PHOTOVOLTAIC MODULE STRUCTURE UNDER THE HIGH DC VOLTAGE STRESS

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Abstract

Today photovoltaic (PV) power sources are often photovoltaic systems of high power and so the string DC voltage can increase to hundreds of volts. Such a high voltage stresses the PV module structure including solar cells, encapsulants, supporting and protecting layers. Attention in our study is focused on changes in the electrical parameters of PV cells and modules due to thermal and potential degradation. Tests were performed on the PV mini-modules. The test modules were subjected to a controlled heat treatment and a 1000 V DC voltage stress, which is often accompanied by potentially induced degradation (PID), in the thermal chamber. Measurement of the electrical parameters of the measured samples was performed before the stress and after possible degradation process.

Keywords: *photovoltaics, encapsulant, degradation, potential induced degradation, architecture, pv installation*

1. INTRODUCTION

Photovoltaics dominates to a large extent among today's alternative electric energy sources to follow technical solutions and policies to limit the greenhouse gasses emission. Continuous increasing of PV power installations is not only the result of pressure and requirements related with global warming process but, on the other hand, photovoltaics has become an undepreciated technical solution for electricity generation and assecuration

of increasing energy consumption. Solar energy sector has attracted more than half of investments, followed by wind power, into renewables. The market forecast stated that the installed PV capacity could overcome 1200 GW by 2023.

Building of often tremendous tens or even hundreds of megawatts PV units is one alternative, but connected with needs to use the large area of often agriculturally exploitable ground. Mounting of PV module array on buildings, either existing or newly built, is another alternative which on one side helps to spare agricultural land and on the other side can alternate exerted building materials like cladding, glassy facades and skylights or roof tiles. Of course, the installed power is limited by convenient building surface area. Actually PV industry offers the possibility for simple connection of PV modules and building structure, so called building added photovoltaics (BAPV) or more sophisticated integration of PV modules into building composition – Building Integrated Photovoltaics (BIPV).

Both, in the standard PV modules and also in BIPV devices, encupsulant is an important component which protect solar cells against outer environmental influences and supports them in electrically and mechanically compact corpus. Encapsulant foils usually cover interconnected solar cells from both sides, top and bottom, and are placed into layered structure between module substrate and superstrate. Among important properties of encapsulant are resistance against humidity, transparency for the visible light radiation, high electric resistance and high electric strength, good ability for lamination treatment and stability of these properties during the whole life-time of PV modules. Far and wide most common material of PV module encapsulant is ethylene vinyl acetate EVA. The thermoplastic copolymer EVA has been used from the very beginning of commercial photovoltaics because it fulfils most of requirements on encapsulant layers within PV module as optical, mechanical, technological and, last but not least, EVA is a convenient low cost material[1]. Degradation and discoloration of EVA laminates under the environmental influences have been the matter of intensive research for many years. The result of this research is increased stability of currently used EVA [2].

On the other hand more other alternative encapsulants have been the matter of interest. Among them, mainly thermoplastic polyurethane (TPU), polyvinyl but

yral (PVB) or polydimethylsiloxane (PDMS), but also others. Their properties, advantages and disadvantages are mentioned and discussed e.g. in [3, 4]. Window glass, either on buildings or also glass for automobile industry have been standardly improved using lamination process with polymeric interlayer [5]. An easy conceive is then the idea to incorporate solar cells within two sheets of window glass and to have got the window with ability to produce the electricity.

Humidity, UV radiation and the temperature are the agents which can result in deterioration of properties of polymeric foil and the focus is then on the resistance against them. When the polymeric material is used as an encapsulant in PV industry, its electric properties must be taken into account and of course optical properties, as well. As for the electric properties, similarly as in the case of standard PV modules, electric resistance, electric strengths, leakage currents and related degradation processes are of great importance. Safety rules related to electric installations and electric equipment need to be also considered.

