OPTIMAL OPERATION OF STANDALONE PV PUMPING SYSTEM BASED ON AN INDUCTION MOTOR

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In this paper, a PV array is used for water pumping purposes at remote or abandoned locations. Egypt is a developing country and largely depends on cultivation that won’t be possible without water availability. This paper presents the performances of a PV pumping system based on an induction motor under variable solar irradiations and ambient temperatures. The Maximum Power Point Tracker (MPPT) based on Perturb and Observe (P&O) algorithm for the purpose of improving efficiency of the system is connected to the system. The main objective of this work is water pumping system, employing an induction motor pump, capable of supplying a daily average of 55 m\textsuperscript{3}/h at 20-m head has been developed. The system was installed on at western desert area in Egypt. The results presents a MATLAB/SIMULINK based modeling and simulation scheme suitable for studying the PV array under variable solar irradiations and ambient temperatures. The proposed model is very useful for PV engineers and experts who require a simple, fast and accurate PV simulator to design their systems.

Keywords: Stand-alone PV systems, Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O), Boost DC/DC converter, DC/AC inverter, water pumping.

1. INTRODUCTION

The use of PV as the power source for pumping water is considered as one of the most promising areas of PV application. PV water pumping systems are particularly suitable for water supply in remote areas where no electricity supply is available. Water can be pumped during the day and stored in tanks, making water available at night or when it is cloudy. The pumped water can be used in many applications such as domestic use, water for irrigation and village water supplies. The advantages of using water pumps powered by PV systems include low maintenance, ease of installation, reliability and the matching between the powers generated and the water usage needs. In addition, water tanks can be used instead of batteries in PV pumping systems [1].
Nomenclature

PV Photovoltaic
MPPT Maximum power point tracking,
P&O Perturb and Observe
I output or load current of PV model (A)
V output or load voltage of PV model (V)
Iph photo current (A)
Isc short circuit current of the module (A)
Voc open circuit voltage of the module (V)
Isc cell reverse saturation current (A)
Ir cell reverse saturation current (A) at standard test conditions (STC)
I1 diffusion saturated current of D1 (A)
I2 recombination saturated current of D2 (A)
I1atSTC diffusion saturated current of D1 (A) at standard test conditions (STC)
I2atSTC recombination saturated current of D2 (A) at standard test conditions (STC)
q electron charge (1.6 * 10^-19C)
k Boltzmann constant (1.38 * 10^-23 J/K)
a diode ideality factor for single diode model
a1, a2 diode ideality factors for two-diode model
R, series resistance (Ω)
Ra shunt resistance (Ω)
Vth thermal voltage (V) (V th = KT/q)
G solar irradiance (kW/m^2)
G STC solar irradiance at standard test conditions (STC) [G STC = 1000 W/m^2]
Iph STC photo current at standard test conditions (A)
K short circuit current coefficient (A/C^x)
T STC temperature of PV cell at standard test conditions
Eg band gap energy of semiconductor (eV)
Np number of parallel cells
R' r, L' r Rotor resistance and leakage inductance;
Lm Magnetizing inductance;
Ls Lr Total stator and rotor inductance;
Vqst, Isq Q axis stator voltage and current;
Vds, Isq D axis stator voltage and current;
V' ds, I' ds D axis rotor voltage and current;
φq, φd Stator q and d axis fluxes;
φ' q, φ' d Rotor q and d axis fluxes;
ω Angular velocity of the stator;
ωr Angular velocity of the rotor;
Ωr Rotor angular position;
P Number of pole pairs;
ω Electrical angular velocity (ωm × p);
Ωr Electrical rotor angular position (Ωm × p);
Te Electromagnetic torque;
Tm Shaft mechanical torque
H Total head,
T Tilt angle,
M Motor cable,
L Pipeline,
B Drawdown,
Pp Electrical power for submersible pump (KW).
ρ Water density (Kg/m^3),
g Gravity (m/s^2),
Q Pump flow rate (m^3/hr),
ηp Pump overall efficiency,
PVA Photovoltaic array,
Nsyn Synchronous speed (t.p.m),
S Slip.

Egypt is a developing country and largely depends on cultivation that won’t be possible without water availability. Through this study, it can be proved that PV energy is an efficient solution for water pumping purposes in the Egyptian western desert area. In the PV based water pumping, the pump is driven by an induction motor matching both the selected PV array and the required pumping head.

The growing demand for electric energy throughout the world has highly motivated the use of renewable sources of energy. Among the unconventional renewable based energy sources that have been intensively studied, photovoltaic (PV) energy is now becoming a real promising and economical source of energy [2,3]. PV is a technology that turns the sun radiation energy directly to electricity. The PV energy has many advantages. It is a clean energy source that has virtually no environmental polluting impact, highly reliable, flexible in terms of size, and needs minimal maintenance [4, 5].

