aPerformance Evaluation of a Solar-Powered Pumping System Using MPPT Technology Under Desert Climatic Conditions

Ali Hussein Al-Safaar[1*]

[1] Department of Horticulture and Landscape Engineering, College of Agriculture, University of Karbala, Iraq

[1]Corresponding author's email: ali.husseinali@uokerbala.edu.iq

Abstract

This study was conducted to investigate the operational response of a solar-powered water pumping system under desert climatic conditions in Karbala Province and how the type of control system and solar radiation level may affect system performance and efficiency. The field experiment was carried out at the desert farm of the Agricultural Extension Center, 20 km southeast of Karbala city, using a solar-powered pumping system that included photovoltaic panels and a multistage submersible pump of approximately 2 hp installed in a well with a depth of about 20 m.

The research work had two factors, the type of control system having 2 levels (C1: conventional operation & C2: or using Maximum Power Point Tracking (MPPT) technology) and three levels for solar radiation intensity classified as low, medium and high.

System performance was investigated, and measured values of voltage, electric current, water discharge rate and system efficiency were compared. The findings indicated that all measurements improved with the MPPT- based control system in comparison to the conventional operating system. Maximum voltage was 228 V, peak current 9·8 A and highest water discharge rate was 34·8 L min^{-1}. The system efficiency reached the highest level of 82.4% when the MPPT control system under with high solar radiation conditions. The results also showed that increasing solar radiation intensity improved overall system performance.

The results from the present study indicate that the application of MPPT-based control systems could potentially increase solar-powered agricultural pumping system performance and lead to operational efficiency under existing climatic conditions (arid and semi-arid regions).

Keywords: Solar water pumping system، Maximum Power Point Tracking (MPPT)، Photovoltaic energy.

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Introduction

Like any other sector, the agricultural sector is getting affected and it needs alternative and sustainable sources of energy to operate the irrigation systems due to increasing petrol costs globally and no electricity supply in some rural areas. Solar energy is one of the most promising renewable energy sources for countries with a desert climate such as Iraq because of its high availability of Solar radiation and it relatively low long-term operating costs. Thus, photovoltaic energy has been an adequate alternative for supplying water pumps in agricultural irrigation systems.

Although solar-powered pumping systems provide multiple benefits, their performance is predominantly affected by continuous variations in the intensity of solar radiation and ambient temperature operating during daytime, which can alter both pump working state and water pumping performance. Moreover, certain conventional control systems may lead to partial loss of available energy with relatively lower-expecting response initially which resulting inefficient qualification of photovoltaic panel output especially in rapidly changing climatic conditions.

Consequently, many recent studies have focused on developing advanced control and energy management strategies to improve the efficiency and stability of solar pumping systems under variable operating conditions.

Based on this information, one of the topics explored was the operation of a water pumping system based on photovoltaic panels and battery storage performing multiple tasks using an advanced controller supported by a Water Cycle Algorithm (WCA) [3]. Apart from the improved pump system stability and reduction of fluctuation during operation relative to classical control methods, their results showed a high-efficiency pump under variable solar radiation conditions.

Likewise, [8] introduced a hybrid control system using fuzzy logic along with (IncCond) technique inside MPPT algorithms. Simulation findings through this study show that under intermittent solar radiation conditions, pump performance can be enhanced; hence the system can be operated more appropriately in desert areas.

Furthermore, [5] modeled a solar pumping strategy with MATLAB/Simulink and optimized various case studies using HOMER software. The results emphasized the critical role of simulation tools in minimizing energy losses and enhancing the efficiency of both operational and economic systems.

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[4] presented an efficient energy management strategy for a standalone photovoltaic-battery water pumping system wherein a novel enhanced Perturb and Observe algorithm is applied to reduce the efficiency loss created under modified solar radiation or battery state variation.

Moreover, advanced control strategies for solar powered water pumps also promises to improve operational performance and system efficiency as per [10]. Similarly, [1] tested a pump driven by a DC shunt motor and controlled by the fuzzy logic algorithm to show that the response speed improved and delay was less than conventional control techniques.

According to a review undertaken recently [7], most of the recent contributions focused on finding superior control strategies and energy management techniques in solar pumping systems, emphasizing the use of intelligent control technologies and high-efficiency motors in order to improve system performance. Moreover, [16] proposed a real world solar water pumping model based on energy optimization strategy and demonstrated stable system performance over varied operating factors.

