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Experimental Investigation and Simulation of High-Performance Photovoltaic Standalone Pumping Systems

Ahmed Althobaiti
Electrical Engineering Department, Taif University , Taif, Saudi Arabia

ABSTRACT–*The focus of this paper is on investigating the optimal operation of an on-site three-phase induction-motor (IM) pumping system that utilizes photovoltaic (PV) power. The study involves both measurement and simulation analyses. The paper aims to investigate and simulate the operation of an on-site induction-motor (IM) pumping system utilizing PV power for optimal performance. To achieve this, the study uses the maximum power point tracking (MPPT) technique and PI controllers as the main control strategy for operating the system to the maximum power point operation as possible, even under variable solar irradiations. In addition, this article describes experiments conducted to evaluate the performance of a stand-alone PV pumping system that utilizes a three-phase induction motor-shunt and centrifugal pump. The study's measurements and simulations show how the unified system operates. The results indicate that the PV array is almost fully utilized, and the motor achieves MPPT transfer. The study highlights the importance of utilizing the available PV power efficiently to achieve the most optimal operation of the pumping system.*

Index Terms –*PVpumping system, experimental investigation, three-phase induction motor, PI controller, maximum power point tracking (MPPT).*

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I. INTRODUCTION

The increasing global demand for electric energy has led to a growing interest in renewable sources of energy (photovoltaic panels, wind turbines) over decade and become more attractive compare with conventional power generation from fusel fuel. PV energy has been studied extensively as one of the most widely promising and cost-effective sources of energy among all various unconventional renewable energy sources[1, 2].

The conversion of solar radiation energy into electricity through PV technology has many advantages. It is considered an environmentally friendly energy source with minimal impact on the environment. PV technology is highly reliable and flexible in terms of size, making it suitable for various applications, from small-scale residential to large-scale commercial installations. Additionally, PV systems require minimal maintenance, making them cost-effective in the long run [3].

PVpumping systems are a popular and sustainable method for water pumping in remote areas where grid electricity is not available especially in urban area to satisfy people needs. These systems use solar energy to provide access to water pumps by converting solar radiation via PV panels, making them an attractive option for irrigation, drinking water supply, and livestock watering.

To investigate and simulate the performance of standalone PV pumping systems, researchers typically use a combination of experimental and numerical methods. Experimental studies involve setting up a PV pumping system and measuring its performance under various operating conditions, such as changes in solar irradiance, water demand, and temperature. These studies can help to identify the key factors affecting the system's efficiency and reliability, as well as provide data for validation of simulation models.

Numerical simulations can be used to model the behavior of the PV pumping system under different conditions and to predict its performance. These simulations are typically based on mathematical models that describe the behavior of the system's components, such as the PV panel, the motor, and the pump. By inputting data from experimental studies, such as the solar irradiance and the water demand, simulation models can predict the system's performance and help to optimize its design control. Overall, the combination of experimental and simulation methods can provide valuable insights into the performance of PV pumping systems and help to optimize their design for maximum efficiency and reliability.

Pumped water from PV powered water pumps can be utilized for various purposes. Furthermore, PV pumping systems can use water tanks instead of batteries, adding to their convenience and practicality [2].

In the past, DC motors were widely used due to their cost-effective power conversion and ease of implementation. However, several existing operational pumping systems that utilize DC motors have encountered maintenance issues, and are limited to low-power PV systems [2]. Among all other AC motors, the use of a PV-powered induction motor (IM) based pumping system is a promising alternative to DC motor schemes, offering higher robustness and lower maintenance requirements [5]-[13].

In [1], the energy efficiency of battery-based PV pumping systems by proposing an intelligent control strategy based on model predictive control (MPC) and particle swarm optimization algorithm(PSO). The proposed method aims to maximize the energy efficiency of the system while maintaining the water demand requirements and prolonging the battery lifetime. The performance of the proposed method is evaluated through simulation and compared with conventional control strategies.

In [2], compare the performance of two PV water pumping solutions: a direct PV pumping system and a lithium battery-based PV pumping system. The study aims to identify the most efficient and reliable solution for water pumping in remote areas. The comparison is based on different parameters, including energy efficiency, cost, and maintenance requirements. The paper also proposes a mathematical model to predict the performance of the two systems under different operating conditions.

The provide insights into the design and optimization of PV pumping systems for domestic water supply applications [3].

