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Photovoltaic panel's angle optimization for a better reflected irradiation collection using empiric data and Excel functions approximation

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***Abstract*— There are many unused surfaces (places) where is practical to install PV panels and still there is a lack of research in this domain. That is why this article presents research for a single row, from W-E, PV panels module output at different installation angle for a better indirect radiation collection, in special areas, like: roof, water-surface and shore. It contains experimental data correlated with simulation data.**

Keywords—renewable energy, photovoltaic panels, indirect radiation, tilt influence, electrical performance.

I. INTRODUCTION

This paper is intended to be used for those who want to install photovoltaic (PV) systems in unusual places or limited spaces, like: water surface, ship, roof, wall, fence etc. Even if you are a researcher or just an enthusiast who wants to install a PV system, you will try to obtain the maximum performance at the lowest price and – this is the idea of this article – install the PV panels in a futurist way for minimizing your practical space. For example, you do not want PV panels occupy your front yard or orchard, or maybe the panels don't look very fancy on your roof. That is why we made a research in this domain.

The first thing you should have in mind when you want to install a PV system is the type of the PV panels. Of course, there are many technologies developed in this moment but there only a few of them on the market at a competitive price. A complete list of technologies with their efficiencies are presented here [2] and a recent advances in solar energy harvesting materials with particular emphasis on photovoltaic materials are presented here [3]. A simple rule of thumb to choose PV cell technologies is: Si-mono or poly crystalline for direct solar irradiation and thin-film a-Si or CIS/CdTl for diffused (cloudy weather) solar irradiation.

The second thing is the cost. You can find a lot of useful information related to PV cost on different markets and for different technologies, presented in an intuitive and ease to understand way here [4].

To maximize production of the PV panels for a special area, it is necessary to find the optimal installation position. It's important to take into consideration the shade areas [5] [6], the indirect irradiation (albedo)[7] [8] and the diffuse solar light [9]–[11].

For maximum production in unusual sites it's not enough to use standard PV system simulation software and it's important to create particular mathematical models to predict and increase the energy output. We encourage the owners to realize a small-scale system and test it in different conditions.

Our research cover four limited space areas (pitch (resin), wet pitch, galvanized cover and matte metal tile) where the indirect irradiation plays an important role for the total output of the system.

II. MATHEMATICAL APPROACH

Mathematical models are an essential tool for understanding and optimizing the performance of PV panels. These models use a range of mathematical equations to simulate the behavior of the solar cells in response to different environmental conditions.

One commonly used model is the single-diode model, which describes the current-voltage characteristics of a solar cell. This model takes into account factors such as the intensity of sunlight, the temperature, and the material properties of the solar cell. Other models, such as the double-diode model, incorporate additional parameters to improve accuracy.

Mathematical models can also be used to optimize the design and performance of PV panels. For example, models can be used to determine the optimal size and orientation of the panels for a given location, or to evaluate the impact of different materials and manufacturing techniques on the efficiency of the panels.

However, it is important to note that these models are based on simplifications and assumptions about the behavior of the solar cells, and may not accurately reflect real-world conditions. Therefore, it is essential to validate these models through experimental measurements and field testing.

Overall, mathematical models play a crucial role in advancing our understanding of PV panels and improving their efficiency and effectiveness as a renewable energy source.

An ideal photovoltaic cell can be considered a diode because the basic structure of a photovoltaic cell is a PN junction, connected in parallel with a current source, this represents the photocurrent produced by solar irradiation.

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Using the diode equation and introducing the photocurrent into it we can obtain the general equation of an ideal photovoltaic cell:

$$I = I_{PH} - I_0(e^{\frac{qV}{K_B T}} - 1) \qquad (1)$$

where, I_{PH} is the photocurrent, I_0 is the indirect diode bias current in the dark, q is the elementary charge, V is the PV cell terminal voltage, K_B is Boltzmann's constant, and T is the temperature in Kelvins.

