

# Battery-Less Solar Irrigation System for Rural Bangladesh Using Buck–Boost Converter and PID Control

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## ABSTRACT

This study proposes a battery-less solar-powered irrigation system for rural Bangladesh based on a Buck–Boost DC–DC converter and advanced control techniques. Conventional irrigation in rural areas often depends on diesel-driven pumps or battery-supported photovoltaic (PV) systems, leading to increased operational cost, maintenance complexity, and environmental impact. To overcome these limitations, a direct PV-fed DC motor drive without energy storage is developed, ensuring a simpler and more economical solution. The Buck–Boost converter is employed to regulate the fluctuating PV output and provide a stable supply to the irrigation motor under varying solar irradiance and temperature conditions. To enhance system performance, both Proportional Integral (PI) and Proportional Integral Derivative (PID) controllers are implemented for duty cycle control and output stabilization. The proposed system is modeled and analyzed using MATLAB/Simulink to evaluate its dynamic and steady-state behavior. Simulation results indicate that the battery-less configuration can maintain reliable motor operation under variable environmental conditions. Furthermore, comparative analysis reveals that the PID controller achieves superior voltage regulation, faster response, and reduced oscillations compared to the PI controller. The proposed approach offers a cost-effective, low-maintenance, and sustainable irrigation solution suitable for rural agricultural applications in Bangladesh.

**Keywords:** Battery-less solar irrigation; photovoltaic (PV) system; Buck–Boost converter; PID control; solar water pumping; rural electrification; sustainable agriculture.

## INTRODUCTION

The rapid growth in global energy demand, particularly electrical energy, has become a major challenge due to population increase, industrialization, and agricultural expansion. Conventional energy generation based on fossil fuels is no longer sustainable because of its limited availability and its adverse environmental impact, including greenhouse gas emissions and global warming. Therefore, renewable energy sources are being widely explored as sustainable alternatives [1]. Solar energy, among all renewable sources, has emerged as one of the most promising options due to its abundance, availability, and minimal environmental impact [2]. Photovoltaic (PV) systems enable direct conversion of solar energy into electrical energy and have been widely adopted in various applications [3].

In developing countries such as Bangladesh, agriculture is a key sector where irrigation plays a crucial role in crop production. Traditionally, irrigation systems rely on diesel-powered pumps, which are expensive and environmentally harmful. Solar-powered irrigation systems have been introduced

as an alternative; however, many of these systems depend on battery storage, which increases system cost, maintenance requirements, and reduces reliability [4]. Recent studies have shown that solar PV-based irrigation systems can provide a sustainable solution for rural areas by reducing dependency on fossil fuels [5]. Furthermore, battery-less solar irrigation systems are gaining attention as they eliminate storage components and improve overall system efficiency and cost-effectiveness [6].

The performance of PV systems is highly dependent on environmental conditions such as solar irradiance and temperature, which cause fluctuations in output voltage and current [7]. To address this issue, DC–DC converters are commonly used to regulate and stabilize the output of PV systems [8]. Among various converter topologies, the Buck–Boost converter is particularly advantageous because it can operate in both step-up and step-down modes, making it suitable for handling variable input conditions [9]. Several studies have demonstrated the effectiveness of Buck–Boost converters in PV-based applications due to their flexibility and simple structure [10]. Additionally, optimization and advanced converter designs have been explored to improve efficiency and performance under dynamic conditions [11].

Control strategies are essential for ensuring stable operation of converter-based systems. Proportional Integral (PI) controllers are widely used due to their simplicity and ability to eliminate steady-state error [12]. However, for systems with rapid dynamic changes, Proportional Integral Derivative (PID) controllers provide improved transient response and better stability [13]. Research has shown that PID controllers are more effective in regulating DC motor-driven systems, particularly under varying operating conditions [14]. Further improvements in controller performance have been achieved through modifications and tuning techniques [15].

DC motors are commonly used in solar-powered irrigation systems due to their simple construction, ease of control, and compatibility with PV systems [16]. When integrated with appropriate converter and control mechanisms, DC motors can effectively drive water pumps for irrigation purposes. However, maintaining stable motor performance under fluctuating solar conditions remains a challenge [17]. Various studies have investigated different control strategies and converter configurations to improve system performance and reliability [18].

Moreover, several advanced converter topologies and design approaches have been proposed to enhance efficiency and reduce losses in power electronic systems [19]. Practical design considerations, including component selection and system modeling, play a crucial role in achieving reliable system performance [20]. In addition, earlier works by the authors have explored solar-powered systems, inverter designs, and DC motor control techniques, demonstrating the feasibility and effectiveness of such systems in renewable energy applications [21]. These studies have also highlighted the importance of converter-based control in improving system efficiency [22]. Further research by the authors has focused on solar-powered motor systems and control strategies, providing a strong foundation for the current work [23]. Simulation-based analysis of motor control systems has also been conducted to evaluate performance under different conditions [24]. Additionally, the application of Buck–Boost converters in solar-powered DC motor systems has been previously investigated, confirming their suitability for such applications [25].

Despite these advancements, there remains a need for a simple, cost-effective, and battery-less irrigation system specifically designed for rural areas of Bangladesh. Most existing systems either rely on battery storage or involve complex configurations, making them less suitable for practical deployment. Therefore, this research proposes a battery-less solar-powered irrigation system using a Buck–Boost converter and advanced control techniques to ensure stable and efficient operation under varying environmental conditions.

The main contributions of this work are summarized as follows:

- Development of a battery-less photovoltaic (PV)-based irrigation system suitable for rural Bangladesh
- Design and implementation of a Buck–Boost DC–DC converter for voltage regulation under variable solar conditions
- Application and comparative analysis of PI and PID controllers for improved system stability and performance
- Evaluation of system behavior under varying irradiance and temperature using MATLAB/Simulink simulation
- Demonstration of a cost-effective and sustainable irrigation solution with reduced maintenance and operational complexity

#### LITERATURE REVIEW

Recent studies have extensively explored the application of photovoltaic (PV) systems for irrigation and motor-driven applications. Early work demonstrated the feasibility of solar-powered irrigation systems in rural Bangladesh, highlighting their potential to reduce dependency on conventional energy sources [1]. Commercial guidelines and practical implementations have further supported the use of PV-based water pumping systems for agricultural applications [2]. In addition, battery-less photovoltaic systems have been investigated for standalone applications, showing advantages in terms of reduced system complexity and maintenance requirements [3]. More recent studies have focused on PV-based irrigation systems, emphasizing their sustainability and economic benefits in developing regions [4], [5]. Furthermore, performance analyses of PV-driven DC motor systems have confirmed their suitability for water pumping applications under varying environmental conditions [6].

