Improved model for estimating PV system production

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***Abstract*— In this paper is presented improved model for estimating the electricity production of photovoltaic (PV) systems. In the literature is known two kinds of models, theoretical one and one based on the measured data on horizontal solar insolation. In second one, solar insolation on panel surface, beside of other parameters, is determinate based on average value of slope factor. This paper gives improvements in model for estimating panel production, determining solar insolation on panel surface based on available data of average ten-minute solar insolation on horizontal surface and ambient temperature, and calculating slope factor for each ten-minute period. Experimental results obtained by the real photovoltaic system mounted on a roof of Faculty served as a verification of described improved model.**

Keywords- output power; photovoltaic system; solar insolation

I. Introduction

Photovoltaic (PV) system is an integrated set of photovoltaic modules and other components, designed so that the primary solar energy directly transform into electricity, which ensures the work of a number DC and/or AC consumers. In photovoltaic systems connected to the distribution grid, the direct current produced by the solar modules is converted to AC power by the inverter, which is connected to the grid, allowing, besides supplying the consumer, energy exchange with the grid [1].

Design of photovoltaic systems is usually done based on their annual energy production, which is also a good parameter for monitoring the long-term performance of a photovoltaic system. To predict the annual energy production of photovoltaic systems, reliable models and methods are needed, considering the stochastic nature of solar radiation and the large number of influencing factors (environmental conditions and system performance) [2]. In the literature [3-6] there are presented models for predicting the power and energy of solar radiation per unit of area (irradiation and insolation).

This paper describes the improved model for estimating PV system production based on measured data of solar insolation on horizontal surface and ambient temperature. Verification of the model was carried out on a real photovoltaic system mounted on the roof of Faculty of Electrical Engineering East Sarajevo. Analytics results and practical measurements are given in following of paper.

II. Photovoltaic System Production Analysis

In order to design a grid connected PV systems, solar energy resources, environmental conditions, and characteristics of all elements of system must be well acquainted. Estimate of solar energy resources is based on measurements and calculations based on solar radiation at the surface on which it is planned to set up the panel. In order to estimate system performance, the rated DC power output of an individual module under standard test conditions (irradiation of 1 kWh/m^2, air mass ratio AM 1.5, cell operating temperature 25°C, modules completely clean) can be used at the beginning of process. In real operating conditions, output power of PV system delivered to the grid P_{AC} is less than the DC output modules at standard conditions $P_{\mathrm{DC(STC)}}$ for due to losses regarding conversion efficiency:

$$P_{\mathrm{AC}} = P_{\mathrm{DC(STC)}} \cdot \eta_{\mathrm{Z}} \cdot \eta_{\mathrm{N}} \cdot \eta_{T} \cdot \eta_{\mathrm{inv}} \quad (1)$$

where η_Z, η_{N} and η_T define efficiency reduction due to dirty of panels, modules mismatch, differences in ambient conditions, and inverter efficiency η_{inv}. The impact of these losses can reduce the output power by 20–40% [1].

The inverter efficiency varies according to the load. Grid connected inverters have efficiency over 90%, except at very low loads. Modules mismatch causes a decrease in the output power of parallel connected modules, because their current-voltage characteristics are not identical.

Another factor that has significant effect on the reduction of output power of panel below the rated value is cell operating temperature. To be able to determine the module efficiency under different ambient conditions it is necessary to calculate the temperature of the module. On the module temperature dominant influence has solar radiation and air-cooling conditions (wind). For each module manufacturer defines the temperature at nominal operating conditions (*NOCT - Nominal Operation Cell Temperature*). The *NOCT* is cell temperature in a module at ambient temperature of 20°C, solar irradiation of 800 W/m^2 and wind speed of 1 m/s. Based on *NOCT* parameter module temperature can be estimated by:

$$T_{\mathrm{cell}} = T_{\mathrm{amb}} + \left(\frac{NOCT - 20}{0.8} \right) \cdot I_{\mathrm{c}} \quad (2)$$

where are: T_{cell} module temperature, T_{amb} ambient temperature, and I_c solar irradiation on the surface of the module.

Due to an increase in temperature of solar cells above the standard value (25°C), and module efficiency reduction of ΔP = -0.5%/°C, output power on DC connectors of the system is given by (3).

$$P_{\text{DC(PTC)}} = P_{\text{DC(STC)}}\left(1 - 0.005(T_{\text{cell}} - 25^0\text{C})\right) \tag{3}$$

Taking into account the above mentioned losses and solar insolation, output power that PV system delivering to grid can be estimated by (4).

$$P_{\text{AC}} = P_{\text{DC(STC)}}\left(1 - 0.005(T_{\text{cell}} - 25^0\text{C})\right) \cdot I_c \cdot \eta_{\text{Z}} \cdot \eta_{\text{N}} \cdot \eta_{\text{inv}} \tag{4}$$

Determination of insolation on the panel surface can be done in two ways, as it described in [1]. The first method is the determination of insolation on the surface of the panel based on extraterrestrial irradiation on a clear day (*Clear day* model - theoretical model), while the second method determines the insolation on the surface of the panel in real conditions based on measured insolation on a horizontal surface. Review of these two methods is given as following.

