Performance Management of Photovoltaic Parallel Pumps for Optimal Hydraulic Power Point Tracking

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Abstract- Photovoltaic (PV) water pumping constitute an innovative solution for sustainable irrigated agricultural. The present study treats technical case related to actual use and performance of PV pumping systems for drip irrigation in Morocco. A management method was proposed to optimally operate PV pumping system and synchronize hydraulic performance to variable daily irradiance. The study showed that use of pumps in parallel improved efficiencies and enlarged daily operating time of the pumping system using only the same installed photovoltaic generator power. The result showed that it is possible to design more economical PV systems as the maximum peak power demand for each month can be satisfied using small power pumps in parallel and adjusting their switch with accordance to varying daily irradiance. This management method optimized the PV hydraulic pumping capacity by up to 20% and help farmers to avoid use of complementary diesel power for satisfying their irrigation.

Keywords Photovoltaic; Pumping System; Parallel Pumps; Hydraulic, Performance; Management Method.

Nomenclature

AC	:	Alternating Current
CP	:	Centrifugal Pump
DC	:	Direct Current
kW	:	Kilo-Watt
kW_p	:	Kilo Watt Peak
MPPT	:	Maximum Power Point Tracking
MWC	:	Meter Water Column
PV	:	Photovoltaic
PVWPS	:	Photovoltaic Water Pumping System
R&D	:	Research and Development
W	:	Watt
WR	:	Water Requirements

1. Introduction

Water availability and accessibility are two main factors for rural development in developing countries. Surface water is becoming unavailable due to scarcity of rainfall in many arid areas. Thus, demand on water cannot be satisfied without using pumping technologies to mobilize deep underground resources. Use of pumping systems has significantly increased to lift underground water. Moreover, low pressurized irrigation technologies are popularized to save water and energy for agricultural production. Efficient PV pumping and irrigation systems and their optimal power management are of importance to improve use of energy in agricultural sector. Management of photovoltaic energy in off grid sites is facing to actual technical and economical tests for adoption as use of conventional energy resources is often expensive. The constraints of using fuel and maintenance of diesel engines push farmers for adopting photovoltaic technologies and promoting sustainable irrigated agriculture system. Photovoltaic pumping technologies were promoted in many governmental strategies to boost use of clean energy for sustainable farming systems. However, R&D actions still needed to improve systems performances and their affordability for large extension of PV technologies in developing countries. Control strategies on PVWPS have been developed by many authors. These strategies focused on optimizing electrical performance. In [1], the authors compared four systems (2P×2S, 2P×1S, 1P×1S and 1P×2S) provided 120W to power a DC SHURflo pump (24 V) for three different heads (10 m, 15 m and 25 m). The results showed that a combination of 2P×1S and 1P×2S PV array configurations were the efficient solutions to power the pump. A reconfiguration controller was used to activate 2P×1S PV to power the system in the morning with a significant starting current. While, the 1P×2S PV array is used to power the system during optimum sunlight. Similarly, in [2], three PV configurations (4P×1S, 2P×2S and 1P×4S) were compared. These configurations are chosen to improve PVWPS performance at low, medium and high irradiance, respectively. The proposed approach makes the system perform, especially in the morning, evening and cloudy weather.

In other studies, the improvements of PVWPS were done using MPPT (Maximum Power Point Tracking) technologies [3-8]. A method based on fuzzy logic algorithm applied to a DC-DC converter was developed. It's revealed that the energy production efficiency was increased compared to those obtained by the system without MPPT [9]. The conventional algorithm IncCond presents an inaccurate solution. In fact, a new strategy control based on a combination with this algorithm and Neural Network has been developed. This intelligent IncCond algorithm intervenes with IncCond when there are no irradiance changes and with artificial neural network elsewhere. The simulation result showed a good stability and fast tracking of the MPP compared to the standard IncCond algorithm [10].