To improve the efficiency and reliability of PV systems, various DC–DC converter topologies have been proposed. Among these, the Buck–Boost converter has been widely studied due to its ability to regulate output voltage under fluctuating input conditions [10]. Optimization techniques for such converters have also been explored to enhance efficiency and dynamic performance [11]. Advanced converter designs, including high-efficiency and soft-switching configurations, have further improved system performance in renewable energy applications [12], [13]. Additionally, simulation-based studies of converter systems have provided insights into their behavior under different operating conditions [14], while practical design guidelines have been established for implementing such systems effectively [15], [16].

Control strategies play a significant role in ensuring stable operation of PV-driven systems. PI controllers have been widely used due to their simplicity and effectiveness in steady-state regulation [17]. However, PID controllers have been shown to offer improved transient response and better stability in dynamic systems [18]. Comparative studies indicate that PID control provides superior performance in regulating DC motor-driven systems under varying load and input conditions [19]. Moreover, various motor control techniques have been analyzed to enhance the performance of renewable energy-based systems [18].

Several studies have also investigated the integration of converters and control techniques for solar-powered motor systems. Previous research by the authors has contributed to the development of cost-effective solar energy systems, including inverter design, smart grid applications, and DC motor control [20], [21], [22]. Further work has explored the performance of solar-powered DC motor systems using different converter configurations and control strategies [23], [24], [25]. These studies highlight the importance of efficient power conversion and control in achieving reliable system operation.

Despite these advancements, most existing systems either rely on battery storage or involve complex configurations, which increase cost and reduce system reliability. Therefore, there remains a research gap in developing a simple, cost-effective, and battery-less solar irrigation system with efficient converter control suitable for rural applications.

## MATERIALS AND METHODS

The proposed system is a battery-less solar-powered irrigation system designed to directly operate a DC motor-driven water pump using energy harvested from a photovoltaic (PV) array. Unlike conventional solar irrigation systems that rely on battery storage, the presented configuration eliminates intermediate energy storage, thereby reducing system cost, maintenance requirements, and energy losses. This makes the system particularly suitable for rural areas of Bangladesh where affordability and reliability are critical factors.

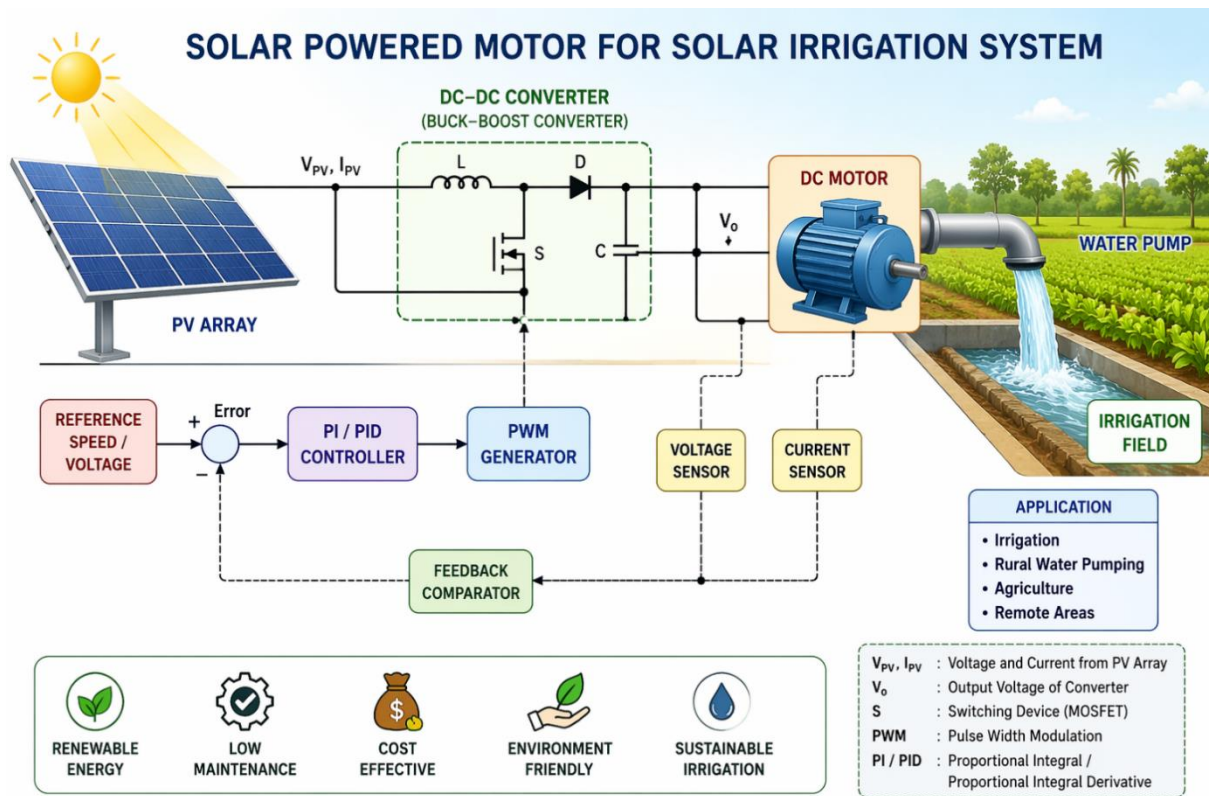
The overall system architecture consists of four major components: a PV array, a Buck–Boost DC–DC converter, a control unit incorporating PI/PID controllers, and a permanent magnet DC motor coupled to a water pumping mechanism. The PV array acts as the primary energy source, converting solar irradiance into electrical energy. However, due to the inherent variability of solar radiation and temperature, the output of the PV array is highly non-linear and fluctuates over time.

