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Influence of supplementary installed optical structures on VA characteristics of photovoltaic modules

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Abstract. This paper focuses on optimisation of energy gains for various types of supplementary installed optical structures on photovoltaic modules.

The project is based on real measurements using modified Flash Tester Unit and theoretical calculations based on modified equations describing the intensity of incident rays. A standard flash tester unit was modified to enable measurements using various spectrum, incident angle and variable composition between direct and ambient intensity while the homogeneity and precision was preserved. In similar way, the conventional equations used for calculations of incident rays on surface of photovoltaic module were modified to describe the angle and surface of optical structures supplementary installed on photovoltaic modules.

Various parameters are used for trimming of the optimisation process. Influence of the optical structure can have either positive impact on produced energy or negative impact while negative or positive impact on light pollution in the surrounding urbanized or populated areas. The main goal is to improve and verify photovoltaic system in real conditions with real light pollution effect defined by the model buildings with integrated renewable energy sources. The system can be later used in general installations on commercial or residential buildings.

Key words. Photovoltaic modules, optical structures, light pollution.

1. Introduction

Photovoltaic arrays of all sizes became conventional part of power sources mix during the last decade. Although these systems contain no mechanical components, they are very sensitive and vulnerable and can significantly influence their neighbourhood.

The main disadvantage of photovoltaic systems from this point of view is installation in the open space and direct exposition to unpredictable ambient conditions. This situation can lead into wide set of unpleasant effects, above all in urbanized, highly populated areas or in traffic corridors. [1, 2].

While the prediction of power generation from weather depending systems is always very challenging, existence of above-described phenomenon can seriously obstruct the residents, participants in road traffic or industrial operations [3].

Multimegawatt photovoltaic arrays and even small family house systems represent either independent energy solution or interesting economical investment, but also significant obstructing and dangerous structures. Unfortunately, the economic benefits often do not comply with safety or health regulations or standards. The reasons are evident. Pre-design computations are usually based on common simulation tools and do not respond to harsh local ambient conditions from the safety and comfort point of view. Significant glares and reflections can confuse not just wild nature animals (birds trying to land on the PV array) but also obstruct residents, dazzle car drivers, train crew or pilots and cause significant discomfort or dangerous situations [1, 2]. An example of unpleasant and dangerous conditions caused by solar system can be seen on Fig. 1.

Fig.1. Obstructing reflections in traffic (Abengoa Solar).

2. Incident rays on surface of photovoltaic modules

The values of global radiation obtained from the meteo station must be recalculated to the surface of the photovoltaic plant (orientation south, inclination 45 °) to determine the production prediction. For the purposes of this study, the methodology using a conversion from the global radiation first to the normal component and then to the generally oriented area [4, 5].

The total intensity of solar radiation is expressed from the arithmetic sum of the direct and diffuse components according to (1).

$$I = I_P + I_D \tag{1}$$

The measured values of global radiation can be similarly decomposed into the sum of the direct and diffuse components on a horizontal surface as in (2).

$$I_G = I_{Ph} + I_{Dh} \tag{2}$$

where IPh represents the intensity of the direct sunlight incidenting on a horizontal surface, which can be expressed as in (3).

$$I_{Ph} = I_{Pn} \sin h \tag{3}$$

and IDh represents the intensity of diffuse radiation incident on a horizontal surface, which is defined corresponding to (4).

$$I_{Dh} = 0{,}33\left(I_0 - I_{Pn}\right)\sin h \tag{4}$$

The value of the normal component IPn can be expressed from the equations 2, 3 and 4. The calculation can be also verified by conversion from the solar constant I0 and the pollution factor Z as in (5).

$$I_{Pn} = I_0 e^{-\frac{Z}{\varepsilon}} \tag{5}$$

where ε is the dimensionless coefficient depending on the altitude of the locality and the height of the Sun above the horizon expressed as (6).

$$\varepsilon = \frac{9{,}38076\left[\sin h + \left(0.003 + \sin^2 h\right)^{0.5}\right]}{2.0015\left(1 - H \cdot 10^{-4}\right)} + 0.91018 \tag{6}$$

where H is the altitude of the site in meters and h is the height of the sun above the horizon. For the model object (UWB Pilsen) is the altitude 353 m above sea level. The height of the Sun above the horizon is calculated respecting the (7).

