Soft Computing Modelling of a Directly Coupled PV Water Pumping System

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Received: 12.07.2016 Accepted:05.03.2016

Abstract- Photo-Voltaic Water Pumping System (PVWPS) is the most suitable system for irrigation in the remote areas. PVWPS may be characterized by its multi- variable-non- linear equations, However, efficient water demand management necessitates fast and accurate water flow rate estimation at actual operating states. This can hardly be achieved with conventional mathematical – based methodologies. The introduced methodology serves for easily water demand estimation . In this paper two of the Soft Computing (SC) techniques are due selected; Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) for PVWPS novel modeling and performance pre-evaluation .The (ANN) model and (ANFIS) models are trained off-line to identify the water flow rate based on air temperature, solar irradiation, and static head as input parameters. An iteration technique which is mathematical–based is also presented for comparison and evaluation purposes. The proposed SC techniques modelling have proven to be efficient in in water flow rate control ,economic feasibility and fault detection.

Keywords Photo-Voltaic Water Pumping System, Soft Computing techniques, Artificial Neural Network, Adaptive Neuro-Fuzzy Inference System.

1. Introduction

Renewable energy has received much attention in many researches such as [1–5], due to its importance as a foundation of an environmentally sustainable low carbon economy. Due to the absence of fuel cost, low maintenance requirement and environmental friendliness the solar energy is more attractive than other renewable energy [6]. The PV system is the energy supply for many applications such as: water supply system in remote area where system is cost effective for long time duration which makes it suitable for grid-isolated rural locations. Without need for fuel or the extensive maintenance required by diesel pumps, Photo-Voltaic Water Pumping System (PVWPS) can provide clear water.

Although high initial cost, PVWPS have several advantages such as easy installation and operation, highly reliable, low operating cost, unattended operation, low maintenance, durable and need not for rendering long pipelines as it can be installed at the site of use [7-8]. PVWPS consists of a PV array, a motor -pump set and a water tank. Induction motor or DC motor are the most common motors used in the PVWPS. The most common pumps used in the PVWPS are centrifugal pumps. Generally, no storage batteries are used in the PVWPS [9].

Researchers in [10-13] have been developed many studies in modeling, optimization and control about PVWPS, which are used to supply water for drinking and irrigation in in remote regions. In 2013, Gopal el al. [14], briefly review the recent published papers related to PVWPS and the importance of modeling using artificial intelligence.
Many researchers develop ANN an ANFIS models for prediction and the water flow rate collected from a PVWPS.
in 2014 and 2015 [15-16]. In 2016, many papers [17-18] have been introduced review on modeling studies in modeling, and maximizing the discharge rate of PVWPS.

This paper presents a novel model and performance pre-evaluation of PVWPS using Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) which are widely used in much industrial application [19]. ANFIS and ANN does not require the detailed derivation of nonlinear equations. After the implementation of each models and comparing its results, it is found that ANFIS network is fast, easy and more accurate.

2. Steady State Model of PVWPS

Isolated system mainly consists of solar cell array, and a Permanent Magnet DC (PMDC) motor coupled to a centrifugal pump as shown in Fig.1. Steady state mathematical models of PVWPS components and their simulated performance characteristics are developed in the following sections

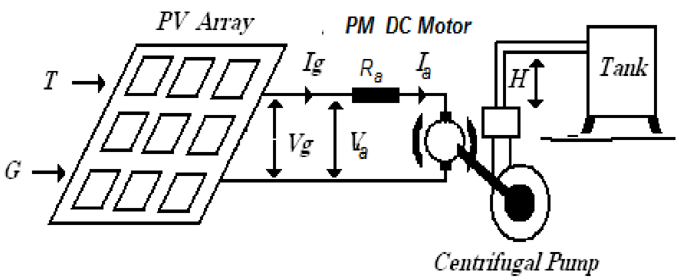


Figure 1: The proposed Photo-Voltaic Water Pumping System.

2.1 PV Generator Model

The PV generator is formed by the combination of many PV modules connected in series and parallel to provide desired value of output voltage and current. The equivalent circuit of solar cell is shown in Fig.2.

