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Combined effect of air temperature and solar radiation on the performance of PV powered water pumping systems

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Abstract: The paper deals with the correlation between solar radiation and the energy production of a stand-alone PV system, aiming to be used for powering the water pumping systems. The estimation of the solar irradiation and the calculation of the I-V characteristics of the photovoltaic modules operating in outdoor conditions are discussed. Based on overall results one can conclude that the presented algorithm may be a feasible solution for sizing the solar power pumping systems with applicability to irrigations and drainages in the western part of Romania.

Keywords: solar radiation, energy production

1. INTRODUCTION

The widespread environmental degradation as a consequence of CO_2 emissions into the atmosphere and the depletion of fossil fuels together with the forecast increase in energy demand have drawn the attention to renewable energy sources. Among a wide range of renewable energy projects in progress throughout the world, solar energy conversion seems to be the most promising for the future.

Solar cells are semiconductor devices designed to transform sunlight into electricity, efficiently and straightforwardly. Many jointly connected solar cells form a photovoltaic module, which is the basic element of each photovoltaic (PV) system.

Among the applications of PV systems, the pumping of water has always been a very efficient solution. The irrigation systems that use PV technology are becoming more and more extensively used in agriculture. Essential in these applications is the current of the pump that has to be kept as small as possible.

Figure 1 shows the block diagram of a solar powered water pumping system. It is a typically stand-alone PV system at which the *gravity* plays the role of energy storage device. The inverter is optional, being used in high power pumping systems. The initial investment is the great disadvantage of all renewable energy systems, including photovoltaics. However, the long lifetime (25 years) and the very low cost of maintenance are the noteworthy advantages of the PV pumping systems. Direct-coupling of the PV generator and the pump is certainly the cheapest solution.

In order to achieve an efficient pumping system one should establish from the beginning: • The water-use (field of use-irrigation, drainage, public consumption); • The source of the water (drilling, dam); • Water storage (will be in reservoir, dam); • The volume of water needed daily; • The difference between ground level and removal of pipe; • Maximum pumping depth; • The total length of the pipe between pump and reservoir; • Maximum depth from the ground.

From these data the required energy for the pumps is estimated. Then, the PV system can be sized. There are two major difficulties encountering by an engineer engaged in such project. First, comes up the question: how accurately the existing data reproduce the real amount and temporal distribution of collectable solar energy. Second, under outdoor conditions the solar irradiance and the ambient temperature are continually varying and at non-standard conditions the characteristics of the modules are often not known. Despite of the abundance of models which translate the modules parameters listed in catalogue into parameters matching outdoor conditions (for instance, see models in [1]), the engineer encounter a problem in selection the appropriate model, able to perform accurately in the interest's location.

The photovoltaic (PV) modules are usually delivered by manufactures accompanied by datasheets listing three points on the current-voltage (I-V) characteristic: the short circuit current, the open circuit voltage and the maximum power point (MPP). These points are measured in standard test conditions (STC). The standard specifies a global solar irradiance of 1000 W/m^2 at normal incidence with a spectral distribution AM1.5G and the solar cell operation temperature of 25°C. By using such scarce information, the mathematical description of the I-V characteristic is always a challenge.

This paper address the two issues listed above: solar data availability and the influence of the meteorological parameters on the efficiency of a PV module. The results can be regarded as a useful tool for assessing the performance of a stand-alone PV

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system mounted in the western part of Romania, taking into account the specific of the pumping water systems.

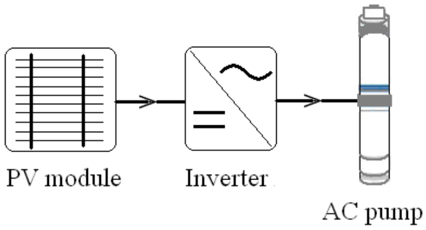

Figure 1. Schematic of a PV powered water pumping system

2. SOLAR ENERGY AVAILABILITY

Accurate solar radiation measurements involve local or global networks. Like most countries, Romania set up a national network for monitoring global solar irradiation on horizontal surfaces contributing to World Radiation Data Centre, located at the Main Geographical Observatory, St. Petersburg, Russia [2]. The national meteorology grid comprises more than 150 meteorological stations. Of these, 35 stations are equipped for solar radiation monitoring but only 8 maintain a long-term global solar irradiation database.

