Design of a PV-Fed Drive System with a Single-Phase Induction Motor for Irrigation Application

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Abstract. This paper presents the design, implementation, and performance evaluation of a photovoltaic (PV)-fed drive system with a single-phase induction motor for irrigation applications. The study focuses on a built hardware setup and strategy to achieve objectives, the setup is consisting of two $100\ W$ solar panels, a $10\ A$ charge controller, a $12\ V$ battery, a $700\ W$ DC to AC inverter, a step-up transformer $12\ V$ DC to $230\ V$, and a single-phase pump coupled with a motor of $0.5\ HP$ $(0.37\ kW)$. The paper discusses the design considerations, system configuration, control strategy, and the efficiency of the PV-fed motor for irrigation purposes. The findings demonstrate the feasibility and effectiveness of using solar energy to power irrigation systems, showcasing the potential for sustainable and energy-efficient agricultural practices.

Keywords: Water Pump Motor, PV panels, inverter, PWM, Solar energy.

1. Introduction

Over the last few years, the increasing demand for sustainable and energy-efficient solutions in various sectors, including agriculture, has been observed. Sustainable agriculture aims to promote environmental friendly and resource-efficient farming practices to ensure long-term food security while minimizing negative impacts on ecosystems and natural resources [1]. Irrigation plays a crucial role in ensuring optimal crop growth and productivity. However, traditional irrigation methods often rely on fossil fuel-based power sources, leading to environmental pollution and rising energy costs. Subsequently, the researchers are involved in harnessing renewable energy, especially solar power, in order to meet the energy needs of irrigation systems [2].

This research aims to explore the feasibility and effectiveness of utilizing solar energy in powering the irrigation process, thereby reducing dependency on conventional power sources and promoting sustainability. The specific research objectives include:

1) To design and implement a PV-fed system with a single-phase induction motor specifically tailored for irrigation applications. The scope of the study encompasses the design considerations, system configuration, control strategy, and performance evaluation of the PV-fed motor coupled with water pump.

2) To demonstrate a control strategy to ensure efficient operation and optimal performance of the PV-fed system.
3) Evaluating the system's efficiency, power output, energy harvesting capabilities, and its ability to meet the irrigation requirements.

It is important to note that while this research project focuses on a specific hardware setup. However, the findings and principles discussed in this paper can be extrapolated to similar PV-fed systems, with varying configurations and components. The study provides an insight to the understanding of utilizing renewable type of energy sources for irrigation applications and to promote sustainable practices in the agricultural sector. It also helps to address the environmental challenges associated with conventional power sources in irrigation systems.

A comparison of the proposed method with the approaches discussed in literature review related to the described application is shown in Table I.

Table 1. Related Literature Review

Authors (Year)	Strategy / Application	Drawbacks
Belfer and Magalhães (2016) [10]	Sustainable Agriculture	Lack of implementation over solar energy based irrigation system
Al-Jarrah et al. (2019) [11]	Provide a review of solar energy application for irrigation in Jordan	The specific details on the motor and pump setup or compare alternative methods are not provided.
Ghaznavi et al. (2014) [12]	Review photovoltaic technologies	The direct addressing to irrigation systems or motor and pump setups is absent.
Daliento et al. (2015) [13]	Discuss the design-oriented assessment of photovoltaic panel orientation for energy capture	The efficiency enhancement strategy is not in agreement with the specific hardware implementation.

In summary, the presented method stands out by providing a comprehensive approach that combines specific hardware components to create an efficient solar-powered irrigation system. It addresses the practical implementation of sustainable agriculture by utilizing renewable energy sources and optimizing water delivery for irrigation purposes. This descriptive analysis provides a comprehensive overview of the software and hardware components, enhancing understanding of their functionality, strengths, and weaknesses. It establishes a foundation for a literature review by highlighting key aspects to explore in similar projects or research in the field.

2. System Design and configurations

This section confers the design and configurations of the proposed system. The overall schematic diagram of the system has been shown in Fig. 1 (Table 1.1). The system consists of PV panels, controllers, battery, inverter and the motor.

