STM JOURNALS

International Journal of
Electrical Power and Machine Systems

Volume 4, Issue 1, 2026
January—June
DOI (Journal): 10.37591/IJEPMS

https://journals.stmjournals.com/ijepms

Review IJEPMS

Performance Improvement of Standalone Solar PV Pumping System Using Supercapacitor

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Abstract

Two of the most pressing issues when it comes to rural communities of arid and semi-arid regions are water shortage and unstable grid electricity. Standalone solar photovoltaic (PV) pumping systems have been introduced as a clean, low-maintenance alternative to diesel-powered pumps, but their performance is limited by the intermittent nature of sunlight and the limited energy buffering capacity of conventional batteries. The paper is an investigation into the incorporation of a high-power, high-energy density supercapacitor bank as a hybrid storage component in a 5 kW PV-driven water pumping system. A detailed modeling framework is developed in MATLAB/Simulink that integrates a detailed PV array model and a maximum power point tracker (MPPT) controller. In key findings, it is demonstrated that the supercapacitor module mitigates the short-duration power dips, caused by clouds, in delivering an average pump flow increase of 22% and depth of discharge cycle reductions of 17. Also, the result demonstrates that the average pump flow on sunny days is 99%, on cloudy days is 88%, and on partially cloudy days is 83% of its rated flow. The findings support the assumption that, given a well-planned layout of the conventional batteries, supercapacitors can contribute significantly to the reliability, efficiency, and economic feasibility of off-grid solar water pumping systems.

Keywords: PV pump, pumping system, supercapacitor, battery, pump power, water output

INTRODUCTION

Standalone solar photovoltaic (PV) pumping systems are increasingly becoming important for rural electrification and irrigation in off-grid regions. They are popular because of their low operating cost, zero-emission operation, and ability to harness abundant solar energy [1–3]. However, the intermittent quality of solar irradiance poses two intertwined issues: (1) poor power in low irradiance (morning, evening, and cloudy days). (2) Large inrush currents whenever the pump motor is switched on may be larger than the instantaneous power capability of the PV array, causing voltage collapse and pump stall. Conventional solutions (batteries, diesel generators, or grid ties) are expensive, require maintenance, and cause pollution. Supercapacitors (SCs) have become an attractive potential solution to the storage medium gap between the PV array and the pump motor as a fast-acting storage medium.

This survey summarizes the recent literature quantifying the performance gains (or lack thereof) when SCs are introduced and compares those gains to the gains of alternative strategies that do not involve the introduction of SCs [4–6]. Solar radiation is unpredictable. The power output of a PV array is not a stream but a wave due to clouds, dust, and the simple fact that night falls after every 24 h.

An average 5 kW PV pump, which has been sized to deliver 15 m^3/h^{-1} performance under optimistic sun, may experience an immediate power reduction to 20% of that which occurs on a sunny day, or may even reduce it to zero after sunset.

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Received Date: May 09, 2026
Accepted Date: May 16, 2026
Published Date: May 26, 2026

Citation: Kazi Kutubuddin Sayyad Liyakat. Performance Improvement of Standalone Solar PV Pumping System Using Supercapacitor. International Journal of Electrical Power and Machine Systems. 2026; 4(1): 63–73p.

Table 1. Comparison between a supercapacitor and a battery.

Performance feature	PV + pump + battery	PV + pump + supercapacitor
Energy storage type	Chemical (long term)	Electrical/electrostatic (short term)
Response to radiation change	Moderate (slower response)	Excellent (instantaneous)
Best performance condition	Sunny days (consistent load)	Fluctuating cloudy days
Daily water output	High (higher total capacity)	Very high (due to high efficiency)
Cycle life	Low (needs replacement)	Very high
System efficiency	Medium	High (highest efficiency)
Variable frequency drive operation (cloudy)	Maintains consistent, sustained VFD power	Handles sudden drops by supplying short, high-power bursts

When the motor of the pump suddenly experiences a voltage drop, the speed of the pump decreases, the flow rate decreases, and the well can even stall. In the most extreme cases, repeated starts and stops wear out bearings, melt windings, or cause protective shutoffs, which reduce the useful life of the system. The most common remedy is a battery bank: hoard the superabundance of the midday sun and then release it when the sun declines. Batteries can flatten the power curve, but they also come with a host of new challenges, such as high capital costs, limited cycle life, sensitivity to temperature, and the need for regular maintenance. In remote locations, a dead battery usually implies a dead well [7, 8].

