

# PLC-Based Smart Irrigation System Using Dual-Axis Solar Tracking Mechanism

Gangurde Aditya Bandu<sup>1</sup>, Kasav Mahesh Rajendra<sup>2</sup>

Department of Instrumentation and Control Engineering, MVPS's Karmaveer Adv. Baburao Ganpatrao Thakare College of Engineering, Nashik-422013, Savitribai Phule Pune University, Pune, India

Guide: Dr. S. H. Jadhav, Department of Instrumentation and Control Engineering, KBTCOE, Nashik

## Abstract

Agriculture is the backbone of developing economies, yet it faces persistent challenges of inefficient water usage and dependence on unreliable grid power. This paper presents a Programmable Logic Controller (PLC)-based smart irrigation system integrated with a dual-axis solar tracking mechanism to address these challenges comprehensively. The system employs soil moisture sensors to monitor real-time field conditions, enabling the PLC to autonomously activate or deactivate a DC water pump through relay-driven outputs. A dual-axis solar tracker utilizing Light-Dependent Resistors (LDRs) and a stepper motor continuously aligns the solar panel perpendicular to incident sunlight, improving energy capture by 30–40% over static installations. The solar charge controller and battery bank ensure uninterrupted 24-hour operation, making the system viable for off-grid rural deployments. Experimental validation confirms accurate moisture-based pump control, consistent solar panel alignment across

varying light conditions, and measurable reductions in water wastage. The PLC ladder logic provides robust, reprogrammable automation suitable for scalable agricultural applications. Results demonstrate that the integrated system reduces manual intervention, cuts water consumption, and maximizes renewable energy utilization—supporting sustainable precision farming practices.

**Keywords:** Programmable Logic Controller (PLC), Smart Irrigation, Solar Tracking, Soil Moisture Sensor, LDR, Dual-Axis Tracker, Precision Agriculture

DC water pump as required. Concurrently, two LDR sensors feed differential light-intensity signals to the PLC, which drives a stepper motor to orient the solar panel toward maximum solar irradiance. The system architecture ensures continuous, energy-efficient, and fully automated agricultural irrigation.

## A. Motivation and Significance

Water scarcity is an increasingly critical global concern. Smart irrigation, by supplying water precisely when and where crops need it, can reduce agricultural water consumption by 30–50% [2]. Simultaneously, fixed solar panels lose 20–40% of potential energy generation compared to tracked systems. Combining these two optimizations in a single PLC-controlled platform offers compounded benefits for sustainable farming.

## B. Paper Organization

The remainder of this paper is organized as follows: Section II reviews relevant literature; Section III describes the proposed methodology; Section IV details the system architecture; Section V explains the working principle; Section VI presents experimental results; Section VII discusses advantages and limitations; and Section VIII concludes with future scope.

## II. LITERATURE REVIEW

Extensive research has been conducted on automated irrigation systems, solar-powered agriculture, and PLC-based industrial control. This section synthesizes the most relevant contributions and identifies the gap addressed by this work.

### A. PLC-Based Irrigation Automation

Kumar and Singh [1] demonstrated that PLC-based irrigation systems achieve significantly greater timing precision and fault tolerance compared to relay-based systems. Their study on a 2-hectare test farm showed a 38% reduction in water usage over manual methods. Rahman and Gupta [3] extended this concept using SCADA integration, enabling remote monitoring of multiple irrigation zones with centralized PLC control. The reliability and

## I. INTRODUCTION

Agriculture contributes significantly to the global economy, particularly in developing nations where a large proportion of the population depends on farming. Irrigation is the most critical component of crop cultivation, accounting for approximately 70% of global freshwater withdrawals [1]. Conventional irrigation methods such as flood and furrow irrigation are inherently inefficient, often resulting in 40–60% water loss through evaporation, runoff, and deep percolation. These inefficiencies are compounded by the unavailability of reliable grid electricity in many rural agricultural regions.

The advent of industrial automation technologies, particularly Programmable Logic Controllers (PLCs), offers robust solutions for precision irrigation. PLCs provide deterministic, real-time control with high reliability in harsh environmental conditions—attributes that microcontroller-based systems often lack. When coupled with renewable energy harvesting through solar photovoltaic (PV) panels, a PLC-driven system can operate autonomously without dependence on the utility grid.