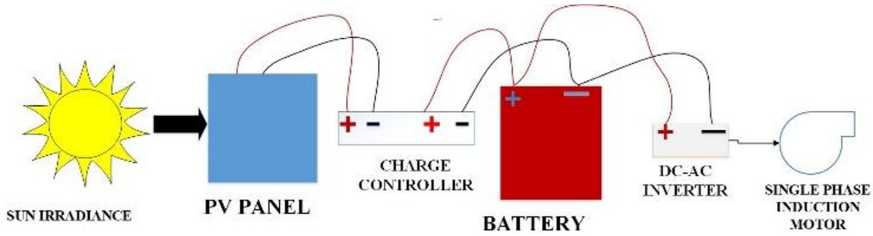

Fig. 1. Wiring diagram of the implemented system

Table 2. List of components and respective ratings

Component Name	Ratings
2 PV Panels	100 W (each)
Solar charge controller	10 A
Battery	12 V
Dc to Ac Inverter	12 V Dc to 12 V Ac
Step Up transformer	700 W
Monoblock Pump	373

2.1 Photovoltaic Panels

The selection and specifications of PV panels are paramount in determining the overall performance of PV-fed systems [3]. Factors such as efficiency, power rating, and durability are considered when choosing the panels. In this project, two solar panels with a power rating of $100\ W$ each are selected. The full parameters specification is mentioned on Table II.
The 2 PV panels are connected in parallel to the charge controller using appropriate wiring and connectors. The PV panels utilized in this work are represented in Fig. 2 (a). A wiring diagram is followed to ensure correct connections and prevent any electrical losses or mismatched voltages. The maximum power point tracking (MPPT), Incremental Conductance Technique is integrated into the charge controller allows it to optimize the power output of the PV panels by tracking the maximum power point under varying sunlight conditions.

Table 3. Specifications of Solar panels

Solar Panel Parameters (Sun-fuel Technologies Model No. SFTI 36P 100W)	
Maximum Power (P_{max})	$100\ W$
Maximum Power voltage (V_{mp})	$18.51\ V$
Maximum Power Current (I_{mp})	$5.41\ A$
Short Circuit current (I_{sc})	$5.89\ A$
Open Circuit voltage (V_{oc})	$21.78V$

2.2 Placement and Orientation

The placement and orientation of the PV panels are essential for optimizing solar energy capture [4]. Factors such as the angle of inclination, azimuth orientation, and shading effects are taken into account to ensure maximum sunlight exposure and energy generation. The panels were placed in a rooftop with $35\ degrees$ from the horizontal.

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2.3 Charge Controller

The charging procedure of battery is regulated by the charge controller. It is carried out by controlling the flow of current from the PV panels. It ensures proper charging and prevents overcharging or deep discharging conditions of battery. The charge controller has the rating of $10\ A$.

The charge controller, (Fig. 2(b)), used in the system, has the function of monitoring the battery voltage, controlling the charging current, and providing protection against overcharging, over-discharging, and short circuits. It may also incorporate maximum power point tracking (MPPT) technology to maximize the power output of the PV panels.

(a) (b)

Fig. 2. (a) Solar Panels used in the implementation of the project (b) Solar Charge Controller

2.4 Battery Bank

The battery serves as an energy storage component in the PV-fed system, providing power during periods of low sunlight or during the night. Batteries play a vital role in solar-powered irrigation systems by storing excess energy generated by the solar panels during the day and providing power during non-sunlight hours, ensuring continuous operation and increased self-sufficiency [5]. In this system we have used a $12\ V$ battery pack, as represented in Fig. 3 (a).

2.5 Single-Phase Induction Motor and Pump

The single-phase induction motor (Fig. 3 (b)) is responsible for driving the irrigation pump, providing the necessary mechanical energy to deliver water for irrigation purposes. Integration of the motor with the pump and hydraulic considerations are vital for efficient and reliable operation. The ratings of the motor pump are: $0.5\ HP\ /\ 0.37kW$ Single Phase Water Pump, Operating Voltage, Current ratings: $220\ V, 2.8\ A\ and\ 2850\ rpm$.