In the laboratory, the term current density is used, which represents the intensity produced by the photovoltaic cell per surface unit. Thus, different types of photovoltaic cells can be compared without making additional calculations for their surfaces.

From equation (1) the expressions for the open circuit voltage V_{OC} and the short-circuit current I_{SC} can be determined. Replacing the current I with the current density J and solving equation (1) for J=0, respectively V=0 we will obtain the following two equations:

$$V_{OC} = \frac{nK_B T}{q}\ln(\frac{J_{PH}}{J_0} + 1) \qquad (2)$$

$$J_{SC} = J_{PH} \qquad (3)$$

From relation (2) it follows that the open-circuit voltage V_{OC} depends on the photocurrent. Which means that the V_{OC} increases with the increase of the irradiation. Another important parameter for open-circuit voltage is temperature. At a first glance of the equation (2) we can say that the open-circuit voltage is directly proportional to the temperature, which is totally wrong. The current density J_0 is strongly influenced by temperature. The higher the temperature, the higher the J_0 and the lower the V_{OC}.

The open-circuit voltage also depends on the band gap of the irradiation absorbing material, the doping level of the intrinsic material and the quality of the material.

From the relation (3) it follows that the short-circuit current density J_{SC} depends on the photocurrent density J_{PH}. At the same time, the short-circuit current density also depends on the spectrum of the incident light, the absorption coefficient of the absorbing material and the probability of absorption.

III. Results

The experiments took place on the Maritime Engineering Faculty roof in “Mircea cel Batran” Naval Academy from Constanta, Romania. The experiment platform had the following structure:

- 4 PV panels of 10Wp;
- 4 loads used also as voltage dividers;
- USB-6008 data acquisition board from National Instruments;
- Laptop with LabView software and DAQ program.

The data acquisition board can measure only voltages on its analog channels. That is why we used a voltage divider for each channel (PV panel) because the maximum voltage that USB-6008 can measure is 10V and the PV output

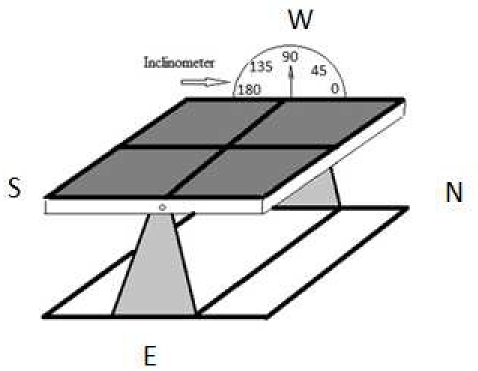

Fig. 1. Schematic drawing of the experimental setup.

voltage exceeds that value. Also, the load resistance was calculated at 44 Ohms to assure the maximum power point of 10Wp with its specific voltage Vmpp = 21V and current Impp = 0,4762A. Because it’s a linear load (resistor) we didn’t calculate the PVs output powers ($P = U^2/R$) and all the comparisons were made relative to Vmpp and not to 10Wp.

The measurements were made at the end of May at midday. The duration of them was short, just a few seconds for each measurement, because the objective was to determine the range of installing angles at which the PV output is at least of 95% of its maximum (test in Standard Test Conditions)[12], [13]. The study does not present an optimization for the entire day/week/month/season.

All four PV panels were fixed in a plane rigid structure in order to move them all in the same time. All installing angle variations ware made only in the horizontal plane. The planes ware installed facing the South. The horizontal angle variation was for 0° (facing the Zenith), 90° facing the South and, in the end, to 180° facing the horizontal roof (center of the Earth); see Fig. 1.

We modified the roof cover with four different materials: pitch (resin), wet pitch, galvanized cover and matte metal tile.

A. Measurement on a pitch (resin) roof

The first experiment was on the normal cover of the faculty roof.

We obtained the results presented in fig. 2. On vertical axes are the voltages of the four PV panels and on horizontal axis are the measurements number. The angle is orange color and its value is dived by 10 in order to put it on the same graphic with voltages.