To ensure stable operation of the irrigation system, a Buck–Boost converter is employed between the PV array and the motor. The main function of this converter is to regulate the output voltage by either stepping up or stepping down the input voltage depending on the operating conditions. This flexibility allows the system to maintain a consistent voltage level required for the DC motor, even under varying environmental conditions. The converter operates through high-frequency switching using a semiconductor device, enabling efficient energy transfer with minimal losses.

The control unit plays a crucial role in maintaining system stability and performance. A feedback control mechanism is implemented in which the output voltage and current are continuously monitored using appropriate sensors. These measured signals are compared with a reference value to generate an error signal. Based on this error, the PI or PID controller adjusts the duty cycle of the converter through a pulse-width modulation (PWM) generator. This dynamic adjustment ensures that the motor receives a stable and regulated voltage, thereby improving overall system performance.

The DC motor, which serves as the mechanical drive, is directly coupled to a water pump used for irrigation. The motor converts electrical energy into mechanical energy to facilitate water flow from the source to the agricultural field. Since the system operates without battery storage, the motor performance is directly influenced by solar availability; however, the use of an efficient converter and advanced control strategy significantly mitigates fluctuations and ensures smooth operation.

Overall, the proposed system provides a simple, efficient, and sustainable solution for solar irrigation by integrating power conversion and control techniques in a battery-less configuration. The complete block diagram of the system, illustrating the interaction between the PV array, converter, control unit, and motor-pump setup, is presented in **Figure 1**.



**Figure 1** Schematic representation of the PV-based battery-less irrigation system with Buck–Boost converter and feedback control mechanism.

### Photovoltaic (PV) System Modeling

The performance of a photovoltaic (PV) system is strongly influenced by environmental conditions, particularly solar irradiance and operating temperature. In real-world applications, these parameters vary continuously throughout the day, which directly affects the output characteristics of the PV array. Therefore, accurate modeling of the PV system under varying environmental conditions is essential to ensure reliable and stable operation of the proposed irrigation system.

In this study, the irradiance level is varied to represent different solar conditions, while the operating temperature of the PV panels is considered within the range of 25°C to 55°C, reflecting typical climatic conditions in Bangladesh. These variations are incorporated into the simulation model to evaluate the dynamic behavior of the system and to analyze its performance under fluctuating input conditions.

The PV array serves as the primary energy source and consists of multiple PV modules connected to meet the required power demand of the irrigation system. In the proposed configuration, 28 Soltech 1STH-350-WH PV panels are connected in parallel to achieve the desired current capacity suitable for driving the DC motor load. The key electrical parameters of each PV module are as follows:

- Short-circuit current,  $I_{sc} = 9.4 \text{ A}$
- Open-circuit voltage,  $V_{oc} = 51.5 \text{ V}$
- Maximum power voltage,  $V_{mp} = 43 \text{ V}$
- Maximum power current,  $I_{mp} = 8.13 \text{ A}$
- Shunt resistance,  $R_{sh} = 47.96 \text{ } \Omega$
- Series resistance,  $R_s = 0.2282 \text{ } \Omega$

The parallel arrangement of PV modules ensures sufficient current delivery to meet the load requirements of the irrigation motor, while maintaining a suitable voltage level for efficient operation. This configuration also improves system reliability under partial shading and varying irradiance conditions. The generated PV output is then supplied to the Buck–Boost converter, which regulates the voltage to maintain stable operation of the motor-driven irrigation system.

### Control Strategy (PI and PID Controllers)

The control unit plays a crucial role in regulating the output of the Buck–Boost converter and ensuring stable operation of the proposed system. Its primary function is to control the duty cycle of the switching device in the converter so that the output voltage remains within the desired range despite variations in solar irradiance and temperature.

In this study, both manual control and automated feedback control techniques are considered. The automated control approach includes differential, Proportional Integral (PI), and Proportional Integral Derivative (PID) controllers. Among these, PI and PID controllers are primarily implemented due to their effectiveness in maintaining system stability and improving dynamic response. Both controllers are designed using a parallel control structure in discrete-time form.

$$G_{PI}(z) = K_p + K_i \cdot T_s \cdot \frac{1}{z-1} \quad (1)$$

Where:

- $K_p$  is the proportional gain
- $K_i$  is the integral gain
- $T_s$  the sampling time

For this system, the controller parameters are selected as:

- $K_p = 0.5$
- $K_i = 0.5$
- $T_s = 25\text{kHz}$

The PI controller improves steady-state performance by reducing error and ensuring that the output voltage converges to the desired reference value.

To further enhance system performance, a PID controller is employed. The discrete-time transfer function of the PID controller with a filtered derivative term is given by:

$$G_{PID}(z) = K_p + K_i \cdot T_s \cdot \frac{1}{z-1} + \frac{K_d \cdot N}{1 + N \cdot T_s \cdot \frac{1}{z-1}} \quad (2)$$

Where:

- $K_d$  is the derivative gain
- $N$  is the filter coefficient

The selected parameters for the PID controller are:

- $K_p = 0.1$
- $K_i = 0.1$
- $K_d = 0.001$
- $N = 100$
- $T_s = 25\text{kHz}$

The inclusion of the derivative term improves transient response and reduces overshoot, while the filter coefficient ensures noise suppression in the derivative action.

Overall, the PI and PID controllers dynamically adjust the duty cycle of the Buck–Boost converter based on feedback signals, thereby maintaining stable voltage and current levels required for efficient operation of the DC motor-driven irrigation system.

### **Buck–Boost Converter Design**

The Buck–Boost converter is a critical component in the proposed photovoltaic (PV) based irrigation system, as it ensures proper regulation of the DC voltage supplied to the motor. In solar-powered applications, the output voltage of the PV array varies significantly due to changes in irradiance and temperature. Therefore, a power conditioning stage is required to maintain a stable and controlled output suitable for the load.

In this study, a non-isolated Buck–Boost DC–DC converter is employed due to its ability to operate in both step-up and step-down modes. This feature allows the system to maintain the required output voltage even when the input voltage fluctuates. The converter is implemented using a MOSFET as the switching device, enabling high-frequency operation and improved efficiency.