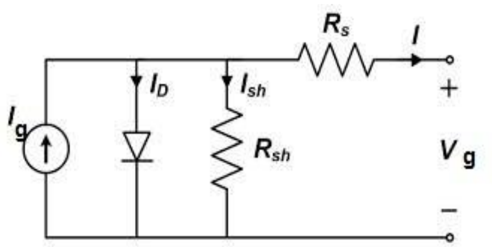


Figure 2: Equivalent electrical circuit of PV cell

The PV generator has nonlinear voltage current characteristic that depends on solar insolation, cell working temperature and connected pattern of cells as given by [20-21];

$$V_g = \frac{1}{\Lambda_g} ln\left(1 - \frac{G\, I_{phg} - I_g}{I_{og}}\right) - I_g R_{sg} \tag{1}$$

$$I_g = G\, I_{phg} - I_{og}\left(e^{\Lambda_g V_g} - 1\right) - \left(V_g / R_{sh}\right) \tag{2}$$

Where; $\Lambda = q/AKT$;

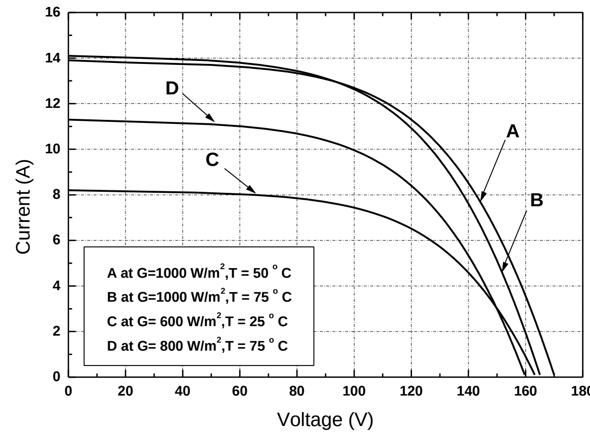
$\Lambda_g = \Lambda / N_s$;

$R_{sg} = (N_s/N_P)\, R_s$;

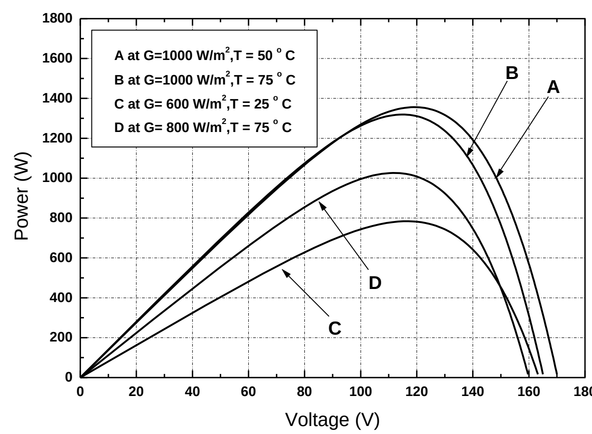
$I_{og} = N_P\, I_o$;

and $I_{phg} = N_P\, I_{ph}$. [22].

The main electrical parameters of PV module used are summarized in Appendix A. The simulated current-voltage and power - voltage characteristics of PV module are shown in Fig.3



(a) The current-voltage characteristics



(b) The power-voltage characteristics

Figure 3: PV module characteristics at different solar insolation, (*G*) and working temperature (*T*).

From Fig.3. It is cleared that the PV characteristics are affected by solar insolation, (*G*) and cell working temperature (*T*).

2.2 Motor-Pump set Model

Motor – pump set is composed of PMDC motor coupled to a centrifugal pump. PMDC is one of the most preferable motor to be used in solar pumping system due to its high efficiency [14], the motor voltage and torque equations under steady-state are;

$$E_b = Ce * \omega_m = V_a - I_a R_a \tag{3}$$

$$T_e = C_e * I_a \tag{4}$$

The pump power and torque equations under steady-state are;