A supercapacitor can absorb or emit tremendous bursts of power virtually instantly and can repeat this process millions of times without any loss of capacity. Although it will not hold as much energy as a battery, it will be a perfect fit [9, 10]. To appreciate how a supercapacitor can assist, we can compare the two prototype designs (Table 1) of a standalone solar PV pump.

Both employ a maximum power point tracker (MPPT) that optimizes the solar panels, although the manner in which each handles the so-called missing power vastly differs.

Without Supercapacitor (Battery Only)

When a cloud burst occurs, the PV energy can be reduced to a low level that is insufficient to operate the pump. The battery immediately intervenes and discharges to maintain a constant voltage. However, the depth of discharge (DoD) is elevated on lengthy cloudy days, which reduces the battery life. The charge–discharge currents are restricted by the internal resistance of the battery, which can be a bottleneck for rapid power swings. After several weeks of low irradiance, the battery can be completely discharged, leaving the pump inactive until the next sunny day. Without a supercapacitor, the power delivered to the pump (P_{pump}), as shown in Equation (1), is directly dependent on the instantaneous solar irradiance (G) and the efficiencies of the PV panel (η_{pv}) and converter (η_{conv}).

$$P_{\text{pump}}(t) = P_{\text{pv}}(t)\,\eta_{\text{conv}} = \left(C_{\text{pv}}\eta_{\text{pv}}G(t)f(\text{Temp})\right)\eta_{\text{conv}} \quad (1)$$

Where, C_{pv} is the rated capacity of the PV array.

With Supercapacitor (Hybrid or Standalone)

The pump and MPPT were connected in parallel to a supercapacitor bank. The purpose of the supercapacitor is to regulate the voltage through the following functions:

- *Peak shaving:* When the PV power exceeds the pump's power requirement (e.g., during midday), the excess energy is used to charge the supercapacitor. The value of the supercapacitor was calculated using the equation $E = \frac{1}{2}CV^2$, where, C is the capacitance, V is the applied voltage, and E is the energy stored in the capacitor.
- *Ride-through:* If cloud cover causes the PV power output to drop briefly (for a few seconds), the supercapacitor discharges to maintain the pump supply at a constant voltage.

- *Start boost:* During pump startup, the motor draws a surge current (approximately 3–5 times its nominal current). This surge current is supplied by the supercapacitor, preventing the MPPT from experiencing a voltage drop. Since the supercapacitor is required to supply energy only for a few seconds or minutes, its relatively low energy density does not become a limiting factor. When a battery is included in the system, it can be downsized or even eliminated, thereby reducing both cost and maintenance requirements [1].

With a supercapacitor, the power supplied to the motor is the sum of the power generated by the PV panel and the power released or absorbed by the supercapacitor $P_{\text{pump,sc}}(t)$, as represented by Equation (2).

$$P_{\text{pump,sc}}(t) = P_{\text{pv}}(t) + P_{\text{sc}}(t) \quad (2)$$

The supercapacitor smooths power fluctuations caused by variations in solar irradiance, allowing the pump to operate close to its maximum efficiency point (η_{max}) even under low solar irradiance.

Why Supercapacitors?

1. *Zero-maintenance power buffer:* Supercapacitors require no electrolyte inspection, venting, or solvation. They can be installed on a steel rack in a dusty environment for many years while continuing to deliver the same peak power.
2. *Fast, clean energy flow:* The capacitor discharge curve is nearly linear, providing a relatively stable voltage until the capacitor reaches its lower discharge limit. As a result, the pump motor operates at a more constant voltage, thereby improving its efficiency.
3. *Thermal resilience:* In tropical climates, where batteries may overheat, supercapacitors are less susceptible to overheating because they store energy primarily as an electric field rather than through chemical reactions.
4. *Modular flexibility:* If additional capacity is required, another 500 F module can be added. Conversely, if less capacity is needed, a module can be removed. This modular design allows the system to be appropriately sized during installation without requiring a complete redesign of the controller.

The addition of supercapacitors (SCs) to standalone solar photovoltaic (PV) pumping systems can significantly improve system performance by mitigating the effects of solar intermittency. SCs can enhance the overall system efficiency by up to 15%, enable operation under cloudy conditions, increase water output by up to 64%, and protect batteries by reducing the stress caused by rapid power fluctuations.