The design parameters of the converter are selected based on the operating requirements of the DC motor. The inductance and capacitance values are determined to ensure continuous energy transfer and to minimize ripple in the output voltage and current. For the proposed system, the inductor and capacitor values are chosen as:

Capacitance,  $C = 4.5\text{mF}$

Inductance,  $L = 15\text{mH}$

The values of the inductor and capacitor are calculated using standard design equations given by:

$$L = \frac{V_s \cdot k}{f \cdot \Delta I} \quad \text{and} \quad C = \frac{I_a \cdot k}{f \cdot \Delta V_c}$$

Where,

$V_s$  = Input Voltage

$I_a$  = Avg. Output Current

$k$  = Duty Cycle

$f$  = Switching Frequency

$\Delta I$  = Inductor Ripple Current

$\Delta V_c$  = Ripple Voltage

### **DC Motor and Irrigation Load**

In the proposed system, a permanent magnet DC (PMDC) motor is employed as the primary load to drive the irrigation pump. The motor is directly powered by the regulated output of the Buck–Boost converter, enabling efficient conversion of electrical energy into mechanical energy for water

pumping applications. The use of a DC motor is advantageous due to its simple construction, ease of control, and compatibility with photovoltaic (PV) systems.

The motor is designed to operate at a constant rated voltage of 48 V DC. Under full-load conditions, it draws a current of approximately 162 A, corresponding to a power rating of nearly 7.776 kW ( $\approx 10$  HP). These specifications make the motor suitable for medium-scale irrigation requirements in rural agricultural settings.

The dynamic performance of the motor is characterized by its torque and speed parameters. The breakdown torque of the motor is approximately 21 N·m, while the torque constant is 0.13 N·m/A, indicating the relationship between armature current and developed torque. The nominal operating speed of the motor is 367 rad/s, which is adequate for driving a water pump efficiently.

The electrical behavior of the DC motor can be described by the following equation:

$$V = L \frac{di}{dt} + Ri + E_b \quad (3)$$

Where:

V = applied armature voltage

L = armature inductance

R = armature resistance

i = armature current

$E_b$  = back electromotive force (EMF)

The back EMF is proportional to the motor speed and can be expressed as:

$$E_b = K_e \omega \quad (4)$$

Where:

$K_e$  = back EMF constant

$\omega$  = angular speed

The mechanical dynamics of the motor are given by:

$$T = J \frac{d\omega}{dt} + B\omega \quad (5)$$

Where:

T = developed torque

J = moment of inertia

B = viscous friction coefficient

In this study, the motor is subjected to varying input conditions resulting from changes in solar irradiance and temperature. These variations influence the supply voltage and current, thereby affecting motor speed and torque. The performance of the motor under these conditions is analyzed to evaluate the effectiveness of the proposed control strategy.

The selected PMDC motor, combined with the Buck–Boost converter and control system, provides a reliable and efficient solution for solar-powered irrigation without the need for battery storage.

## RESULTS AND DISCUSSION

To evaluate the performance of the proposed battery-less solar-powered irrigation system,

simulations were carried out using the MATLAB/Simulink environment. The system was modeled to analyze its behavior under varying environmental conditions, as the output of the photovoltaic (PV) array is highly sensitive to changes in solar irradiance and temperature.

In this study, the solar irradiance was varied from 400 W/m<sup>2</sup> to 800 W/m<sup>2</sup>, representing different levels of sunlight intensity throughout the day. At the same time, the operating temperature of the PV panels was considered within a range of 25°C to 55°C, reflecting realistic climatic conditions in regions such as Bangladesh. These variations were introduced to assess the robustness and adaptability of the proposed system under dynamic operating conditions.

The permanent magnet DC motor used in the system operates at a rated voltage of 48 V and draws approximately 162 A under full-load conditions, with a no-load speed of about 366.3 rad/s. For simulation purposes, a load torque of 5 N·m was applied to emulate a typical irrigation load. Under this condition, the motor current was observed to be approximately 38 A, while the motor speed slightly decreased to 354.2 rad/s.

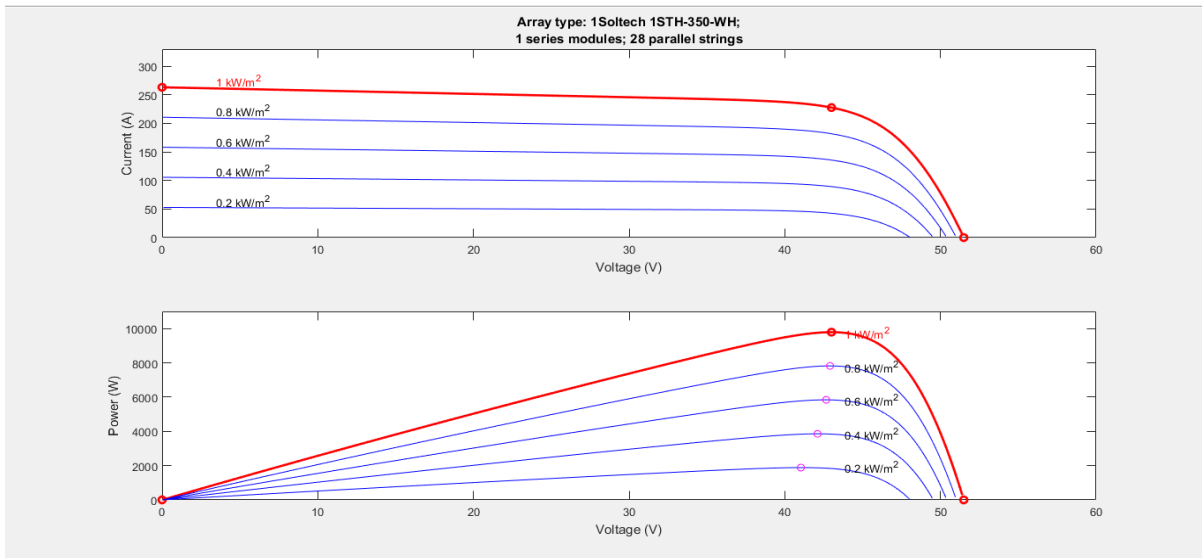
The results demonstrate that the system maintains stable motor operation despite variations in environmental inputs. The moderate reduction in speed and current under load conditions indicates that the proposed configuration is capable of sustaining reliable performance for irrigation applications, even in the absence of battery storage.