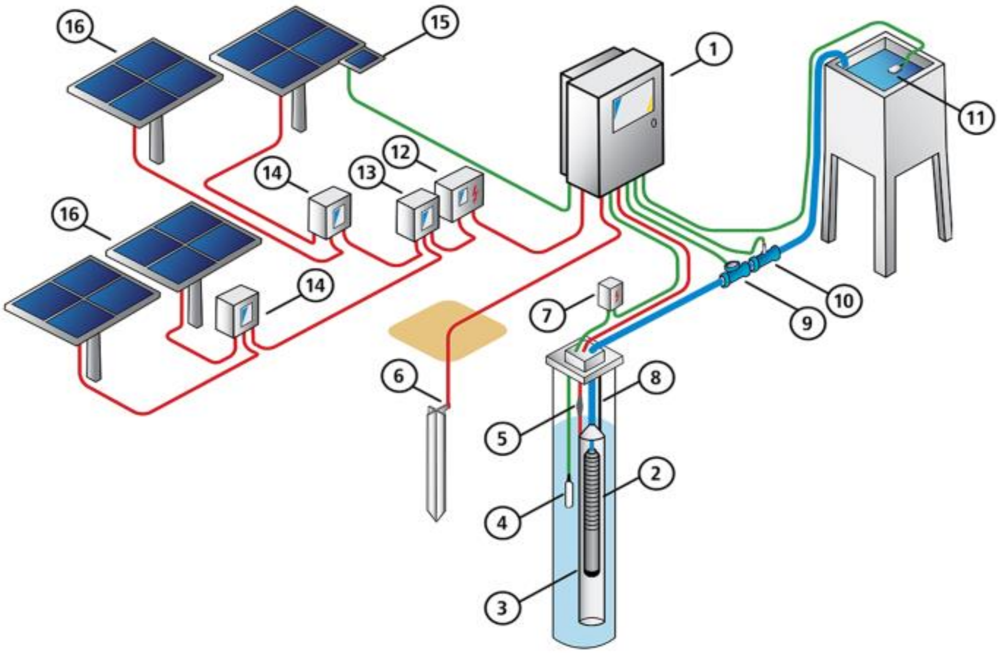
In this paper, a model consisting of two primary schemes, namely the power scheme and the control scheme, is proposed for a standalone PV pumping system. Experimental work has been carried out in this study to assess the performance of the system. The evaluation focused on a case study of a three-phase induction motor-shunt with a centrifugal pump for performance analysis.

II. DESCRIPTION OF THE SYSTEM UNDER STUDY

PV systems have developed as a promising alternative energy source for various applications, including water pumping systems. The application of PV technology for water pumping has gained considerable attention in recent years, particularly for remote areas that lack access to reliable electricity grids or when the gird is not possible. The standalone PV pumping system consists of a PV array, a DC/ACconverter, and an IM coupled to a centrifugal pump.

The PV array converts PV energy into electrical energy, which is utilized to run the induction motor and pump water from a source to a destination. However, the efficiency and reliability of standalone PV pumping systems depend on various factors, including the solar radiation, temperature, and load conditions. To optimize the performance of standalone PV pumping systems. The measurement and simulation for an induction motor and a centrifugal pump. The study focuses on the implementation of maximum power point tracking (MPPT) control technique with PI controllers under varying solar irradiations. The results of the study demonstrate the efficient utilization of available PV power for the optimal operation of standalone PV pumping systems.

Fig.1 show, the system layout for case study of PV pumping system. Presents the layout of the PV pumping that is investigated in the study. It is composed of several components, including a PV array, a solar charge controller referred to as the MPPT controller, and three-phase IM shunt with a centrifugal pump. Each component is described thoroughly in the following sections. The figure provides a comprehensive illustration of all the components that make up the PV pumping system.



1. PSk2 Controller	9: Meter for Water
2. Centrifugal Pump	10. Sensor for Pressure
3. Tube of Stilling	11. Switch for Float
4. Probe of Well	12. PV Protect
5. Splice Kit of Cable	13. PV Combiner
6. Rod of Grounding	14. PV Disconnect
7. Protector for Surge	15. PV Module for Sun Switch
8. Safety Rope	16. PV Generator

Fig. 1: system layout for case study of PV pumping system.

A. PVAmodeling under study

Fig. 2 show, the mathematical model the PV array where employs various equations and formulas. These equations are derived based on the characteristics and behavior of the PV equivalent circuit. To model the behavior of the PV cells and modules, the paper utilizes a two-diode equivalent circuit-based model [14]. The current-voltage curve's characteristic equation is presented below:

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_{s1}} \left\{\exp\left(\frac{\mathrm{V + I\,R_s}}{\mathrm{a_1.V_T}}\right) - 1\right\} - \mathrm{I_{s2}} \left\{\exp\left(\frac{\mathrm{V + I\,R_s}}{\mathrm{a_2.V_T}}\right) - 1\right\} - \left(\frac{\mathrm{V + I\,R_s}}{\mathrm{R_{sh}}}\right) \tag{1}$$

where $\mathrm{I_{ph}}$is the photon current ,$\mathrm{R_{sh}}$ is the shunt resistance , $\mathrm{R_s}$ is the series resistance. V is the voltage. $\mathrm{a_1}$, $\mathrm{a_2}$ are the ideality factors.

The PV cell is a mathematical model that represents the behavior of a PV cell based on its electrical characteristics. In order to study the system PV pump behavior, the model is used to analyze and optimize of a PV cell simplified circuit.The circuit comprises two diodes $\mathrm{D_1, D_2}$ and other circuit elements such as a resistor, a current source, and a capacitor. The first diode$\mathrm{D_1}$ represents the current generated by theilluminated PN junction of the cell, while the second diode $\mathrm{D_2}$ models the recombination of carriers in the bulk of the cell.

The two-diode model used in photovoltaic cells assumes the presence of two diodes with different saturation currents (Is1 and Is2) and ideality factors (a1 and a2). The ideality factor describes the deviation of the diode from ideal behavior when forward biased. Compared to the single-diode model, the two-diode model is considered to be more accurate for PV cells since it considers the recombination of carriers that takes place in the bulk of the cell.