2. PHOTOVOLTAICS AS AN INTEGRAL PART OF BUILDING STRUCTURE

When photovoltaics is incorporated, fully integrated, into the structure of already existing or newly built building fulfilling the function of e.g. windows, roof tiles, skylights, cladding or shielding elements, produced electricity is an extra profit of such solution, which enters into the final economic balance. PV element becomes a new design element, more-functional one, which allows changes and new opportunities in the design of the building and architectural opinion on function of building envelope, shapes or impact of the light. Moreover, BIPV represents also specific architectural means of expression and also approach and message of author himself. Of course, the investment price of BIPV is higher in comparison with standard rack mounted PV and also in comparison with standard building materials. The placement of PV modules in power plants quite strictly obeys optimized orientation in space with regard to spatial orientation, sun position and particular place, what is not generally possible to follow with BIPV and especially when photovoltaics should be adapted to older buildings.

Building integration of photovoltaics is preconditioned by fulfilment of demands usually required from building materials. These are requirements related with 1) environmental and weather influences like protection against rain, cold, heat, admission, reflection or shading the light radiation; 2) structural and building static requirements like structural stability, weight carrying stability, durability, fire protection and many more; 3) requirements that stem from the needs of the occupants, e.g. light comfort, protection against view inside or spatial separation; 4) design requirements – design image, dialogue with surrounding, shapes and colours or identity; 5) emissions and imissions protection [6].

3. BIPV OPTIONS

Photovoltaic systems based on BIPV can be looked on either from energy generation point of view (energy efficiency, energy storage, grid-on or grid-off system), or from the point of view of used solar cell/module material (bulky crystalline solar cells, thin film, opaque or transparent/semitransparent) or from design aspects point of view (cell/module design, shape, colour, geometry). In every cases BIPV must fulfil requirements on building materials and building elements regardless they are used on the roof, façade, window or wherever. Quite comprehensive review study of the performance of many various BIPV installations is reviewed in [7].

Fig. 1. Building integrated photovoltaics

Among photovoltaic components we can list PV foils, PV tiles, PV modules – often specially designed regarding the shape and colour – and PV glazing [8, 9]. For today, silicon is the most common material used for BIPV application and also in photovoltaics generally. Crystalline silicon PV elements are more extended but thin films are on the way, too [10]. Tilted area is more convenient for PV installation in temperate zones of Europe with regard to optimal electricity production. That means that tilted roofs are naturally convenient. Going northward the optimized tilt angle is increasing [11]. Of course vertical walls and variously shaped roofs and skylights are also a suitable alternative. Examples are shown in Fig. 1.

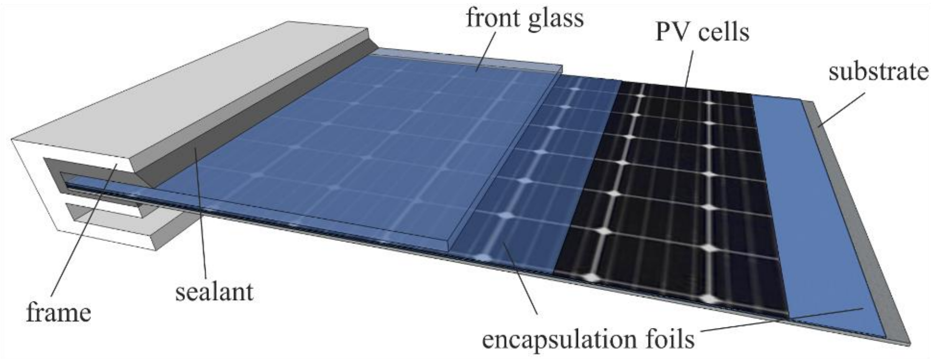


Fig. 2. Structure of a thin-film photovoltaic module

Important task is thorough design of illumination in internal space. PV transparent walls, skylights, shading elements and glazing are those factors to be considered by designers. The light and especially daylight is a significant component of the creative architectural process in the designing the future architecture [12].

First, either in the case of existing or newly designed building the process of assessment of the potential for BIPV should be carefully accomplished with respect to suitability of building skin [13].

