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Modelling and Estimation of the Hourly Flow Rate of a Photovoltaic Water Pumping System Using Polynomial Regression Method: Experimental Validation

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Abstract**—***In this paper, a numerical model has been introduced to estimate the flow rate of a photovoltaic water pumping system (PVWPS), using Polynomial Regression (PR) technique. The model has been validated experimentally using collected data by an experimental PVWPS installed at Madinah location (Saudi Arabia). The results show that the processing scheme has good estimation accuracy and better generalization ability. Developed model can estimate accurately the hourly flow rate based on measured hourly air temperature and solar irradiation, as input parameters, and they can be also used to control the PVWPS by making a comparison between measured and estimated hourly flow rate. Furthermore, operators can benefit from the proposed model. In fact, once their own PVWPS model is designed, they can predict its flow rate given the weather forecasts for the following hours.*

Keywords—Photovoltaic water pumping system; water flow rate estimation; polynomial regression

I. INTRODUCTION

Photovoltaic water pumping systems (PVWPS) become very important in the renewable and green energy fields, in the last few years, particularly in rural areas where over three billion people live [1]. In these places a considerable amount of solar radiation is available but have no access to electrical grids. Additionally, there is need for such energy systems to replace those depending on petroleum-based fuels, wood and charcoal from the forest, which pollute the environment. The optimum utilization of water and energy resources has become an essential issue especially in areas of high quality solar potential. Usually, the water demand increase is related to the insolation increase, therefore the implementation of a photovoltaic system serving the water pumping concept proves to be a perfect energy solution. The greatest advantage of this system is that no battery storage is required; instead the pumped water is stored in reservoirs.

There are several theoretical and experimental studies about photovoltaic (PV) water pumping systems, which are installed in remote regions to supply water for drinking and irrigation [2–5]. As indicated in [6-9] efforts have been done for modelling, optimization and control of PVWP systems. A model for the optimization of a photovoltaic water pumping system is developed based on the concept of the Loss of Power Supply Probability (LPSP) and the life cycle cost concepts [10]. Bouzidi [11] the authors showed that the size of the storage tank has an influence on the reliability and the system sizing, so it should be treated with particular attention. Numerical method based on the LPSP is used to size the pumping system for a given reliability at minimum cost. Recently more than one hundred published papers related to water pumping systems based on renewable energy source are briefly reviewed by Gopal el al. [12]. They conclude that renewable energy sources play a vital role in reducing the consumption of conventional energy sources and its environmental impacts for water pumping applications. The authors mentioned also the importance of techno-economic feasibility and the use of artificial intelligence based modelling for pumping systems. Martire et al. [13], presented a model based on energy considerations for the prediction of hourly water flow rate has been developed. The authors have concluded that the developed process can be used as an optimization tool to design a new pumping system.

Basically water flow rate amount can be controlled by a mathematical model. The flow rate (Q) in PVWP systems is mainly influenced by weather conditions, especially solar irradiance (G) and air temperature (T) variations, thus the relationship between Q, T and G can be expressed as $Q=f(T,G)$. It is however, difficult to find a simple and accurate analytical model due to influence of the environmental factors (stochastic variation of G and T). Hence, the development of an accurate numerical model to estimate the real flow rate of a PVWPS based on experimental measured solar irradiation and air temperature is very important, so, it can be used for checking the performance of the system, possible faults in the system and making an economic decision.

To our knowledge, relationships between the flow rate, solar irradiance and air temperature are not available in literature. The main objective of this work is to develop suitable models based on Bivariate Polynomial Regression (BPR) for estimating the hourly water flow rate for an

experimental PVWPS installed at Madinah site [14] which is used for irrigation. An experimental dataset (solar irradiation, air temperature and water flow rate) has been used to develop and to verify the developed numerical models.

The paper is organized as follows: A system description and database are presented in Section 2. Developed models based on the polynomial regression techniques are provided in Section 3. The results and discussions are given in section 4.