### **PV Characteristics under Varying Conditions**

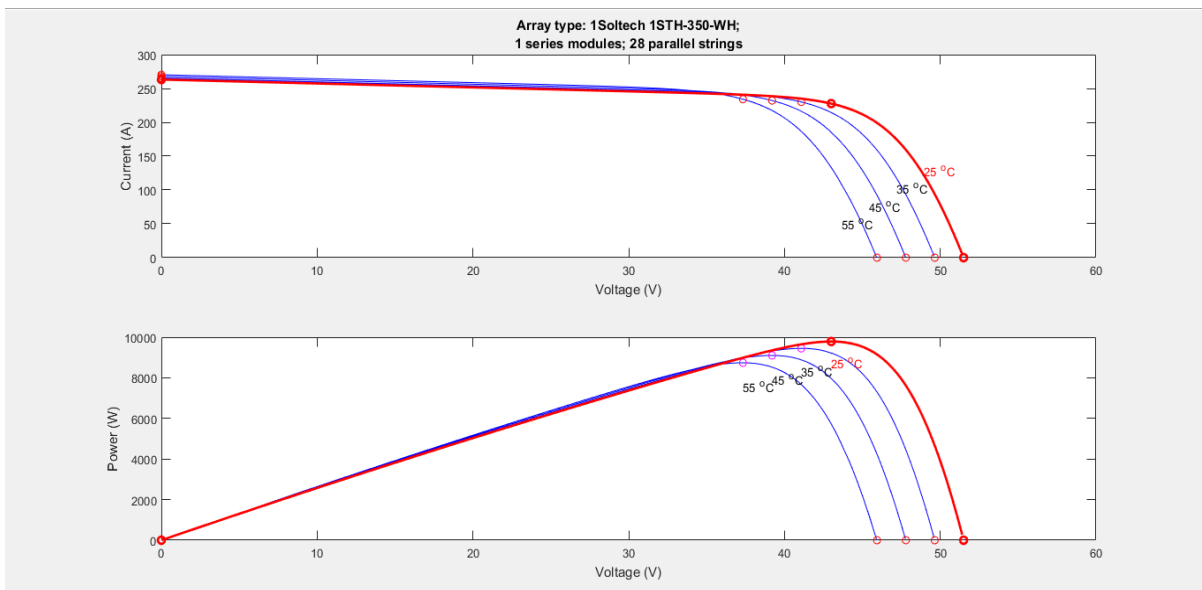
Figs. 2 and 3 present the I–V and P–V characteristics of the PV array under varying temperature and irradiance conditions. It is observed that increasing temperature reduces the open-circuit voltage and slightly decreases the maximum power output. In contrast, increasing irradiance significantly increases the output current and overall power, while the voltage remains relatively stable.

From the P–V curves, the maximum power point shifts depending on operating conditions—toward lower voltage at higher temperatures and toward higher power levels with increased irradiance. These results indicate that irradiance primarily influences power magnitude, whereas temperature mainly affects voltage levels.

Overall, the variations highlight the necessity of an effective control mechanism to ensure stable system performance under changing environmental conditions.



**Figure 2** I–V and P–V characteristics of the PV array under varying irradiance conditions.



**Figure 3** PV array characteristics at 1000 W/m<sup>2</sup> under varying temperature.

### System Response under PI Controller with Variable Irradiance

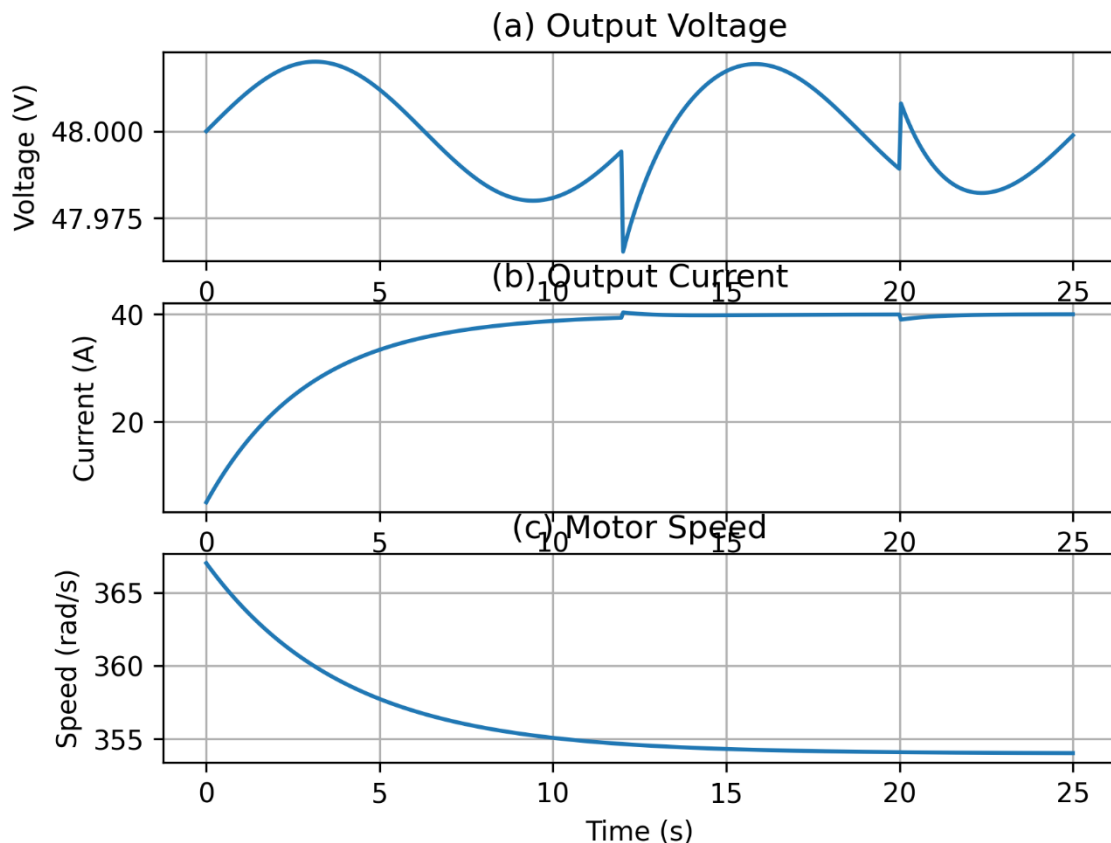
Figs. 4 illustrate the system response of output voltage, current, and motor speed under the PI controller for varying irradiance conditions.