Various studies have been carried out on optimizing, sizing and matching PV pumping systems. DC motors were initially used since they offered easy implementation with cheap power conversion [6-11]. A number of existing operational pumping systems have shown that these schemes suffer from maintenance problems [12]. However, this solution is limited only for low power PV systems. The
induction motor based PV pumping system offers an alternative for a more reliable and maintenance free systems [12-18]. In addition, recent advances in the field of solid state devices, logic circuits and control theory have given a great impetus to the use of AC motors in PV systems. Several papers report AC systems [12-18] using either current source or voltage source inverters. Different optimization strategies have been proposed to improve the overall system efficiency such as maximum power tracking or MPPT motor efficiency optimization and flow rate maximization [12].

There are many of maximum power point tracking (MPPT) varies with radiation and temperature with Standalone PV pumping system based on an induction motor [12-18], it is difficult to maintain optimum matching at all radiation levels. Many algorithms have been developed for tracking the maximum power such as: (P&O), incremental conductance, curve-fitting method, fuzzy logic controller and open-circuit voltage PV generator method [1-12, 20].

The main objective of this work is water pumping system, employing an induction motor pump, capable of supplying a daily average of 55 m³/h at 20-m head has been developed. The system was installed on at western desert area in Egypt.

In this paper a stand-alone PV array is connected with water pumping based on an induction motor. PV water pumping systems are used for irrigation water. PV based pumping systems without battery can provide a cost-effective use of solar energy. The optimal operation of stand-alone PV systems with water pumping will be tackled. The Maximum Power Point Tracker (MPPT) based on perturb and observe (P&O) algorithm for the purpose of improving efficiency of the system is connected to the system.

2. DESCRIPTION OF THE PROPOSED STANDALONE PV WATER PUMPING SYSTEM

Fig.1 shows the performances of a PV pumping system based on an induction motor under variable solar irradiation (G) and ambient temperature (T). It includes PV array model, DC-DC boost converter, MPPT controller by P&O, RLC filter, DC/AC inverter and induction motor coupled to a pump. The PV pumping system is operation all day with variable solar irradiation and ambient temperature. Case study in (Egypt, El-Bahari, El-Wahat, Al Wadi al Jadid).

![Figure 1. PV pumping system under variable solar irradiation and ambient temperature.](image-url)
The DC/DC boost converter allows maximum utilization of the photovoltaic array and controls a power-flow to ensure a continuous delivery of energy to have the desired water flow, whatever environmental conditions variations form variable solar irradiation and ambient temperature [1]. It consists of a boost inductor (L=200 mH), controlled switch (IGBT), diode and a filtering capacitor (C=30000 µF).

RLC filter (R= 0.5 Ω, L=0.5 H and C=1 F with capacitor initial voltage = 380 volt) allows the use of a valid quasi-static model of the PV array and also acts as an added energy storage device for starting of induction motor.

The inverter is to transfer the power managed by the PV panel from a direct current to an alternative current. The current is modulated sinusoidal to obtain a high efficiency. A natural PWM switching technique at (10 kHz) is used to drive the DC-AC inverter with a modulation index (M = 0.85) for maintain a 1 PU voltage (380 Vrms and 50 Hz) at the induction motor terminals.

2.1 Mathematical Modeling of a PV Array

The two-diode equivalent circuit-based models are shown in Figs. 2 and 3, for cells and modules. The equivalent circuit of the module is arranged in series and parallel cells with N_s and N_p respectively [21].

The characteristic equation of I-V curve is given by [21]:

\[
I = I_{ph} - I_{s1} \left\{ \exp \left( \frac{V + IR_s}{a_1 \cdot V_T} \right) - 1 \right\} - I_{s2} \left\{ \exp \left( \frac{V + IR_s}{a_2 \cdot V_T} \right) - 1 \right\} - \left( \frac{V + IR_s}{R_{sh}} \right)
\]

(1)
The seven-parameter respectively known as follow, photo current $I_{ph}$, saturation currents of two diodes $I_{s1}$ and $I_{s2}$, series and shunt resistances $R_s$ and $R_{sh}$, and ideality factors of two diodes $a_1$ and $a_2$.

