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PERFORMANCE AND TESTING OF A SMALL ROOF PHOTOVOLTAIC SYSTEM

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The small PV system installed on the roof of the building of the Faculty of Electrical Engineering and Information Technology in Bratislava has been monitored and its long-term behaviour investigated. After three year operation the changes in PV module properties have been checked and the ageing process has been evaluated using the polarization index dependence and charging current measured and compared on aged and non-aged modules.

Keywords: PV module, power performance, degradation, high voltage stress

1 INTRODUCTION

Photovoltaic (PV) modules, principal and integral part of photovoltaic electricity generator, are intended to be long-term and stabile electric devices. Installed PV systems have become reliable and belong to potential alternatives for power supplies. A PV system can be rated in a simple way from very small one unit of watt to large tenths of MW installations and so serve to feed either electronic or electric equipment on smaller scale or public electric grid.

A small solar electric system installed on private or public houses with the installed power capacity of a few to tenths kW can be a reliable and pollution free unit for electric power generation. The cost effectiveness increases with decreasing investment cost as we have witnessed lately. PV provides cost-effective electricity production in remote places where no grid and power lines are available and impossible or costly to be built.

Because of the modularity, the PV system can be designed to fulfil any feeding requirement. On the other hand, it has to be taken into account that the access to electricity from the PV system is only during the time when solar radiation is available in sufficient amount.

The principal part of any PV system is a PV module. Todays PV modules consist of a certain amount of interconnected solar cells semiconductor structure based on various materials. Crystalline silicon, either mono-, poly- or multi-crystalline is the main solar cells material. Besides silicon, a scale of other semiconductor materials [1,2] are widely used to produce this elementary photovoltaic unit.

2 SOLAR ELECTRIC MODULE

The basic unit of the PV system is a solar PV module rated according to the amount of cells included and according to the area from a few watts (or even less in some special micro-application) to hundred watts in the case of installations intended for electricity production for house or industrial consumption. A typical solar module consists of:

- transparent top cover from glass or plastics,
- solar cells encapsulated between two foils or sealed by casting material,
- a rear substrate layer, usually glass or polymer sheet,
- aluminium frame (in order to simplify the construction or decrease the cost also frameless modules are produced).

The data-sheet of a commercially available module provides more details about its energy performance, typically including:

- the maximum power and electric parameters obtained in laboratory at standard test conditions (STC),
- influence of operating temperature,
- influence of radiation intensity.

The standard test conditions, *eg*, the radiation of 1000 $\mathrm{W/m^2}$, are not generally common during the operation of the module in outer environment and the result is a lower power value than the rated peak-power. The whole day operation, when the radiation values are continuously changing and so does the generated power, can be considered more realistic. The global-average day in terms of radiation levels, ambient temperature and air mass shall to be taken into consideration.

The performance of a PV array is usually specified according to the amount of electricity produced under certain conditions during a certain period of operation. The following factors are considered when presenting the array energy performance:

- solar cell (module) electrical performance characterization,
- determination of degradation factors and the extent of degradation in comparison to former values (electric parameters),

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- estimation of environmental influences and consideration of their impact, when operated at other than standard temperature,
- calculation of the array power output.

The home or other purpose small PV system array is usually planned and constructed without any moving parts and without any extra equipment on a lightweight structure either directly on the roof or on a supporting construction on a tilted or horizontal roof. Also modules are produced that may replace the roof tiles.

In the case of a grid-connected PV system the cooperation with the grid provider is important. One needs to get and involve information about:

- equipment required to connect the system to the grid,
- requirements of grid power provider,
- state and community codes and requirements.

Connection of PV system to public grid requires additional equipment for:

- power conditioning,
- safety measures,
- metering devices and instrumentation.

3 PV MODULE ENCAPSULANT TESTING

The experience gained 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 [3].

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

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

- capacitance charging current (related to geometric or ideal capacitor),
- polarization current,
- leakage or conduction DC current.

Unlike the capacitance and polarization currents, the leakage current is independent of the time of applied voltage. The polarization current in a layered insulating structure is the sum of charging currents of the capacitor related to the polarization currents of a real or technical capacitor. Slow dielectric interfacial polarization within the layered insulating system appears to be quite effective.

Quantities like complex impedance/admittance, permittivity or loss factor are usually investigated in order to characterize the measured structure and its behaviour [4-10].