Data measured on the Solar Platform of the West University of Timisoara (http://solar.physics.uvt.ro/) are used in this study [3]. DeltaOHM LP PYRA 02 first class pyranometers which fully comply with ISO 9060 standards and meet the WMO requirements are employed. The sensors are integrated into an acquisition data system based on National Instruments PXI Platform. Measurements are performed all day long at equal time intervals of $\Delta\tau = 15\,s$.

Fig. 2 shows global H_g and diffuse H_d solar irradiations data recorded in 2009 on the Solar Platform. Table 1 summarizes monthly averages of daily global and diffuse irradiation computed from the daily series of data. In 2009, the measured value of the yearly mean of daily global solar irradiation in Timisoara was 3.34 kWh/m^2.

The spatial density of the meteorological stations equipped for solar radiation measurement is very low and numerical methods became a practical alternative. Usually, solar irradiation under H is estimated in a process that runs in two steps. First solar irradiation clear sky condition is computed. Second, clouds cover influence is taken into account via an Ångström-Prescott type-like equation classically derived from sunshine duration or cloudiness (for example see [4]).

For finding H_0, a usual method is the integration of a clear sky solar irradiance model in order to obtain daily, monthly or yearly irradiation:

$$H_0\left[\text{Wh/m}^2\right] = \frac{24 \cdot 3600}{2\pi}\int G_0(\omega)\,\mathrm{d}\,\omega \quad (1)$$

where ω is the hour angle. Equation (1) points out that an accurate clear sky irradiance model, G_0, is a prerequisite for accurately evaluation of the collectable solar energy. Numerous clear sky solar irradiance models are constructed empirically mainly by fitting the data collected from an evanescent area.

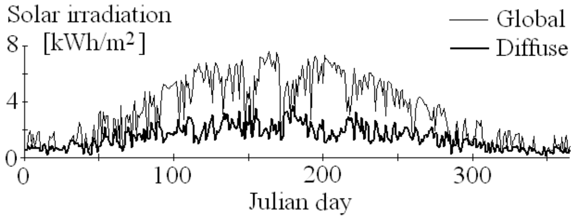

Figure 2. Daily global and diffuse solar irradiation recorded on the Solar Platform during 2009

Despite the disadvantage of being closely related to their parental place, empirical class models are often preferred due to their simplicity.

Hottel et al. [5] is an empirical model for direct solar irradiance applicable up to 6 km altitude:

$$G_{0A} = G_{ext}\left[a_1 + a_2 \exp\left(-\frac{a_3}{\sin h}\right)\right]\sin h \quad (2)$$

where G_{ext} is the extraterrestrial solar irradiance and

$$a_1 = 0.4327 - 0.00821(6 - z)^2 \quad (3a)$$

$$a_2 = 0.5055 + 0.00595(6.5 - z)^2 \quad (3b)$$

$$a_3 = 0.2711 + 0.01858(2.5 - z)^2 \quad (3c)$$

The Bugler model [6] is also an empirical model but for diffuse solar irradiance:

$$G_{0B}\left[\text{Wm}^{-2}\right] = 16h^{0.5} - 0.4h \quad (4)$$

where the sun elevation angle h is in degrees.

The Hottel and Bugler models may be used together for computing global solar irradiance under clear sky .

In order to compute the daily global solar irradiation H from the values estimated under clear sky H_0 an Ångström like-type equation has been used:

$$H = H_0\left(0.2881 + 0.7429\sigma^{0.6168}\right) \quad (5)$$

where σ is the daily relative sunshine duration.

In order to assess the quality of solar radiation models, two statistical indicators are commonly used: *rmse* - relative root mean square error and *mbe* - mean bias error. The two indicators are defined as follows:

$$RMSE \equiv \left[\frac{1}{M}\sum_{i=1}^{M}\left(c_i - m_i\right)^2\right]^{1/2} \quad (6)$$

$$MBE \equiv \frac{1}{M}\sum_{i=1}^{M}(c_i - m_i) \quad (7)$$

where c and m refer to computed and measured values, respectively, while M is the sample size. In order to compare models quality applied to sample with different magnitude, these indicators are used normalized to the mean μ of measured data: $rRMSE = RMSE/\mu$, and $rMBE = MBE/\mu$.