Similarly, [13] highlighted that the latest advancement in solar water pumping systems highly relies on incorporating suitable smart control methodologies, sensors and various motor arrangements to enhance system performance and energy consumption efficiency. Similarly, [11] validated the ability of Incremental Conductance in maximum power point tracking fusing with photovoltaic system efficiency. At the same time, [15] effectively tested some IoT technologies for mobile applications to remotely control solar-powered water pumps, also supporting flexible and smart irrigation systems. Further, [14] argued the significance of adopting intelligent technologies and advanced control systems for enhancing agricultural system sustainability and minimizing losses in operation, especially for renewable energy sources.

However, most previous studies focused mainly on simulations or controlled conditions.

Despite the progress achieved in solar-powered pumping systems, limited information is still available regarding their performance under actual desert field conditions. Therefore, this study aimed to experimentally evaluate the performance of a solar-powered pumping system under different control systems and solar radiation levels under actual field conditions.

Material and Methods

Experimental Site

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The field experiments were also performed on the desert farm of Agricultural Extension Center, 20 km southeast of Karbala Province. Most months of the year are characterized by high average temperatures and higher levels of solar radiation intensity, which makes use in agriculture of a solar-powered pumping systems more suitable. Also, there is a semi-arid area with limited access to conventional energy sources, making the use of renewable energy sources important for operating agricultural irrigation systems.

Solar-Powered Pumping System

The pumping system in this study was composed of four monocrystalline photovoltaic panels, each with a rated power of 550 W, providing an electrical energy total capacity of 2200 W connected to supply the electric energy needed for functioning the pumping system. Such photovoltaic panel was chosen due to its suitability for desert operating conditions, mainly higher efficiency and ability to operate under high temperatures.

A suitable multistage submersible pump of approximately 2 hp was installed in a 20 m deep well and connected to the photovoltaic system for water lifting and delivery to an irrigation storage tank.

Furthermore, a Maximum Power Point Tracking (MPPT) solar controller was integrated into the system to maximize the power output of all PV panels and ensure adequate voltage and current levels during operation. The control system has been applied to achieve better pump efficiency and reduced energy losses during times with low solar radiation levels or while the speed of photovoltaic (PV) source varies in magnitude.

Control System Design and Operation

A solar controller with MPPT technology was used to regulate power transfer between the photovoltaic panels and the electric motor of a pump. This methodology provides continuous monitoring of maximum power point from photovoltaic panels to enhance the solar energy utilization under a variety of operational conditions, thus improving overall system efficiency and reducing energy losses.

During daytime operation, the controller regulated the voltage and current supplied to the motor according to the available solar radiation intensity to match the available operating conditions. This aided in minimizing the fluctuations during pumping and enhancing water discharge performance, especially under changing solar radiation levels or high ambient temperature.

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Furthermore, the pumping system was connected with measuring devices to track various electrical and hydraulic parameters during operation to assess the performance of the system under true field conditions. The measurements included voltage and current meters, solar radiation meter and volumetric-time method for water discharge measurement.

Experimental Procedure

A field experiment was conducted to evaluate a solar-powered pumping system under different operating conditions. during the summer season at the desert farm of the Agricultural Extension Center in Karbala Province.

The study is based on making comparisons between the effects of control system type and solar radiation levels.

The experiment included two main factors:

First factor: Control system type
This factor included two levels:

C1: Operation using a conventional controller.
C2: Operation using a controller equipped with Maximum Power Point Tracking (MPPT) technology.

Second factor: Solar radiation level
This variable was categorized into three levels based on daily operating periods as follows:

S1: Low solar radiation (<500 W/m²), representing morning conditions.
S2: Medium solar radiation (500–800 W/m²), representing periods before and after noon.
S3: High solar radiation (>800 W/m²), representing midday conditions.

The experimental treatment combinations resulting from the interaction between the two study factors are shown in Table (1).

Control system type and solar radiation levels as the studied background variables in this experiment were organized through factorial experiment design. Measurements were repeated over several operating days to reduce the effect of daily environmental variations on the recorded values.

The pumping system was operated during the day using just the electricity from the PV panels; no battery storage was used. System performance was monitored from 8:00 a.m. to 4:00 p.m., and samples were taken continuously during operation.

Studied Parameters

The performance of the solar-powered pumping system was evaluated based on several electrical and hydraulic parameters, including:

1. **Voltage**
   To monitor the voltage supplied to the motor during operation.
2. **Current**
   To monitor variations in electrical load during different operating periods.
3. **Water Discharge**
   To determine the water discharge rate per unit time.