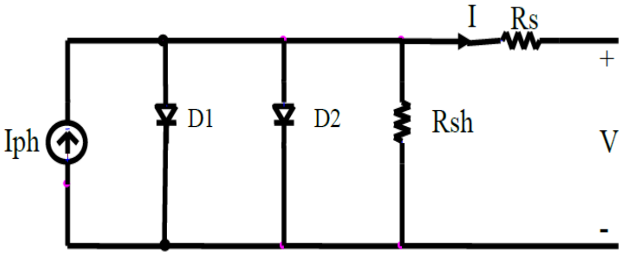


Fig. 2. The two-diode equivalent circuit of a PV cell.

B.Three-phase IM model

An IM is an electric motor that transforms electrical energy into mechanical energy using electromagnetic induction. The motor comprises a stator, which contains three sets of windings that produce a rotating magnetic field, and a rotor, typically made of conductive bars or an aluminum die-cast cage, that rotates within the stator's magnetic field [12].

Electromagnetic torque equation:

$$\mathrm{T_e} = \mathrm{K_1} * (\mathrm{I_{sq}} * \varphi_r) \quad (2)$$

where Te is the electromagnetic torque, $\mathrm{I_{sq}}$ is the current in the stator quadrature axis, φ_r is the rotor flux, and k1 is a constant related to the motor geometry.

Rotor flux can be found from the following equation :

$$\varphi_r = \mathrm{K_2} * (\mathrm{V_t} / (\mathrm{f} * \mathrm{N_r}) \quad (3)$$

where Vt is the stator voltage, f is the supply frequency, Nr is the rotor speed, and k2 is a constant related to the motor geometry.In the addition, stator voltage is calculated from the following equations:

$$\mathrm{V_{ds}} = \mathrm{R_s} * \mathrm{i_{ds}} + \mathrm{L_s}\frac{\mathrm{dids}}{\mathrm{dt}} + \omega_r * \mathrm{L_s} * \mathrm{i_{qs}} \quad (4)$$

To mathematical equations are commonly used. The following equations describe the relationships between the motor's electrical and mechanical characteristics. They are often used to develop control algorithms and optimize motor performance [6, 14]:

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega}(\varphi_{ds}\boldsymbol{i}_{qs} - \varphi_{qs}\boldsymbol{i}_{ds}) \quad (5)$$

$$P_m = T_{load} * \omega_m \quad (6)$$

$$\frac{d\omega}{dt} = -(p/J)(T_e - T_p) \quad (7)$$

where the torque of electromagnetic is (Te), power of motor output (Pm), torque of water pump (Tp), speed of rotor (ωr), velocity of stator angular (ωs), stator q and d axis fluxes ($\boldsymbol{\varphi_{qs}}$and $\boldsymbol{\varphi_{ds}}$), stator q and d axis current ($\boldsymbol{i_{qs}}$and $\boldsymbol{i_{ds}}$), pole pairs (p), and total inertia (J).

C. PI Control

The proportional-plus integral control (PI) is a common control technique constituent product an output proportionate to the instantaneous error, while the integral control component produces an output proportional to the integral of the error. The block diagram of the PI controller is shown in Fig.3. The transfer function of the conventional PI controller can be expressed as [12]:

$$G_s(s) = K_p + K_I / s \quad (8)$$

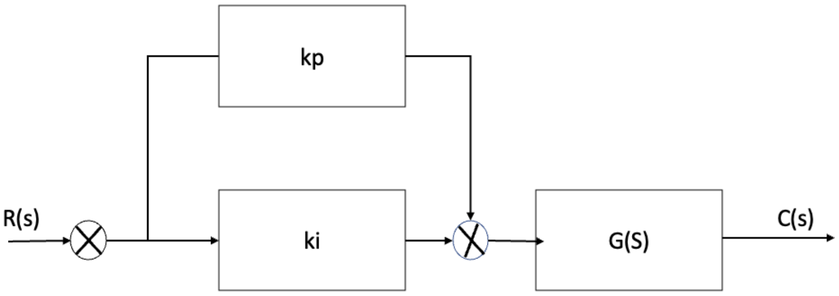


Fig. 3 Block Diagram of PI Controller.

III. A CASE STUDY FOR PV PUMPING SYSTEM

A. PV Array for Case Study

The PV array described in Table 1 is depicted in Fig. 4. These modules can be connected in series to increase voltage or in parallel to increase current for large-scale power generation while Fig. 5 illustrates the PV array connection of PV modules.

Table (1): Electrical specification of PV generator

PV generator	
Ambient temperature[°C]	25
Solar radiation [W per m2]	1000
Pmax [KW]	9.36
Vmax [V]	667
Imax [A]	14
Voc [V]	850
Isc [A]	15

Fig. 4: general site of PV pumping system.