Table 1. Monthly mean of daily global $\bar{H}_g$ and diffuse $\bar{H}_d$ solar irradiation calculated using solar irradiance data recorded in 2009 on the Solar Platform of the West University of Timisoara

Month	01	02	03	04	05	06	07	08	09	10	11	12
$\bar{H}_g$ [kWh/m2]	0.92	1.63	2.72	5.01	5.43	5.35	6.13	5.07	3.85	2.01	1.19	0.64
$\bar{H}_d$ [kWh/m2]	0.62	0.94	1.52	1.84	2.31	2.30	1.94	1.96	1.64	1.13	0.64	0.44

In terms of statistical indicators, the results of testing the model (Eqs. 1-5) against data measured during 2009 on the Solar Platform are: *rRMSE* = 7.9% and *rMBE* = 4.2%, demonstrating an acceptable accuracy.

Since the majority of the pumping stations operates continuously throughout the year, an estimation of available solar energy during a typical meteorological year [7] is recommendable.

3. PV MODULES OPERATION IN OUTDOOR CONDITIONS

Results of monitoring of a 90W commercial PV module during October 2009 on the Solar Platform demonstrate a net difference between its efficiency measured outdoor $\eta_m = 10.1\%$ and that measured in the standard test condition (STC) $\eta_{STC} = 14.6\%$. It means that when a PV system is sizing, using the PV module efficiency from datasheet leads to almost 30% under-sizing, which is completely undesirable.

The results presented in this section, are based on experimental data collected during April 2011 on the Solar Platform. The experimental setup consisted on a PV module FVG 90M [8] that was connected directly to an active load, aiming to roughly track MPP. The system voltage, current and temperature have been monitored continuously. At the same time the total solar irradiation was measured on the module direction: South, 45° tilted in respect to the horizontal ground. Data has been recorded with four samples per minute, the total number of recordings on each channel being of 84 400.

Fig. 3 shows the module efficiency in outdoor conditions computed from hourly data recorded during 10AM to 17PM in every day of April 2011. It can be seen that the module efficiency varies continuously from a day to another, from an hour to another. The module efficiency computed with hourly recordings falls in the range 9%…11.5%, rather far from $\eta_{STC} = 14.05\%$ measured at STC [9].

This experiment reveals the importance of accurately estimation the PV module parameters in outdoor condition. In Romania the equipment for testing the PV modules operating in outdoor conditions is very rare. Thus, the numerical methods became a useful alternative.

In order to predict the I-V curve of a PV array operating in arbitrarily solar irradiance and temperature conditions, a balance between accuracy and simplicity may be obtained with the following algorithm. The starting point is the Shockley's equations of a solar cell [1]:

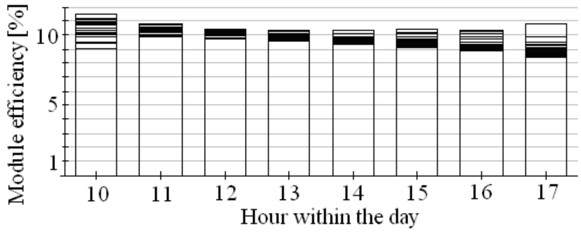

Figure 3. Module efficiency in every hour between 10AM and 17PM during April 2011. Data recorded on the Solar Platform has been used

$$I = I_L - I_0\left[\exp\left(\frac{e(V+IR_S)}{mk_BT_c}\right)-1\right]-\frac{V+IR_S}{R_p} \quad (8)$$

Where 1 I_{SC} represents the short circuit current, V_{OC} is the open circuit voltage, T_c is the cell temperature and k_B stand for the Boltzmann's constant. Considering R_p ideal (R_p = infinite), the approximation $I_L = I_{SC}$, Eq.(8) can be rewritten as:

$$I(V) = I_{SC}\left[1-\exp\left(\frac{e(V-V_{OC}+IR_S)}{k_BT_c}\right)\right] \quad (9)$$