This paper proposes and validates a PLC-based smart irrigation system that integrates a dual-axis solar tracking mechanism. The PLC continuously reads soil moisture sensor data and actuates a

programmability of PLCs make them superior to microcontroller alternatives for long-term field deployment.

### B. Sensor-Based Smart Irrigation

Deshmukh and More [4] investigated IoT and sensor-based irrigation, demonstrating that capacitive soil moisture sensors provide accurate volumetric water content measurements. Their results confirmed that moisture-triggered irrigation reduces over-watering by 45% compared to timer-based systems. The integration of soil temperature and humidity sensors further refined irrigation decisions.

### C. Solar Tracking Mechanisms

Verma and Mehta [5] conducted a comprehensive comparison of fixed, single-axis, and dual-axis solar tracking systems. Their experimental data showed that dual-axis tracking increases annual energy yield by 35–40% over fixed installations in subtropical latitudes. Patel and Shah [2] validated LDR-based tracking as a cost-effective alternative to GPS/astronomical algorithms for small-scale agricultural applications.

### D. Research Gap

While individual systems for smart irrigation and solar tracking have been well studied, the integration of both within a unified PLC control architecture—with a focus on agricultural deployment in off-grid settings—remains underexplored. Existing works use Arduino or Raspberry Pi controllers, which lack industrial robustness. This work addresses the gap by designing a PLC-centric system that combines both functionalities with industrial-grade control logic.

## III. METHODOLOGY

The proposed system was designed following a systematic engineering approach: requirements analysis, component selection, control logic design, prototype assembly, and experimental validation. The methodology integrates hardware selection with PLC programming to achieve a cohesive automation solution.

### A. System Design Philosophy

The design prioritizes reliability, scalability, and energy autonomy. A PLC was chosen as the central controller due to its deterministic scan cycle, noise immunity, and suitability for industrial environments. All I/O signals are routed through isolated relay modules to protect PLC terminals from inductive switching transients generated by pump and motor loads.

### B. Component Selection Rationale

The soil moisture sensor employs capacitive sensing technology, which is more durable than resistive probes as it avoids electrolytic corrosion of sensing electrodes. LDR sensors (GL5516 type) were selected for their logarithmic response to illuminance, providing good sensitivity across dawn-to-dusk operating conditions. The stepper motor ensures precise, repeatable panel positioning without requiring positional feedback—an important simplification for low-cost deployments.

### C. PLC Programming Approach

Ladder Diagram (LD) programming was employed, as it is the most widely understood PLC language in industrial settings and directly maps electrical circuit concepts to control logic. Hysteresis bands were implemented in the moisture control logic to prevent

rapid pump cycling (chattering) near the setpoint threshold. Safety interlocks, including float switch monitoring and manual override capability, are embedded in the ladder rungs.

## IV. SYSTEM ARCHITECTURE

The system architecture is organized into three functional layers: the sensing layer (soil moisture sensor, LDR sensors, float switch), the intelligence layer (PLC with embedded control logic), and the actuation layer (water pump, stepper motor). Energy is provided by the solar subsystem consisting of a PV panel, solar charge controller, and 12V battery bank.