$$P_L = 9.810 * Q * H \tag{5}$$

$$T_L = K_P * {\omega_m}^2 \tag{6}$$

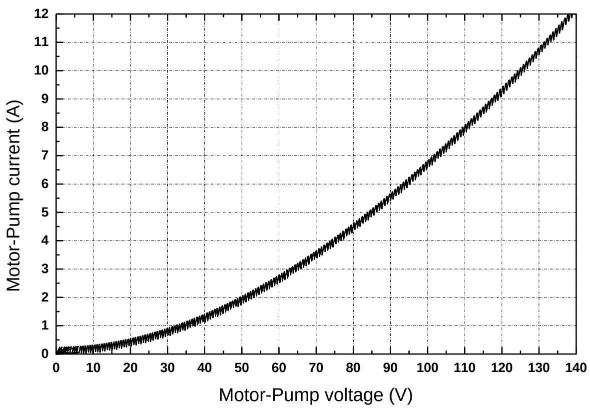
At steady state ($T_e = T_L$), load curve equation will be as follow;

$$K_P {V_a}^2 - 2K_P\, V_a\, I_a R_a - {C_e}^3 * I_a + K_P {I_a}^2 {R_a}^2 = 0 \tag{7}$$

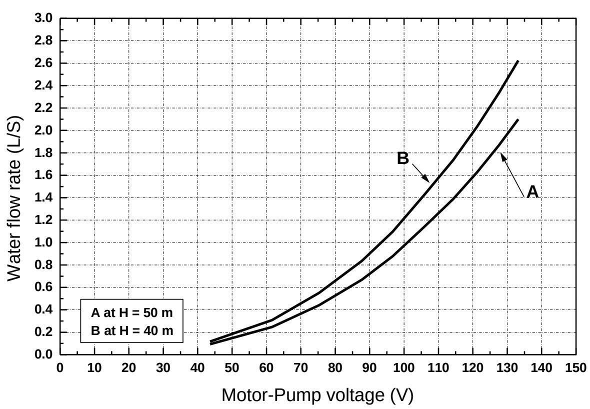
According to operating point of the motor – pump system, the water flow rate can be determined as shown below;

$$9.810\; Q\; H\; C_e^{\;3} = \eta_P K_P \,(V_a - I_a R_a)^3 \qquad (8)$$

The main parameters of the PMDC motor and the centrifugal pump used are summarized in Appendix A. The motor–pump system characteristics are shown in Fig.4



(a) The current-voltage characteristics



(b) The flow rate-voltage characteristics

Figure 4: Motor–Pump characteristics at different total static heads (*H*).

From Fig.4. It is cleared that Motor–Pump characteristics are affected by at different total static heads (*H*).

3. Performance Analysis of PVWPS using Iteration technique

The operating points of the PVWPS can be obtained by solving equations (2) and (7). So equation (8) may be used to determine the water flow rate value. The values of solar insolation, (*G*), cell working temperature (*T*) and total static heads (*H*) affect on the PVWPS main performance parameters, water flow rate. This section investigates this effect using iteration technique depicted in the flowchart shown in Fig. 5.