$$\sin h = \sin\delta * \sin\varphi + \cos\delta * \cos\varphi * \cos\tau \tag{7}$$

where φ is the latitude value of the site (for the model object: 49 ° 43´22 “). The value of τ indicates a time angle of 15 ° for each full hour, with positive values from noon (south) to evening (west) and negative values towards morning (east). The value of σ represents the solar declination for a given calendar day, which can be obtained exactly from astronomical yearbooks or determined for technical purposes by a simplified calculation according to standard CSN 730581 [6] according to (8).

$$\delta = 23{,}45 * \sin(0{,}98 * D + 29{,}7 * M - 109) \tag{8}$$

where M indicates the order of the calendar month in the year and D the order of the day of the month. From the normal value, the intensity of the direct component of solar radiation can finally be determined on a generally oriented surface as in (9).

$$I_p = I_{Pn} \cos\gamma \tag{9}$$

if γ is the actual angle of incidence of the rays on the sunlit surface, expressed as (10).

$$\cos\gamma = \sin h . \cos\alpha + \cos h \sin\alpha \cos(a - a_s) \tag{10}$$

where α is the angle of inclination of the illuminated surface from the horizontal plane (45 ° for the model object) and as is the azimuth angle of the normal of the illuminated surface measured with the same orientation as the time angle τ (0 ° for the model object). The value of a represents the azimuth [7, 8] of the sun (oriented in a similar way) and expressed by the relations defined as (11).

$$\sin a = \frac{\cos\delta}{\cos(h)} * \sin\tau \tag{11}$$

The diffusion component of solar radiation on a generally oriented free surface is determined from the equation shown in (12).

$$I_D = 0{,}5\left(1 + \cos\alpha\right)I_{Dh} + 0{,}5r\left(1 - \cos\alpha\right)\left(I_{Ph} + I_{Dh}\right) \tag{12}$$

3. Measurements using modified flash tester unit Pasan Sun Simulator 2C

Measuring photovoltaic modules under standard test conditions (STC) is the only way to assess their features, performance and quality. STC includes following conditions: cell temperature of 25 °C, AM 1,5 Global spectrum and irradiance of 1000 Wm^{-2}. This standard allows comparison of different photovoltaic modules under the same conditions. The measurements are usually performed with usage of professional testers, such as the Pasan Sun Simulator 2C, which measures the volt-ampere characteristics of the module in a short time, so that the temperature of the module cannot be increased [9, 10]. The results of the STC measurements provide important parameters such as maximum power, efficiency and other electrical properties that are essential for the correct sizing and operation of PV systems, but do not allow to compare the power generation under any other conditions (diffuse or indirect illumination, illumination from various angles etc.) [11, 12].

The original Pasan Sun Simulator 2C was modified to accommodate measured photovoltaic module on an adjustable angle. The adjustment is possible on vertical and horizontal direction with precision of 1°. Another modification was made inside the black chamber to enable measurements on indirect rays and ambient illumination (additional diffraction surfaces and apertures) [13]. The modifications are presented on Fig. 2.

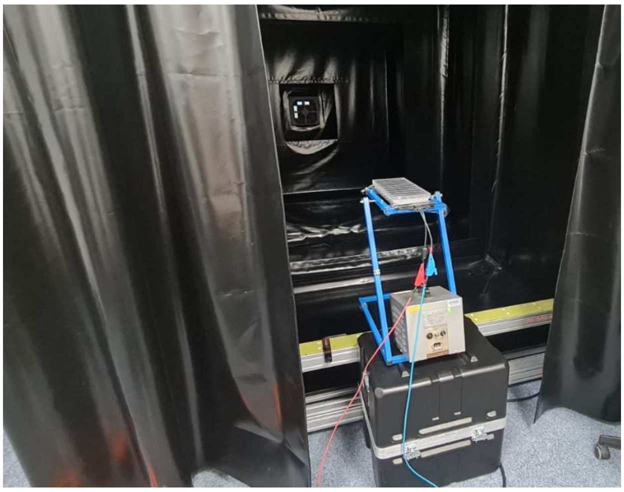

Fig.2. Overview of modified Flash Tester Unit (Pasan Sun Simulator 2C).