However, in hydraulic part, few works focused on performance to optimize operating points of centrifugal pump (CP) and yield daily working efficiencies according to irradiance occurrence. In [11] control strategies approach to match between the PV array and motor to achieve maximum mechanical power were proposed for two PVWPS. The first system used DC motor while the second system utilized induction motor. In the first case, the extraction of maximum mechanical power was done by controlling the excitation of the motor. On the other case, the maximum power was obtained by controlling the frequency of the voltage source inverter. The results showed that the maximum mechanical power extracted from separately excited DC motor is higher than that in an induction motor. Meanwhile, use of affinity law is of importance to vary centrifugal pump characteristics as any change of rotating speed result in pump flow rate, head, and power changes [12, 13]. Modeling of centrifugal pump behavior can be done using system curves involving parameters of rotation speed, flow rate and power inputs to compute the head output accordingly to the irradiance intensity [14-18]. The affinity laws were used to optimally manage PV pumping system and maximize daily water volume output [9, 19-21]. The authors adapted the affinity laws to achieve the pump hydraulic requirements while the power delivered to the pump motor remains unchanged by shifting the pump to operate around new pump curves. Moreover, another promising solution based on testing performance using genetic optimization coupled to use of experimental data was developed [22]. The experimental test was based on mounting four centrifugal pumps in parallel scheme. The results showed that the algorithm proposed and the enhanced system design involved a minimization of power consumption and maximization of system overall efficiency. The system was supplied by electrical energy, which is not efficient for use in agricultural irrigation systems.

The present study consists on testing, for the same installed power of PVWPS, two scenarios of mounting parallel pumps compared to use of one large pump as adopted case by farmers. The three scenarios were evaluated to maximize the water pumped amount with reference to the installed PVWPS power and to potential irradiance during usual irrigation peak months of June, July and August.

2. Materials and Methods

2.1 PVWP irrigation system description

The study was based on a PVWPS of 120 panels (DAQO NEW ENERGY, 230 W_P) mounted in 6 strings of 20 panels. The PV generator serves an inverter (KEB F5) of 22 kW coupled to a three-phase submersible pump (SAER S181A1) for pumping water from a deep well of 60 m and storing it in a tank of 2000 m^3.

2.2 Approach for PV Power management

The Performance of the existing PVWPS (22 kW) was evaluated with three scenarios to test management method of splitting and switching pump powers for better electric and hydraulic performances according to daily change of solar irradiance. The 1st scenario (22 kW) adopted by the farmer couldn't operate more than 6 hours per average daily time of 10 hours, as it is based on a pump that required a high power and couldn't perform at low irradiance during early morning and late afternoon.

The finality of proposing this management method converges with possibility of extending the system operating time and also satisfying irrigation water requirements. Electrical and hydraulic daily data measurements were done to evaluate PVWPS performance between 10 am and 4 pm. The solar irradiance occurrence was actually not sufficient to continuously operate the three phase AC motor/pump at the required steady state speed range (without stopping and speed fluctuation problems). Measurements were taken at 11:00 am, taking into account the system boot, which was only done around 10:30 am. To have an adequate exploitation of the PVWPS power, centrifugal pump for three configurations were tested. These configurations were: one large pump power (1st scenario: 22 kW), two medium pump powers (2nd scenario: 2*11 kW) and small pump powers (3rd scenario: 3*7.5 kW), were compared. The pumps were mounted in parallel scheme "Fig.1" and switched according to supply of the installed PV array power (22 kW_P) and its potential variation with reference to daily solar irradiance.

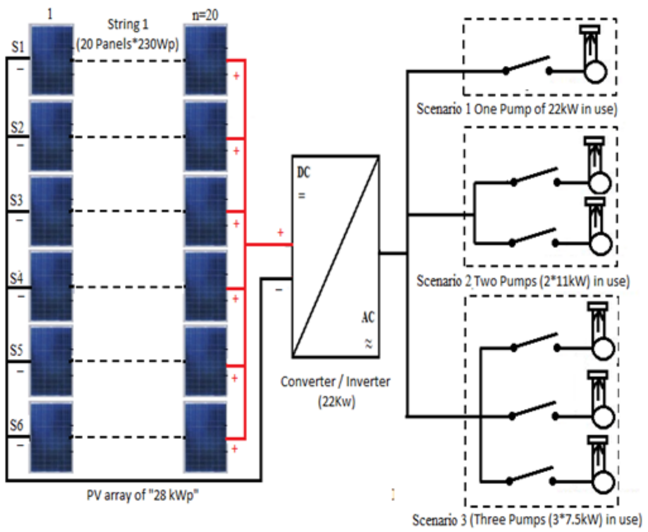

Fig. 1: Three proposed scenarios of photovoltaic water pumping systems.