A. Determination of insolation using „Clear Day” model

Solar radiation reaches the solar panels in the form of beam (direct), diffused and reflected radiation. These components of solar radiation on the solar panel in a clear day can be calculated on the basis of extraterrestrial solar insolation [1]. Solar radiation in the form of beam radiation that reaches the earth’s surface is less than extraterrestrial radiation due to absorption and scattering in the atmosphere. Evaluation of beam irradiation of the earth's surface is given Bouquer-Lambert law:

$$I_B = Ae^{-km} \tag{5}$$

where I_B represent beam radiation on the earth’s surface, A extraterrestrial flux that entering in the atmosphere, k is coefficient of attenuation of solar radiation in the Earth's atmosphere (optical depth), and m is air mass ratio. Calculation of the values present in the previous equation is done according to the relations given in [1]. The total insolation I_c on the surface of the panel is given by:

$$I_C = I_{BC} + I_{DC} + I_{RC} \tag{6}$$

where I_{BC} represent beam insolation on the panel surface, I_{DC} diffuse radiation of the panel, and I_{RC} reflected radiation by surfaces in front of the panel, respectively. These components of total solar insolation can be calculated according to the following relationship:

$$I_{BC} = I_B \cdot \cos\theta = I_{BH} \cdot R_B \tag{7}$$

$$I_{DC} = I_{DH} \cdot \left(\frac{1 + \cos\Sigma}{2}\right) \tag{8}$$

$$I_{RC} = \rho\left(I_{BH} + I_{DH}\right)\left(\frac{1 - \cos\Sigma}{2}\right) \tag{9}$$

where are: θ incidence angle, Σ tilt angle of the panel, ρ ground reflectance, R_B slope factor, I_{BH} beam insolation on a horizontal surface, I_{DH} diffuse insolation on a horizontal surface.

The beam insolation on a horizontal surface I_{BH} and diffuse insolation on a horizontal surface I_{DH} is calculated as follows:

$$I_{BH} = I_B \sin\beta \tag{10}$$

$$I_{DH} = C \cdot I_B \tag{11}$$

where C represents sky diffuse factor.

B. Determination of insolation using model based on measured insolation at a horizontal surface

In order to extrapolate measured data of the total horizontal insolation I_H, which were collected for a given period, to arbitrarily oriented solar module it is necessary to decompose the total horizontal insolation at appropriate direct-beam I_{BH} and diffuse I_{DH} component [1,6,7,8]. For the determination of the total horizontal insolation components it is necessary to calculate the clearness index K_T. Clearness index can be calculated for each day or as average monthly index. It is define as the ratio of the average horizontal insolation I_{HAV} and extraterrestrial insolation on a horizontal surface I_{0AV}.

$$K_T = \frac{I_{HAV}}{I_{0AV}} \tag{12}$$

Higher value of clearness index means that the sky and atmosphere is clear and lower value indicates overcast conditions. The average daily on a horizontal surface I_0 can be obtained by integrating total extraterrestrial insolation from sunrise to sunset and its projection on a horizontal surface.

The diffuse portion of horizontal insolation can be estimated by using Liu-Jordan's empirical relation who gives correlation between the diffuse component of insolation on a horizontal surfaces and clearness index [1,9].

$$\frac{I_{DHAV}}{I_{HAV}} = 1.39 - 4.027 \cdot K_T + 5.531 \cdot K_T^2 - 3.108 \cdot K_T^3 \tag{13}$$

The direct-beam component of insolation on the surface of the panel is calculated based on the relation (14), while other two components can be obtained based on (8) and (9).

$$I_{BC} = I_{BH} \cdot \frac{\cos\theta}{\sin\beta} = I_{BH} \cdot R_B \tag{14}$$

Incidence angle θ, between the collector and beam, depends on the orientation of the panel, panel inclination, altitude angle β and the solar azimuth, so that slope factor is changed during the day. If it is known only the information of the average monthly (or daily) values of horizontal insolation, it is necessary to calculate the average value of the slope factors [1,9].

$$\overline{R}_B = \frac{\cos(L-\Sigma)\cdot\cos\delta\cdot\sin H_{SRC} + H_{SRC}\cdot\sin(L-\Sigma)\cdot\sin\delta}{\cos L\cdot\cos\delta\cdot\sin H_{SR} + H_{SR}\cdot\sin L\cdot\sin\delta} \tag{15}$$

The average value of the slope factor is estimated by averaging the value of $\cos\theta$ over those hours of the day in which the sun is in front of the panel and dividing that by the average value of $\sin\beta$ over those hours of the day when the sun is above the horizon. Expression (15) used in [1] represents a closed-form solution for those averages.