Glares on photovoltaic modules are significant problems that can affect their efficiency and performance. Glare occurs when light hitting the module surface is not fully absorbed and some is reflected back into the environment. This phenomenon can be caused by several factors, including the glass surface finish, the angle of incidence of light, and the cleanliness of the module surface1. Glare can be very unpleasant as described in first paragraphs and also reduce the amount of light available for power generation.

Various technologies and materials are used to minimize the glares. One of the most effective methods is the application of anti-reflective coatings to the glass surface or usage of textured surfaces that scatter light and reduce the intensity of glare. Similar surface textures can be used simultaneously to increase the generated power. The most simple examples are various modifications of Fresnel lens. Fig. 3 presents a measurement of a glare on the surface of a sample of standard photovoltaic module using the modified flash tester unit Pasan Sun Simulator 2C, while Fig. 4 shows original VA characteristics of the sample module measured at STC and avoiding reflections.

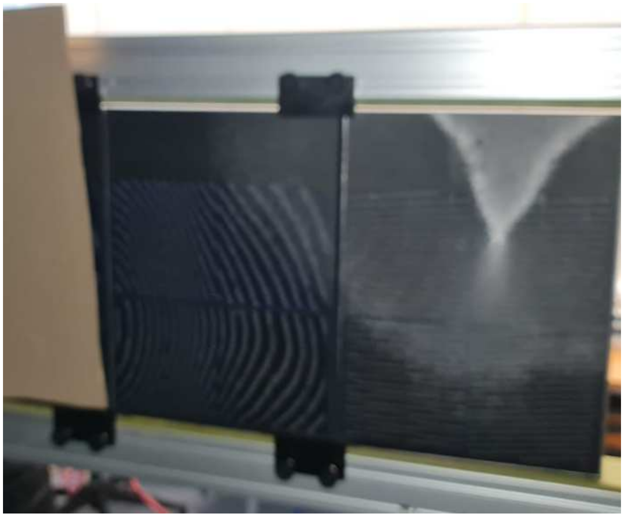

Fig.3. Glare on a sample photovoltaic module (modified Pasan Sun Simulator 2C).

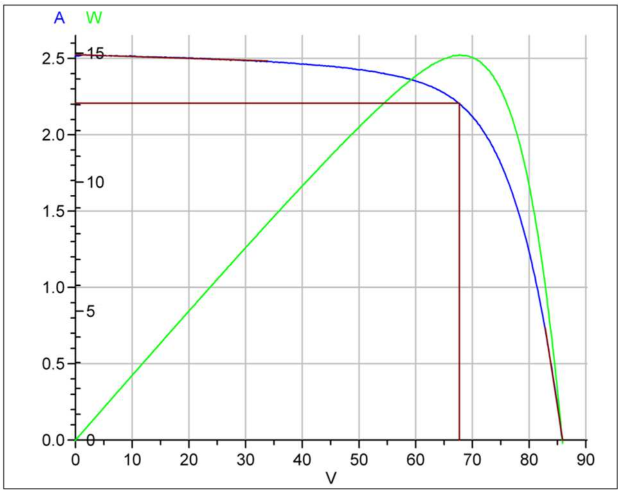

Fig.4. VA characteristics of the sample photovoltaic module without reflections (modified Pasan Sun Simulator 2C).

Various techniques including non-reflective coatings can be used to decrease the influence of the reflections and glares. These layers (often nano structures) are very thin and sensitive to ambient conditions and can require periodical renovations (repainting).

Other option is to use specific optical structures or textures bellow the final surface of the module. If these structures are not covered under the covering glass, they very intensively collect various pollutants from ambient environment and decrease the generated power. Fig. 5 shows details of the reflection on the surface of the sample photovoltaic module (original surface). The figure shows that approximately one fifth of the surface is affected by glares.