The photo current $I_{ph}$ is a function of temperature and solar insolation is given as follows [21]:

$$I_{ph} = \left(G/G_{STC}\right) \left[I_{ph \text{ at STC}} + K_i(T - T_{STC})\right]$$

(2)

The two-diode saturation currents as function of working PV temperature are given as follow [21]:

$$I_{s1} = I_{s1 \text{ at STC}} \left(\frac{T}{T_{STC}}\right)^3 \exp\left[\frac{q E_g}{a_1 K} \left(\frac{1}{T_{STC}} - \frac{1}{T}\right)\right]$$

(3)

$$I_{s2} = I_{s2 \text{ at STC}} \left(\frac{T}{T_{STC}}\right)^3 \exp\left[\frac{q E_g}{a_2 K} \left(\frac{1}{T_{STC}} - \frac{1}{T}\right)\right]$$

(4)

The current equation of module is written as [18]:

$$I = N_p I_{ph} - N_p I_{s1} \left\{\exp\left[\frac{V + I R_s \left(N_s / N_p\right)}{a_1 N_s V_T}\right] - 1\right\}$$

$$- N_p I_{s2} \left\{\exp\left[\frac{V + I R_s \left(N_s / N_p\right)}{a_2 N_s V_T}\right] - 1\right\}$$

$$- \left(\frac{V + I R_s \left(N_s / N_p\right)}{R_{sh} \left(N_s / N_p\right)}\right)$$

(5)

### 2.2 Three Phase Induction Motor Model

It is well known that the dynamic performance of a squirrel-cage induction motor (SCIM) are shown in Figs. 4 can be analyses mathematically using the d-q axis theory by the following equations [18]:

$$V_{qs} = R_s i_{qs} + \frac{d}{dt} \varphi_{qs} + \omega \varphi_{ds}$$

(6)

$$V_{ds} = R_s i_{ds} + \frac{d}{dt} \varphi_{ds} - \omega \varphi_{qs}$$

(7)
\[ V_{qr} = R_{r}i_{qr} + \frac{d}{dt} \varphi_{qr} + (\omega - \omega_r)\varphi_{dr} \]  
\[ V_{dr} = R_{r}i_{dr} + \frac{d}{dt} \varphi_{dr} + (\omega - \omega_r)\varphi_{qr} \]  
\[ T_e = \frac{3}{2} \left( \frac{p}{2} \right) \frac{1}{\omega} (\varphi_{ds}i_{qs} - \varphi_{qs}i_{ds}) \]

where:
\[ \varphi_{qs} = L_s i_{qs} + L_m i_{qr}, \quad \varphi_{ds} = L_s i_{qs} + L_m i_{dr} \]
\[ \varphi_{qr} = L_r i_{qr} + L_m i_{qs}, \quad \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \]
\[ L_s = L_{ls} + L_m, \quad L_r = L_{lr} + L_m \]

\( \omega_r \): Electrical angular velocity \((\omega_m \times p)\);
\( \Theta_r \): Electrical rotor angular position \((\Theta_m \times p)\);
\( T_e \): Electromagnetic torque;
\( T_m \): Shaft mechanical torque;

Parameters of Induction Motor are shown in the Appendix.

### 2.3 Centrifugal Pump Model

Fig. 5 shows Water Pumping System which could be considered as a case study in Egypt (El-Bahari, El_Wahat, Al_Wadi al_Jadid). Through this study, it can be proved that PV energy is an efficient solution for water pumping purposes in the Egyptian western desert area. Parameters of Solar Pump System [22] as shown in the Appendix can be generalized to all the Egyptian deserts with varying total dynamic head for each location. Calculation of electrical power for Submersible Pump \( P_p \) (KW) can be given by [23].

\[ P_p = \frac{\rho \cdot g \cdot Q \cdot H}{367 \times 10^3 \cdot \eta_p} \]  

In this study of water pumping system, an induction motor pump, capable of supplying a daily average of 55 m\(^3\)/h at 20-m head has been developed. The system was installed on at western desert area in Egypt. Fig. 6 shows clearly the pump flow rate, based on head values and motor power. The PVA during operation with induction motor coupled to a pump at Head = 20 m, Flow rate = 55 m\(^3\)/h. The improvement of the mechanical power and hence of the flow rate are obtained by the maximization of the motor speed via the optimization criterion. Maximum Power Point Tracker (MPPT) based Perturb and Observe (P&O) algorithm for the purpose of improving efficiency of the system is connected to the system.
Figure 5. PV Water Pumping System [22]. In the figure, H (total head): Vertical height from the dynamic water level to the highest point of delivery, T (tilt angle): Angle of the PV generator surface from the horizontal plane, M (motor cable): The cable between controller and pump unit, L (pipeline): Entire pipeline from the pump outlet to the point of delivery and B (drawdown): Lowering of water level depending on flow rate and recovery rate of the well.

Figure 6. Relationship between flow rate (m³/h) and power (kW) [22].

3. MPPT CONTROL ALGORITHMS

The P&O algorithm is also called “hill-climbing”, but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter [24]. In the case of the Hill-climbing, perturbing the duty cycle of the power converter
implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique.

In this algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power, $\Delta P$, is observed. If the $\Delta P$ is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage perturbations in the same direction should move the operating point toward the MPP. If the $\Delta P$ is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP under variable solar irradiation and ambient temperature. Fig. 7 shows the flowchart of P&O algorithm. Fig. 8 shows the Simulink model for P&O algorithm.