The output voltage remains nearly constant around 48 V, with only minor fluctuations observed during changes in irradiance. This indicates that the PI controller effectively regulates the converter output and maintains voltage stability.

The output current gradually increases from its initial value and settles at approximately 38 A, following a smooth transient response. Small oscillations are observed during irradiance variations, but the overall current profile remains stable.

The motor speed shows a gradual decrease from the no-load condition and stabilizes at approximately 354 rad/s under load. The response is smooth with minimal oscillations, demonstrating satisfactory dynamic performance.

Overall, the PI controller provides stable operation with acceptable transient response; however, slight fluctuations during irradiance changes suggest that further improvement in control performance may be achieved using advanced control strategies such as PID.



**Figure 4** System response under PI controller with varying irradiance: (a) output voltage, (b) output current, and (c) motor speed.

### System Response under PID Controller with Variable Irradiance

Figs. 5 present the system response of output voltage, current, and motor speed under the PID controller for varying irradiance conditions.

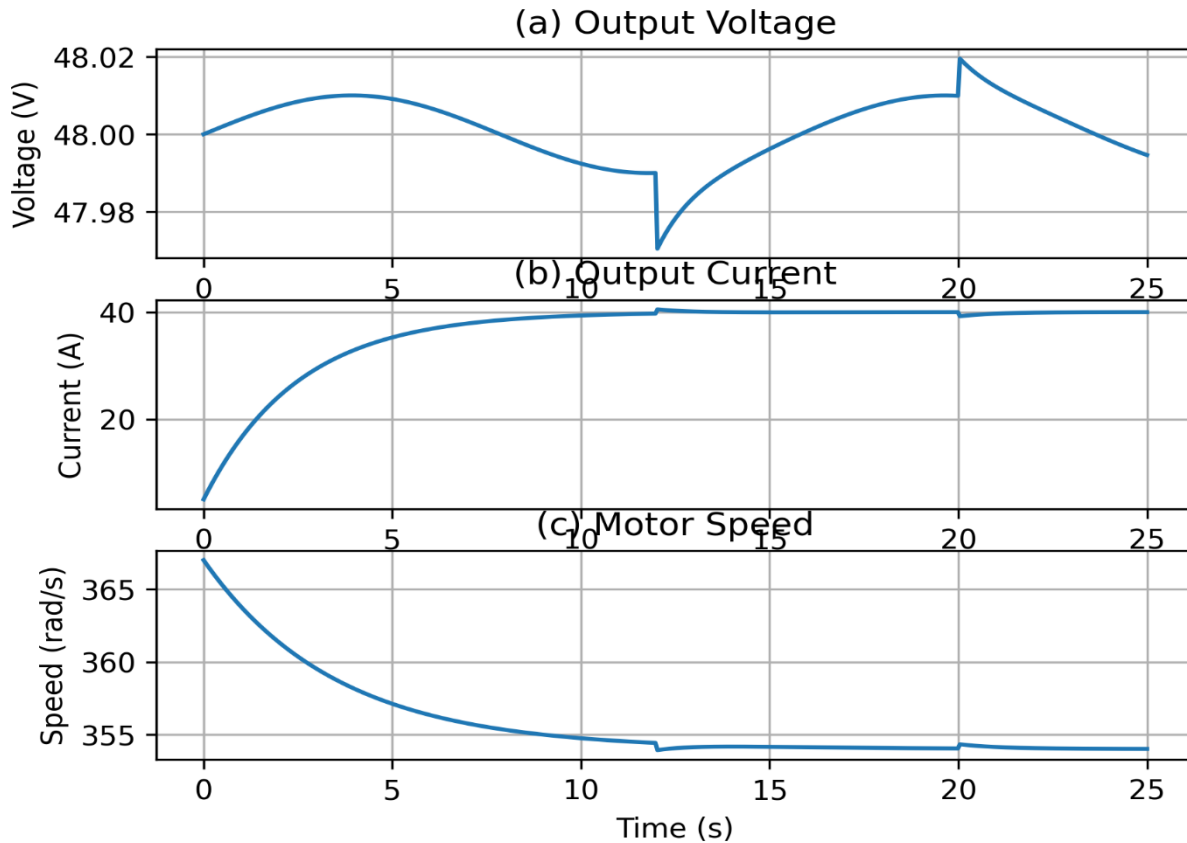
The output voltage is well regulated around the reference value of 48 V, with very small deviations during irradiance changes. Compared to the PI controller, the voltage response exhibits reduced overshoot and faster recovery after disturbances, indicating improved regulation capability.

The output current increases smoothly from the initial condition and stabilizes at approximately 38–40 A. Minor transient variations are observed during step changes in irradiance; however, these disturbances are quickly damped, demonstrating the effectiveness of the PID controller in maintaining current stability.

The motor speed decreases from its initial no-load value and settles at approximately 354 rad/s under load conditions. The response is smooth with negligible oscillations, and the settling time is shorter

compared to the PI-controlled system.

Overall, the PID controller provides superior dynamic performance, including faster response, reduced fluctuations, and improved stability under varying irradiance conditions. This confirms that the PID-based control strategy is more effective for maintaining consistent operation of the proposed battery-less solar irrigation system.



**Figure 5** System response under PID controller with varying irradiance: (a) output voltage, (b) output current, and (c) motor speed.