In this paper, it will be shown that the calculation of the slope factor by procedure of averaging results in an error in the assessment of irradiation on the PV panel, and consequently, an error in the estimation of power production. It be clearly highlighted the difference between instantaneous and average slope factor and their impact on the estimation of power production.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In this chapter, practical realization of one PV system with weather measurement equipment, mounted on a roof of Faculty of Electrical Engineering East Sarajevo is given.

Figure 1. PV panels and weather measurement equipment mounted on the roof of Faculty

Test results, obtained by the simulation of two models described before (in Matlab/Simulink environment) and practical measurement of horizontal irradiation and PV system output power are described.

In Fig.1. is shown *Prostar Solar Model. PR75Wp/24V* four panels connected by two in series ($P_{DC(STC)}$ = 2x75 = 150 Wp), oriented on the south and fixed by angle of 33^0 (optimal angle for region of Sarajevo). Measurement equipment with data logger iBOX-EKO21N-v7 is also installed on the roof measuring the wind speed, wind direction, horizontal solar irradiation and environmental temperature. Detailed information about measurement equipment can be found in [10].

PV panels are connected to the load via converter with MPPT function (with P&O algorithm implemented). This converter was developed as prototype at the Faculty, represents a Buck-Boost converter controlled by dual current mode control and efficiency of 93%. The lack of equipment for grid connection, system was connected to the active load of R = 15 Ω (Fig.2.). Measurement of the output current and voltage were carried out every ten minutes during period of 11 a.m. to 1 p.m. at Wednesday May 7th 2014, covering the solar noon at that way.

Results of measurements of solar radiation on horizontal surface and ambient temperature, as well as measurement of PV system output power are given in Table I.

As can be seen from Table I, average solar irradiation on horizontal surface was from 800 to 900 W/m^2 during the period of measurement. But, in some time interval solar irradiation on horizontal surface was less than average (point at 11:10 and 11:20), that cause lower production of PV system. Also, from experimental results of PV system output power is verified that ambient temperature has influence of energy production. At point of 12:40 and 12:50 output power of PV system has the same amount 112.8 W, although the solar insolation is higher in second case. This is result of the increase the temperature in second case and its negative influence on energy production.

Figure 2. Test equipment with measuring instruments and MPPT converter

TABLE I. MEASURED PARAMETERS OF SOLAR INSOLATION ON HORIZONTAL SURFACE, AMBIENT TEMPERATURE AND PV SYSTEM OUTPUT POWER

Time period	Solar irradiation [W/m^2]	Ambient temperature [$^{\circ}$C]	PV system output power [W]
11:00	873.9	20.53	113.8
11:10	501.3	21.24	67.3
11:20	724.3	20.96	99.2
11:30	831.7	20.99	109.8
11:40	839.1	23.23	108.4
11:50	839.1	23.14	109.1
12:00	842.4	24.27	107.7
12:10	816.4	24.56	106.1
12:20	867.1	23.58	111.6
12:30	873	23.92	112.6
12:40	878.2	24.24	112.8
12:50	882.6	24.51	112.8
13:00	903.5	24.7	114.5

In Fig.3. and Fig.4. the components of the solar radiation on panel obtained by two described models and measured solar insolation on horizontal surface are shown. “Clear day” model as theoretical model does not respect the terms of cloudiness, and as such gives estimated solar insolation components (Ic, Ibc, Idc, Irc) different from measured solar insolation (Ih), as it is shown on Fig.3. A better estimation of solar irradiation components is achieved using the realistic model (including suggested adjustment) with respect the terms of cloudiness. As it is shown on Fig.4., total solar irradiation on panel and its components have the same shape and follow behavior of measured solar irradiation on horizontal surface. Difference between total solar irradiation on panel and measured solar irradiation on horizontal surface, is in additional amount of solar irradiation on panel due to diffuse and reflection of solar radiation, which brings more PV system output power production.