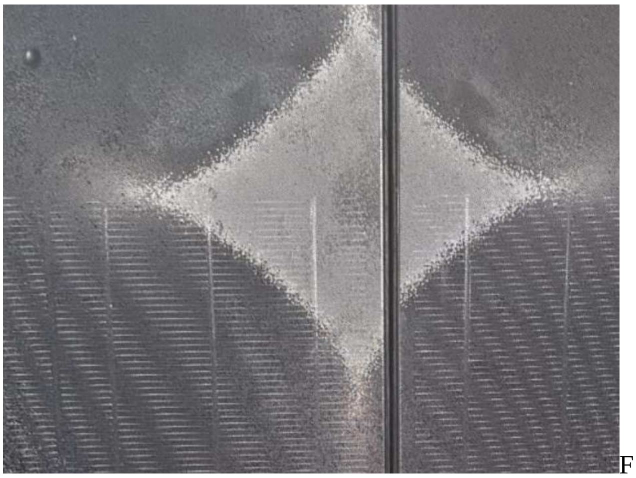
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Fig.5. Original glare on the sample photovoltaic module (modified Pasan Sun Simulator 2C).

Fig. 6 demonstrates results of optimized structure on the surface of the same sample of photovoltaic module reducing the intensity of the reflected glares and modifying their projection into concentrical circles or ellipses.

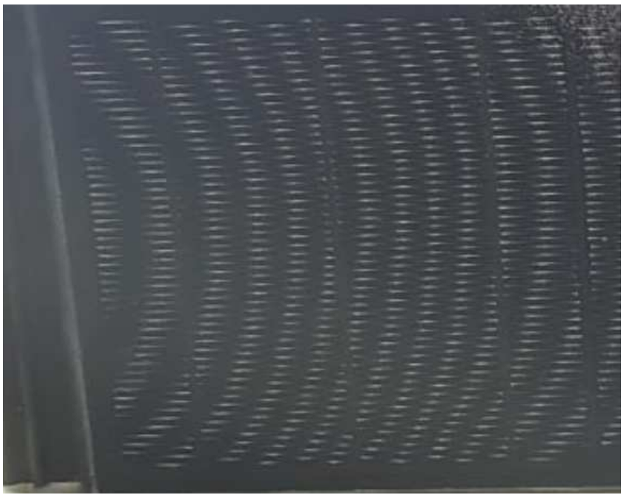

Fig.6. Optimized glare on the sample photovoltaic module (modified Pasan Sun Simulator 2C).

It is evident that intensity distribution through the entire surface is almost constant. The deviation between its maximum and minimum is less than 3 % while in the case of the original panel it differs for more than 22 % with very contrast boundaries.

Fig. 7 shows influence of the optical structure on VA characteristic caused by eliminated reflections. If compared to reference situation shown on Fig. 4, the current is, of course, a bit lower. This is the result of the additional optical structure that behaves like an optical element with the transparency lower than 100 %. The advantage of this layer is evident if compared to Fig. 8 and Fig. 9, where the original panel without the optical structure is affected by strong reflections causing non-homogenous illumination and thus reaction of inbuilt bypass diodes.

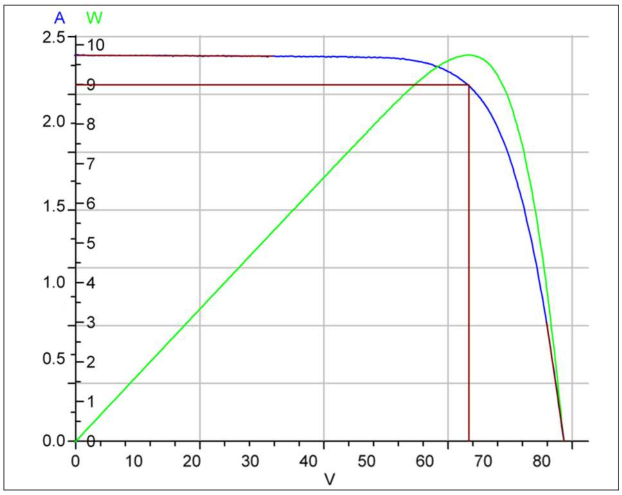

Fig.7. VA characteristics of optimized sample photovoltaic module with limited reflections (modified Pasan Sun Simulator 2C).