Performance evaluation of each scenario was based on comparing the amount of pumped water and the required water volume. Optimal energy management of a centrifugal pump consists on maximizing use of the available energy from the PV generator using adequate pump power to be operated at higher rotational speed (around frequency of 50 Hz) and higher yield. In fact, actual flow rate provided by a pump depends on its rotational speed, consequently on the potential frequency processed by the connected inverter according to occurring solar irradiance. The flow rate of a centrifugal pump can be governed "Eq. (1)" to adequately adjust its efficiency and optimally exploit varying occurrence of a daily solar irradiance. The characteristic curve of a pump turning at constant rotational speed is presented by the following equation:

$$H = aQ^2+bQ+c \tag{1}$$

Where: H, Q and a, b, c are head, flow rate, and constants are coefficients of the characteristic curve for a specific rotational speed and rotor diameter of a centrifugal pump, respectively [23].

Centrifugal pumps are governed by affinity laws "Eq. (2)" showing impact of rotational speed change on flow rate, head and power. The affinity laws are of importance to manage pump rotational speed point for better energetic and hydraulic performance. The affinity law expressions are given for a fixed rotor diameter by the following equations [24].

$$(Q_1/Q_2) = (N_1/N_2);\ (H_1/H_2) = (N_1/N_2)^2;$$

$$(P_1/P_2) = (N_1/N_2)^3 \tag{2}$$

Where, H, Q, N and P are head, flow rate, rotational speed and power, respectively. Mathematical models for CP are developed in the researches [25, 26].

The method proposed to improve performance management of PV pumping systems is based on determining optimal centrifugal pump parameters according to affinity law and available photovoltaic power supplied by a PV generator. In fact, the power produced by a photovoltaic generator and supplied to a centrifugal pump mainly depends on irradiance potential G:

$$P = G*A*\eta PV*\eta inv \tag{3}$$

Where: A, ηPV and ηinv are photovoltaic generator surface, photovoltaic panel output and photovoltaic inverter output, respectively.

The third affinity law "Eq. (2)" can be used to find a second operating point of the pump rotational speed N_2 corresponding to a power P_2. Characteristic curves for a centrifugal pump can be given for two rotational speeds N_1 and N_2 as follow:

$$\{H_1 = a_1.Q_1^2 + b_1.Q_1 + c_1\ (N_1) \tag{4}$$

$$\{H_2 = a_2.Q_2^2 + b_2.Q_2 + c_2\ (N_2)$$

By applying law affinity, parameters a_2, b_2 and c_2 can be computed using the following equations:

$$a_1 = a_2;\ b_1 = b_2.\ (N_2/N_1);\ c_1 = c_2.\ (N_2/N_1)^2 \tag{5}$$

Then, for a constant head H corresponding to potential of the PV pumping system, the pumped flow rate for a given irradiance G is as follow:

$$Q_2 = [-b - (b^2-4.a_2.(c_2 - H))1/2]/2.a_2 \quad (6)$$

3. Results and Discussions

Evaluation of the pumping systems showed a possibility of improving its energetic and hydraulic performances and using only photovoltaic array for covering average daily water requirement. The study case based on a 22 kW PVWPS showed that installation of one large pump cannot work widely at its nominal frequency (50 Hz) to satisfy conditions of maximum daily efficiency according to irradiance occurrence. Our measurements showed that maximum operating frequency (84%) occurred only for a few number of hours (four to five hours per day). Difficulty of reaching nominal frequency and operating pump at its nominal speed during a daily period is due to inefficiently operating a large pump power (22 kW) at low and medium irradiance conditions (from 200 to 600 W/m²). However, the photovoltaic generator was only adequate for optimal pump operating at a higher irradiance period (> 600 W/m²). Use of small and medium pump powers mounted in parallel greatly improved operating conditions of the pumps for relatively lower irradiance, longer day period and higher efficiency. Choosing medium (2*11 kW) and small (3*7.5 kW) pump powers helped to improve PV energy use and hydraulic performance of the PVWPS for effective head of 70 m. Indeed, the system showed that both scenarios were better to satisfy water requirements in the three peak months (June, July and August). The daily water requirements were evaluated at 522.6 m^3, 595.1 m^3 and 618.2 m^3 for June, July and August, respectively (Figs 2.a, 2.b and 2.c).