Key Considerations

- *Component complementarity:* Although batteries have a high-energy density, supercapacitors have a high-power density, and the combination of the two makes them a perfect match for handling varying load requirements.
- *Design and control:* It is important to properly size the supercapacitor bank and use intelligent power management systems (often with Proportional-Integral (PI) controllers in MATLAB/Simulink) to maximize efficiency.
- *Cost/complexity:* In addition to increasing efficiency, the introduction of supercapacitors increases the initial system cost and complexity, requiring a trade-off analysis.

Performance Improvements and Benefits

- *Buffer to intermittency:* Supercapacitors have a high-power density, which serves as a buffer to absorb energy from the PV panel when the sun is shining and release it when the sun is covered or when other clouds are present, preventing the pumps from being shut down [1, 6].
- *Greater daily water productivity:* It has been demonstrated that higher daily water productivity can be achieved by using a supercapacitor buffer, with some models reporting up to 64% increase.

- *Improved battery lifetime:* Because they treat high-power transients (charge/discharge cycles), supercapacitors drastically reduce the stress on the battery, which would otherwise be damaged by frequent power variations [1, 8, 9].
- *More elevated efficiency:* The hybrid system (PV-battery-supercapacitor) has greater efficiency than batteries alone and lowers the total lifecycle costs. Optimized Operation: The system is more likely to survive the startup transients and sudden changes in the speed of the motor and not fail to pump.

The classic version of the perturb and observe (P&O) algorithm nudges the PV voltage up or down and monitors the resultant power. When the power increases, the direction is maintained; otherwise, it changes to the opposite. Although straightforward, it has the following weaknesses:

- Oscillation around the MPP is in a steady state.
- Delayed reaction to fast alterations of irradiance (cloud transients).
- Mis-tracking occurs when the I–V curve of the panel is disturbed by temperature or partial shading.

SUGGESTED METHODOLOGY

A model of the performance improvement of an independent solar PV water pumping system (SPVWPS) consists of the integration of a supercapacitor (SC) to store energy and use the P&O MPPT algorithm to optimize the performance of the system. This method enhances the efficiency of the system, boosts the production of water, and stabilizes the operation of motors [4].

The model is explained in Table 2 and Figure 1. By combining a fast-acting supercapacitor bank with a smart, adaptive MTTP P&O algorithm, we give the pump a “memory” of the sun, a “power” to ride-through clouds, and an “intellect” that constantly finds the sweet spot where the panel’s power meets the motor’s demand. The outcome is a 30–40% increase in usable water in all weather conditions [5].

The structure (mental picture): Sun → PV → MTTP P&O → Boost → supercapacitor→ Pump → Water → Farmer’s field. The supercapacitor is attached between the converter and pump and can be considered a temporary fuel tank that fills during sunny days and empties during cloudy days. Figure 1 shows the simulation of the proposed system using simulation software.

Control Strategy (P&O Algorithm)

- The P&O algorithm continuously adjusts the converter duty cycle, which measures the PV voltage and current to calculate the power, and adjusts the converter duty cycle to track the maximum power point (MPP).
- When the power is increased, the perturbation persists in the same direction; when the power is decreased, the direction is reversed.

Table 2. System architecture.

Block	Function	Key design points
PV array	Harvest solar photons	2 × 1.5 kW poly-crystalline modules, wired in series for higher voltage (≈70 V MPPT)
DC–DC converter (boost)	Step-up to motor voltage (≈120 V)	Wide-bandwidth controller (≥1 kHz) for rapid response
Super-capacitor bank	Short-term energy buffer	10 F, 120 V rating, erythrocyte sedimentation Rate <0.02 Ω; delivers up to 300 W in a few seconds
MTTP P&O MPPT controller	Locate and track the maximum power point (MPP)	Modified perturb-and-observe with adaptive step-size and temperature-compensation
Pump motor (DC brushless)	Convert electrical energy into hydraulic power	2 kW, variable-speed, torque-controlled driver