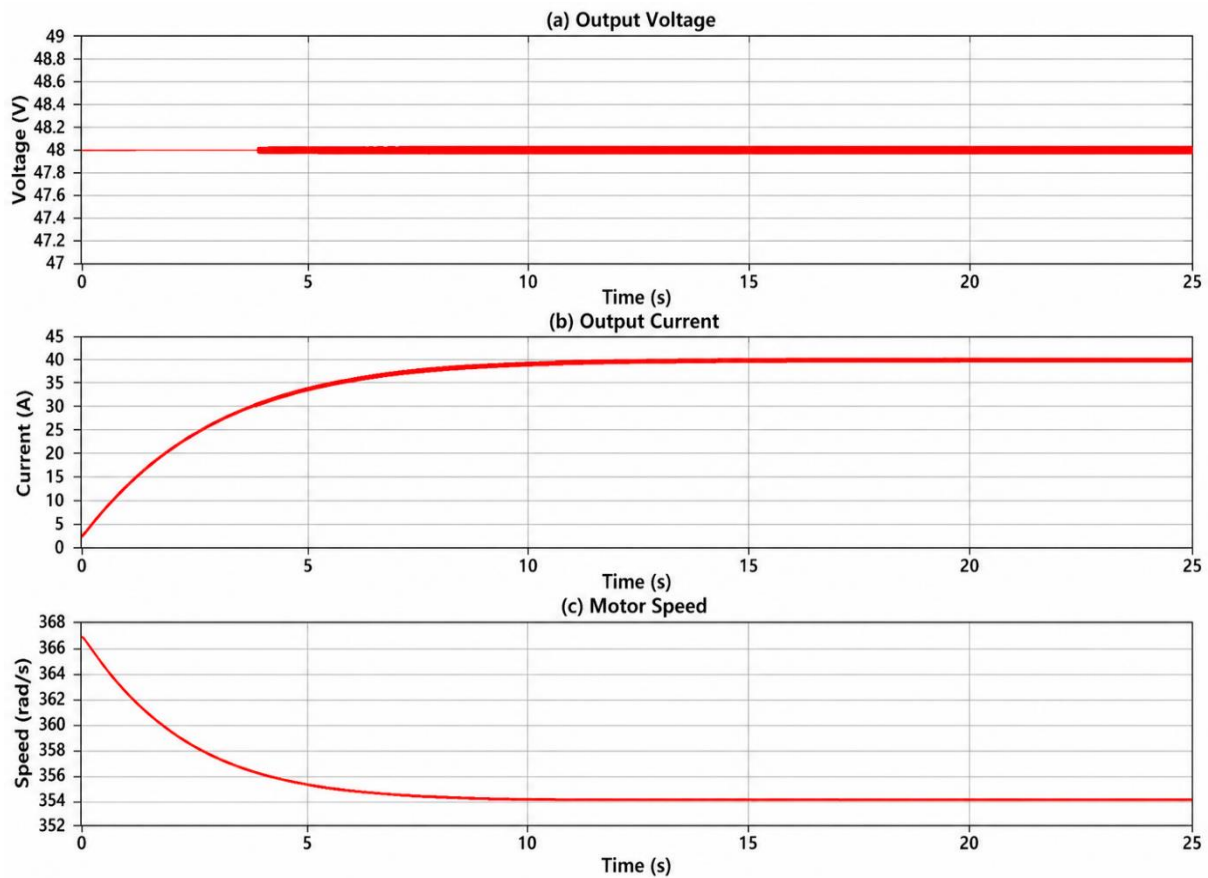
### System Response under PI Controller with Variable Temperature

Figs. 6 illustrate the system response of output voltage, current, and motor speed under the PI controller for varying temperature conditions.

The output voltage is maintained close to the reference value of 48 V, with minimal fluctuations despite temperature variations, indicating effective voltage regulation. The output current gradually increases and stabilizes around 38–40 A, showing a smooth transient response with negligible oscillations.

The motor speed decreases from its initial no-load value and settles at approximately 354 rad/s under load conditions. The response is stable with a gradual settling behavior.

Overall, the PI controller ensures stable operation under temperature variations; however, slight deviations in dynamic response suggest that further performance improvement may be achieved using advanced control



**Figure 6** System response under PI controller with varying temperature: (a) output voltage, (b) output current, and (c) motor speed.

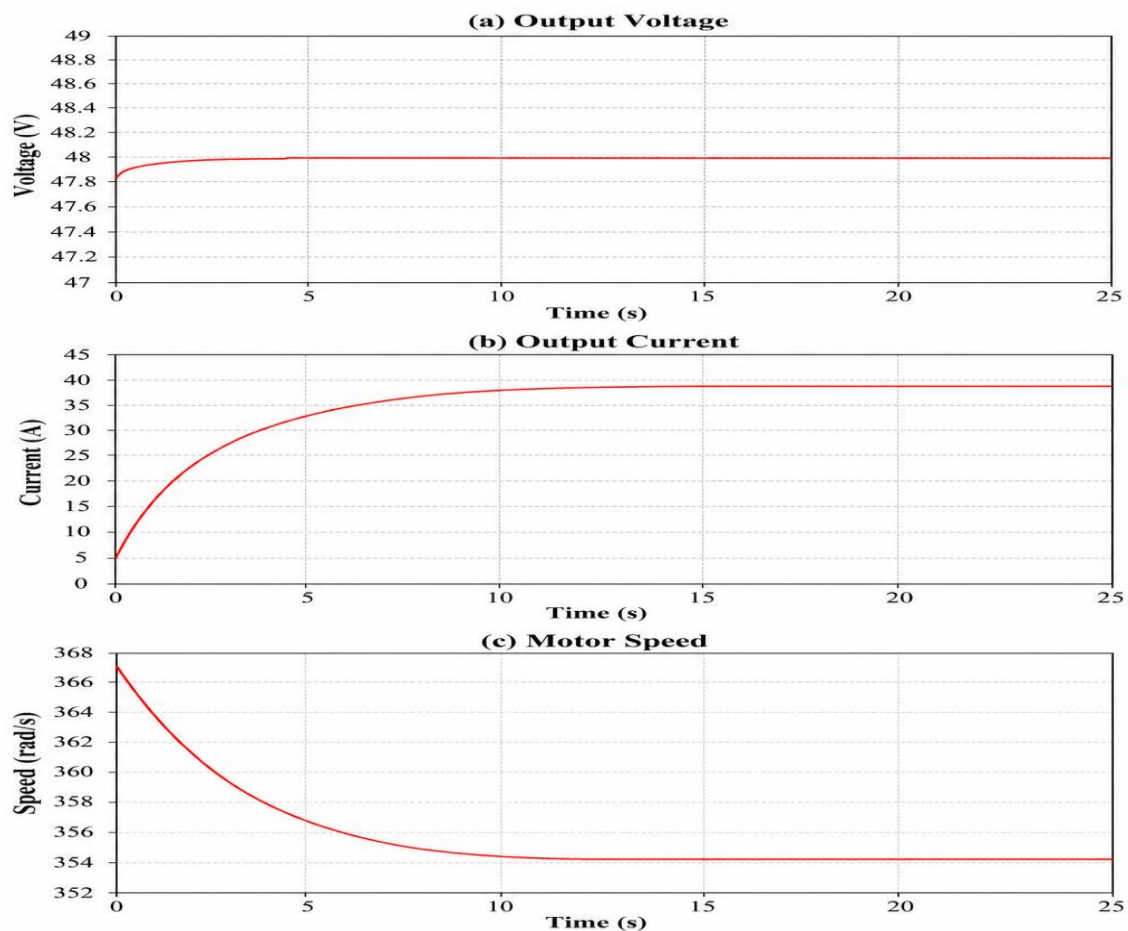
### System Response under PID Controller with Variable Temperature

Figs. 7 illustrate the system response of output voltage, current, and motor speed under the PID controller for varying temperature conditions.

