation data is presented in Fig. 1. As it can be seen in Fig. 1 four resonance frequencies of a typical 2 m x 1.5 m solar panel have been acquired by application of FEM analysis

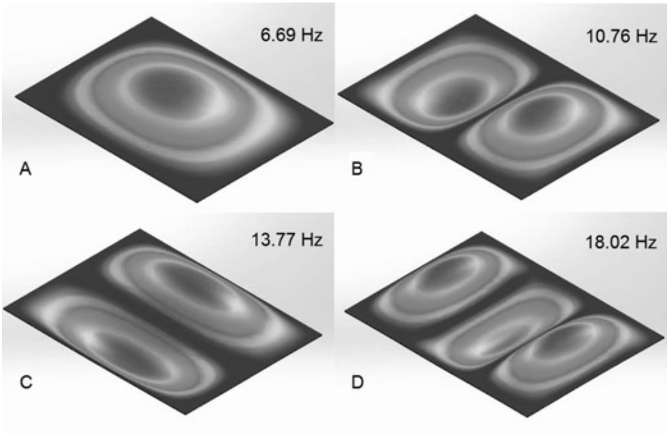

Fig. 1. Finite element method analysis modelling data, where A: characteristic frequency of 6.69 Hz; B: characteristic frequency of 10.76 Hz; C: characteristic frequency of 13.77 Hz; D: characteristic frequency of 18.02 Hz

3. Experimental setup for estimation of mechanical stress

As it was mentioned above in order to simulate the mechanical stress the photovoltaic module might be experiencing in the real weather conditions a vibrational stand has been used. The alteration of the magnitude and the frequency of the vibrations allows to simulate dynamic mechanical stress due to burst of heavy wind the photovoltaic modules may be experiencing. In the experimental setup the solar panel has been attached to the shaker and the arrays of 3-axis acceleration sensors have been applied to the solar panel corners, the back plate, the middle point and the shaker itself. The block diagram of the resultant dynamic mechanical load generating facility is shown in Fig. 2. The position and the quantity of sensors that are shown in the block diagram do not scale with the prototype facility and are shown for schematic purposes. The simultaneous data acquisition, the control of the frequency and the magnitude of the vibrations have been performed and monitored using a computerized setup.

The sensors that have been used in the study are the miniature triaxial piezoelectric accelerometers (“Brüel & Kjær”, 4506). The sensors have been chosen based on the evaluation of the best combination of high sensitivity, low mass and small dimensions. Also low output impedance allowed using long cables. The sensitivity of the device is 100 mV/g. As it was mentioned above both the shaker and the sensors have been connected to the computer, which allowed alteration of the amplitude of vibrations, vibration time, frequency and direction. The photographs of the experimental facility are shown in Fig. 3. The proposed experimental setup is capable of delivering controlled cyclic mechanical loads. The range of shift of the panel plane is 0 – 0.3 mm and the frequency of vibrations could be varied in the range of 0 – 40 Hz. The parameters are sufficient to simulate all possible harsh weather conditions like wind or snow bursts in Europe. Appli-