High voltage can lead to module degradation by multiple mechanisms. The voltage bias degradation is linked to the leakage current. Electric charge flows from the 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 a specific location within PV module. This effect results in persistent polarization [11].

4 PV SYSTEM MONITORING

Long time monitoring of incident solar irradiation on the location can be helpful to optimize the performance of PV systems. The easiest and most accurate way to determine the amount of incident solar energy is measurement of the intensity of solar irradiation in the given location. Necessary data on the availability of solar irradiation and supplied energy can, in principle, be obtained by pyranometric measurements. An important prerequisite for the results of measurements of solar irradiation necessary to describe the actual relevancy of solar irradiation on the site is that the measurements represent averages for a long time, as recorded by pyranometer with digital recording devices with the possibility to collect a suitable number of samples in a chosen time period.

Processing and interpretation of the measured data according to the appropriate standards or internationally applicable methods seems to be more difficult. Moreover, if a failure occurs of the data acquiring device, there is a problem of data completion. In this paper we will attempt to interpret the results obtained from the measurements on an experimental and small educational PV system. Results shown in this paper were recorded and evaluated from 20th November 2011 to 26th March 2013.

The designed photovoltaic system consists of two polycrystalline PV panel branches. Each branch consists of three panels of the same type, first Solara ($U_m = 18.0$ V, $I_m = 4.72$ A, $P_m = 85$ W) and second SunTech ($U_m = 17.6$ V, $I_m = 4.8$ A, $P_m = 85$ W) connected in series. The total active surface area (A_a) is 1.587 m^2 for SunTech panels and 1.687 m^2 for Solara panels. Each branch is grid tied by support of the GRIDFIT 250 LV solar inverter, with maximum peak power tracking function. Geographical parameters of the installed PV system are GPS 48.153 N, 17.073 E, orientation south, angle 45 degrees. This PV system with maximal theoretical power 2 × 255 W was built for experimental and educational purposes.

All physical quantities regarding the experimental photovoltaic system (incident solar irradiation energy, temperature, DC voltage and DC current in PV branches) are measured and processed by means of Prolog logging system.

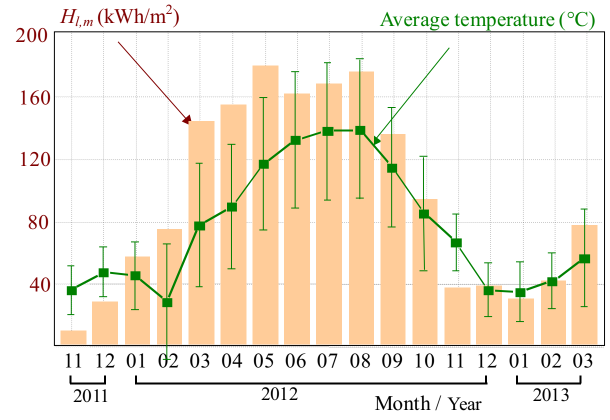

Fig. 1. Monthly incident solar energy $H_{I,m}$ on an area of 1 m^2 on the monitored PV system site and average monthly panel temperatures with standard deviation bars

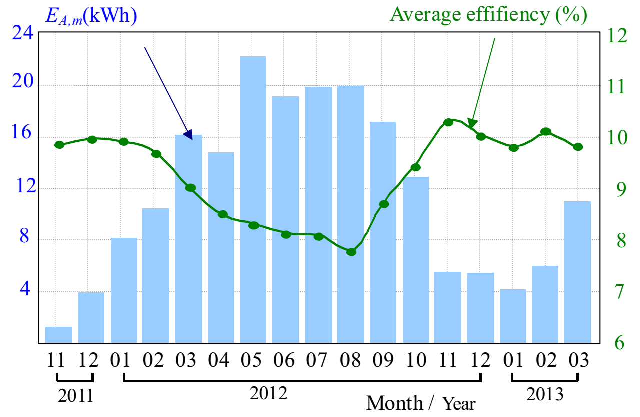

Fig. 2. Monthly energy production and monthly average efficiency

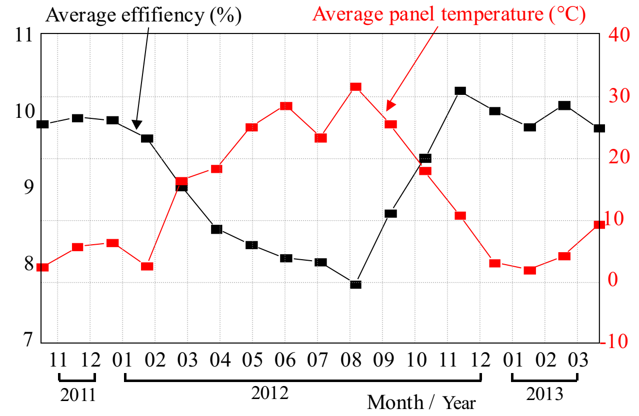

Fig. 3. Monthly average efficiency and average temperature during energy production