The water discharge rate was calculated by measuring the volume of pumped water during a specified time interval according to the following equation:

$$Q = \frac{Vw}{t} \quad ……….1$$

Where:

• Q = Water discharge rate (L min^{-1})
• Vw = Volume of pumped water (L)
• t = Pumping time (min)

4. **System Efficiency**
   To evaluate the efficiency of solar energy utilization in operating the pumping system.

System efficiency was calculated based on the relationship between the hydraulic output power and the electrical input power supplied to the system according to the following equation:

$$\eta = \frac{\text{Pout}}{\text{Pin}} \times 100 \quad ……..2$$

Where:

η = System efficiency (%)
Pout = Hydraulic output power (W)
Pin = Electrical input power supplied to the system

The hydraulic power was calculated according to the following equation:

$$Pout = \rho g Q H \quad …….. 3$$

Where:

Pout = Hydraulic output power (W)
ρ = Water density (kg/m^3)
g = Gravitational acceleration (m/s^2)
Q = Water discharge rate (m^3/s)
H = Total pumping head (m)

Water discharge values were converted to m^3/s before hydraulic power calculation.

Solar radiation intensity and ambient air temperature were also recorded throughout the experimental period to monitor operating conditions and interpret any variations that might occur in system performance during different daytime hours.

Results and Discussion

Effect of Control System Type and Solar Radiation Level on the Voltage of the Pumping System

As presented in Table (2), the results indicate how solar radiation intensity and control system type affects the voltage values of a solar-powered pumping system. The results showed

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clear differences between control systems under different solar radiation levels.

The highest value of voltage was obtained under the interaction of MPPT control system and high solar radiation level (C2×S3) of 228 V, while the lowest value was under conventional control system with low solar radiation level (C1×S1) of 168 V.

As solar radiation intensity increased, voltage values also increased for both control systems due to the better electrical behavior of photovoltaic panels, and by extending the available energy for operation.

These results are similar with a study by [12] in which they proved that as the intensity of solar radiation at any location increases, it helps to improve the performance of photovoltaic systems and also increase the efficiency of operation of solar-powered pumping systems due to the large amount of energy produced by photovoltaic panels during periods with high values.

Effect of Control System Type and Solar Radiation Level on the Electric Current of the Pumping System

The results presented in Table (3) revealed a clear effect of both control system type and solar radiation level on the electric current values of the solar-powered pumping system. The electric current values increased gradually with increasing solar radiation intensity in both control systems due to the increase in electrical energy generated by the photovoltaic panels during daytime operation.

The highest current value was recorded under the interaction between the MPPT-based control system and high solar radiation level (C2×S3), reaching 9.8 A, whereas the lowest current value was observed under the interaction between the conventional control system and low solar radiation level (C1×S1), reaching 5.9 A. The results also showed that the use of an MPPT controller contributed to improving current output compared with the conventional operating system under all solar radiation levels.

This may be attributed to the ability of the MPPT system to improve the utilization of available solar energy under different operating conditions, which contributed to maintaining more stable current output and reducing fluctuations during operation. This was reflected in improved system operating efficiency and reduced electrical losses associated with changing climatic conditions. Furthermore, increasing solar radiation intensity naturally increases the amount of energy received by the photovoltaic panels, thereby increasing the current supplied to the pumping unit.

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These findings agree with those reported by [2], who indicated that the use of Maximum Power Point Tracking (MPPT) techniques contributes to improving photovoltaic system performance and enhancing the utilization efficiency of available energy, which directly improves electric current characteristics and reduces energy losses under variable operating conditions..

Effect of Control System Type and Solar Radiation Level on Water Discharge Rate of the Pumping System

The results presented in Table (4) showed that the impacts of control system type and solar radiation level along with their interaction were clearly demonstrated in the water discharge rate of the solar-powered pumping system. In both systems the discharge rate increased progressively with higher solar radiation intensities, which resulted from more electrical energy supplied to the pump and better performance of pump operation at daytime.

The highest water discharge rate (34.84 L min^{-1}) was recorded with the interaction of MPPT -based control system and high solar radiation level (C2×S3), while the lowest water discharge rate (20.62 L min^{-1}) was recorded under the interaction between the conventional control system and low solar radiation level (C1×S1) The findings also revealed that the application of an MPPT controller had a noticeable effect on water discharge rate at all solar irradiance levels compared to the conventional operating system.