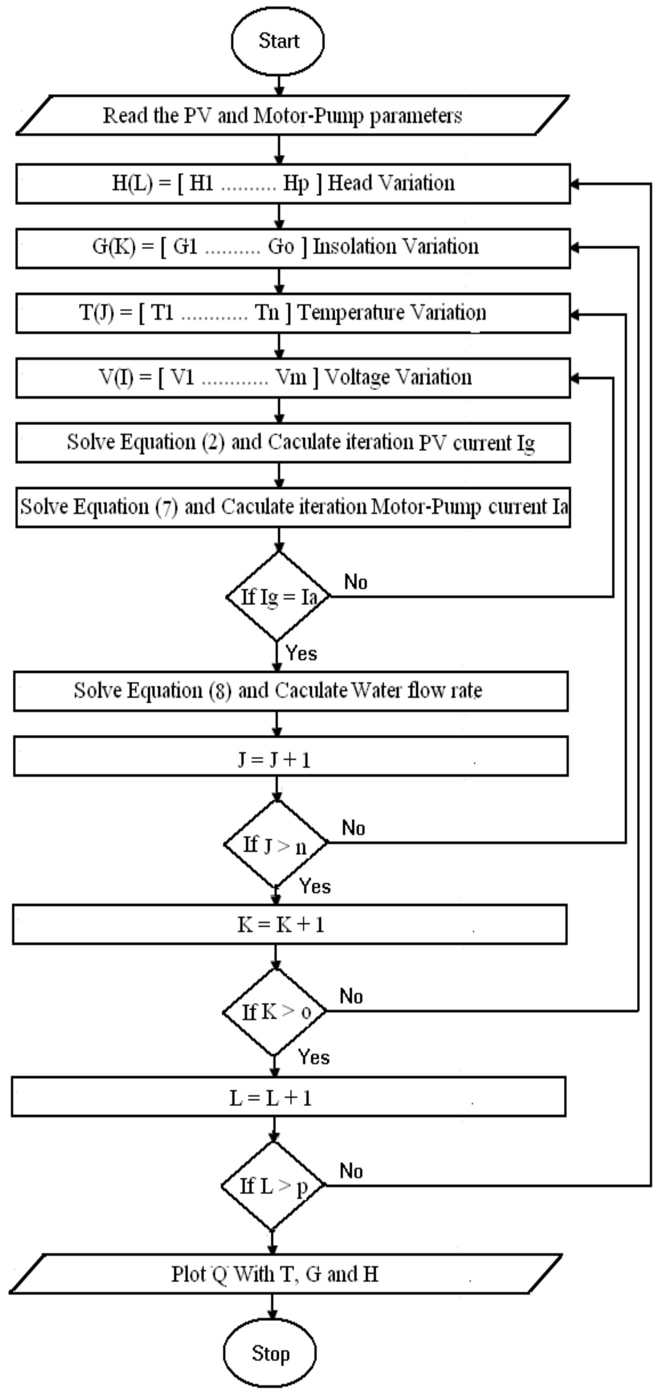


Figure 5: Procedure of PVWPS performance analysis using iteration technique

The water flow rate is computed for different operating conditions defined by of solar insolation, (*G*) variation, cell working temperature (*T*) variation and total static heads (*H*) variation. So complete analysis is done at different loading as shown in Fig. 6, Fig. 7 and fig. 8.

The water flow rate of PVWPS significantly increases with solar insolation increasing at constant temperature and head as shown in Fig. 6. Where higher cell working temperature at constant insolation and head, will leads to slight decrease in Water flow rate of PVWPS as shown in Fig.7. From Fig. 8 , it is clear that water flow rate of PVWPS decreases; as the total static head increases, at constant insolation and temperature .

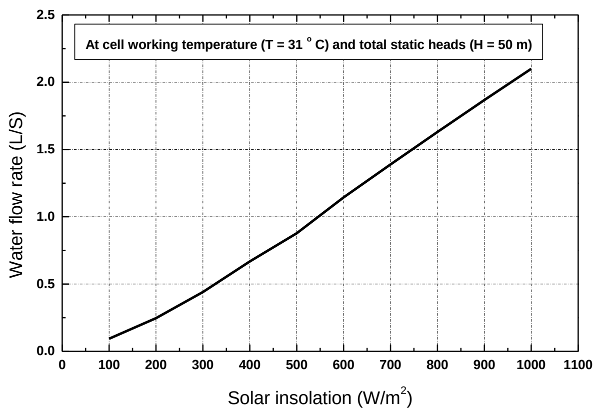


Figure 6: Variation of the Water flow rate of PVWPS with solar insolation at constant temperature and head.

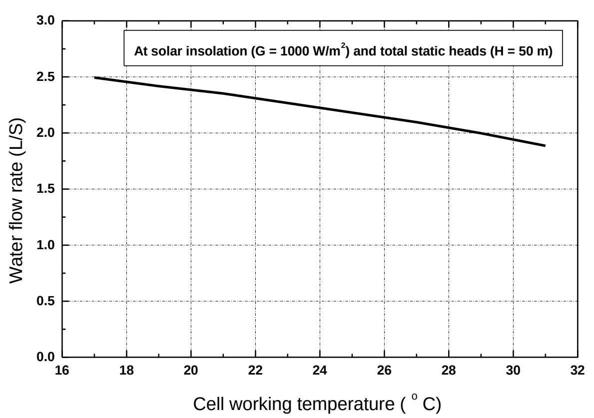


Figure 7: Variation of the Water flow rate of PVWPS with cell working temperature at constant insolation and head.