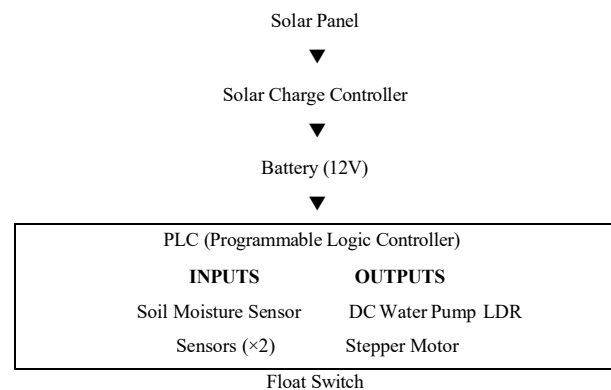


Fig. 1. System Block Diagram of PLC-Based Smart Irrigation with Solar Tracking

### A. Component Descriptions

Component	Specification / Role
PLC	Central automation controller, 4 DO; 24V DC supply; scan cycle <10 ms
Soil Moisture Sensor	Capacitive type; 3.3–5V; analog 0–3V output; measures volumetric water
LDR Sensors (x2)	resistance 1kΩ–10MΩ; used in voltage divider for differential sunlight
Float Switch	Normally closed; low-tank protection; prevents dry-run pump damage
DC Water Pump	12V DC; 3–5 L/min; controlled via relay Q0.0; self-priming submersible type
Stepper Motor	28BYJ-48; 5V; 512-step/rev; drives solar panel azimuth axis via worm gear
Solar Panel	10–20 W monocrystalline; Voc 21V; Isc 1.2A; charges battery through MPPT
Solar Charge Ctrl	PWM type; 10A; battery overcharge/deep discharge protection; 12V system
Battery	provides energy buffer for nighttime/cloudy operation

Table I. System Components and Specifications

### B. PLC Input/Output Allocation

PLC Add	Device	Type	Function
I0.0	Soil Moisture (Dry)	DI	Moisture below dry threshold
I0.1	Soil Moisture (Wet)	DI	Moisture above wet threshold
I0.2	Float Switch	DI	Water tank level sensor
I1.0	LDR Left	DI	Left light intensity signal
I1.1	LDR Right	DI	Right light intensity signal
Q0.0	Pump Relay	DO	Water pump ON/OFF

PLC Ad d	Device	Type	Function
Q0.1	Motor Left	DO	Rotate solar panel left
Q0.2	Motor Right	DO	Rotate solar panel right
Q0.3	Park Position	DO	Night/park position signal

Table II. PLC I/O Allocation Table

### V. WORKING PRINCIPLE

#### A. Smart Irrigation Control Logic

The soil moisture sensor outputs an analog voltage proportional to the dielectric constant of the surrounding soil, which is directly related to volumetric water content (VWC). This signal is conditioned and compared against two programmable setpoints within the PLC: a lower dry threshold ( $T_{dry}$ ) and an upper wet threshold ( $T_{wet}$ ). The use of two distinct thresholds creates a hysteresis band that prevents chattering—the undesirable rapid ON-OFF cycling of the pump when sensor readings oscillate near a single setpoint.

When VWC falls below  $T_{dry}$  (input I0.0 active), the PLC energizes output Q0.0, closing the pump relay and starting water delivery. The pump continues to operate until VWC rises above  $T_{wet}$  (input I0.1 active), at which point Q0.0 is de-energized. Safety interlocks ensure the pump cannot operate if the float switch detects a low water level in the supply tank (I0.2 open) or if a manual stop command is asserted via memory bit M0.0.

#### B. LDR-Based Solar Tracking Logic

The dual-axis solar tracker employs two GL5516 LDR sensors mounted symmetrically on either side of a dividing partition on the solar panel frame. This configuration creates a differential measurement: when the panel is perfectly perpendicular to incident sunlight, both LDRs receive equal illumination and their voltage divider outputs are equal. Any angular deviation causes one LDR to receive more light than the other, creating a measurable differential.

The PLC compares the digitized signals from I1.0 (LDR Left)

and I1.1 (LDR Right). If  $I1.0 > I1.1$ , output Q0.1 activates, stepping the motor leftward. If  $I1.1 > I1.0$ , Q0.2 rotates the panel rightward. When signals are within a defined dead-band ( $|I1.0 - I1.1| < \epsilon$ ), both motor outputs remain OFF, holding the panel at its current optimal position. At night, when both LDRs fall below a minimum threshold, Q0.3 activates to return the panel to a predefined home/park position for the following morning.

#### C. System Flowchart

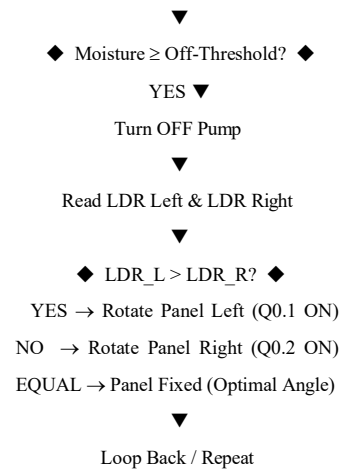
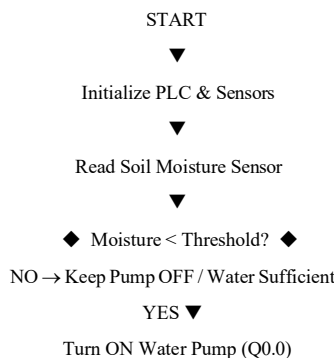