4. COMMON PV MODULE UNIT

Standard PV module shown in Fig. 2 is framed construction while thin film PV modules are mostly frameless constructions. Metallic frame is a construction element which makes easier manipulation with the module and its mounting. Frameless PV modules require some kind of supporting beam rails and fixing clamps (Fig. 3). Mounted modules must withstand environmental influences. From the mechanical point of view, mainly blast of wind, and the stress due to various thermal dilatability of used materials. Third common option is the case when solar cells are mounted between two glass sheets and used in spite of windows or glassy shading elements or skylights. As already mentioned above, encapsulant is important PV module element which must fulfil mechanical, optical and electrical function.

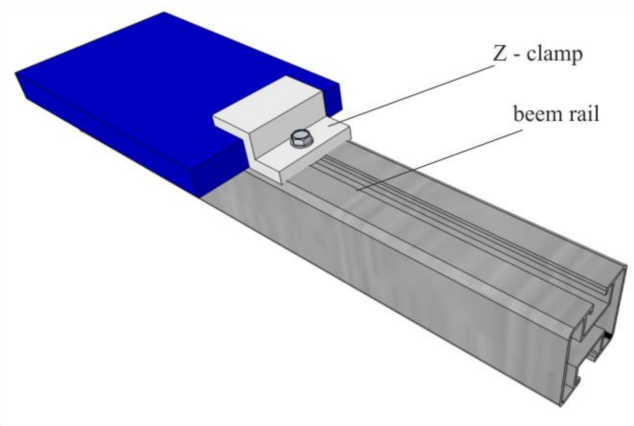


Fig. 3. Installation of frameless thin-film photovoltaic module

PV cells and modules are subjected to a degradation process due to their specific construction and materials used. The degradation is demonstrated especially when the properties of the material for encapsulation deteriorate. Organic encapsulating materials are used to protect cells and their interconnections from external influences. The parameters of the cells themselves deteriorate also. The degradation process results in:

- Decreased efficiency
- Change of electrical parameters such as insulation or series resistance.
- Damage of the lamination which is manifested by impaired protection against external influences, especially from the moisture.
- Colour changes of the encapsulant reduces its transmittance and thus reduces the generated current.

These changes do not manifest themselves individually, but are interrelated, which ultimately leads to the "aging" of the module and a decrease of efficiency. From the point of view of electricity production, the stability of solar cells and their parameters is important, but also the stable properties of covering materials to keep their transparency and electrical insulation. Furthermore, changes in conductivity of interconnections (deterioration of contact properties) as well as the formation of leakage paths due to deterioration of the insulating properties of the encapsulation material contribute to the overall degradation.

External influences that are directly related to the deterioration of PV cells include the ambient temperature, which also activates the degradation processes in the organic enclosure materials, as well as the humidity of the environment. The efficiency of the cells is also affected by the UV radiation, which the module continuously absorbs. An important factor is electrical stress, which also leads to degradation processes. Electrical stress is connected with the influence of atmospheric electricity, direct or indirect lightning effects, overvoltage from electric net and bias of interconnected PV modules themselves.

5. POTENTIAL INDUCED DEGRADATION

Potential induced degradation (PID) is often under the PV system bias and is encouraged by increased temperature and humidity. Solar cells in long series strings can be exposed to higher DC voltage, which is precondition for PID effect [14, 15]. The PID effect is basically interlayer polarization which leads to degradation of PV modules and which is related to the potential difference of electrified modules to ground. PID can lead to irreversible degradation of silicon in the modules due to interlayer polarization. In particular, those modules degrade that are closest to the negative pole in a series of connected modules. At the end of the row of modules where the ground is, the voltage to ground can reach a value between minus 250 to minus 450 V (Fig. 4). The frame of the PV modules, on the other hand, has a potential of 0 V, because it must be earthed for safety reasons. As a result, leakage currents and polarization can occur between the cells of the module and its frame which inappropriately alters the VA characteristics of the cell/module. Ion mobility accelerates with increasing humidity, temperature and voltage. In the case of a PV cell or module, the components used have the great influence on the degradation, in particular the cover foils/sheets, the encapsulating materials, the anti-reflective layer (ARC) but also the cover glass used, and in particular present sodium ions with high mobility. Sodium ions migrate further into the module structure due to the negative voltage. They reach the ARC layer and the boundary between the ARC and the EVA film. Conversely, negative ions travel from the cell structure toward the aluminium frame. Finally this creates a leakage current. Potential induced degradation is either the matter of used solar cells/modules or the PV system as a whole [16].