The difference could be due to high utilization of solar energy during MPPT operation, enabling better pump performance and increase in water discharge rate. Moreover, the increased operational power resulted in a more pronounced rotation of the motor and facilitated water flow into the storage tank.

These results are consistent with those reported by [6] who reported that a better energy management in solar pumping leads to achieve better pump operating efficiency and pumped water quantity, especially for irrigation periods associated high solar radiation what provides sufficient operating power during irrigation operation.

Influence of the Control System Type and Level of Solar Radiation on Pumping System Efficiency

The results presented in Table (5) **revealed that the performance of the pumping system was strongly influenced by both control system type and actual solar radiation level operating during testing. As solar radiation intensity increased, the system efficiency improved gradually; however, the improvement was more obvious with the MPPT-based control**

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system than that with the conventional operating system.

The interaction between the MPPT control system and high solar radiation level (C2×S3) showed the highest system efficiency with 82.4%, while the lowest efficiency value **was obtained from interaction between the conventional control system and low solar radiation level (C1×S1)** reaching **61.7%. These results show that the variation in voltage and current produced by a photovoltaic system helps to improve efficiency of operating with pump, thanks to reducing energy losses.** The use of **the MPPT-based control system to allow the pumping system to** operate near the maximum power point **during different operating periods, which improved solar energy utilization and maximized solar-to-useful power conversion efficiency for water pumping.**

These results are consistent with the findings reported by [9], who noted that Maximum Power Point Tracking (MPPT) techniques increase the efficiency of photovoltaic systems, improve the operational efficiency of renewable-based systems and reduce energy losses; These MPPT techniques **extract more power from photovoltaic panels** than conventional control systems **thus improving the performance of solar-powered pumping system under variable conditions.**

Table (1). Experimental design and treatment combinations

Treatment	**Control system type**	**Solar radiation level**
T1	Conventional control (C1)	Low radiation (S1)
T2	Conventional control (C1)	Medium radiation (S2)
T3	Conventional control (C1)	High radiation (S3)
T4	MPPT-based control (C2)	Low radiation (S1)
T5	MPPT-based control (C2)	Medium radiation (S2)
T6	MPPT-based control (C2)	High radiation (S3)

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Table (2). Effect of control system type and solar radiation level on voltage (V)

Solar radiation level	Conventional control (C1)	MPPT-based control (C2)
S1 : Low radiation (<500 W/m²)	168	182
S2: Medium radiation (500–800 W/m²)	191	208
S3: High radiation (>800 W/m²)	214	228

Table (3). Effect of control system type and solar radiation level on electric current (A)

Solar radiation level	Conventional control (C1)	MPPT-based control (C2)
S1 : Low radiation (<500 W/m²)	5.9	6.8
S2: Medium radiation (500–800 W/m²)	7.4	8.5
S3: High radiation (>800 W/m²)	8.6	9.8

Table (4). Effect of control system type and solar radiation level on water discharge rate (L/min)

Solar radiation level	Conventional control (C1)	MPPT-based control (C2)
S1 : Low radiation (<500 W/m²)	20.62	24.33
S2: Medium radiation (500–800 W/m²)	26.81	30.92
S3: High radiation (>800 W/m²)	31.51	34.84

Table (5). Effect of control system type and solar radiation level on system efficiency (%)

Solar radiation level	Conventional control (C1)	MPPT-based control (C2)
S1 : Low radiation (<500 W/m²)	61.7	68.9
S2: Medium radiation (500–800 W/m²)	70.8	77.6
S3: High radiation (>800 W/m²)	76.9	82.4

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Conclusion

1. The solar-powered pumping system showed satisfactory performance under desert climatic conditions. The use of the MPPT controller contributed to improving voltage and current performance, increasing water discharge rate, and enhancing overall system efficiency compared with conventional operation.
2. Increasing solar radiation intensity improved the performance of the pumping system. The best operating results were achieved under the interaction between the MPPT-based control system and high solar radiation conditions, indicating the suitability of solar-powered pumping systems for agricultural applications in arid and semi-arid regions.

Recommendations

1. The use of MPPT-based control systems is recommended in solar-powered agricultural pumping systems because of their role in improving operational efficiency and enhancing pump performance under fluctuating solar radiation conditions.
2. Further studies are recommended to evaluate the performance of solar-powered pumping systems using different pump types and control methods, with particular attention to the effect of different climatic conditions on operating efficiency in Iraqi desert environments.

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