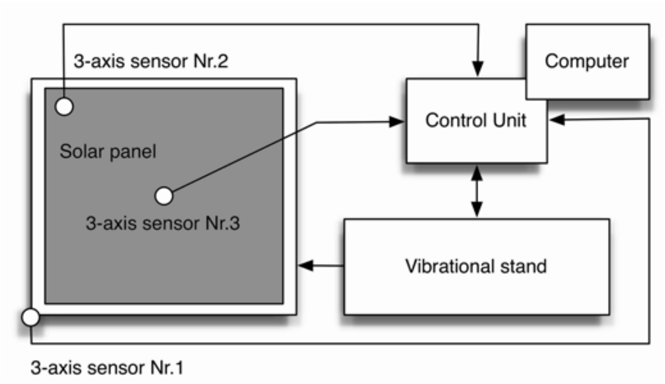

Fig. 2. The block diagram of the dynamic mechanical load generating facility

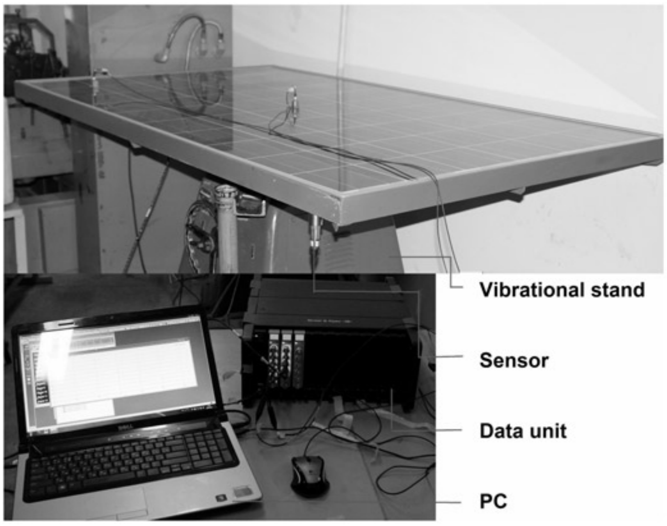

Fig. 3. The photographs of the experimental facility for estimation of mechanical load influence on photovoltaic cells

cation of the proposed setup allows determination of the vibrational resonance frequencies and based on the performed analysis develop reinforcements for the solar panel. It will allow reducing the amount of microcracks appearing in the crystalline structure.

4. Results

During experiments the magnitude and the frequency of the vibrations have been altered in the range of 0 – 0.3 mm and 0 – 40 Hz, respectively. The ranges have been selected in accordance to meet the goal of accurate simulation of real weather conditions when short bursts of heavy wind are possible. The vibration spectrums of the solar panels have been analyzed. A typical resultant response spectrum due to external shockwaves of the 2 m x 1.5 m solar panel is shown in the Fig. 4. An array of 6 acceleration sensors has been used, 3 of which where positioned in the central part of the panel and other 3 closer to corners of the photovoltaic module under investigation. As it can be seen in Fig. 4 during investigation it was determined that there were several characteristic frequencies in the range of 0 – 40 Hz: 7.2 Hz, 10.1 Hz, 13.5 Hz and 17.5 Hz.

The difference between simulation and experimental data was 7.1%, 6.1%, 2% and 2.9%, respectively, which is in acceptable compliance. Based on the acquired data the experiment has been narrowed to the frequency of 17.5 Hz because it was presumed that there was the highest probability of micro fractures in the crystalline structure of photovoltaic cells to occur when the modules are subjected to dynamic mechanical load. The exposure time to the mechanical stress under these conditions has been varied in the range of 0.1 – 3 hours.

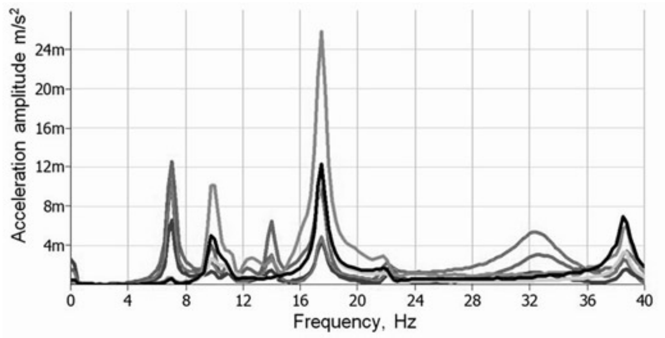

Fig. 4. The resultant response spectrum to shockwaves of the 2 m x 1.5 m photovoltaic module, where: red, green, blue are the responses of the sensors in the central part of the panel; orange, yellow, black are the responses of sensors positioned closer to corners of the photovoltaic module.