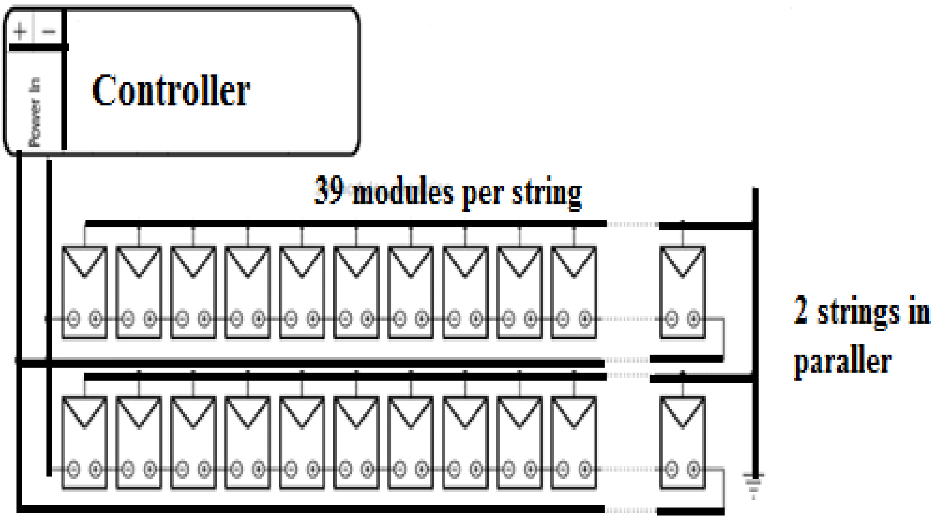


Fig. 5: Wiring diagram for PV array.

B. Centrifugal Pump and Controller PSk2

The centrifugal pump and controller are important componentsby a standalone PVA. The controller is responsible for regulating the operation of the pump to ensure optimal performance, while the pump is responsible for moving water from one location to another. The PSk2 controller is commonly used in PV pumping systems and comes with a number of features including control inputs for dry running protection, remote control, and DC to AC inverter, as well as protection against reverse polarity, overload, and over temperature. Additionally, the controller also includes an integrated MPPT function, which ensures that the PV array is always operating at its maximum power output under different operating conditions. It is a type of pump that uses an impeller to create a flow of fluid. The impeller rotates at a high speed, which creates a centrifugal force that pushes the water through the pump and out the other side. PV-powered water pumping systems often use centrifugal pumps because they have high efficiency, low maintenance requirements, and can function well under diverse conditions. The combination of a centrifugal pump and controller offers a dependable and effective solution for pumping water in isolated or off-grid areas using solar power.

Fig. 6 displays the centrifugal pump and controller used in the PV pumping system. The PSk2 Controller comes with various control inputs for functions such as dry running protection, remote control, and DC to AC inverter. It is also protected against reverse polarity, overload, and over-temperature. In addition, the controller has an integrated MPPT function for maximum power point tracking. Technical specifications for the centrifugal pump and controller can be found in the table 2.

Fig. 6: Centrifugal Pump and Controller PSk2

Table (2): Electrical specification of Pump system and PSk2 Controller

Pump system	
Motor power [kW]	8.230
Motor voltage [V]	380
Motor current [A]	14
Motor speed [rpm]	3075
Frequency [Hz]	50
Flow rate [m³/h]	55
PSk2 Controller	
Pmax	9.5 kW
Vmax	850 V
Optimum Vmp>	575 V
Motor current max.	14 A
Efficiency max.	98 %
Ambient temp.	-30...50 °C
Enclosure class	IP54

IV. MEASUREMENT RESULTSOF CASE STUDY PV PUMPING SYSTEM

The PV system consists of a PV array connected to an MPPT solar charge controller and a three-phase IM shunt with a centrifugal pump, as shown in Fig. 5. The system was tested using the specific parameters listed in table 1 and 2.

Fig. 7 displays how the solar radiation rises from 6 a.m. to 12 noon and then drops during the last hours of the day, from 1 p.m. to 4 p.m. Meanwhile, Fig. 8 indicates a correlation between the energy output (in kWh) and the time of day, where energy production is seen to increase as solar radiation levels rise. Similarly, Fig. 9 illustrates a link between water flow rate (in m3 per hour) and the time of day, where increased solar radiation levels lead to higher water flow rates. Therefore, the data in Fig. 7 to 9 demonstrate that as solar radiation levels increase, the electrical energy and water flow rate also increase.Fig. 7, 8, and 9 various parameters of the system throughout the day. As shown in Fig. 7, solar radiation starts to increase in the morning and reaches its peak around midday before gradually decreasing in the afternoon. This pattern is dependable with the typical solar radiation pattern in most regions.

Fig. 8 demonstrates the impact of solar radiation on the energy output of the PV system. As solar radiation rises, the energy output also rises, and vice versa. This relationship is critical for optimizing the system's performance since it enables the battery banks to store excess energy generated during peak solar radiation hours for later use when solar radiation is low.

Similarly, Fig. 9 illustrates the correlation between solar radiation and water flow rate. As solar radiation levels increase, the water flow rate also increases, allowing for better irrigation of the fruit farm. This relationship is critical for ensuring that the irrigation system is supplied with the required amount of water to meet the crop's water needs.Overall, the data presented in Fig. 7 to 9 demonstrate the importance of solar radiation in the system's performance, and how the system's various components are interrelated and dependent on each other.