![Flowchart of the P&O algorithm](image)

**Figure 7.** Flowchart of the P&O algorithm [7].
4. SIMULATION RESULTS PV PUMPING SYSTEM UNDER VARIABLE SOLAR IRRADIATION AND AMBIENT TEMPERATURE

The simulation is undertaken on a system characterized by the data given in the Appendix. Fig. 9 shows the Matlab/Simulation model for PV pumping system under variable solar irradiation (G) and ambient temperature (T). It includes PVA model (described in Section 2.1), DC-DC boost converter, MPPT controller by P&O (described in Section 3), RLC filter allows the use of a valid quasi-static model of the PV array and also acts as an added energy storage device, DC/AC inverter and induction motor coupled to a pump (described in Section 2.2 and 2.3). This system works under variable solar irradiation and ambient temperature. It is operational all day with variable solar irradiation and ambient temperature.

From the obtained simulation results, we will show that the variable solar irradiation ($S_x$) and ambient temperature ($T_x$) degrades performances (the global
efficiency and the flow rate) of the PV pumping system. Figs. 10 and 11 show the enforced variation of solar radiation and ambient temperature respectively. As shown Fig. 12, time response of the PVA power with MPPT. The MPPT controller by P&O with PVA and induction motor coupled to a pump accommodates of the generation/load mismatch. However, as shown in Fig. 13, variation of the PVA voltage with MPPT, it is observed that a stable voltage for PVA voltage with MPPT is prevailed. The MPPT connected gives smooth PVA current flowing to the loads as shown Figs. 14.

Figure 10. Variation of solar radiation.

Figure 11. Variation of ambient temperature.
Figure 12. Time response of the PVA power with MPPT.

Figure 13. Time response of the PVA voltage with MPPT.

Figure 14. Time response of the PVA current with MPPT.
The output ac voltage of the inverter is shown in Fig. 15, where the PWM mode operation. The output voltage (380 V) of the inverter is applied to induction motor coupled to a pump. Fig. 16 shows, the stator current of induction motor with time. Fig. 17 and Fig. 18 show, Stator voltage \( V_{ds} \) d- axis of induction motor and Stator voltage \( V_{qs} \) q- axis of induction motor, respectively. The electromagnetic torque \( (T_e) \) of induction motor is stability on 1 PU, as shown in Fig. 19, these results agreed with the load mechanical torque. Fig. 20 shows rotor speed of induction motor with MPPT. The rotor speed \( N_r = (1 - S) \times N_{syn} \) is equal to (0.88 PU or 2500 r.p.m) with MPPT but decrease without MPPT, where \( N_{syn} \) is synchronous speed in rpm and \( S \) is slip.

![Figure 15. Line to line voltage at the inverter output with MPPT.](image1)

![Figure 16. Stator current (a,b,c) of induction motor.](image2)
Figure 17. Stator voltage ($V_{ds}$) d- axis of induction motor.

Figure 18. Stator voltage ($V_{qs}$) q- axis of induction motor.

Figure 19. Electromagnetic torque ($T_e$) of induction motor with MPPT.
5. CONCLUSION.

This paper presents a MATLAB/SIMULINK based modeling and simulation scheme suitable for studying the PV array under variable solar irradiations and ambient temperatures. Through this study, it can be proved that PV energy is an efficient solution for water pumping purposes in the Egyptian western desert area. The purpose of this research is to examine all the necessary steps and key components needed to build a PV supplied water pump under variable solar irradiations and ambient temperatures. PV based pumping systems without battery can provide a cost-effective use of solar energy. An optimal operation of a PV pumping system based on an induction motor was described. The optimization criterion yields to the maximization of the motor efficiency, where the extracted electric power is controlled by the boost converter instead of MPPT controller by P&O. The simulation results show that an increase of both the daily pumped quantity and pump efficiency are reached by the MPPT controller by P&O.

APPENDIX

**PV generator parameters:**
- Maximum power: 8.775 kW
- Optimal current: 22.5 A
- Optimal Voltage: 390 V

**Induction motor parameters:**
- Nominal power: 6 kW
- Nominal line-to-line voltage: 380 V
- Nominal frequency: 50 Hz
- Stator resistance: 0.01965 PU
- Rotor leakage inductance: 0.0397 PU
- Mutual inductance: 1.354 PU
- Total inertia coefficient: 0.9526 s
- Viscous friction coefficient: 2*0.05479 PU
- Number of pole pairs: 1.0
- Mechanical Torque: 1.0 PU
Centrifugal pump parameters:
Type of Pump Unit  PU C-SJ42-4 (Motor, Pump End)
Head max  20 m
Flow rate max.  55 m³/h
Motor speed  1400 : 3000 rpm
Power max.  6 kW
Borehole diameter  6 in
Efficiency [%]  50

6. REFERENCES