II. System Description and Database

A. System Description

The Madinah region, in Saudi Arabia is classified as semi-arid area and has a great potential of solar radiation [15]. The daily annual average yield ranges from 4.5 KWh/m^2/day to 8.5 KWh/m^2/day, on the inclined PV surface. A PV water pumping system is set up in a real well of 120 m depth. The PVWPS comprises: a photovoltaic generator of 1.8 KW, submersible helical pump (SQF.5-2), an electromagnetic flow meter and Agilent data logger system connected to a computer for data acquisition and treatment (Fig.1a). The PV array configuration consists of 24 modules of multi-crystalline silicon (75W/20V).The tilt angle is equal to the latitude of the site (25°) facing south. The experimental photovoltaic water pumping system is shown in Fig.1.b. The best PV array configuration chosen [14] as (8Sx3P) which means 24 modules connected in three parallel strings with 8 serial PV modules in each. A maximum power point tracking (MPPT) system is integrated into the helical pump used. The simulated I-V and P-V characteristics curve of the PV array are shown in Fig. 2.

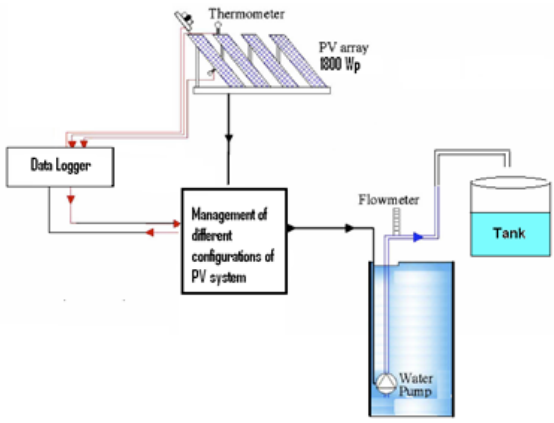

Fig.1.a. The PV water pumping with monitoring system

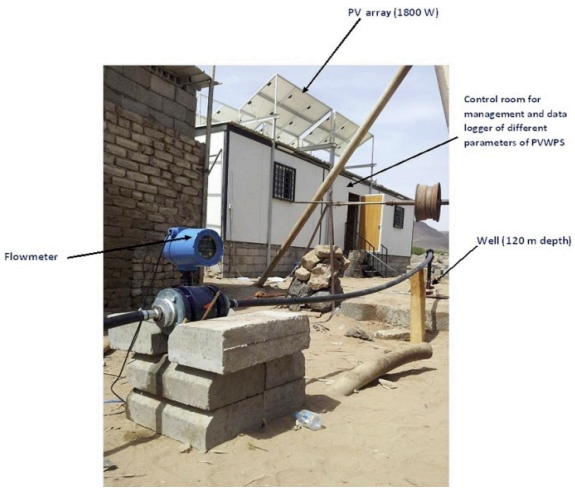

Fig.1.b The experimental photovoltaic water pumping system

B. Database

The experimental PVWPS installed at Madinah site is operational from May 2012 until now. The main measured parameters are: PV voltage (V), PV current (A), air temperature (^{o}C), global solar irradiation (Wh/m^2), flow rate (m^3/day) and water level (m). The PVWPS is dedicated to a palm farm as indicated in [14]. Figures 3a, 3b, and 3c show the measured solar irradiation, air temperature and the water flow rate for a period from 1st June to 2nd July of 2012.

III. Bivariate Polynomial Regression Models

The aim of this section is to show detailed of the BPR models developed to estimate nonlinear hourly flow rate using measured air temperature and solar irradiation. Polynomial regression is based on the same idea as basic linear regression, except that the relationship between the independent and dependent variables is non-linear. Often, the first step of the modelling process consists of simply looking at data graphically and trying to recognize trends. In the following, we develop the BPR models and calculate its parameters.

Two variables polynomial regression of total degree *n* model can be constructed as follows [16]:

$$P(x,y)=\sum_{k=0}^{n}\sum_{i=0}^{k}\beta_{ik}x^{i}y^{k-i} \qquad (1)$$

Where, *x, y* and *P* represent the temperature (*T*), the solar irradiation (*G*) and the water flow rate (*Q*) respectively.