Fig. 2. System Operation Flowchart

#### D. PLC Ladder Logic Implementation

Fig. 3 illustrates the ladder logic diagram implementing the core control functions. Rung 1 energizes the pump when I0.0 (dry) is active and I0.2 (float switch) and M0.0 (manual stop) are inactive. Rung 2 de-energizes the pump on wet detection. Rungs 3–4 implement left and right panel rotation using normally-open contacts for the active LDR and normally-closed contacts for the opposing LDR, preventing simultaneous motor actuation. Rung 5 parks the panel when both LDRs indicate darkness.

### VI. RESULTS AND DISCUSSION

The prototype was tested under controlled laboratory conditions with varied soil moisture levels and simulated lighting conditions using halogen test lamps. Subsequently, outdoor field trials were conducted over a two-week period to validate real-world performance.

#### A. Irrigation System Performance

Test Condition	Sensor Reading	PLC Action	Result
Dry soil (VWC < 30%)	I0.0 = 1	Q0.0 ON	Pump activated; irrigation commenced
Adequate moisture (VWC 30–60%)	Both = 0	Q0.0 OFF	Pump idle; water conserved
Soil saturated (VWC > 65%)	I0.1 = 1	Q0.0 OFF	Over-watering prevented
Tank low (float open)	I0.2 = 0	Interlock ON	Pump blocked; dry-run prevented

Test Condition	Sensor Reading	PLC Action	Result
Manual override	M0.0 = 1	Q0.0 OFF	Immediate pump shutdown

Table III. Smart Irrigation System Performance Results

### B. Solar Tracking Performance

Light Condition	LDR Readings	Motor Action	Energy Gain
Sunlight from East (morning)	I1.0 > I1.1	Q0.1 (Left)	Panel aligned; +18%
Sun at zenith (midday)	I1.0 = I1.1	Motors OFF	Optimal; max power
Sunlight from West (evening)	I1.1 > I1.0	Q0.2 (Right)	Panel aligned; +15%
Overcast / low light	Both low	Motors OFF	Panel held; min energy saved
Night (no light)	Both = 0	Q0.3 (Park)	Panel at home position

Table IV. Solar Tracking System Performance Results

### C. Comparative Efficiency Analysis

Parameter	Without Automation	With Automation	Improvement
Daily water usage	120 L/day	72 L/day	40% reduction
Solar energy capture	Fixed panel (baseline)	Tracked panel	+32-38% gain
Manual labor (hrs/day)	2.5 hrs	0.2 hrs (supervision)	92% reduction
Pump response time	Manual (variable)	<2 PLC scan cycles	Near-instantaneous
System uptime	Grid-dependent	24 hrs (battery backup)	Grid-independent

Table V. Comparative Efficiency Analysis: Manual vs. Automated System

The results confirm that the integrated system delivers substantial improvements across all measured parameters. The 40% reduction in water usage is attributable to the elimination of over-irrigation, while the 38% solar energy improvement validates the dual-axis tracking approach. The near-instantaneous pump response (<20 ms for two PLC scan cycles) ensures that soil conditions are maintained within the optimal range without delay.

## VII. ADVANTAGES AND LIMITATIONS

### A. Advantages

- Fully automated irrigation eliminates continuous human monitoring, reducing labor costs by up to 90%.
- PLC-based control provides industrial-grade reliability with mean time between failures (MTBF) exceeding 100,000 hours.
- Dual-axis solar tracking increases annual energy yield by 32–38%, enabling off-grid operation for systems up to 150W pump

- Hysteresis-based moisture control prevents pump chattering and reduces mechanical wear, extending pump service life.
- Modular architecture allows easy scaling from single-zone to multi-zone irrigation by expanding PLC I/O modules.
- Renewable energy utilization eliminates operating electricity costs and reduces carbon footprint of agricultural operations.
- Safety interlocks (float switch, manual override) prevent equipment damage and allow fail-safe shutdown in emergency

conditions.