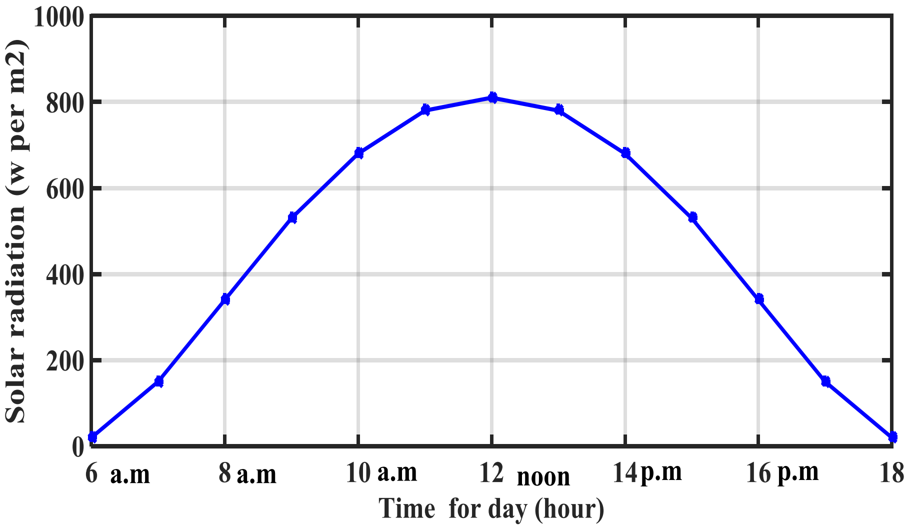


Fig. 7: Relationship between solar radiation and hours for day.

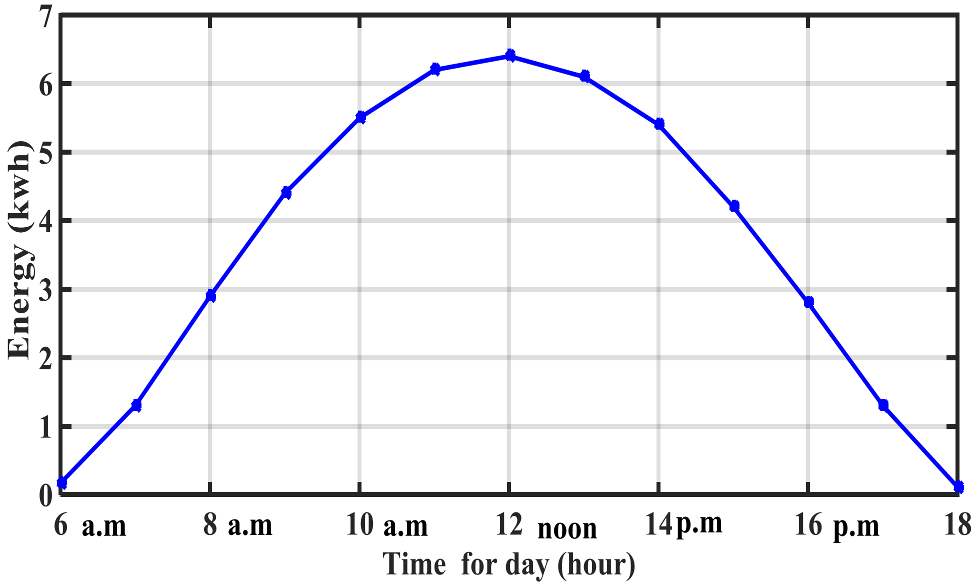


Fig. 8: Relationship between energy (kWh) and hours for day.

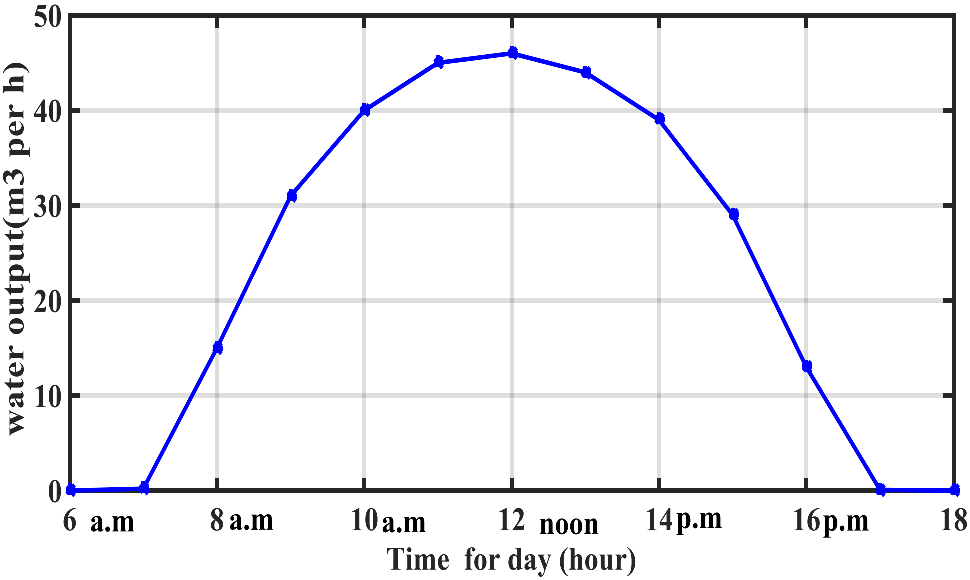


Fig. 9: Relationship between water flow rate (m^{3}per hour) and hours for day.