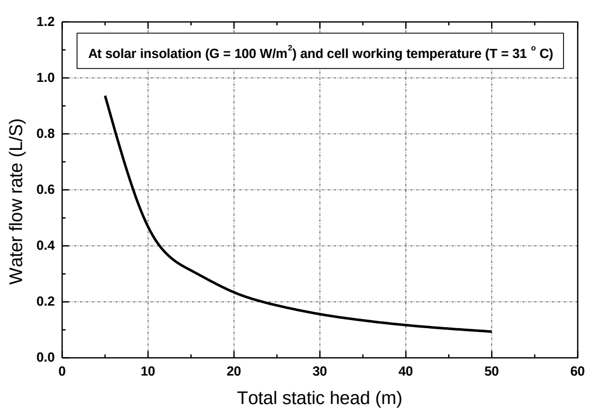


Figure 8: Variation of the Water flow rate of PVWPS with total static heads at constant insolation and temperature.

4. ANN and ANFIS for Water Flow Rate Identification

As it is desired to reach water flow rate accurately and fast due to unexpected change in the surrounding conditions, it is better to use soft computing techniques for modeling PVWPS. It is noted that the system equations are non-linear, resulting in a complex mathematical model. Thus ANN and ANFIS are used to estimate the amount of flow rate accurately.

4.1 Artificial Neural Network (ANN)

ANN models can be defined as "a computing system made up of a number of simple, highly interconnected processing elements, which process information by its dynamic state response". These ANNs operate like a black box model, requiring no detailed information about the system. Instead they learn the relationship between the input parameters, controlled and uncontrolled variables by studying previously recorded data and it so able to deal with complex systems with many interrelated parameters [23].

In this work, three layers neural network (having an input layer, a 2- hidden layers and an output layer) have been used, together with a tansigmoidal activation function and supervised training via a feed forward back-propagation technique, with RMSE = 0.0924.

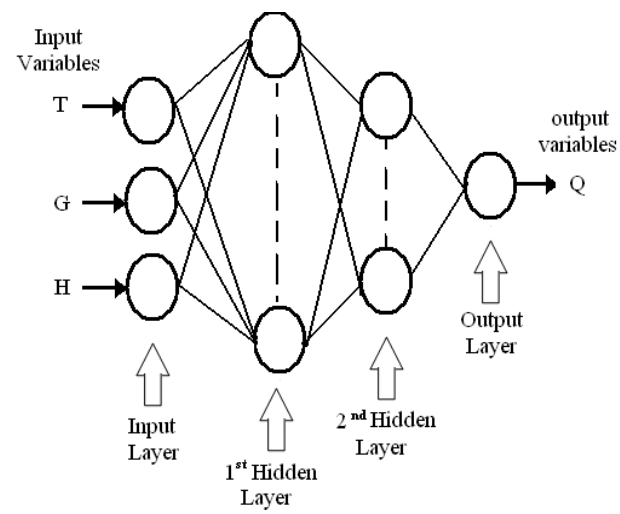


Figure 9: Schematic diagram of the construction of the adopted neural network model

4.2 Adaptive Neuro - Fuzzy Inference System (ANFIS)

Adaptive Neuro-Fuzzy Inference System (ANFIS) is a hybrid intelligent system which consists of a combination of fuzzy inference system with neural network, so it has two advantages; the advantage of dealing with linguistic expressions understandable to human experts (if-then) rules and the advantage of having the ability of being trained by samples of input output data.

The idea of neural network and fuzzy inference combination in controller design is to design a system that uses a fuzzy system to represent knowledge in a linguistic way and has the learning ability of neural network that can adjust the membership functions parameters directly from data in order to improve the system performance [24].

The ANFIS network is based upon a first order Takagi‑Sugeno model and is comprising of five layers.
In this work, membership functions are chosen to be gbell membership function for all the inputs where it is given a good outputs compared the others membership functions as shown in Fig. 10. With RMSE = 0.02525
In the second layer, the minimum error value of three input weights is calculated by rules firing strengths determination.
In the third layer, normalize the rules firing strengths.
In the fourth layer, compute the contribution of each rule towards the overall output.
In the fifth layer, compute the overall output as the summation of contribution from each rule.