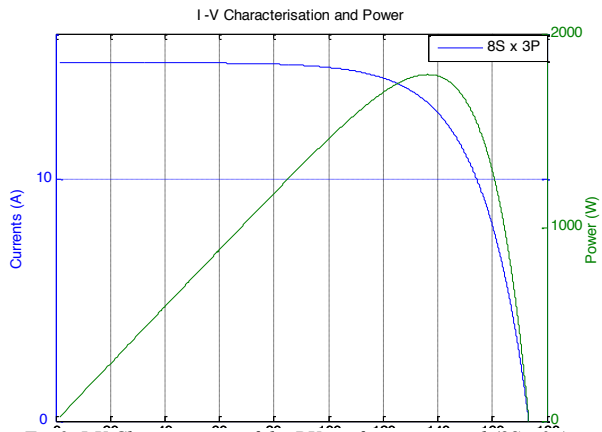

Fig.2. I-V Characteristic of the PV configuration used (8S x 3p)

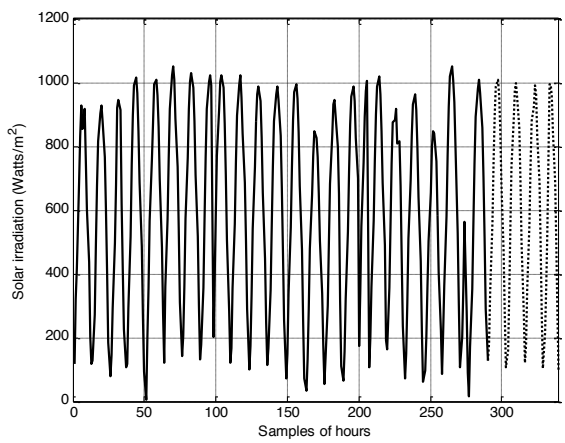

Fig.3a. Measured solar irradiation 1st June-2nd July: 1st -28th June BPR parameters estimation period (solid), 29th june-2nd July testing period (dot)

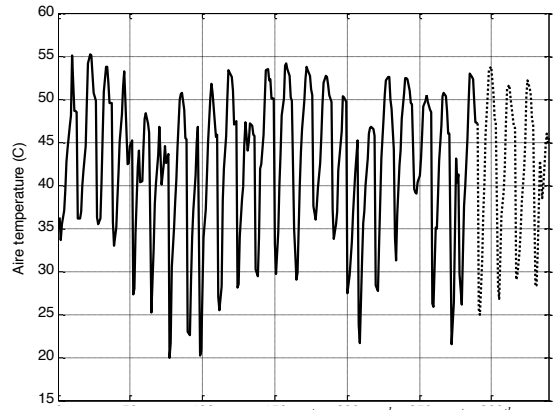

Fig.3b. Measured air temperature, 1st June-2nd July: 1st -28th June BPR parameters estimation period (solid), 29th june-2nd July testing period (dot)

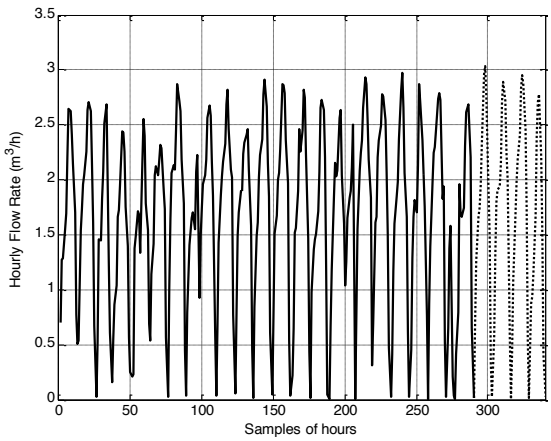

Fig.3c. Measured Hourly flow rate 1st June-2nd July: 1st -28th June BPR parameters estimation period (solid), 29th june-2nd July testing period (dot)