Fig. 8 presents VA characteristic of the original module without the optical structure with 10 % of area affected with reflections. Influence of 1 bypass diode reacting on the reflection is evident.

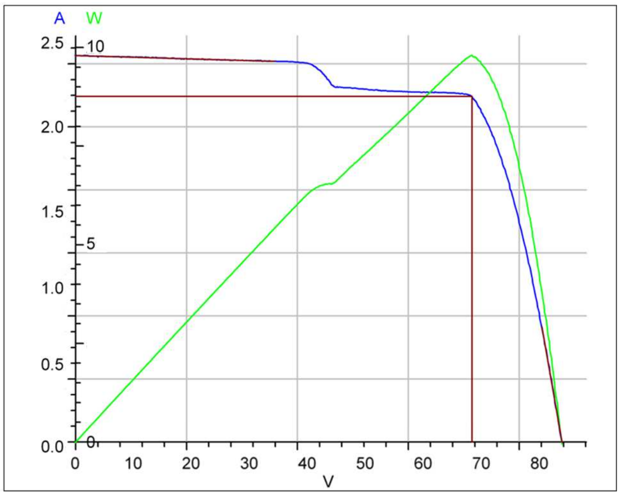

Fig.8. VA characteristics of original sample photovoltaic module with 10 % reflections (modified Pasan Sun Simulator 2C).

Presented VA characteristic shows 2 local maximums of the current and power function described in (13).

$$\mathrm{Max}(I, P) = d(I, P)/dt \tag{13}$$

It demonstrates an example of proper reaction of inbuilt bypass diode. Glares on the surface of tested photovoltaic module significantly decrease its power and efficiency. In this case, both maximums are very close to each other but the difference in generated power is noticeable. In fact, it is inverted situation with soft shadows.

If we use the power optimizers in this case, it is very difficult to correctly detect the global maximum of both functions (I, P) and not all used algorithms are capable of that. The golden rule of photovoltaic – try to avoid as much shadows as possible – applies in reflections in the very same way with the very same results.

Fig. 9 shows yet more unpleasant situation, where the reflections covering 20 % of modules area (without optical structures) affects both bypass diodes what leads to significantly lower current and thus very noticeable decrease of power generation.

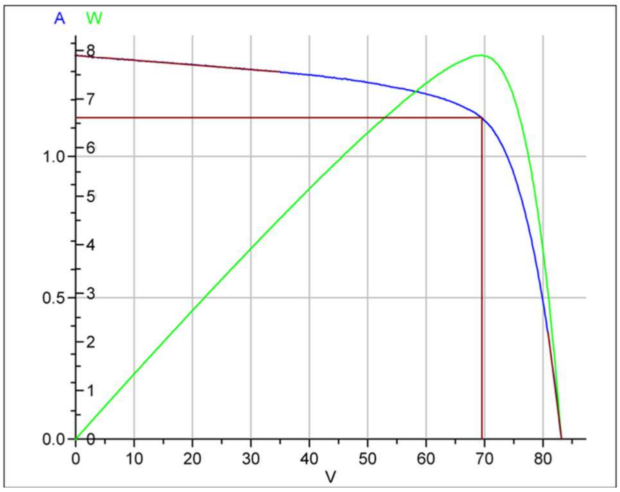

Fig.9. VA characteristics of original sample photovoltaic module with 20 % reflections (modified Pasan Sun Simulator 2C).

The real influence of tested additional optical structure installed on sample photovoltaic module can be read in detail in the Table I. Average values (I_{MPP}, U_{MPP}, P_{MPP}) from 10 measurements are presented for every single case.

Table I.: Influence of the optical structure

	Original	With structure	1 bypass diode affected	2 bypass diodes affected
I_{MPP}	2,23	2,12	2,01	1,11
U_{MPP}	6,81	6,71	6,69	6,74
P_{MPP}	15,19	14,22	13,44	7,62

4. Conclusion

Presented experiments proved interesting effect of special optical structures to decrease the influence of glares and reflections on the surface of photovoltaic modules. The difference depends on the size of the reflections.

Further research will continue with the directional characteristics and on the optimization of the structures to multidirectional effect.

Acknowledgement

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