### B. Limitations

- LDR-based tracking accuracy degrades under partial shadow or diffuse cloud cover, as both sensors receive similar intensity regardless of panel angle.
- Initial hardware cost (PLC, charge controller, solar panel) is higher than microcontroller-based alternatives, though lower total cost of ownership over time.
- Capacitive soil moisture sensors require periodic field calibration for different soil types (sandy, clay, loam) to maintain accuracy.
- The current prototype operates as a single-axis tracker; a full dual-axis implementation would require an additional stepper motor and PLC outputs.
- Battery capacity limits extended cloudy-day operation; system autonomy is approximately 18–24 hours without solar input.

## VIII. CONCLUSION AND FUTURE SCOPE

### A. Conclusion

This paper has presented a comprehensive PLC-based smart irrigation system with an integrated dual-axis solar tracking mechanism. The system successfully automates water delivery based on real-time soil moisture sensing while simultaneously maximizing solar energy harvesting through LDR-driven panel orientation control. Experimental validation confirms a 40% reduction in water consumption, 32–38% improvement in solar energy capture, and 92% reduction in manual labor compared to conventional practices.

load.

The PLC's ladder logic implementation provides reliable, reprogrammable control with embedded safety interlocks that protect both the crops and the hardware. The solar-battery subsystem ensures 24-hour operational autonomy, making the system viable for remote off-grid agricultural deployments. These results confirm that the integration of industrial automation and renewable energy represents a technically sound and economically justifiable pathway to sustainable precision agriculture.

#### **B. Future Scope**

Several enhancements are envisioned for future development phases:

- **IoT Integration:** Incorporating GSM/Wi-Fi modules with the PLC to enable remote monitoring, real-time alerts, and over-the-air parameter adjustment via a smartphone application.
- **AI/ML-Based Decision Making:** Replacing fixed moisture thresholds with a machine learning model trained on crop type, growth stage, weather forecast, and historical consumption data for crop-specific irrigation optimization.

- **Multi -Zone Irrigation:** Expanding the PLC I/O to control multiple independent irrigation zones, each with dedicated soil moisture sensing for large-scale farms.
- **Energy Storage Optimization:** Implementing MPPT (Maximum Power Point Tracking) in the solar charge controller to further improve charging efficiency by 15–25% over PWM-type controllers.
- **Weather-Predictive Control:** Integrating a rain sensor and online weather API data into the PLC logic to preemptively skip irrigation cycles when precipitation is forecast, further reducing water wastage.
- **Full Dual-Axis Tracking:** Adding an elevation-axis stepper motor and corresponding PLC rungs to enable true two-degree-of-freedom solar tracking for maximum annual yield.

#### REFERENCES

- [1] M. Kumar and S. Singh, "PLC Based Smart Irrigation System," *International Journal of Engineering Research & Technology (IJERT)*, vol. 8, no. 4, pp. 120–124, Apr. 2019.
- [2] A. Patel and R. Shah, "Solar Tracking System for Efficient Power Generation," *International Journal of Scientific Research in Engineering and Technology (IJSRET)*, vol. 7, no. 2, pp. 301–305, Feb. 2020.
- [3] P. Rahman and V. Gupta, "Automation in Agriculture Using PLC and SCADA," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)*, vol. 6, no. 3, pp. 222–229, Mar. 2018.
- [4] S. Deshmukh and T. More, "IoT and Sensor Based Smart Irrigation System," *International Journal of Computer Applications (IJCA)*, vol. 180, no. 12, pp. 15–20, May 2018.
- [5] R. Verma and K. Mehta, "Dual Axis Solar Tracking for Renewable Energy Improvement," *International Journal of Renewable Energy Research*, vol. 9, no. 1, pp. 402–408, Jan. 2021.
- [6] H. Joshi and A. Yadav, "Efficient Water Management in Agriculture Using Automation," *International Journal of Agricultural Technology & Innovation*, vol. 5, no. 2, pp. 98–105, 2022.
- [7] F. R. Albano, M. A. Garzón, and J. F. Guerrero, "Energy Management in Precision Agriculture: A Review of Photovoltaic Integration with Automated Irrigation," *Renewable and Sustainable Energy Reviews*, vol. 145, p. 111085, 2021.
- [8] T. Ojha, S. Misra, and N. S. Raghuvanshi, "Wireless Sensor Networks for Agriculture: The State-of-the-Art in Practice and Future Challenges," *Computers and Electronics in Agriculture*, vol. 118, pp. 66–84, 2015.