3.1 First scenario

This scenario evaluated the performance of one large pump power (22 kW) as the reference case actually adopted, and the pump characteristic curve relative to nominal operating speed is as follow:

$$H = -0.0036\,Q^2 - 0.4909\,Q - 134.05 \quad (7)$$

Where the constants are the characteristic curve coefficients of one large pump (SAER S181A1/5) obtained using manufacturer data.

Results in “Fig.2.a” showed limitation to satisfy water requirement as the pump cannot efficiently operate in low irradiance (less than 352 W/m²). Even if the daily operating period was 9 hours, the daily pumped water was 455 m^3, 541 m^3 and 581 m^3 for June, July and August, respectively.

The water requirement are not satisfied in this scenario as the pumped water volumes were only 86%, 91% and 93% of the required water volumes for June, July and August, respectively.

3.2 Second scenario

Implementation of this scenario was based on two similar pump powers mounted in parallel (2*11 kW), and their characteristics curve at nominal operating speed is as follow:

$$H = -0.0035\,Q^2 - 0.0905\,Q + 132.97 \quad (8)$$

Where the constants are the characteristic curve coefficients of one medium pump (Grundfos SP 150S -8) obtained using manufacturer data.

Figure 2.b showed that use of two pumps increase the daily operating period to more than 10 hours. This increase is due to possibility of operating one pump at in low irradiance (less than 200 W/m²) and engaging the second pumps as irradiance became higher than 460 W/m². Consequently, the daily pumped water was increased to cover water demand by 103%, 102% and 103% for June, July and August, respectively.

3.3 Third scenario

This scenario consisted on using three small pumps mounted in parallel, and their characteristic curve is represented as follow:

$$H = -0.0571\,Q^2 - 2.8571\,Q + 187.14 \quad (9)$$

Where the constants are the characteristic curve coefficients of one small pump (Grundfos SP 77S -20) obtained using manufacturer data.

Figure 2.c showed considerable improvement of daily operating period (about 12 hours). This increase is due to the importance of using adapted pump power to take advantage from low irradiance occurring during sunrise and sunset periods. In fact, PV generator was optimally adapted by operating one pump at low irradiance (less than 200 W/m^2), two pumps as irradiance reached between 200 and 450 W/m^2 and three pumps for irradiance higher than 450 W/m². Such scenario satisfied water requirement by 108%, 104% and 104% for June, July and August, respectively.

Water requirements are satisfied by 90% (1^{st} scenario), 103% (2^{nd} scenario) and 105% (3^{rd} scenario). It is better to adopt two or three pump mounted in parallel than choosing on pump of similar installed power “Fig.3”. Better performance of both scenario 2^{nd} and 3^{rd} is due to adaptation of PV power potential to improve pumps operating and management satisfying higher hydraulic efficiencies.