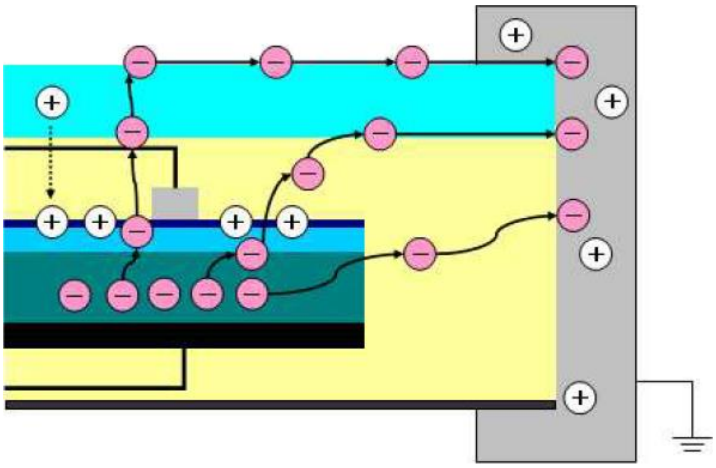


Fig. 4. Schematic indication of the charge flow leading to the PID process

The PID process can be treated by early intervention and the modules are regenerated applying the opposite voltage. Their performance can be returned to their original values within a few days. During long-term PID process, the modules are irretrievably damaged and so their performance.

6. EXPERIMENTAL

The test samples were subjected to accelerated aging in a climate chamber at a temperature of 60 °C and under connected dc voltage of 1000 V for 96 hours. To determine the change in cell parameters, selected electrical parameters were measured using DC voltage before they were placed in the climatic chamber and after the test. Their volt-ampere characteristics were measured. The polarization index PI was determined from time dependences of dc current. DC current was measured with KEITHLEY 617 under DC voltage 1000 V. The current-voltage characteristics under illumination were measured with illumination by Oriel Newport 32193A Full Solar Spectrum Simulator and four-quadrant source KEITHLEY 2440 5A SourceMeter. The influence of the accelerated ageing on the electrical parameters of the test modules has been assessed from the differences of the measured values before and after ageing treatment. Three various encapsulants, EVA, PVB and TPU underwent the experiment whereby encapsulated solar cells were produced on P-type silicon substrate. Configuration of samples is shown in Fig. 5. Additional metallic sheets as electrodes were incorporated in order to measure the dielectric properties of encapsulant. The configuration of the samples is specified in Tab. 1.

Module	Structure of the module
EVA6	EVA+PEP black
EVA8	EVA+PEP black+VERTEX
PVB28	glass+PVB+glass
TPU27	glass+TPU+glass
TPU2	TPU+PEP black+VERTEX

Table 1. Structure of prepared experimental modules.

PEP is layered structure polyvinyl fluoride – polyethylene terephthalate, VERTEX is commercial substrate material which replaces the substrate glass of the module.