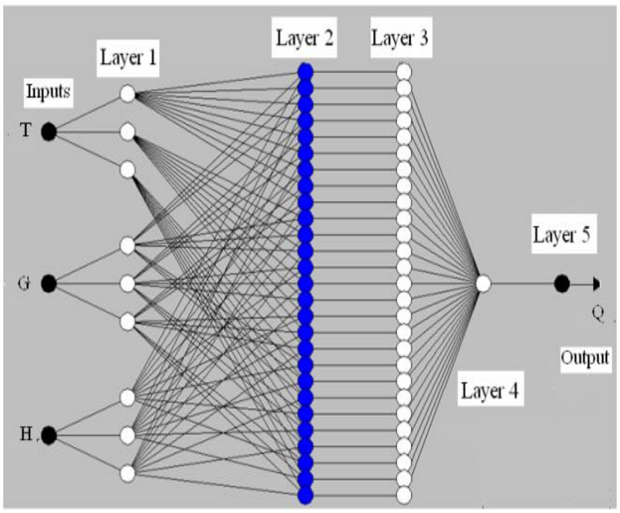


Figure 10: Schematic diagram of the adopted ANFIS model

5. PVWPS Model using SC

In this section, the previously described identification iteration techniques for water flow rate are applied to design the SC model of PVWPS using ANN and ANFIS. To investigate the performance of the proposed strategies under different conditions, extensive simulations are conducted.
Table 1. Shows sample of the data used for testing the performance of the SC models SC models at different operating conditions.
The Mean Sum Square Error (MSSE) can be obtained for SC models with reference to iteration data as follow;

$$\text{MSSE} = \frac{\sum_{1}^{patterns}(Q_{iteration} - Q_{soft\ computing})^2}{number\ of\ patterns} \quad (9)$$

It is found that MSSE for ANN model is 4.87186*10 $^{-4}$ and for ANFIS model, is 2.00018* 10 $^{-5}$. From previous results, it is observed that MSSE of ANN model is about 24.36 times as compared with the MSSE of ANFIS model.
From the comparison between the different PVWPS models; it illustrates a very good agreement between data obtained by the prescribed methods but with short time for SC models. Also it is clearly shown from the results obtained that the ANFIS present a better accuracy than the results obtained by the ANN for each signal tried before.

Table 1. Sample testing data sets from iteration model and that predicted by SC models.

Patterns	Inputs			Iteration Results	ANN Results	ANFIS Results
	T	G	H	Q	Q	Q
1	31	200	50	0.24653	0.22888	0.25093
2	31	400	50	0.66831	0.67527	0.65597
3	31	600	50	1.14371	1.13403	1.13897
4	31	800	50	1.62989	1.64038	1.62695
5	31	1000	50	2.09969	2.09982	2.09619
6	31	100	10	0.46814	0.50115	0.46895
7	31	100	20	0.23407	0.24393	0.23313
8	31	100	30	0.15605	0.15649	0.15654
9	31	100	40	0.11704	0.12025	0.11797
10	31	100	50	0.09363	0.09131	0.09274
11	17	1000	50	2.49092	2.48628	2.49406
12	19	1000	50	2.41829	2.40575	2.41717
13	21	1000	50	2.3468	2.31066	2.3521
14	27	1000	50	2.09969	2.09982	2.09619
15	29	1000	50	2.00317	1.93948	1.99768

6. Conclusion

The computation of water flow rate of PVWPS using conventional iteration technique has been found to be complex and take long time with fatigued mathematical procedures.
The application of a SC technique for steady state analysis of PVWPS has been demonstrated and has been found to be very effective for accounting the complex characteristics of this system. ANFIS technique is superior in comparison with ANN technique as declared in MSSE values and it is worthy and beneficial towards accuracy and steady state analysis time than conventional techniques.
Further, no assumptions or complex computations are required for SC models.