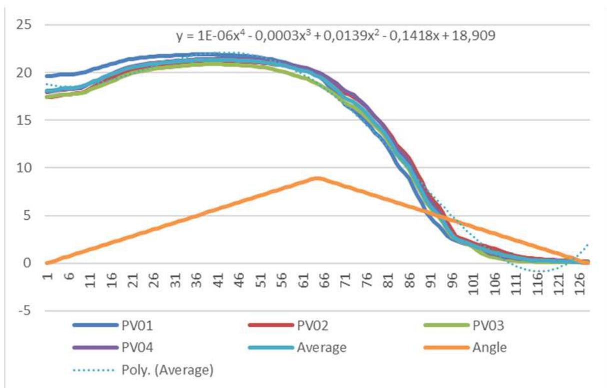

Fig. 2. PVs output for incident angle 180° variation on a pitch roof.

The average value for all PV panel and for entire variation of the incident angle is 11,05V which correspond to 52,6% from its maximum power output voltage (21Vmpp).

The maximum output voltage average is 21,35V which corresponds to 101,6% from its maximum power output voltage.

The approximation polynomial formula is:

$$y = 1E\text{-}06x^4 - 0,0003x^3 + 0,0139x^2 - 0,1418x + 18,909 \quad (4)$$

For that period of the day it resulted that the angles for which the PV output is almost 100% are between 30 and 80 degrees. Which means that reflected irradiation has a powerful impact on the total incident irradiation. Also, a pitch roof, which has small sand pieces on it, it is a good reflector.

B. Measurement on a wet pitch (resin) roof

The second experiment was on the normal cover of the faculty roof but after we added water on it.

We obtain the results presented in fig. 3.

The average value for all PV panels and for entire variation of the incident angle is 15,73V which corresponds to 74,9% from its maximum power output voltage (21Vmpp).

The maximum output voltage average is 23,46V which corresponds to 111,7% from its maximum power output voltage.

The approximation polynomial formula is:

$$y = 2E\text{-}06x^4 - 0,0004x^3 + 0,0185x^2 - 0,1598x + 20,687 \quad (5)$$

For that period of the day, it resulted that the angles for which the PV output is almost 100% are between 27 and 95 degrees. Which means that reflected irradiation has a powerful impact on the total incident irradiation. Also, a wet pitch roof is a better reflector than a dry one.

C. Measurement on a galvanized cover roof

The third experiment was on a galvanized cover installed on a small part from the faculty roof.

We obtain the results presented in figure 4.

The average value for all PV panels and for entire variation of the incident angle is 15,90V which corresponds

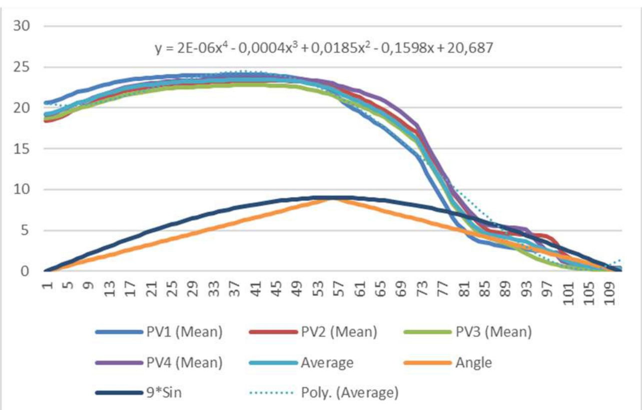

Fig. 3. PVs output for incident angle 180° variation on a wet pitch roof.