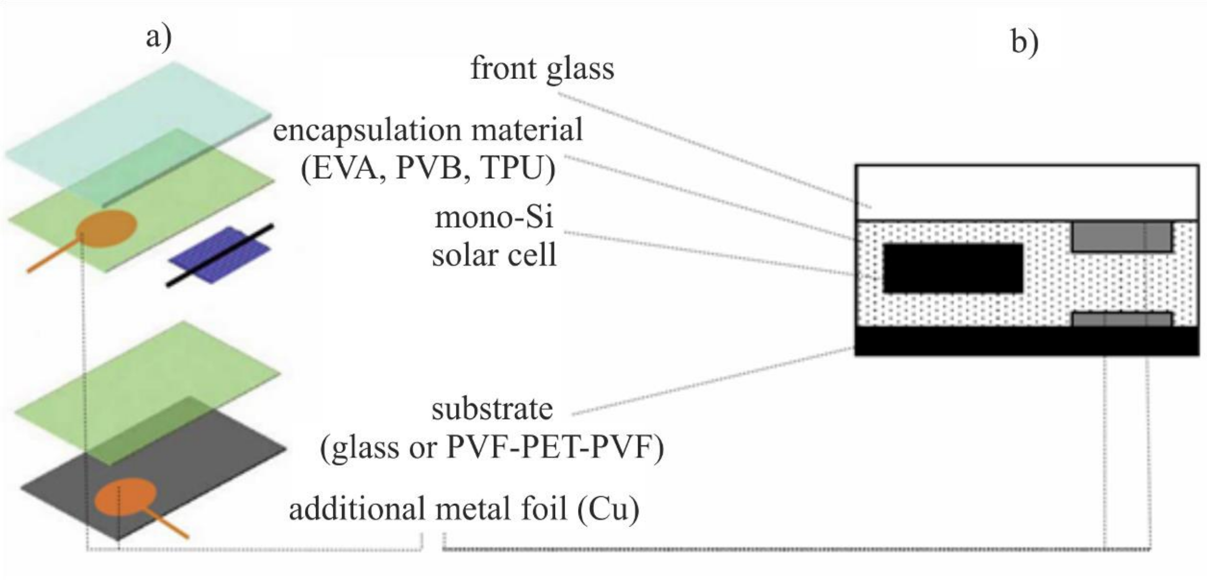


Fig. 5. Configuration of the tested photovoltaic samples

Electric DC non-destructive measurement methods on insulating structures include, in particular, the measurement of the time dependence of the current at the selected voltage or measurement of the time dependence of the current, resp., and evaluation the polarization index (PI). Insulation resistance (IR) and polarization index are two generally accepted diagnostic tests for the insulation condition of tested material

The current which flows through the insulator after the applying DC voltage has more components, like:

I_L - surface leakage current,

I_R - conduction current,

I_P - polarization absorption current,

I_C - capacitive charging current.

The shape of the time dependence of total measured current depends on the relation among particular contributions. First two of them are time independent and last two are the cause of time dependence of measured DC response. The current, sooner or later, depending on physical transport processes, stabilises. It is common to measure the resistance or current after 15, 60 and 600 seconds and calculate polarization index $PI_{60/600}$ or $PI_{15/60}$. Polarization index PI < 1.5 indicates the bed condition of insulation while PI > 4 indicates very well insulation. PI < 1.5 means that conduction paths (leakage) are very effective.

In the case of humid insulation the electrical properties can even improve after the thermal treatment. It is related with the escape of humidity from the bulk or from the surface of insulator. Slower degradation process can be overlapped by this process.

7. RESULTS AND DISCUSSION

The time dependences of measured current at DC voltage 1000 V for the samples with EVA, PVB and TPU encapsulant are shown in Fig. 6 and calculated values of PI are in table format, Tab. 2. The influence of accelerated ageing is apparent on EVA and PVB samples.