V. SIMULATION RESULTS AND DISCUSSION

To investigate the impact of changing solar irradiation on the performance of PV pumping system, the study employed a MATLAB/Simulation model. The system's parameters were extracted from the data provided in the study. The model comprised a PV array (PVA) connected to a diode (D1), as well as an RLC filter.

Fig. 10 displays the power-voltage(P-V) and the current-voltage (I-V) curves for the PV array, while Fig. 13 presents the related graphs for different solar radiations (800 to 1000 W/m²) and a constant temperature. The PV module output current rises as the solar radiationrises, as shown in Fig. 10a. Similarly, Fig. 10b shows that the maximum power generation rises as the radiation increases. As depicted in Fig. 10a, the output current of the PV module rises as the radiationrises. Similarly, Fig 10b shows that the maximum power generation also rises as the PVradiationrises.

Fig. 11 illustrates the requireddistinction of PV radiation, and Fig. 12 displays sample results of the PVA power with the difference of PV radiation. Fig11 illustrates the enforced disparity of PV radiation, and Fig. 12 shows the sample results of the PVA power with the variation of solar radiation. The results demonstrate that the presence of the controller enables the PVA to operate nearer to the optimalpath of the MPPT. Overall, from figures above, show the relationship between the solar irradiation and the PVA output, indicating that the system operates efficiently and effectively.

The results reveal that the presence of the controller enables the PVA to run closer to the optimum track of the maximum power. The PVA voltage with the controller ranges between 700 and 720 V, as shown in

Fig. 13, while Fig. 14 displays the sample results of the PVA current with the variation of solar radiation. Fig. 13 presents the related graphs for different solar radiations (800 to 1000 W/m²) and a constant temperature. This figure shows that the PVA voltage with the controller ranges between 700 and 720 V. Additionally, Fig. 14 displays the sample results of the PVA current with the variation of solar radiation.

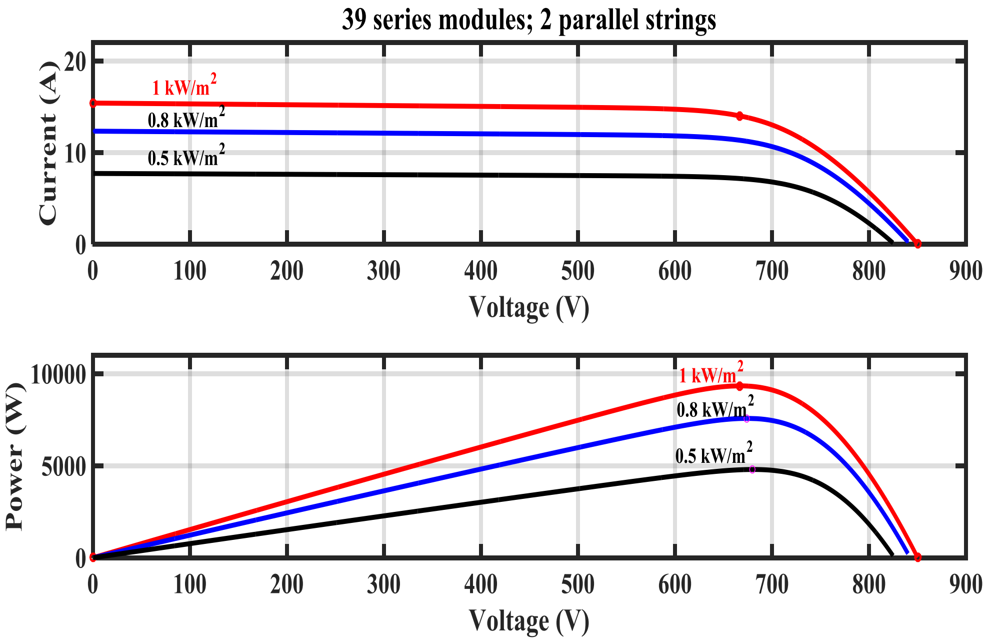


Fig. 10: PV Array (39 series modules and 2parallel strings).

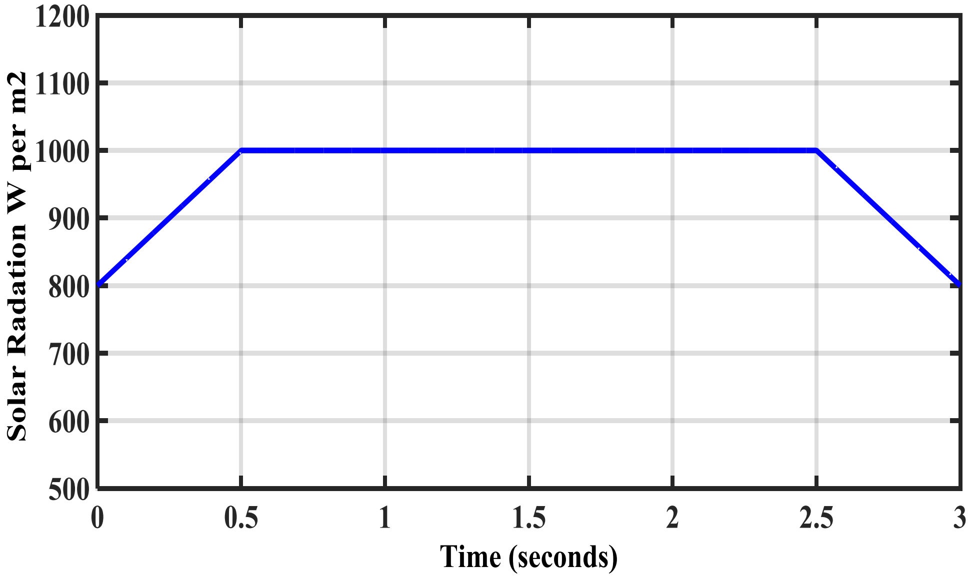


Fig. 11: The performance of solar radiation with time.