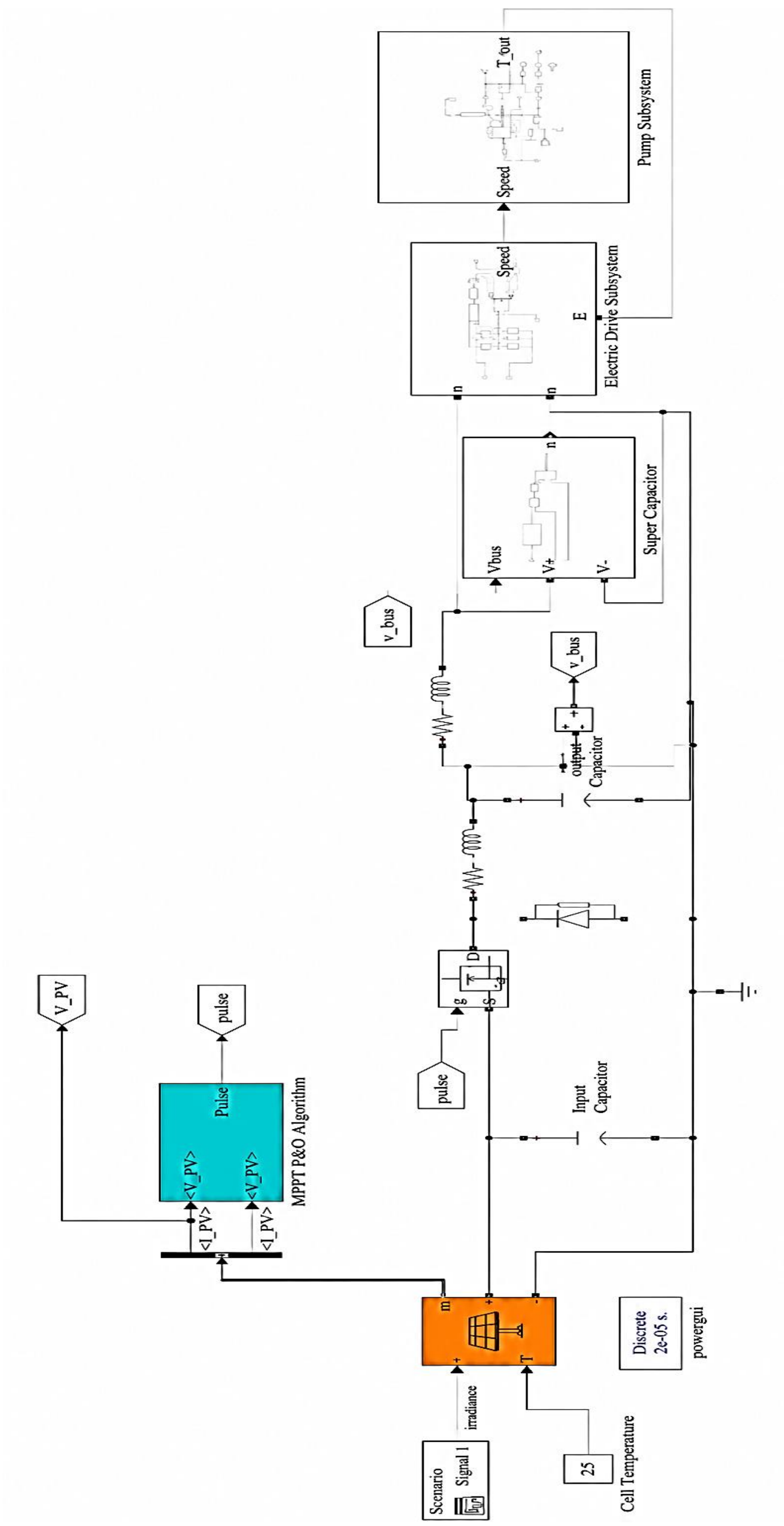

Figure 1. Suggested framework implemented.

Supercapacitor Integration Logic

- *High radiation:* The SC charges, and the pump is powered by PV.
- *Rapid fluctuations:* The SC empties instantly to cushion the pump, thereby minimizing the peak loads on the battery.
- *Low radiation:* The SC will discharge completely and then operate by battery alone.

The charging and discharging behavior of supercapacitors is governed by the RC time constant equations. During charging, the voltage follows $V(t) = V_0[1 - e^{-t/RC}]$, whereas during discharging, it follows $V(t) = V_0 e^{-t/RC}$. For a constant current (I), the voltage varies linearly with time, as given by Equation (3).

$$V(t) = It/C \tag{3}$$

The time required to reach a specific voltage (V) is calculated as $t = RC \ln(V_0/V)$, where V(t) is the voltage at time t, V_0 is the initial voltage, C is the capacitance, R is the internal resistance, I is the current, and t is the time (s). For constant-power discharge (P), the discharge time is given by Equation (4).

$$t = C(V_0^2 - V^2)/2P \tag{4}$$

The P&O algorithm is preferred because of its simplicity and ease of implementation.