Data logging device does the recording of the instantaneous average values of solar irradiation (pyranometer Kipp&Zonen CMP 6), voltage, current of illuminated panels and voltage drop on Pt100 (temperature measurement) in 5 minute time intervals. Data logging device sends the measured values to an on-line accessible back up server in selected time intervals (24 hours in our case).

Derived parameters related to the PV system performance may be calculated from the recorded data using standard mathematical operations over reported periods which are longer than the recording interval r (such as hours, days, weeks, months or years, but expressed in units of hours). To calculate any energy quantities from their corresponding measured power parameters over the reporting period τ, the mathematical relation following [12] are used and discussed in more detail in [13]. Laboratory equipment set up and devices descriptions are in [14, 15].

5 EXPERIMENTS AND DISCUSSION

The experimental data were logged and then results were calculated from 20th November 2011 to 26th March 2013. This represents more than 1 300 000 experimental points of measured and logged parameters. These were statistically processed in Matlab environment.

Monthly incident solar energy on an area of 1 m^2 on the monitored PV system site and average monthly panel temperatures are shown in Fig.1.

Figs.2 and 3 show the temperature, energy production and average efficiency of SunTech branch during energy production for each month. According to this dependence it is clear that the heat in summer months is reducing the efficiency of solar energy to electrical energy conversion, although the yield is higher in sunny summer months. The minimum average efficiency was observed in August 2012 (7.77%) and the maximum in colder sunny days in November 2012 (10.27%). The maximum energy production of SunTech branch was in May 2012 (23.98 kWh) and the minimum in December 2011 (4.25 kWh). Maximum energy production in percent was supplied in May 2012 (12.96%).

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

A simple equivalent circuit of resistor R_s connected in series to resistor/capacitor R_p/C_p connected in parallel is generally adopted. Under DC conditions the capacitor is loaded and characterized by time constant that equals to $R_sR_pC_p/(R_s+R_p)$.

The DC resistance is measured at a voltage of at least 500 V and 50 MΩ is accepted according to the standards issued by the International Electrotechnical Commission. It should be remarked that the value of insulation resistance is a matter of material used on one hand and the matter of geometry on the other hand.

The currents through the insulator or resistance measured at DC voltage are time dependent quantities. Polarization index k_p test uses in essence the polarization