Appendix A

The parameters of the system under study are shown below;

PV array data at G = 1000 W/m^2 and T = 25^o C [25]	
N_s	9*36 = 324 cell
N_P	18 cell
R_s	0.05 Ω .
I_{ph}	0.756 A
I_o	0.45*10 $^{-3}$ A
$1/\Lambda$	(1 / 13.68) V
DC Motor date [25]	
V_a	120 V (rated motor voltage)
I_a	9.20 A (rated armature current)

R_a	1.5 Ω .
C_e	0.621 V/(rad/sec).
ω_m	157.1 rad/sec. (rated shaft speed)
Load data	
K_P	0.00019557 N.m / (rad/sec)^2

References

[1] X. Liu and X. Kong, " Nonlinear Model Predictive Control for DFIG-Based Wind Power Generation," IEEE Trans. Automation Science and Engineering, vol. PP, issue 99, pp. 1–10, Oct.2013.

[2] R. J. Wai, W. H. Wang, and C. Y. Lin, "High-performance stand-alone photovoltaic generation system," IEEE Trans. Ind. Electron., vol. 55,no. 1, pp. 240–250, Jan. 2008.

[3] M. H. Todorovic, L. Palma, and P. N. Enjeti, "Design of a wide input range DC–DC converter with a robust power control scheme suitable for fuel cell power conversion," IEEE Trans. Ind. Electron., vol. 55,no. 3,pp. 1247–1255, Mar. 2008.

[4] S. K. Kim, J. H. Jeon, C. H. Cho, J. B. Ahn, and S. H. Kwon, "Dynamic modeling and control of a grid-connected hybrid generation system with versatile power transfer," IEEE Trans. Ind. Electron., vol. 55,no. 4,pp. 1677–1688, Apr. 2008.

[5] M. Cirrincione, M. Pucci, and G. Vitale, "A single-phase DG generation unit with shunt active power filter capability by adaptive neural filtering," IEEE Trans. Ind. Electron., vol. 55, no. 5, pp. 2093–2110, May 2008.

[6] Yi-Hua Liu , Chun-Liang Liu , Jia-Wei Huang , Jing-Hsiau Chen, "Neural-network-based maximum power point tracking methods for photovoltaic systems operating under fast changing environments" , Solar Energy, Vol. 89, pp. 42 - 53, March 2013.

[7] M.Abu-Aligah, " Design of Photovoltaic Water Pumping System and Compare it with Diesel Powered Pump", Jordan Journal of Mechanical and Industrial Engineering, (JJMIE), Vol. 5, No. 3, pp. 273 - 280, June 2011.

[8] P.Andrada and J.Castro, " Solar photovoltaic water pumping system using a new linear actuator ", International Conference on Renewable Energy and Power Quality (ICREP'07), 28-30th March, 2007, Sevilla, Spain

[9] A. Hamidata, and B. Benyoucef, " Mathematic models of photovoltaic motor-pump systems", Renewable Energy, Vol. 33, pp. 933 - 942, 2008.

[10] B.G. Belgacem, " Performance of submersible PV water pumping systems in Tunisia", Energy for Sustainable Development, Vol. 16, pp. 415–420, 2012.

[11] A. Boutelhig, Y. Bakelli, I. Hadj Mahammed, and, A. Hadj Arab, " Performances study of different PV powered DC pump configurations for an optimum energy rating at different heads under the outdoor conditions of a desert area", Energy, Vol. 39, pp. 33-39, 2012.

[12] A.E. Badoud, M. Khemliche, B. Ould Bouamama, S. Bacha, Lavado, snd, L.F. Villa, " Bond graph modeling and optimization of photovoltaic pumping system: Simulation and experimental results " , Simulation Modelling Practice and Theory, Vol. 36, pp. 84–103, 2013.

[13] S. Haddad, A. Mellit, M. Benghanem, and , K.O. Dafallah, " Modelling and Estimation of the Hourly Flow Rateof a Photovoltaic Water Pumping System Using Polynomial Regression Method: Experimental Validation " , International Scientific Journal Environmental Science, Vol. 3, Issue 2 , pp 93-97, June 2014.

[14] C. Gopal, M. Mohanraj, P. Chandramohan, and, P. Chandrasekar, " Renewable energy source water pumping systems —A literature review," Renewable and Sustainable Energy Reviews, Vol. 25, pp. 351–370, 2013.

[15] S. Haddad, A. Mellit, M. Benghanem, and , K.O. Dafallah, " ANNs-based modeling and prediction of hourly flow rate of a photovoltaic water pumping system: Experimental validation ", Renewable and Sustainable Energy Reviews, Vol. 43, pp. 635–643, March 2015.