Difference in PV system production based on two models and experimental results is shown on Fig.5. It is obvious that estimating PV system production based on “Clear day” model could give an incorrect value of energy production with which is plan to design PV system. Verification of the realistic model, based on measured parameters of solar insolation on horizontal surface and ambient temperature, shows that estimated PV system production is very close to the one with experimental measured results. Minor variations in the graphs (Pac-Realistic model and Pacm) may be due to wrong assessment of efficiency factors due to panel dirty and modules mismatch as well as acceptable error of measurement instruments.

On the other hand, influence of calculating slope factor on determining solar insolation on panel surfaces as well as estimating panel production, can be seen on Fig.6. and Fig.7.

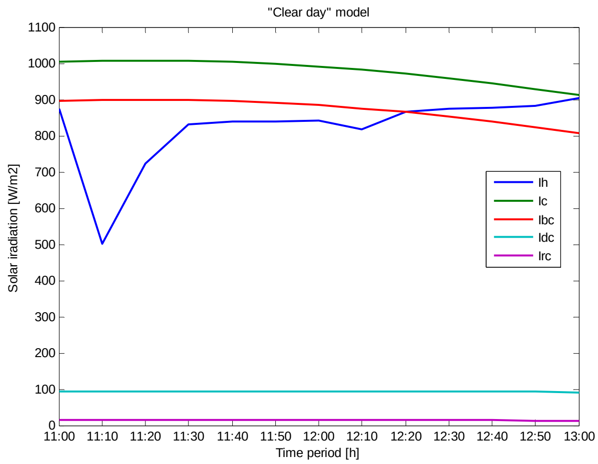

Figure 3. Measured solar insolation on horizontal surface and total solar insolation on panel with its component obtained with “Clear day” model.

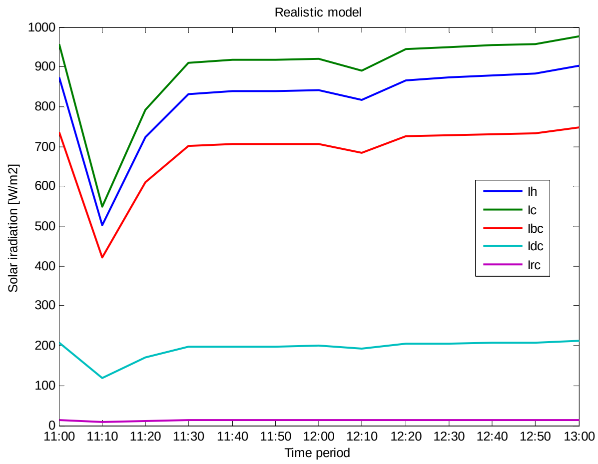

Figure 4. Measured solar insolation on horizontal surface and total solar insolation on panel with its component obtained with realistic model.

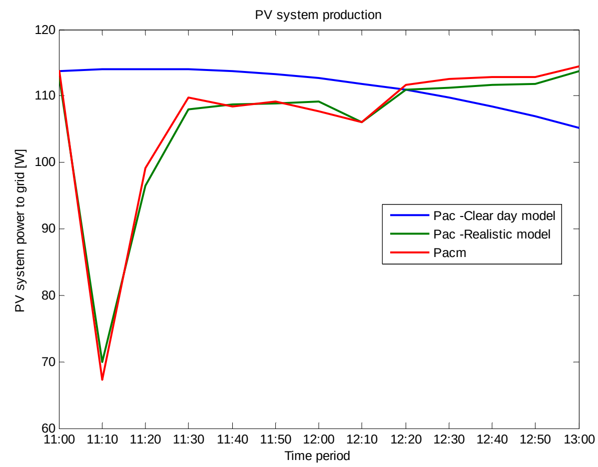

Figure 5. Experimental results of PV system output power with estimating one obtained with given models.

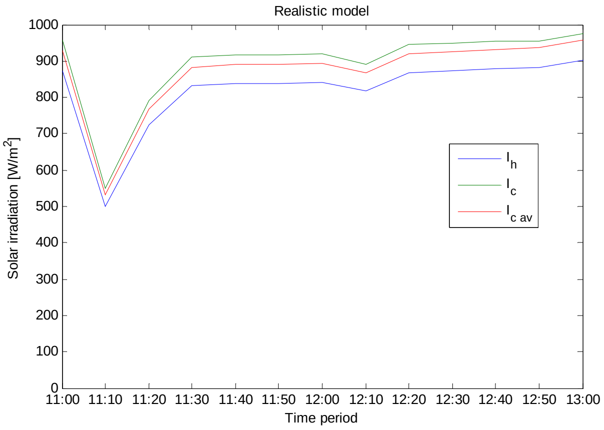

Figure 6. Measured solar irradiation on horizontal surface and total solar irradiation on panel determined based on average and instantaneous slope factor.