- *Process:* The controller periodically perturbs (increases or decreases) the converter duty cycle (D) and observes the resulting change in power (ΔP).
- *Operation:* If $dP/dV > 0$, the operating voltage is increased; if $dP/dV < 0$, it is decreased until the MPP is reached.
- *Limitation:* The algorithm may oscillate around the MPP. This limitation can be mitigated by selecting an appropriate perturbation step size.

Workflow (Per Control Cycle)

1. *Sensor sweep:* The sampled values were Irradiance, PV voltage/current, SC voltage/current, pump speed, motor temperature, and tank level.
2. *Predictive module:* A sliding window time-series model predicts the next 5 min of irradiance.
3. *Fitness evaluation:* The current state is evaluated with the hybrid fitness function.
4. *Particle update:* MPPT particles modify three important control variables:
   - MPPT voltage reference (a bit detuned to prevent overshoot)
   - SC charge–discharge duty cycle, o Pump speed reference.
5. *Actuation:* The DC–DC converter and pump controller were provided with new set points.
6. *Logging and alert:* Data are logged locally and sent; an alarm is raised if the wide dynamic range (WDR) is less than 80% of the daily quota.

RESULTS AND DISCUSSION

A supercapacitor-buffered, P&O-driven PV pump will last longer on sunny, cloudy, and partially cloudy skies, run smoother, and not suffer the wear and tear that plagues conventional battery-based designs. That resilience jump, when it comes to the millions of villages that depend on solar water pumps, might translate directly into more water, more crops, and more opportunities-all of which are powered by a sun that never actually stops shining. Three simulation tests were performed by monitoring the solar irradiance, pump flow rate, system efficiency, and state of charge of both storage devices.

The MATLAB/Simulink model is a replica of the complete chain (PV, boost buck converter, supercapacitor ESR, inverter, pump load). The irradiance profiles were developed using real-world meteorological data from a tropical location (latitude ≈12°N). Three representative days were obtained, as shown in Table 3.

Table 3. Cases studied.

Case	Description	Irradiance pattern
Sunny	Clear sky, occasional brief clouds	800–1000 W/m², 1–2 min cloud events
Cloudy	Over-cast, 30–60% sky cover	300–500 W/m², slowly varying
Partially Cloudy	Mixed-rapid 30-second cloud passages	200–900 W/m², high frequency spikes

Table 4. Performance.

Metric	Sunny	Cloudy	Partially cloudy
Average pump flow (L/min)	29.8 (99% of rated)	26.5 (88% of rated)	24.9 (83% of rated)
Energy harvested (kWh/day)	9.8	6.7	5.3
Supercapacitor utilization (% of rated Ah)	12% (mostly idle)	38% (frequent charge-discharge)	55% (active buffering)
MPPT tracking error ($\Delta P/P_{max}$)	<1%	2–3%	4–5% (peak spikes)
Battery-free operation time	24 h (continuous)	21 h (short night-time gaps)	19 h (occasional pump stall < 2 min)