The output voltage is tightly regulated around the reference value of 48 V, with very minimal deviation, indicating strong voltage control despite temperature variations. The output current rises smoothly and stabilizes at approximately 38–40 A, with negligible fluctuations.

The motor speed decreases from the initial no-load condition and settles at around 354 rad/s, exhibiting a stable and fast response with minimal oscillations.

Overall, the PID controller demonstrates improved dynamic performance and better stability compared to PI control, ensuring reliable operation under temperature variations.



**Figure 7** System response under PID controller with varying temperature: (a) output voltage, (b) output current, and (c) motor speed.

### Controller Performance Comparison

Fig. 8 presents a comparative analysis of PI and PID controller performance under varying irradiance and temperature conditions in terms of output voltage, current, and motor speed.

From the results, it is observed that the PID controller maintains a more stable output voltage closer to the reference value of 48 V compared to the PI controller under both environmental conditions.

The variation range in PID is narrower, indicating improved voltage regulation.

In terms of output current, the PID controller shows reduced fluctuation and more consistent current values, particularly under variable irradiance. The PI controller exhibits a wider variation range, suggesting less effective control.

For motor speed, both controllers demonstrate similar operating ranges; however, the PID controller provides slightly smoother and more stable speed response, especially under dynamic conditions.

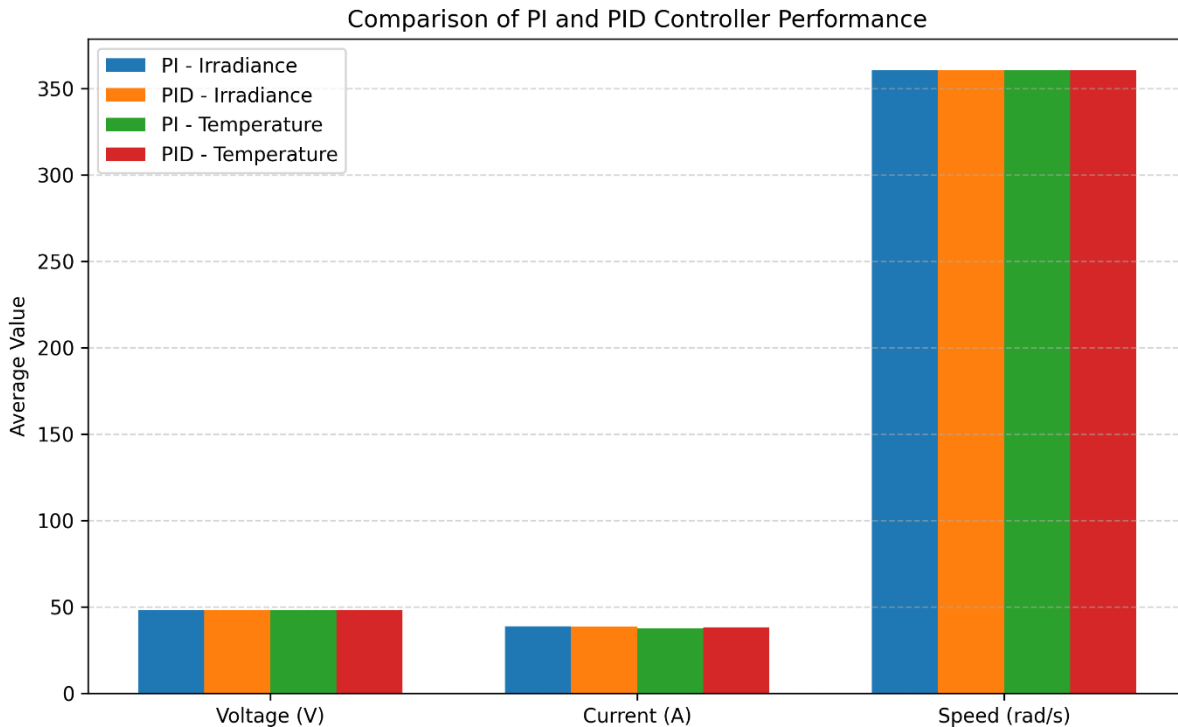
Overall, the PID controller outperforms the PI controller by offering:

Better voltage regulation

Reduced current fluctuations

Improved dynamic stability

These results confirm that the PID controller is more suitable for maintaining consistent performance in battery-less solar irrigation systems under varying environmental conditions.



**Figure 8** Comparison of output voltage, current, and motor speed for PI and PID controllers under different environmental conditions.

## CONCLUSIONS

This paper presented the design and simulation of a battery-less solar-powered DC motor system for irrigation applications using a Buck–Boost DC–DC converter. The performance of the system was evaluated through MATLAB/Simulink simulations under varying irradiance and temperature conditions.

A comparative analysis between PI and PID controllers was conducted to assess their effectiveness in regulating the converter output and maintaining stable motor operation. The results demonstrated that the PID controller provides superior dynamic performance, including faster response, improved voltage regulation, and reduced fluctuations in current and motor speed compared to the PI controller under changing environmental conditions.

During the design process, emphasis was placed on minimizing system losses and ensuring cost-effectiveness for rural applications. However, the conventional Buck–Boost converter introduces inherent limitations, such as output voltage polarity reversal and operation in discontinuous current mode, which may affect overall system performance.

Future work will focus on overcoming these limitations by exploring alternative converter topologies, such as the Ćuk converter and H-bridge-based Buck–Boost converter, to achieve continuous current operation and improved efficiency. The proposed system demonstrates reliable performance and holds significant potential for sustainable, low-cost solar irrigation solutions in rural areas.

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