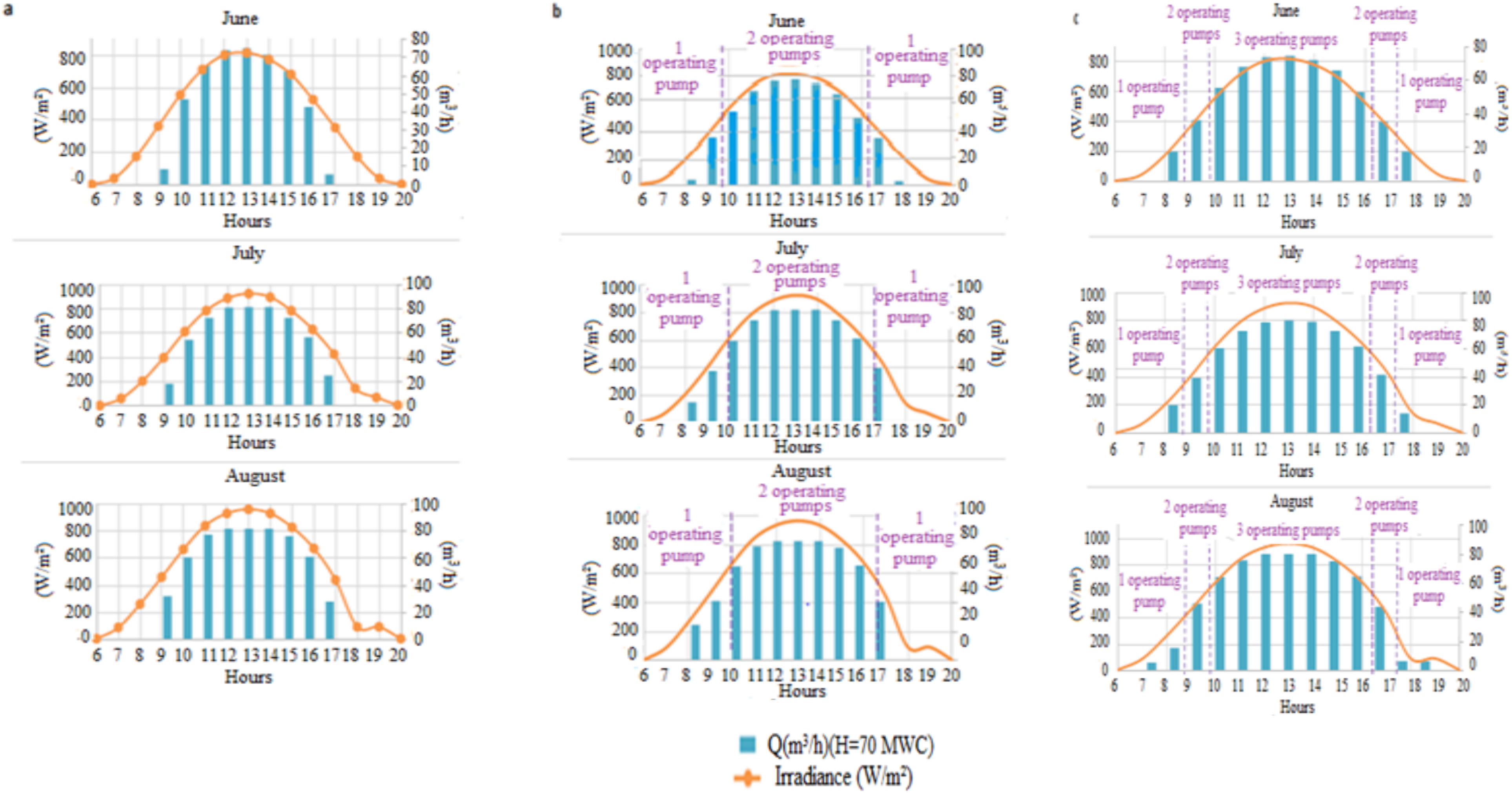

Fig.2: (a) Average daily pumped water versus irradiance using one large pump of (22kW); (b) Average daily pumped water versus irradiance using two small pumps (2*11); (c) Average daily pumped water versus irradiance using three small.

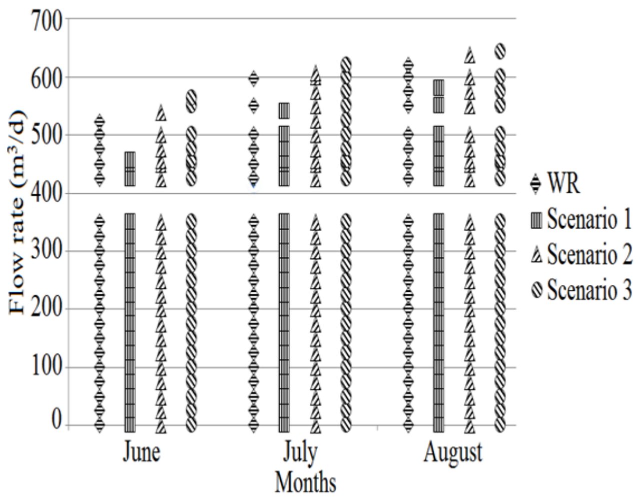

Fig.3: Average daily water requirements and pumped volumes.