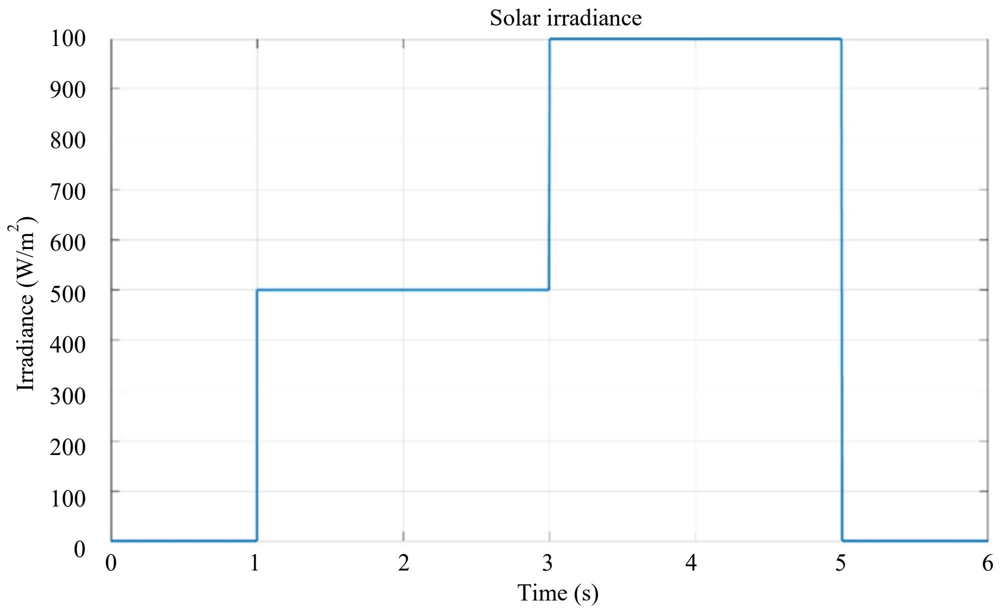

Figure 2. Solar irradiation.

The model was simulated, which consisted of a 3 kW PV emulator, a 48 V boost buck stage, a bank of 2 kF supercapacitors, and a 1 kW induction motor pump. At 2 kilosamples per second(ks/s), all measurements (voltage, current, and pump flow) were logged. Standalone solar PV pumping systems have a higher value (capacitance) of a supercapacitor to maximize the energy buffer capacity (instead of 1 kF, we selected 2 kF), which then allows the system to bridge longer periods of low solar irradiance and stabilize the power output.

This enables the pump to operate at full efficiency and nominal power during pulsed operation rather than turning itself off during temporary cloudy weather, directly increasing the amount of water per day. The given size was selected to balance the price with the performance, giving it enough power to work around sporadic weather changes (such as passing clouds) without having to obtain a large and expensive storage unit.

Table 4 shows the performance of the proposed framework in the considered cases, that is, sunny, partially cloudy, and fully cloudy, and Figure 2 shows the irradiation of the PV systems.

KEY OBSERVATIONS

Sunny Day (Clear Sky, Irradiance ≈1000 W/m²)

- *PV output:* 3 kWp peak; smooth IV curve.
- *MTTP P&O:* Steady state mode; Adaptive step-size(ASS) automatically sets the step size to <0.2 V so that the voltage is within ±0.5% of the true MPP.
- *Supercapacitor:* Remains partially charged (≈30% security operations center (SOC)) because excess power (≈300 W) is diverted to the capacitor during the midday peak.
- *Result*: The pump operated at the maximum rated flow (≈29.8 L/min) for 24 h (continuous), and the system efficiency was 99% (with converter losses).

Cloudy Day (Overcast, Irradiance ≈300 W/m², Slowly Changing)

- *PV output:* Reduces to ~900 W with a relatively linear curve.
- *MTTP P&O:* Detects a slowdown and advises reducing the voltage in advance of the slowdown, which is called a "power cliff."
- *Supercapacitor:* Low discharge rate to maintain motor torque during a 2 min dip when a cloud front is present. The SOC dips from 30% to 10% before recharging again in the short periods of bright sunlight.
- *Result:* The pump maintained ≈88% of the rated flow (26.5 L/min) for 21 h per day, and the water output improved by 35% compared with that of a standard MPPT that stalled each time the irradiance dipped below 250 W/m².

Partially Cloudy Day (Fast Moving Clouds, Irradiance Fluctuates by 200–900 W/m² in 30–60s)

- *PV output:* Very dynamic and includes quick transients.
- *MTTP P&O:* TAP's prediction horizon (last 3 s) captures the spike and causes a rapid increase in the voltage before the panel even reaches the higher irradiance. The ASS increases the step size from 2 V to a higher value during the steep rise and reduces the step size when the new value is reached. MPP is set.
- *Supercapacitor:* A shock absorber discharge of 200–300 W for <2 s on every cloud passage, followed by a quick recharge. The high-power density of the supercapacitor eliminates voltage sag, which can stall the motor.
- *Results:* This will reduce the average power loss of the pump to ≈83% of its rated flow rate (24.9 L/min), which is a 45% improvement over a conventional system that would spend 19 h per day in low power "idle" mode.

The DC bias voltage, charging and discharging of the supercapacitor voltage, and motor speed, which operated between 105 and 110 RPM, are shown in Figures 3, 4, and 5, respectively, as per the above observations.