The selection of a single-phase induction motor for irrigation purposes requires careful consideration of various factors such as motor power, efficiency, starting torque, and reliability. These considerations ensure that the motor is suitable for the specific irrigation system requirements, providing efficient and reliable operation [6].

2.6 DC to AC Converter

Inverter selection and sizing are critical to tone with the power demands of the irrigation system and maximize energy conversion efficiency [7]. The inverter (Fig. 3 (c)), converts the DC power produced by the PV panels and stored in the battery.

The $12\ V$ DC power reserved in the battery is converted to $220\ V$ AC power using the DC to AC converter. The converter is configured and operated between $100\ V - 300\ V$ and $50\ Hz$ frequency for the single-phase induction pump motor. PWM is maintained to ensure the motor operates within its specified voltage range.

The inverter used in the system has a power rating of $700\ W$ which is compatible with the motor's power requirements that is $373\ W$. Pulse width modulation (PWM) topology was employed based on the specific system requirements.

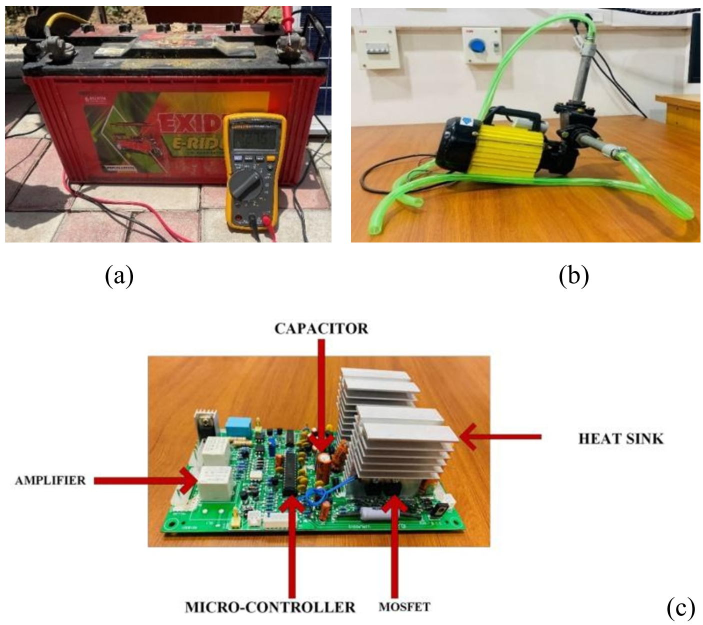

Fig. 3 (a) Battery Bank utilized in the system, (b) Single Phase AC Water Motor Pump, (c) DC to AC Inverter PCB (Some major components are labelled)

3. Hardware Setup Implementation

In this section, the implementation of the proposed system is presented. The overall system used in the laboratory set-up is shown in Fig. 4. During the implementation, several factors are considered, especially when dealing with different conditions on different days. Some aspects are: Solar panel placement, water source and storage, identifying a reliable water source and ensuring an efficient storage system are essential. The system was implemented in both sunny and shading conditions in different days. The most important things that need to be taken care during implementations is personal safety, and isolating all the open wires. Also check the output voltage and current of inverter to avoid overload to the system.
The challenges faced during implementation were the varying weather patterns, as adapting the system to these specific conditions requires careful planning and customization.

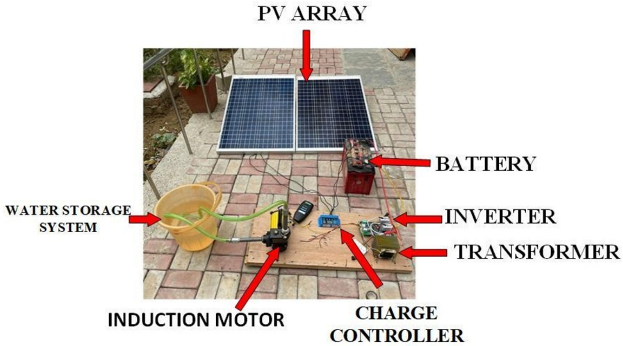

Fig. 4. Implementation of the overall system

Once the solar irrigation system was connected and operational, the initial response was observed through observations. The energy generation by monitoring the solar panel's power output can indicate if it is generating sufficient energy to power the irrigation system.