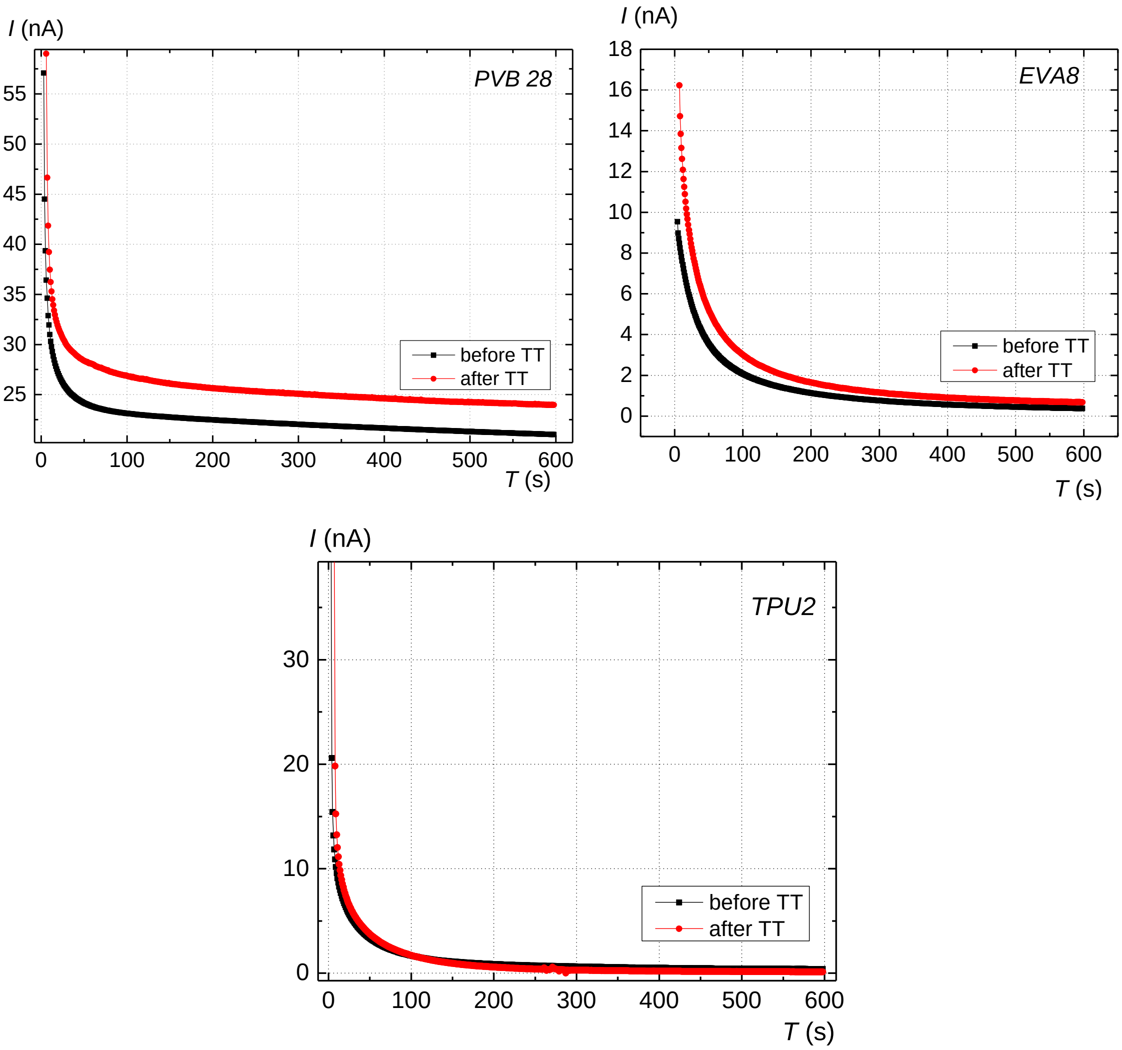


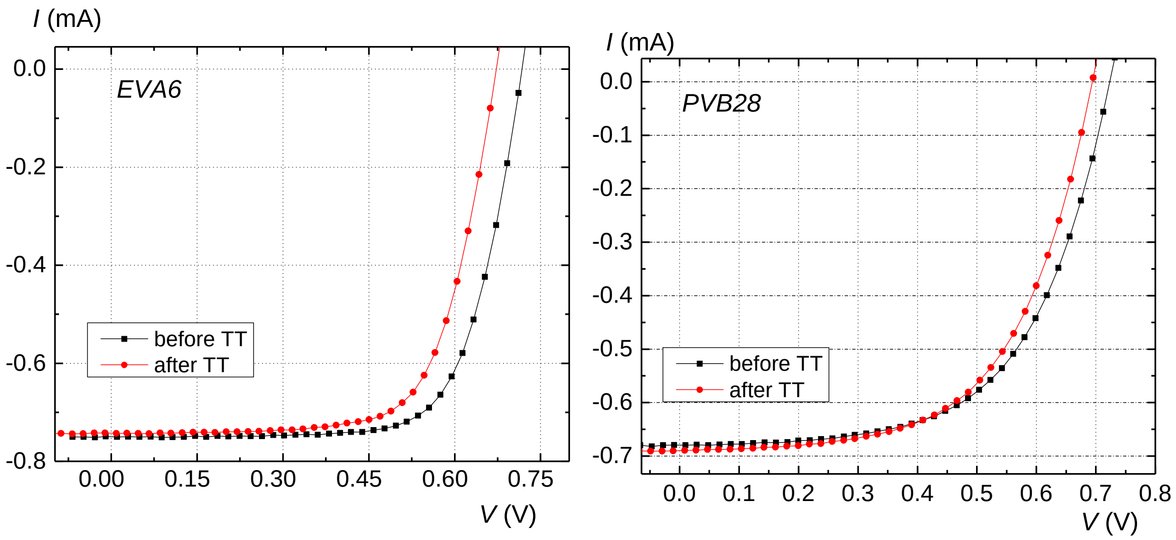
Fig. 6. The time dependences of measured current at DC voltage 1000 V

The conductivity increased after the treatment at 60 °C and DC bias 1000 V for 96 hours. As for insulation resistance, the samples PVB28 and TPU27 are in insuficient state what is demonstrated by low PI. As we already mentioned above, the increase of PI has been not supposed, but this is the case of EVA6 and TPU27. The escaped humidity can be the simple reason. On the other hand the delamination of the module and interlayer dielectric polarization resulting from it can be more important damage. We did not test the samples on delamination in this experiment.

Module	**EVA6**	**EVA8**	**PVB28**	**TPU27**	**TPU2**
PI – before TT	3,24	8,28	1,133	1,08	7,28
PI – after TT	4,21	6,62	1,129	1,21	7,08

Table 2. Polarization index calculated before and after thermal ageing treatment (TT) of biased samples.