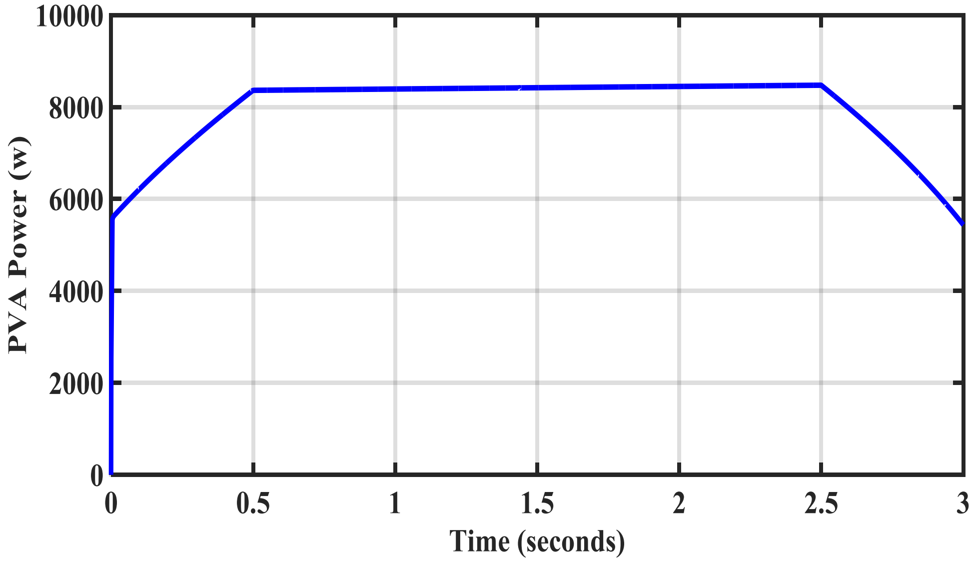


Fig. 12: The performance of the PVA power with time.

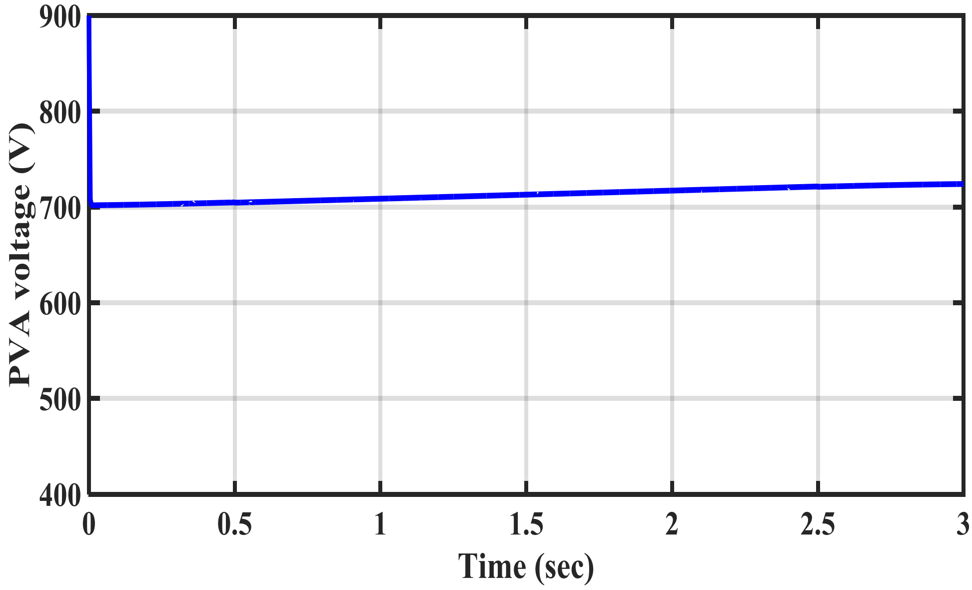


Fig. 13: The performance of the PVA voltage with time.