A. Bivariate Quadratic Polynomial Regression Model

By taking n =2 and using the above model we can estimate the flow rate Q by the following relation:

$$Q(T,G) = \sum_{k=0}^{2}\sum_{i=0}^{k} \beta_{ik} T^i G^{k-i} \qquad (2)$$

We expand the last formula; we find the bivariate quadratic polynomial model:

$$Q(T,G)= \beta_{00}+ \beta_{01}G+ \beta_{11}T+ \beta_{12}TG+ \beta_{02}G^2+ \beta_{22}T^2 \qquad (3)$$

β_{00}: constant, β_{01}, β_{11}: linear effect parameters, β_{02}, β_{22} : quadratic effect parameters and β_{12}: interaction effect parameter of T and G on Q.

The term $\beta_{12}TG$ measures the dependence of the partial regression slope of Q against T on the value of G and the dependence of the partial regression slope of Q against on the value of T.

B. Bivariate Cubic Polynomial Regression Model

By taking n=3, a bivariate cubic polynomial model can be easily driven from the formula (1)

$$Q(T,G)=\alpha_{00}+\alpha_{01}G+\alpha_{11}T+\alpha_{02}G^2+\alpha_{12}TG+\alpha_{22}T^2+ \alpha_{03}G^3+\alpha_{13}TG^2 +\alpha_{23}T^2G+ \alpha_{33}T^3 \qquad (4)$$

Where: α_{03} and α_{33} are the cubic effect parameters, α_{00}: constant, α_{01}, α_{11}: linear effect parameters, α_{02}, α_{22}: quadratic effect parameters and α_{12}, α_{13}, α_{23}: interaction effect parameters.

IV. Results and Discussions

The hourly flow rate of pumped water on June month and first two days of July is shown in Fig. 3(c). It has been measured using the photovoltaic pumping system described in Section 2. The system starts to pump in the morning and stops in the afternoon without any external intervention and operates with a good adaptation with the available solar irradiation.

Firstly, 28 days of June are used to estimate the parameters of BQPR-model, whereas the last two days of June (29th and 30th) and the first two days of July (1st and 2nd) are used to test the performance of the developed mathematical model. The simulation was done with the software package MATLAB using developed code.

Using the same dataset we have developed a cubic model based on BPR technique. The goal is to compare the results obtained by different polynomial orders and to demonstrate the effectiveness of the simple bivariate quadratic regression model. Choosing bivariate quadratic regression model instead of cubic model is to avoid increasing complexity of the model without adding much accuracy.

Table 1 and Table 2 show the estimation of the BQPR and BCPR parameters, respectively, using MATLAB programming software. Measured versus estimated (BQPR and BCPR) values of the hourly flow rate for 4 days are plotted in Fig. 4. As can be seen, the estimated values are close to the experimental ones, but that does not exclude the need for more performance criteria to validate the effectiveness of the estimation.

Performances of BQPR and BCPR were compared with respect to determination of correlation coefficient (R), mean square error (MSE), root mean square error (RMSE), and mean absolute error (MAE) and relative percentage error (RPE). These performance measures are given in the appendix.

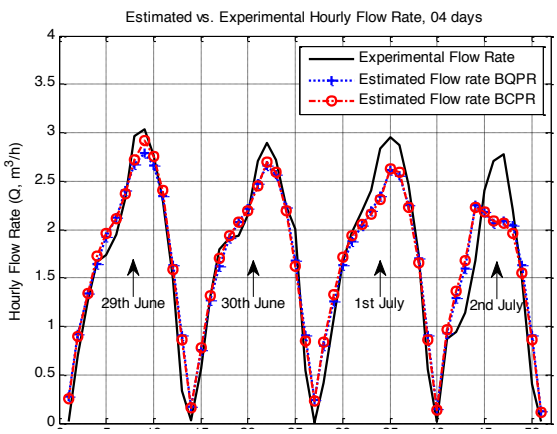

Fig.4. Experimental and estimated hourly water flow rate using BQPR and BCPR models