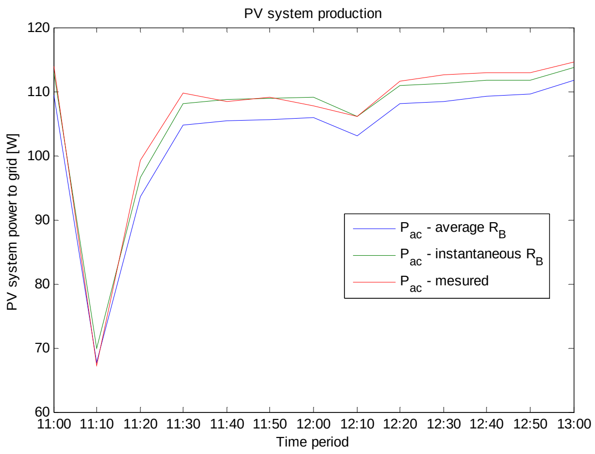

Figure 7. Experimental results of PV system output power compared with estimating ones based on different calculation way of slope factor.

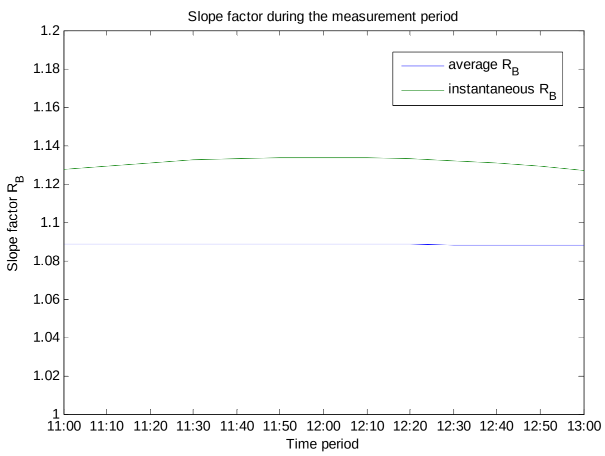

Figure 8. Difference between average and instantaneous slope factor during the measurement period.

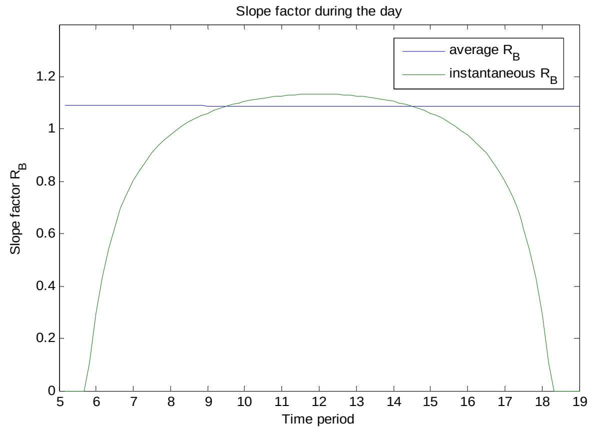

Figure 9. Difference between average and instantaneous slope factor during the day.

Simulation results from Fig.6. shows that the solar insolation on panel surface calculated with average slope factor (referred to the [1]) has the smaller values in comparison to the solar insolation calculated based on instantaneous slope factor. Therefore, the estimated PV panel production (shown on Fig.7.) is lower when the average slope factor is used. Error in power production obtained with average slope factor calculation relative to measured output power is -3.14%, while the error obtained with instantaneous slope factor calculation is -0.47% (for the measurement period). In Fig.8. and Fig.9. the average and instantaneous slope factor during the measurement period and during the day are drawn, respectively. It is clear that from 9 a.m. until 3 p.m. instantaneous slope factor has higher value than average one, so the solar insolation, as well as power production, is higher, but the question is what happens beyond this time period related to power production and determination of solar insolation in cases of use the instantaneous or average slope factor. The answer lies in fact that the solar irradiation in that period is much lower than in period when instantaneous slope factor has higher value relative to average, so the impact on the power production will be small.

IV. CONCLUSION

Considering the stochastic nature of solar radiation and the large number of influencing factors (environmental conditions and system performance), to estimate the PV system production it is suitable to use a model based on knowledge of the solar insolation on horizontal surface and ambient temperature. Results of estimated PV system production with improved model realized in Matlab/Simulink environment well matched with experimental results measured from real PV system installed on a roof of Faculty of Electrical Engineering East Sarajevo. From previous, it can be concluded that the difference in the calculation of the slope factor (instantaneous and average), has an impact on the estimation of power production. By using the instantaneous slope factor for estimation of PV system production, a minor error occurs while designing the PV system.

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