4. Analysis outcomes and discussions

The proposed hardware system was designed and implemented in Electrical Engineering Department, Delhi Technological University, Delhi, India. The daily irradiance values of the area, during May, are around 6 to 7 kW/m^2 and an average temperature of $40°C$ and $13.5\ h$ of daily length in hours of sunlight [8-9].

4.1 Analysis at irradiance level of 7.1 $\mathrm{kW/m^2}$

Initially, in a sunny condition, total voltage of $19.51\ V$ is obtained from each Solar panel. The currents obtained from one solar panel is $2.0\ A$ and from second panel is $2.3\ A$. As the panels are connected in parallel, the voltage is maintained at 18 V and the current is measured as $5.3\ A$. The solar panels are connected to the charge controller which controls the voltage and drops it to around $12.9\ V$, the voltage drop is due to the charge controller which prevents the battery from overcharging. This voltage charges the battery system. Hence, the battery obtains $12.65\ V$ DC on its terminals, as presented in Fig. 5 (a).
The output voltage from battery is $12.65\ V$ and $5.3\ A$ current, these values are same as the inverter input. Using PWM technique, the inverter converts the $12.65\ V$ DC to $12.65\ V\ rms$ AC. The single-phase inverter, with current rating of $1.6\ A$, is connected with a step-up transformer which boosts the voltage level from $\sim 12\ V$ AC to $\sim 230\ V$ AC. The output voltage from the inverter terminals is 230 V AC.
This voltage is supplied to the motor pump, which pumps the water and irrigates.

The overall load current of the system is given by Equation (1):

$$I = \frac{P}{V} \tag{1}$$

Where, P is the output power from the motor, and V is the battery terminal voltage. Hence, the calculated current is 31 A. The measured total current of the system was 37.3 A (Fig 5 (b)) due to occurrence of voltage dips in the system as a result of losses.

(a)

(b)

Fig. 5 (a) Battery Output terminals (In multi-meter), **(b)** Total Output current of the system

PWM Control Technique is a widely employed method for controlling the speed and power delivery of motor drives. The simple PWM technique implemented in this research involves generating a square wave signal with varying duty cycles. The inverter controls the width of the pulses, determining the average voltage supplied to the motor. By adjusting the duty cycle, the effective voltage can be modulated, allowing for precise control over the motor's speed and torque. It requires minimal complexity of hardware and software, making it suitable for low-power systems like a $700\ W$ inverter driving a single-phase $220\ V$ AC motor pump.

PWM gives the desired square pulses, as presented in Fig. 10. When the inductive load is connected, acting like the motor pump, the square waves shape an inductive form (Fig. 6). After connecting an inductive load such as a motor to the output of the inverter, the inductive characteristics of the load come into play. Inductive loads, by nature, resist changes in current flow. When the square wave voltage transitions from the high level to the low level (or vice versa), the inductive load opposes this change and tends to maintain the current flow. This opposition to changes in current causes the waveform to become more sinusoidal. The inductive load smoothens out the sharp transitions of the square wave and results in a waveform that resembles a sinusoidal waveform.

From the system, it can be seen in Fig.7 (a), that the input current waveform to the inverter is typically a DC current from the solar panel, having amplitude of $2.0\ A$.

The inverter output current waveform, as can be seen in Fig. 7 (a), is square waveform, as we have used PWM technique. It is having RMS value of $1.8\ A$, measured through HIOKI 3288-20 Clamp ON AC/DC HiTester. Some distortions can be seen due to the presence of inductive load, i.e., single phase AC motor.