TABLE I. ESTIMATION OF THE BQPR PARAMETERS

β_{00}	β_{01}	β_{11}	β_{12}	β_{02}	β_{22}
1.8574	0.0019946	- 0.076802	7.0301×10^{-5}	-2.4712×10^{-6}	0.0006268

TABLE II. ESTIMATION OF THE BCPR PARAMETERS

α_{00}	α_{00}	α_{00}	α_{00}	α_{00}	α_{00}	α_{00}	α_{00}	α_{00}	α_{00}
-2.1085	0.004114	0.23491	-2.861×10^{-06}	-2.411×10^{-05}	-0.0073083	1.352×10^{-11}	1.465×10^{-08}	8.857×10^{-07}	6.617×10^{-05}

The estimation of the BQPR and BCPR performance parameters are reported in Table 3. The correlation coefficients for the BQPR and BCPR models are found both as 97%. But if we have a look at other numerical performance parameters reported in Table 2 (RMSE less than 0.3, RPE less than 1.1% and MAE is less than 0.23), we can see that there is a slightly difference in term of estimation efficiency between the two models and we can easily observe the accuracy of these models to estimate the hourly water flow rate directly from metrological data (air temperature and solar irradiation). Figures 5a and 5b show a scattered plot with the best fit line of the experimental hourly flow rate versus the estimated one.

With respect the above results, we can conclude that the main advantages of these models is that they do not require any additional information about the PVWP system, only a dataset of inputs (solar irradiance and air temperature) and outputs (water flow rate) of the system is required. It has been also observed that 28x12 samples are sufficient to estimate the polynomial coefficients efficiently. The techniques demonstrated by MATLAB computer simulation could be adopted by other photovoltaic water pumping systems where the water flow rate, air temperature and solar irradiation data are available.

TABLE III. PERFORMANCE PARAMETERS OF THE DEVELOPED BQPR AND BCPR MODELS

Method	**BCPR**	**BQPR**
Performance		
Correlation Coefficient (R) %	97%	97%
Mean Absolute Error(MAE)	0.2217	0.2262
Mean Squared Error (MSE)	0.0782	0.0793
Root Mean Squared Error (RMSE)	0.2797	0.2816
Relative Error Percentage (RPE)	1%	1%

V. CONCLUSION AND PERSPECTIVE

In this work, simple and accurate models for estimating the water hourly flow rate of a PVWP system installed at Madinah, Saudi Arabia, have been developed. An experimental dataset of air temperature, solar irradiation and flow rate values has been used to develop and testing the models (BQPR and BCPR). The proposed models showed good estimation, therefore, it can be concluded that using BPR techniques for estimating the hourly flow rate based on air temperature and solar irradiation data is very promising for substantially reducing the computational effort.

A perspective of this work is to enhance and use these techniques in another PVWPS, so we can take advantage of the developed methodology. In addition, more effort will be devoted to investigate the impact of other parameters on the flow-rate (such as humidity, well depth, etc)

APPENDIX

$$R = \frac{\sum_{i=1}^{N}(Q_i - \overline{Q_i})(\hat{Q}_i - \overline{\hat{Q}_i})}{\sqrt{\sum_{i=1}^{N} Q_i - \overline{Q_i})^2 \sum_{i=1}^{N}(\hat{Q}_i - \overline{\hat{Q}_i})^2}}$$

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(Q_i - \hat{Q}_i)^2$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Q_i - \hat{Q}_i)^2}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|Q_i - \hat{Q}_i\right|$$

$$RPE = \frac{\sqrt{\sum_{i=1}^{N}(Q_i - \hat{Q}_i)^2}}{\sqrt{\sum_{i=1}^{N} Q_i^2}} \times 100$$

Where Q_i is the experimentally flow rate, $\hat{Q}_i$ is the estimated one by the models, $\overline{Q_i}$, $\overline{\hat{Q}_i}$ is the mean value of Q_i and $\hat{Q}_i$ respectively; N is the number of data.

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