[16] R. K. Kharb, S. L. Shimi, S. Chatterji, and, M. F. Ansari, " Modeling of solar PV module and maximum power point tracking using ANFIS ", Renewable and Sustainable Energy Reviews, Vol. 33, pp. 602–612, March 2014.

[17] Rahul Rawat, S.C. Kaushik, and Ravita Lamba, " A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system", Renewable and Sustainable Energy Reviews, Vol. 57, pp.1506-1519, May 2016.

[18] Azzedine Boutelhig, Amar Hadj Arab, and Salah Hanini, " New approach to exploit optimally the PV array output energy by maximizing the discharge rate of a directly-coupled photovoltaic water pumping system (DC/PVPS)" , Energy Conversion and Management, Vol. 111, pp. 375-390, March 2016.

[19] Menghal, P.M. and Laxmi, A.Jaya," Adaptive Neuro Fuzzy based dynamic simulation of induction motor drives" IEEE International Conference on Fuzzy Systems (FUZZ), 2013, Hyderabad, India

[20] A. Chermitti , O. Boukli-Hacene, A. Meghebbar , N.Bibitriki, and A. Kherous," Design of a library of components for autonomous photovoltaic system under Matlab/Simulink ", Physics Procedia, Vol. 55, pp. 199 - 206, 2014.

[21] K. Visweswara, " An Investigation Of Incremental Conductance Based Maximum Power Point Tracking For

Photovoltaic System ", Physics Procedia, Vol. 54, pp. 11- 20, 2014.

[22] O.Atlam, and M. Kolhe, " Performance evaluation of directly photovoltaic powered DC PM (direct current permanent magnet) motor - propeller thrust system", Energy, vol. 57, pp. 692–698, August 2013

[23] M. Veerachary and N. Yadaiah, " ANN Based Peak Power Tracking for PV supplied DC motors",, Solar Energy Vol. 69, No. 4, pp. 343–350, 2000.

[24] H. Hamdan, " An Exploration of the Adaptive Neuro-Fuzzy Inference System (ANFIS) in Modelling Survival", Ph.D. Thesis, School of Computer Science, Nottingham University, Nottingham, United Kingdom. March 2013.

[25] J. Appelbaum and M.S. Sarma, " starting and steady state characteristics of DC motors powered by solar cell generators", IEEE Transactions on Energy Conversion, Vol. EC1 , No. 1, pp. 17-25, March 1986.

Nomenclature

V_g	PV generator voltage, in Volt.
I_g	PV generator current, in Ampere.
P_g	PV generator output power, in Watt.
V_{gm}	PV generator maximum voltage
I_{gm}	PV generator maximum current
P_{gm}	PV generator maximum output power
I_{ph}	Insolation photo current per cell
I_{phg}	Insolation photo current of the PV generator
I_o	Reverse saturation current per cell
I_{og}	PV generator reverses saturation current.
R_s	Series resistance per cell, in Ohm.
R_{sh}	Shunt resistance per cell, in Ohm.
R_{sg}	PV generator series resistance, in Ohm.
N_s	Series- connected solar cells
N_P	Parallel - connected solar cells
q	Electron charge, 1.602 x 10^{-19} C
K	Boltzmann constant, 1.38 x 10^{-23} J/k
T	Cell working temperature in, ^{o}C
A	Completion factor.
Λ	PV cell constant in, (1/V)
Λ_g	PV generator constant in, (1/V)
G	Solar insolation (irradiance) level in kW/m^2.
V_a	DC motor armature voltage, in Volt.
I_a	DC motor armature current, in Ampere.
R_a	Armature resistance, in Ohm.
E_b	Back emf voltage, in Volt.
T_L	Load (pump) torque, in N.m.
T_e	Motor developed torque, in N.m.
C_e	Motor constant , in V/(rad/sec).
K_P	Load (pump) constant, in N.m / (rad/sec)^2.
P_a	DC motor input power, in Watt.
ω_m	DC motor speed, in rad/sec.
Q	Water flow rate, in L/sec.
H	Total static head, in m.
P_L	Load (pump) power, in Watt.
η_P	Load (pump) efficiency, in % .