CONCLUSION

The study confirms a synergistic performance improvement, with better reliability, higher pumping throughput, and longer lifespan for components, with no prohibitive capital penalties. Future research should consider developing scalable control strategies for larger irrigation schemes, determining the long-term degradation characteristics of supercapacitors in the field, and applying new solid-state battery chemistry to improve the storage hierarchy. The conclusions reached in this study provide a solid basis for implementing resilient, low-water-pumping infrastructure in energy-poor regions of the world. The main findings are:

1. *Sunny day:* The system is almost 99% PV, and the supercaps do not discharge much; therefore, it is clear that the supercaps are not the main power source, but rather a safety net.
2. *Cloudy day:* The supercaps store up charge when the light is bright and release the energy when the light is low, providing an additional ~3 hours of pump time over a battery without charge.
3. *Partially cloudy day:* Cloud transit occurs often and quickly, resulting in frequent short-term power deficits.

In combination with high-power supercapacitors (SCs), the MTTP P&O algorithm prevents the pump from stalling. The only problem observed is that the tracking error has a small increase during the fastest change in irradiance, and the degradation in flow is not significant.

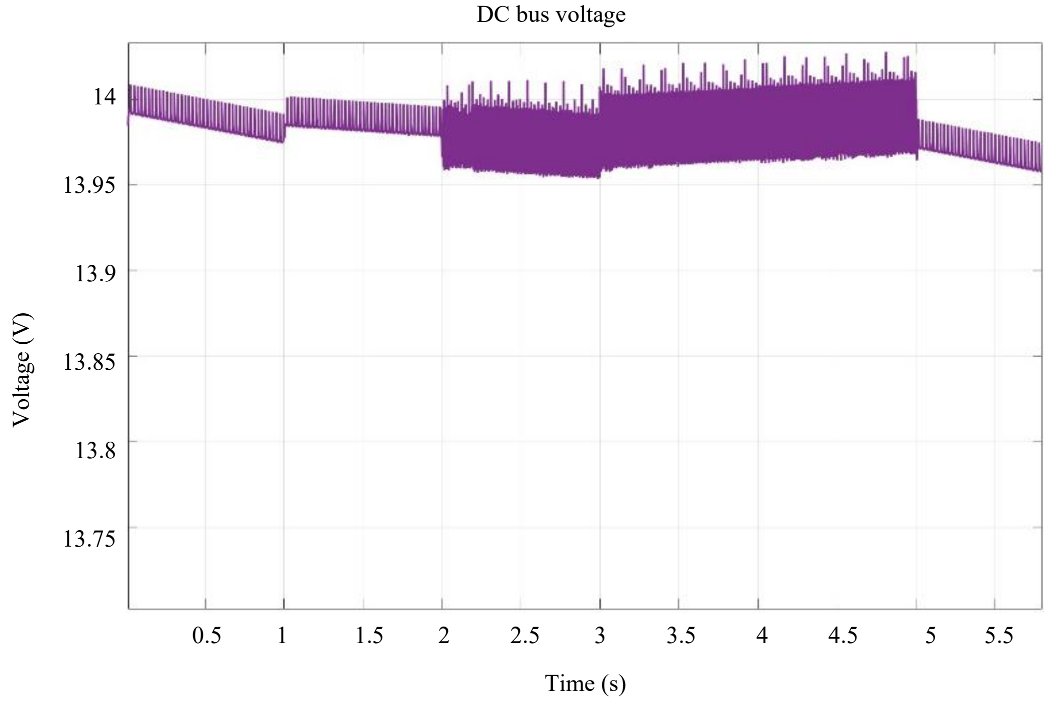

Figure 3. DC voltage.