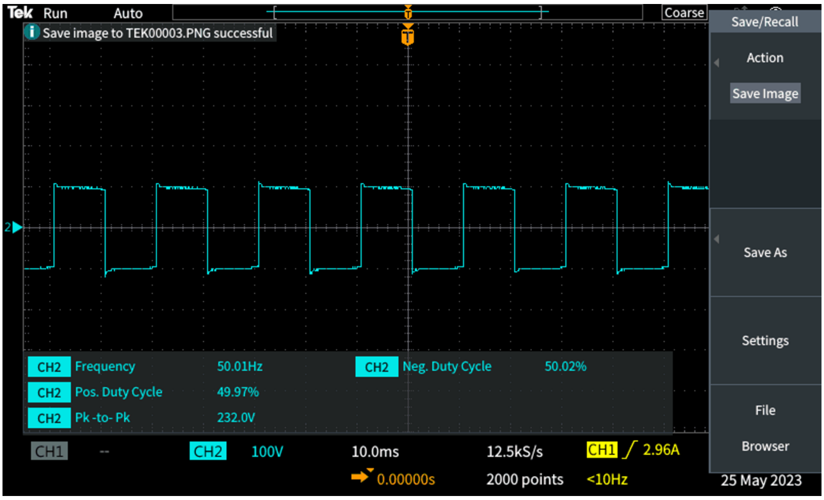

Fig. 6. Inverter Voltage Output waveform with load

A. Analysis at different irradiance levels

This study has been performed in different shading conditions, i.e., temperature and irradiance levels. On a sunny day in month of May irradiance reaches up to 7.1 kW/m^2, and on the same month but with shading conditions irradiance levels can be around 6 kW/m^2. Under partial shading conditions weather, the current from the panel drops up to maximum 20 %.

It was noticed that the motor speed is influenced by the solar irradiance or the intensity of sunlight falling on the solar panels. As the irradiance increases, the motor speed tends to increase and vice-versa, as can be perceived from Fig. 7 (b) (Table 7-b.1).

B. Comparative Analysis of proposed method with conventional methods

A comparative analysis is conducted between the designed PV-Fed system with a single-phase induction motor for irrigation application and conventional systems used for irrigation. The purpose of this analysis is to evaluate the advantages and disadvantages of the designed system in comparison to traditional approaches. It explores how the PV-Fed system outperforms or falls short when compared to conventional systems, which typically rely on fossil fuel-powered pumps or grid electricity. The benefits and limitations of the designed System are represented in Table III.

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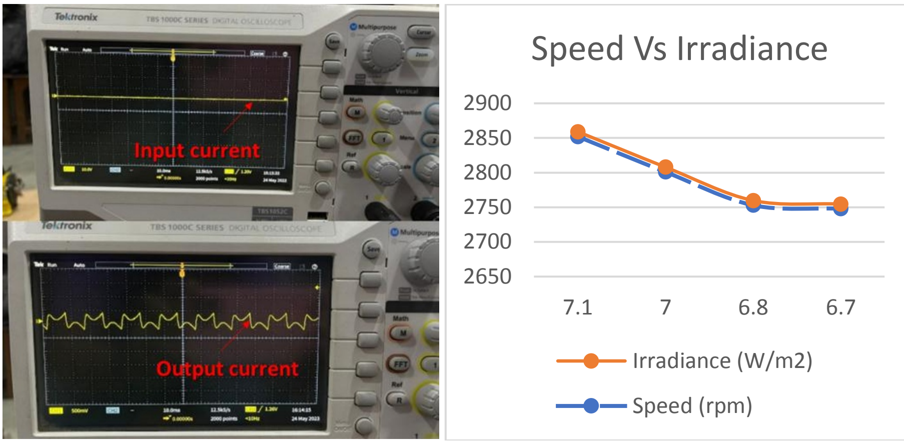

(a) (b)

Fig. 7. (a) Input current of inverter VS Output current of inverter (yellow) waveforms, (b) Speed Vs Irradiance Performance

Table 7-b.1. Comparative Results for variation in Irradiance of Solar Panel with respect to the Motor Speed

Speed (Rpm)	**Irradiance (Kw/m^2)**
2852	7.1
2801	7.0
2753	6.8
2748	6.7

Table 3. Benefits and Limitation of the proposed system over conventional methods