Each time after exposure the photovoltaic modules have been checked using electroluminescence technique [3]. The modules have been connected tothe 35 V DC power supply and a constant current have been maintained. The resultant luminescence of silicon has been observed using computerized CCD camera in the infrared region in dark room to remove any influence of light on the experiment. During each experiment the number of resultant micro cracks has been calculated and further exposure to mechanical stress has been carried out. The images of selected clusters of a photovoltaic module after exposure to 0.2 mm vibrations for 30 minutes are shown in Fig. 5.

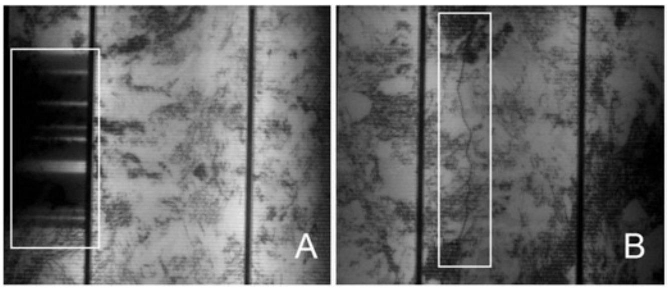

Fig. 5. Images of selected clusters of a photovoltaic module after exposure to 0.2 mm vibrations for 30 minutes, where A: damage of photoreflective layer; B: Microcrack in the crystalline structure

As it can be seen in Fig. 5 after exposure to dynamic mechanical loads defects in the crystalline structure of photovoltaic cells have appeared. In Fig. 5 (A) damage of the photoreflective layer could be observed. This defect is common on solar panels in operation and as a result less light could pass through the layer. In Fig. 5 (B) a microcrack could be observed. Such defects result in the disturbance of the current flow and in the worst-case scenario the whole cluster is not functioning, which negatively affects the output power of the panel.

5. Discussions/Conclusions

A computerized vibrational stand for simulation of the real weather conditions causing dynamic mechanical stress on the photovoltaic cells has been applied to determine the influence of the mechanical stress on the appearance of micro fractures in solar panels. It was determined that there were several resonance frequencies of 7.2 Hz, 10.1 Hz, 13.5 Hz and 17.5 Hz. The FEM simulation was in acceptable compliance with the experimental results. The highest response to shockwaves was observed at the 17.5 Hz frequency, therefore experiments under these conditions have been performed. It has been shown that external mechanical stress results in the damage of the crystalline structure of the photovoltaic cells. The appearance of micro cracks and damage of the photoreflective layer was observed during experiments. It was shown that the low frequency mechanical loads simulating windy weather could cause considerable damage to the photovoltaic cell and therefore reduce the effectiveness of the module. Since the stated working cycle of a photovoltaic cell is assumed to be 15 – 20 years it is crucial to perform express mechanical load tests to ensure decent performance of the system. The proposed setup and analysis method is applicable for the investigation of the dynamic mechanical loads influence on the crystalline structure of the photovoltaic cells.

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Nikolaj VIŠNIAKOV
Welding Research and Diagnostics Laboratory, Faculty of Mechanics
Vilnius Gediminas Technical University
J. Basanavičiaus str. 28, Vilnius LT-03224, Lithuania

Artūras KILIKEVIČIUS,
Department of Mechanical Engineering
Vilnius Gediminas Technical University
J. Basanavičiaus str. 28, LT-03224 Vilnius, Lithuania

Jurij NOVICKIJ
Audrius GRAINYS
Vitalij NOVICKIJ
High Magnetic Field Institute, Faculty of Electronics
Vilnius Gediminas Technical University
Naugarduko street 41, Vilnius LT-03327, Lithuania

E-mails: nikolaj.visniakov@vgtu.lt, arturas.kilikevicius@vgtu.lt, jurij.novickij@vgtu.lt, audrius.grainys@vgtu.lt, vitalij.novickij@vgtu.lt