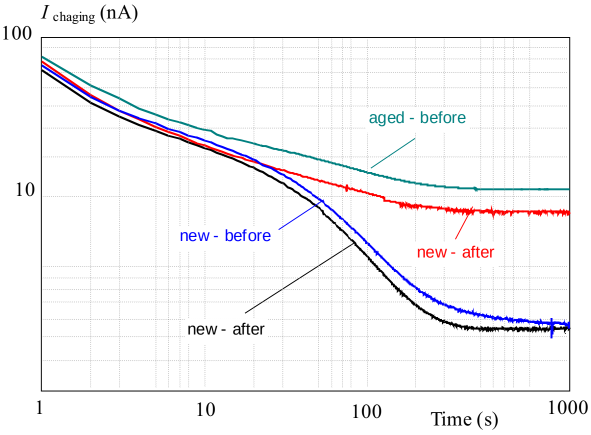

Fig. 4. Time dependence of charging current

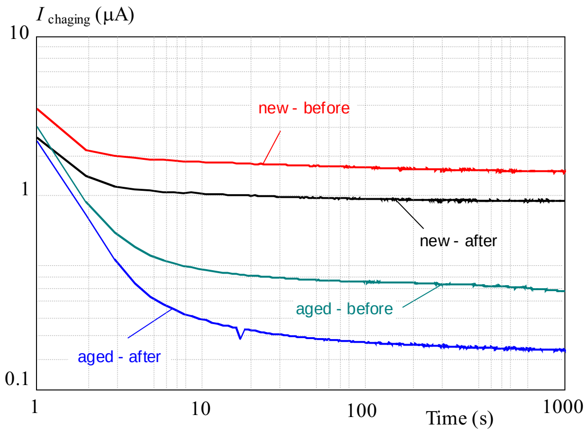

Fig. 5. Time dependence of charging current

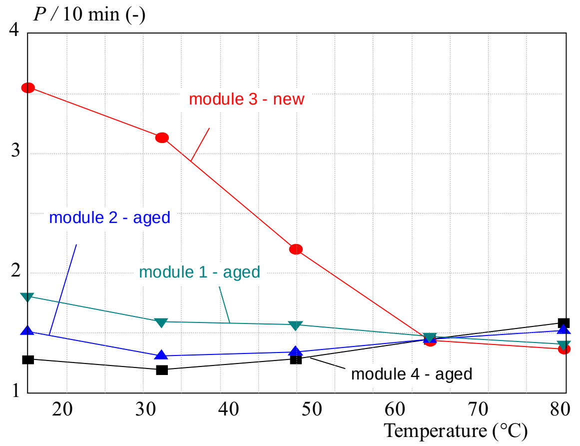

Fig. 6. Polarization index (10 min) as a function of temperature

current as a reference with which it compares the contribution of the leakage current. Polarization index k_p is a sensitive parameter for monitoring the changes in the insulation.

$$k_p = \frac{R_{\text{ins}}(10min)}{R_{\text{ins}}(1min)} = \frac{i(1min)}{i(10min)}$$

The value of k_p should be greater than one for proper insulation. The time dependent resistance of the insulator is the result of time dependent currents appeared when the DC voltage is applied to. Under the influence of electric potential (high voltage stress) on a grounded PV module structure also ionic current leaks which can lead to degradation designated as potential-induced degradation (PID).

For evaluation of the used PV modules degradation, measurements on a module after three years of operation on the roof and on another module stored in laboratory were performed and compared. In other to obtained more detailed information, all modules underwent high voltage stress at 1000 V DC for 48 hours and then potential induced degradation was checked by charging and discharging current measurements.

The chosen electrical properties of PV modules in the delivered state (as new) and after 3 years of operation (aged) were compared by means of charging current measurements. The applied measuring DC voltage was set to 1000 V between the short-circuited module terminals (−) and aluminium frame (+), and the total measuring time was set to 1800 seconds. The results compare the measurements at 20 °C and 80 °C.

These measurements were followed by application of 1000 V DC voltage for a 48 hour period at 80 °C for PID tests of the investigated samples. After PID treatment, again, the procedure of loading currents measurement was performed at 20 °C and 80 °C.

Figure 4 shows results of charging currents measured at 20 °C. The tested module in the delivered state shows significantly lower values of the charging current, higher values of insulation resistance in the described measurement connection. Measurements of charging currents show slightly lower values of charging currents after PID treatment at 20 °C.

Figure 5 shows the results of charging currents measurements at 80 °C. The tested module in the delivered state shows higher values of the charging current at 80 °C. Measurement of charging currents for both samples show a decrease of the charging currents after PID treatment also at 80 °C.

Polarization index k_p of non-aged (new, module 3) stored in the laboratory and of three modules operated on the roof was calculated and the results are compared in Fig. 6. Good quality insulation is expected to have k_p higher than 1. All modules fulfil this condition. The value of k_p at temperatures close to room temperature is remarkably higher in the case of non-degraded module stored in laboratory. The lower k_p of aged modules is caused most probably by the humidity absorbed into the encapsulant structure of the module during the operation in outer environment. The presence of humidity affects the conductivity increases the conduction current (DC conduction) and hereby the value of k_p increases. Increasing temperature results in escape of humidity from the insulation and the values of k_p are similar for all modules when the measurement is performed at 80 °C.

6 CONCLUSION

The aim of this paper was to evaluate the operation of the small PV system installed on a supporting tilted construction on a flat roof. The installed modules and their electric properties were compared with the module of the same type stored in laboratory. Their electric behaviour can be clearly distinguished with regard to their history and express the difference between non-aged and aged modules. The time dependence of the charging current as a response to potential induced degradation (PID) shows the difference but also the temperature behaviour of the polarization index can distinguish degraded and non-degraded modules without previous PID process.

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