Benefits	**Limitations**
Renewable Energy Utilization: The system harnesses solar energy, which is a clean and renewable resource. It reduces the dependence on non-renewable energy sources and minimizing greenhouse gas emissions.	*Weather Dependency:* The system's performance relies on solar radiation, making it susceptible to variations in weather conditions. It delivers reduced efficiency during cloudy days or at night.
Cost Savings: By utilizing solar power, the system can potentially reduce electricity costs associated with conventional systems, especially in areas with ample sunlight.	*Initial Cost:* The initial investment for installing the PV-Fed system, including solar panels, batteries, and converters, may be higher compared to conventional systems. However, long-term cost savings can outweigh the initial investment.
Environmental Impact: The use of solar energy helps mitigate environmental degradation by reducing carbon footprint and air pollution associated with conventional systems.	*System Maintenance:* Regular maintenance of solar panels, batteries, and other components is necessary to ensure optimal system performance and longevity. Proper maintenance practices need to be implemented to maximize system efficiency.

C. Real time scenario about the yields of the outcome

PV-fed induction motor systems offer a reliable and sustainable solution for irrigation, allowing farmers to optimize water usage, increase crop productivity, and reduce dependency on traditional power sources. In practical scenario the proposed system can be implemented in:

1. *Remote Agricultural Areas:* The presented systems for irrigation can be implemented in remote agricultural areas where grid connectivity is limited or unreliable [14]. These areas often lack access to traditional sources of electricity, making it difficult for farmers to power their irrigation systems. By installing a solar panel array and coupling it with an induction motor, farmers can harness solar energy to operate their irrigation pumps independently of the grid. This enables them to efficiently irrigate their crops and sustain agricultural practices in remote locations without relying on conventional power sources.

2. *Off-Grid Farms:* PV-fed induction motor systems are also suitable for off-grid farms that are not connected to the main electricity grid. In such scenarios, farmers can install solar panels on their farm premises and use the generated solar energy to power an induction motor for irrigation purposes. This eliminates the need for costly diesel generators or the hassle of extending grid lines to the farm. By utilizing solar power, farmers can irrigate their fields effectively and sustainably, reducing operational costs and environmental impact.

5. Conclusion and findings

The research study on the design of a PV-Fed system with a single-phase induction motor for irrigation application has provided valuable insights into the efficiency, power output, irrigation performance, and economic viability of the system. Through a thorough analysis of various aspects, the following conclusions and findings have been derived:

- When there is shading conditions or cloudy days, the initial current from the2 panels connected in parallel drops more than 80% compare to its maximum current output. Only around 20% of the maximum current is used. The 2 panels were connected in parallel and each has 5.41 A as maximum current, ideally the total current would be 10.82 A, but in practice it’s not possible, due to various factors, as panel efficiency as weather conditions. In a sunny day we got 5.41A as total current output and in shading conditions we got only 2.1 A as current output from panels.
- The utilization of a simple PWM technique offers several advantages, including simplicity, cost-effectiveness, energy efficiency, and accurate speed control.
- When inductive loads are connected to the terminals of the inverter, the inductive characteristics of the load come into play, the load smoothers out the sharp transitions of the square wave and results in a waveform that resembles a sinusoidal waveform.
- The PV system demonstrated efficient conversion of solar energy into electrical power, while the motor and pump exhibited good performance in delivering water from a water storing system of 25 litres for irrigation purposes, the water flow rate was around 64 milliliters per minutes (ml/min).

Comparative analysis with conventional systems highlighted the advantages of the PV-Fed system. It also showcased the limitations of the system.

The findings of this research have several practical implications and open up avenues for future research in the field of PV-Fed systems for irrigation applications. The designed system holds promise for sustainable irrigation practices, especially in areas with limited grid access or high reliance on conventional energy sources. The practical implications include: *1. Adoption of Renewable Energy for Irrigation; 2. Improved Efficiency and Performance; 3. Cost Optimization and Affordability; 4. Integration with Smart Technologies*

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