The current-voltage characteristics under illumination were changed after the ageing treatment, as well (Fig. 7). As an adequate criterion we can use the produced power in Maximum Power Point, which decreased practically in all cases. The decrease was mainly by the decreased open circuit voltage. The time of ageing 96 hours under mentioned condition was not too long to develop more complex processes, so we ascribe the power drop to the PID process.



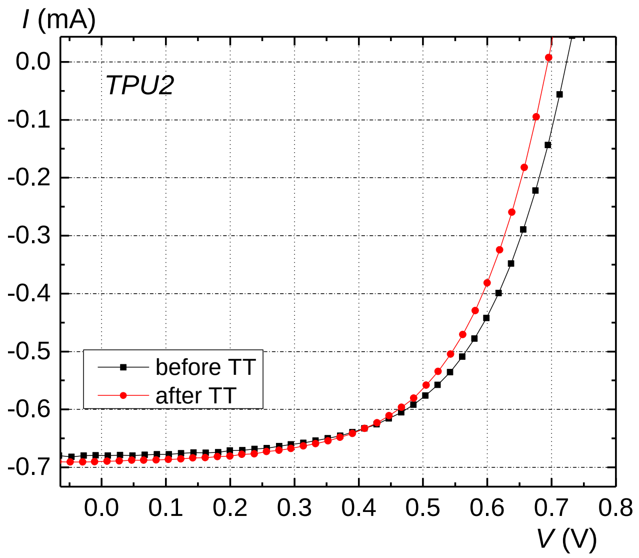


Fig. 7. Illustration of PID effect on the measured I-V characteristics of chosen samples

8. CONCLUSION

We have tested various encapsulation materials for photovoltaic application in the structure of photovoltaic module. Experimental modules were of standard type or such as applied for PV windows or shading elements. It was shown that produced experimental modules are sensitive on PID process and so their incorporation into PV system must be carefully considered. The PID process changes the insulating properties and the leakages have increased but also the produced electricity can be affected.

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