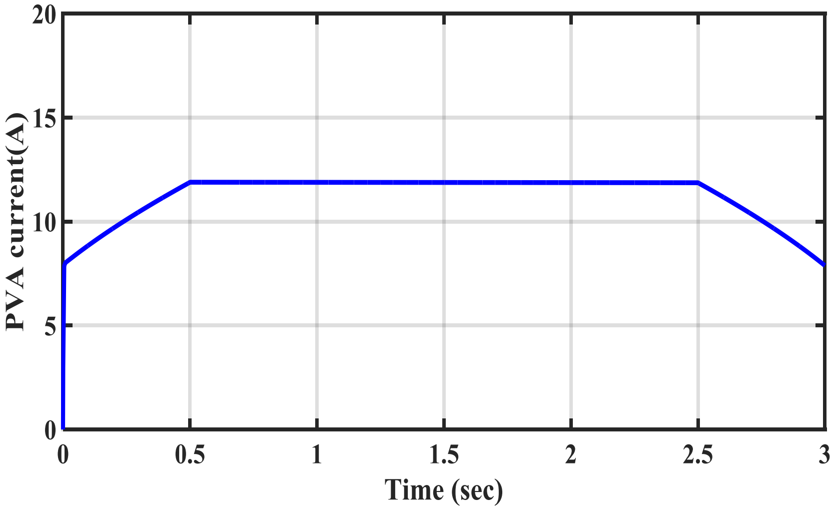


Fig. 14: The performance of the PVA current with time.

VI. CONCLUSIONS

The present paper has provided a detailed investigation of a PV pumping system with an induction motor load. Through experimental and MATLAB/Simulink simulation results, it has been demonstrated that the proposed system is highly suitable for water pumping. The performance analysis of the system under varying solar radiation conditions was made possible by utilizing the two-diode equivalent circuit model for the PV array, which accurately represents the behavior of the system.The PV pumping system with an induction motor load has been comprehensively analyzed in this study. Both experimental and MATLAB/Simulink simulation results demonstrate that the system is an efficient method for water pumping. The two-diode equivalent circuit model accurately describes the system's characteristics under various solar radiation conditions. By utilizing the MPPT controller, the maximum power point of the PV array can be tracked, leading to increased system efficiency. The analysis of the induction motor load and centrifugal pump performance confirms that the system can deliver the necessary water flow rate. The experimental results are in agreement, demonstrating the stability of the system with the controller. The results indicate that as PV radiation rises, the system's electrical energy and water flow rate also increase. Overall, the study confirms that PV energy is a sustainable and efficient solution for water pumping in remote or abandoned locations. The focus of the study was to improve the pumping system, and the results demonstrate its effectiveness in water pumping applications.

REFERENCES

[1]. M. Gasque et al., "Energy Efficiency Optimization in Battery-Based Photovoltaic Pumping Schemes," in IEEE Access, vol. 10, pp. 54064-54078, 2022.

[2]. S. Orts-Grau et al., "Photovoltaic Water Pumping: Comparison Between Direct and Lithium Battery Solutions," in IEEE Access, vol. 9, pp. 101147-101163, 2021.

[3]. S. Meunier et al., "Sensitivity Analysis of Photovoltaic Pumping Systems for Domestic Water Supply," in IEEE Transactions on Industry Applications, vol. 56, no. 6, pp. 6734-6743, Nov.-Dec. 2020.

[4]. M. E. Ropp and S. Gonzalez, “Development of a MATLAB/Simulink model of a single-phase grid-connected photovoltaic system,” IEEE Trans. Energy Convers, vol. 24, pp. 195-202, March 2009.

[5]. Y. Mahmoud and H. H. Zeineldin, “A simple approach to modeling and simulation of photovoltaic modules,”IEEE Trans. Sustainable Energy, vol. 3, no. 1, pp. 185 – 186, January 2012.

[6]. M. Akbaba, “Matching induction motors to PVG for maximum power transfer,” Renewable Energy, pp.31-38, 2007.

[7]. Z. A. Firatoglu and B. Yesilata, “New approaches on the optimization of directly coupled PV pumping systems,” Solar Energy, vol. 77, pp. 81–93, 2004.

[8]. A.A. Ghoneim, “Design optimization of photovoltaic powered water pumping systems,” Energy Conversion andManagement, vol. 47, pp. 1449–1463, 2006.

[9]. A Betka, A. Moussi, “Performance optimization of a photovoltaic induction motor pumping system,” Renewable Energy, vol. 29, pp. 2167–2181, 2004.

[10]. N. K. Jain, “Singh Steady and transient characteristics of a single stage PV water pumping system,” Energy Systems, 05 Dec 2014**..**

[11]. A. Dauda, and M. M. Mahmoud, “Solar powered induction motor-driven water pump operating on a desert well, simulation and field tests,” Renewable Energy, pp. 701-714, 2005.

[12]. M. Arrouf, N. Bouguechal, “Vector control of an induction motor fed by a photovoltaic generator,” Applied Energy, vol. 74, pp. 159–167, 2003.

[13]. M. A. S. Masoum, H. Dehbonei, and E. F. Fuchs, “Theoretical and experimental analyses of photovoltaic systems with voltage and current based maximum power-point tracking,” IEEE Trans. Energy Convers., Vol. 17, No. 4, pp. 514–522, Dec. 2002.

[14]. A. A. Elbaset, H. Ali and M. Abd-ElSattar, “Novel seven-parameter model for photovoltaic modules,” Solar Energy Materials and Solar Cells, vol. 130, pp. 442–455, November 2014.

[15]. J. Dancker, P. D. Martinez and M. Wolter, "Impact of Heat Pumps, Rooftop PV, and Hydrogen Blending on Gas-Electricity Distribution Networks in Northeast US," in IEEE Access, vol. 11, pp. 12963-12972, 2023.

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