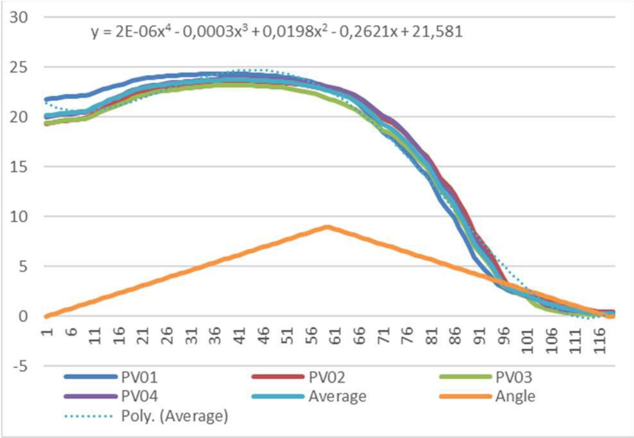

Fig. 4. PVs output for incident angle 180° variation on galvanized roof.

to 75,7% from its maximum power output voltage (21Vmpp).

The maximum output voltage average is 23,72V which corresponds to 113% from its maximum power output voltage.

The approximation polynomial formula is:

$$y = 2E\text{-}06x^4 - 0,0003x^3 + 0,0198x^2 - 0,2621x + 21,581 \quad (6)$$

For that period of the day, it resulted that the angles for which the PV output is almost 100% are between 20 and 100 degrees. Which means that reflected irradiation has a powerful impact on the total incident irradiation. Also, a galvanized roof is a better reflector than all we have tested.

D. Measurement on a matte metal tile roof

The fourth experiment was on a matte metal tile roof installed on small part from the faculty roof.

We obtain the results presented in fig. 5.

The average value for all PV panels and for entire variation of the incident angle is 15,28V which corresponds to 72,8% from its maximum power output voltage

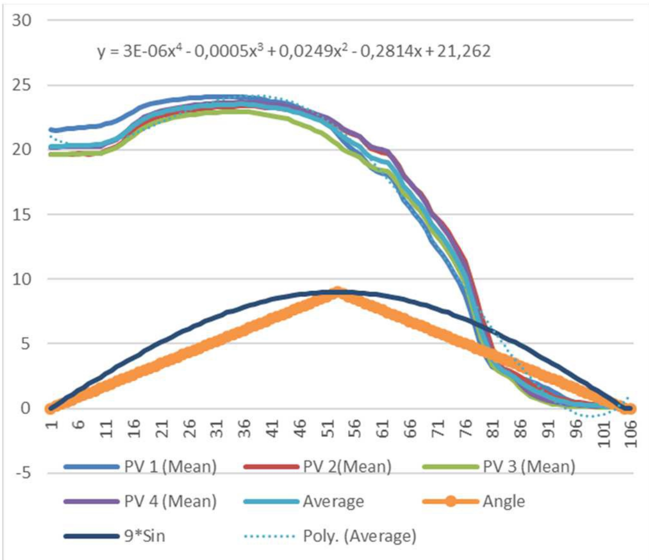

Fig. 5. PVs output for incident angle 180° variation on matte metal tile roof.

(21Vmpp).

The maximum output voltage average is 23,52V which corresponds to 112% from its maximum power output voltage.

The approximation polynomial formula is:

$$y = 2E{-}06x^4 - 0{,}0003x^3 + 0{,}0198x^2 - 0{,}2621x + 21{,}581 \quad (7)$$

For that period of the day, it resulted that the angles for which the PV output is almost 100% are between 35 and 95 degrees. Which means that reflected irradiation has a powerful impact on the total incident irradiation. Also, a matte metal tile roof is a better reflector than pitch, but worse than galvanized one.

IV. Conclusions

In conclusion, the incident irradiation is a critical factor that affects the performance of PV panels. The amount of sunlight received by the solar panels directly impacts their output power and efficiency. Therefore, PV panel installations should be designed based on the incident irradiation levels in the specific location. It is important to note that incident irradiation levels can vary throughout the year, depending on factors such as weather conditions, location, and time of day. Therefore, it is crucial to consider the variability of incident irradiation when planning and designing PV systems to maximize their energy output and ensure their long-term viability.

Our experiments showed that it's important to have measurements for specific unusual applications of PV modules. In this way you can maximize production and can install PV module on vertical walls or shores if you have a good reflection surface in front of them.

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