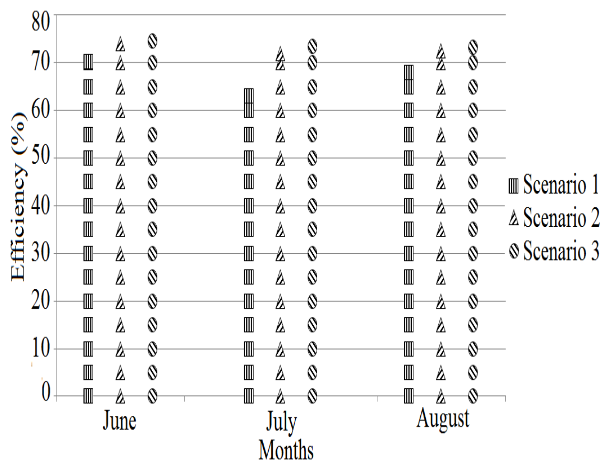

Fig. 4: Pump powers management vs hydraulic efficiencies (Three scenarios).

The average pump yields were 67%, 72.16% and 73.18% for 1st, 2nd and 3rd scenarios, respectively "Fig.4".

Installation of PVWPS based on one large pump power (case of 22 kW) is not adequate as its optimal operating is only ensured during peak solar irradiance period around midday. This study case showed that use of three small pump powers (7.5 kW) in parallel instead of a single large pump (22 kW) was effective solution to enlarge PVWPS service period and to improve their energetic and hydraulic performances.

4. Conclusion

This study was based on evaluating a performance of PVWPS. The proposed power management method in this study case showed feasibility of using only PV energy supply to totally cover water requirements of irrigated system. In fact, using a set of pump powers mounted in parallel instead of using one large pump of equivalent power can be an effective solution for enlarging operating period of PVWPS and taking more advantage from daily period irradiance to reach high hydraulic efficiencies.

References

[1] 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, DOI: 10.1016/j.energy.2011.10.016, Vol. 39, pp. 33–39, 2012.

[2] ZM. Salameh, and F. Dagher, "The effect of electrical array reconfiguration on the performance of a PV-powered volumetric water pump", IEEE Trans Energy Convers, DOI: 10.1109/60.63135, Vol. 5, pp. 653-658, 1990.

[3] I. Chtouki, P.Wir, M.Zazi, B. Collicchio, and S. Meddour, "Design, Implementation and Comparison of Several Neural Perturb and Observe MPPT Methods for Photovoltaic Systems", International Journal of Renewable Energy Research, Vol. 9, pp. 757-770, 2019.

[4] A. Dolara, S. Leva, G. Magistrati, M. Mussetta, E. Ogliari, R. Varun Arvind, "A Novel MPPT Algorithm for Photovoltaic Systems under Dynamic Partial Shading - Recurrent Scan and Track Method", 5th International Conference on Renewable Energy Research and Applications (ICRERA) IEEE, Birmingham, UK, pp. 1112-1127, 20-23 November 2016.

[5] D. Haji , N. Genc, "Fuzzy and P&O Based MPPT Controllers under Different Conditions", 7th International Conference on Renewable Energy Research and Applications (ICRERA) IEEE, Paris , France, pp. 649-655, 14-17 October 2018.

[6] K.Amara, A. Fekik, D. Hocine, M. L. Bakir, E. Bourennane, T. A. Malek, A. Malek, "Improved Performance of a PV Solar Panel with Adaptive Neuro Fuzzy Inference System ANFIS based MPPT", 7th International Conference on Renewable Energy Research and Applications (ICRERA) IEEE, Paris , France, pp.1098- 1101 , 14-17 October 2018.

[7] Y. Soufi , M. Bechouat , S. Kahla, K. Bouallegue, "Maximum power point tracking using fuzzy logic control for photovoltaic system", 2014 International Conference on Renewable Energy Research and Application (ICRERA) IEEE, Milwaukee, WI, USA , pp. 902- 906, 19-22 October 2014.

[8] K. Kajiwara, H. Tomura, N. Matsui, F. Kurokawa, "Performance-Improved Maximum Power Point Tracking Control for PV System", 7th International Conference on Renewable Energy Research and Applications (ICRERA) IEEE, Paris , France, pp. 1153-1156, 14-17 October 2018.

[9] M. Algazar, H. AL-monier, H. Abd EL-halim, and M. Salem, "Maximum power point tracking using fuzzy logic control", Electrical Power and Energy Systems, DOI:10.1016/j.ijepes.2011.12.006, Vol. 39, No. 1, pp. 21–28, 2012.