In Eq. (9) the short circuit current is assumed to be related only on total solar irradiance G:

$$I_{SC}(G) = \frac{I_{SC,STC}}{G_{STC}}G \quad (10)$$

The open circuit voltage is assumed to be linked only on cell temperature:

$$V_{CD}(T_c) = V_{CD,STC} + \left(T_c - T_{c,STC}\right)\frac{dV_{CD}}{dT_c} \quad (11)$$

The cell temperature is always above the environment temperature and roughly is linear dependent on incident solar flux:

$$T_c = T_a + C_tG \quad (12)$$

where the parameter C_t is:

$$C_t = \frac{NOCT(°\text{C}) - 20°\text{C}}{800\ \text{W/m}^2} \quad (13)$$

Nominal Operating Cell Temperature (*NOCT*) varies between 42°C and 50°C leading to a C_t ranging between 0.027 and 0.037 °Cm²/W.

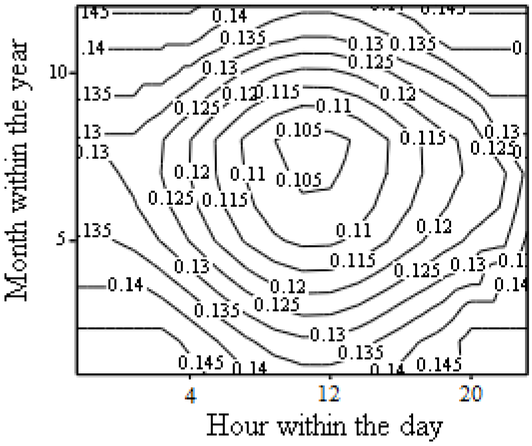

Figure 4. Efficiency of the module FVG 90M PV estimated with Eqs. (9-14) when it operates in the specific climate of the Timisoara town

The equations (9-12) were applied to compute the FVG90M module efficiency operating under outdoor conditions in the town of Timisoara. The PV module has been assumed mounted facing to South and inclined with β = 45º. The calculation was made on hourly basis. The monthly mean values of global solar irradiation were estimated with the Hottel and Bugler models (Eqs. 1-5). These values have been breaking down to hourly values with the algorithm from [9] which then have been converted into total values of solar irradiation on the tilted surface $H(\beta)$ using the equation [10]:

$$H(\beta) = \frac{\cos\theta}{\sin h} H_b + \frac{1+\cos\beta}{2} H_d + \frac{1-\cos\beta}{2} a H_0 \quad (14)$$

In Eq. (13) H, H_b and H_d are the global, beam and diffuse solar irradiation on the horizontal surface, respectively. θ is the incidence angle on the tilted surface and h is the sun elevation angle in the middle of the every hour. For albedo an isotropic model has been assumed, i.e. a = 0.2.

The results are summarized in Figure 4. Visual inspection shows that the estimated values of the PV module efficiency decrease from 14.5% in the morning hours to 10.5% in the middle of the summer days. Thus, the module efficiency is closely to the one predicted in standard test conditions $\eta_{STC} = 14.05\%$ only in the winter. In the middle of the April days the estimated efficiency of the module is around 11.5% with approximately one percent over the measured values, which demonstrate a reasonable accuracy of the translation model.

4. CONCLUSIONS

In this study results of assessing the performance of a PV module operating under outdoor conditions are reported. Both experimental and numeric approaches have been employed. In order to apply the algorithm monthly mean of hourly solar irradiation and air temperature, which are generally available quantities.

The numerical results show that the proposed algorithm exhibits an acceptable level of accuracy for practical purposes. The algorithm quickly calculates the variation of PV module conversion efficiency during a year in specific conditions. The algorithm is general in that it can be applied in any location and for any PV module, knowing the catalogue specification.

However, since data collected on the Solar Platform of the West University of Timisoara were used in this study, the results are mainly useful for engineering engaged in solar water pumping projects developed in Banat, Western Romania.

To conclude, overall results demonstrate the importance of translation of the V-I characteristics of a PV module from STC to the real point of operation in sizing a PV system for water pumping.

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