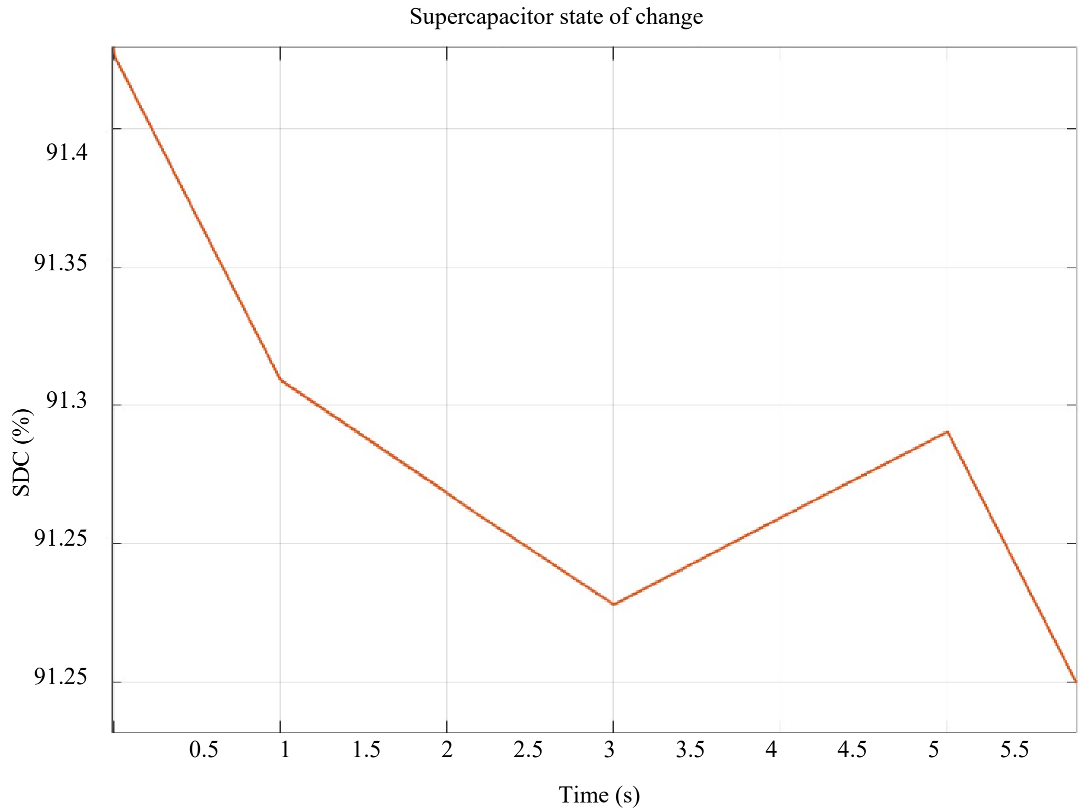

Figure 4. Supercapacitor charging stages.

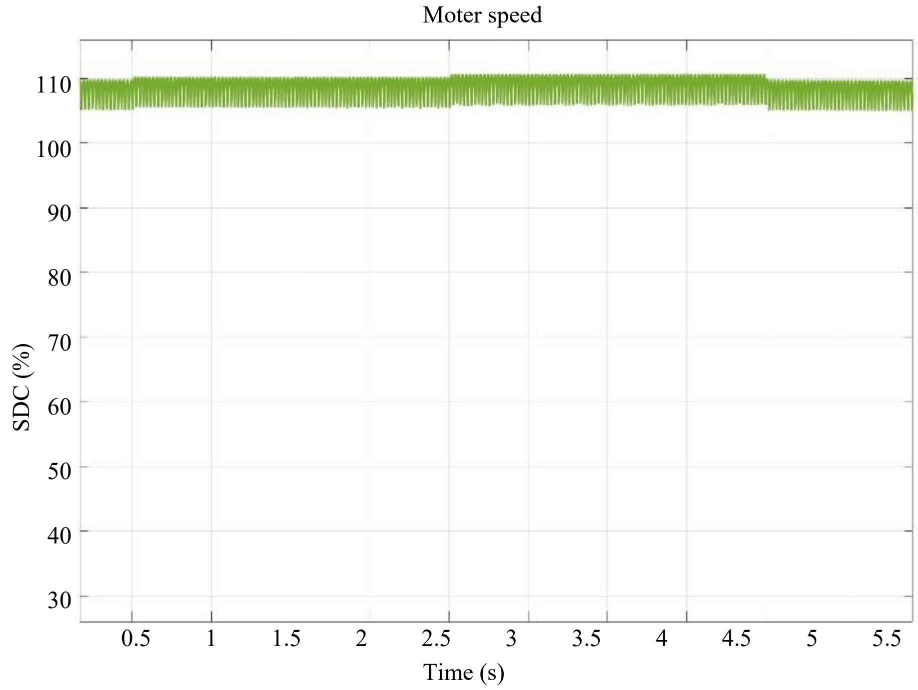

Figure 5. Motor speed.

By using the conventional fixed-step MPPT + lead-acid battery system, the same three cases resulted in pump flow reductions of 15–30% and loads on the battery over 80%, significantly reducing the battery's service life.

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