[10] B. Sefriti, and I. Boumhidi, "Neural network incremental conductance MPPT algorithm for photovoltaic water pumping system", 10th International Conference on Intelligent Systems: Theories and Applications (SITA) IEEE, Rabat, Morocco, pp. 1-6, 20-21 October 2015.

[11] AM. Zaki and MN. Eskander, "Matching of photovolatic motor-pump systems for maximum efficiency operation", Renew Energy, DOI:10.1016/0960-1481(95)00133-6, Vol.7, pp. 279–288, 1996.

[12] M. Arrouf, S. Ghabrour, "Modelling and simulation of a pumping system fed by photovoltaic generator within the Matlab/Simulink programming environment", The Ninth Arab International Conference on Solar Energy (AICSE-9), Kingdom of Bahrain, pp. 23–30, 30 April 2007.

[13] K. Sumit, K. Rizwan and J. Kaushar, "Modeling, Analysis and Control of Solar Water Pumping System", International Conference on Impending Power Demand and Innovative Energy Paths, JNU NEW DELHI, India, pp. 356-363, 2015.

[14] T. Ahonen, J. Tamminen, J .Ahola, J. Viholainen, N. Aranto, and J. Kestilä, "Estimation of pump operational state with model-based methods", Energy Conversion and Management, DOI:10.1016/j.enconman.2010.01.009, Vol. 51,No.6, pp. 1319–1325, 2010.

[15] A. Kalaiselvan, S. Umashankar, S. Paramasivam, and H. Norbert, "Real Time Simulation of Variable Speed Parallel Pumping System", 9th International Conference on Applied Energy, ICAE2017, Cardiff, UK, pp. 2102-2108, 21-24 August 2017.

[16] Z .Zhang, A. Kusiak, Y. Zeng, and X. Wei, "Modeling and optimization of a wastewater pumping system with data-mining methods", Applied Energy, DOI:10.1016/j.apenergy.2015.11.061, Vol. 164, pp. 303–311, 2016.

[17] W .Chang, J. Chang, H. Yin, W. Wang, H. Chung, Y. Chang, "Energy saving algorithm for pumping systems based on fuzzy decision making", IEEE International Conference on Systems, Man, and Cybernetics, COEX, Seoul, Korea, pp. 2395–2400, 14-17 October 2012.

[18] M. Izquierdo, J. Jimenez, A. M Del Sol, "Matlab Software to Determine the Saving in Parallel Pumps Optimal Operation Systems, by Using Variable Speed", IEEE Energy 2030 International Conference on Energy, Atlanta, GA USA, pp. 1-8, 17-18 November 2008.

[19] N. Chandrasekaran, and K. Thyagarajah, "Simulation and Experimental Validation of AC Motor and PMDC Motor Pumping System Fed by Photovoltaic Cell", Indian Journal of Engineering and Material Sciences, Vol. 21,No. 1, pp. 93-103, 2014.

[20] A. Marchi, A. Simpson, and N. Ertugrul, "Assessing Variable Speed Pump Efficiency in Water Distribution Systems", Drinking Water Engineering and Science, DOI:10.5194/dwes-5-15-2012, Vol. 5, pp. 15-21, 2012.

[21] S. Khader, and A. Daud, "PV-Grid Tie System Energizing Water Pump", Smart Grid and Renewable Energy, Vol. 4, pp. 409-418, 2013.

[22] P. Olszewski, "Genetic optimization and experimental verification of complex parallel pumping station with centrifugal pumps", Applied Energy, DOI:10.1016/j.apenergy.2016.06.084 ,Vol.178, pp. 527–539, 2016.

[23] J. Paugh, Head vs Capacity Characteristics of Centrifugal Pumps, Chemical Engineering, New York, N.Y. 1984.

[24] S. Wilson, Pump Affinity Laws for Centrifugal Pumps, N.Y. 2009.

[25] A. Ghoneim, "Design optimization of photovoltaic powered water pumping systems", Energy Conversion and Management, DOI:10.1016/j.enconman.2005.08.015, Vol. 47, No. 11, pp.1449–1463, 2006.

[26] J. Appelbaum, "Starting and steady-state characteristics of DC motors powered by solar cell generators", IEEE Transaction on Energy Conversion, DOI:10.1109/TEC.1986.4765665, Vol. EC-1, No. 1, pp. 230-237, 1986.