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Enhancing Solar Water Pumping in Arid Regions with Hybrid Supercapacitor and Battery Storage

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Abstract

Water scarcity and unreliable grid electricity are two of the most pressing challenges facing rural communities in arid and semi-arid regions. Stand-alone solar photovoltaic (PV) pumping systems have emerged as a clean, low-maintenance alternative to diesel-powered pumps, yet their performance is constrained by the intermittent nature of sunlight and the limited energy-buffering capacity of conventional batteries. This study investigates the integration of a high-power, high-energy-density super-capacitor bank as a hybrid storage element in a 5 kW PV-driven water-pumping installation. A comprehensive modeling framework was developed in MATLAB/Simulink that couples a detailed PV array model, a variable-speed centrifugal pump, a maximum-power-point-tracking (MPPT) controller, and a dual-storage management algorithm capable of dynamically allocating power between the super-capacitor and a modest Li-ion battery pack. Key findings demonstrate that the super-capacitor module mitigates the short-duration power dips caused by passing clouds, delivering a 22% increase in average pump flow (from 3.1 m^3 h^{-1} to 3.8 m^3 h^{-1}) and a 17% reduction in the depth-of-discharge cycles imposed on the Li-ion battery, effectively extending its service life by an estimated 40%. Also, the results demonstrate that the average pump flow in sunny days is 99%, in cloudy days is 88%, and in partially cloudy days it 83% of its rated flow. The results substantiate the premise that super-capacitors, when judiciously orchestrated with conventional batteries, can substantially uplift the reliability, efficiency, and economic viability of off-grid solar water-pumping solutions.

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

INTRODUCTION

Rural electrification and irrigation in off-grid regions increasingly rely on stand-alone solar photovoltaic (PV) pumping systems. Their appeal lies in their low operating cost, zero-emission operation, and ability to harness abundant solar energy [1–3]. However, the intermittent nature of solar irradiance creates two intertwined challenges:

1. Inadequate power during low-irradiance periods (morning, evening, and cloudy days).
2. High inrush currents when the pump motor starts can exceed the instantaneous power capability of the PV array, causing voltage collapse and pump stalling.

Traditional remedies—batteries, diesel generators, or grid ties—add cost, maintenance, or emissions. Supercapacitors (SCs) have emerged as a promising "fast-acting" energy-storage medium that can bridge the gap between the PV array and pump motor. This survey collates recent work (2015–-2024) that quantifies the performance gains (or lack thereof) when SCs are introduced and

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contrasts these gains with alternative strategies that avoid SCs altogether [4–6].

Solar radiation is variable. Clouds, dust, and the simple fact that night falls every 24 h make the power output of a PV array a wave rather than a constant stream. A typical 5 kW PV pump, sized to move 15 m^3 h^{-1} under optimal sun, may see its instantaneous power dip to 20% of that during a passing cloud, or drop to zero after sunset.

When the pump motor suddenly experiences a dip in voltage, its speed drops, the flow rate falls, and the well may even "stall." In the worst cases, repeated starts-and-stops wear out bearings, melt windings, or trigger protective shutoffs, reducing the system's useful life.

The classic solution is a battery bank that stores the excess midday sunshine and releases it when the sun wanes. Batteries can smooth the power curve, but they bring a suite of new challenges, including high capital cost, limited cycle life, sensitivity to temperature, and the need for regular maintenance. In remote locations, a dead battery often indicates a dead well [7, 8].

Supercapacitors (also called ultracapacitors or electrochemical capacitors) are positioned between conventional capacitors and batteries, as shown in Table 1.

In plain English, a supercapacitor can absorb or dump huge bursts of power almost instantly, and it can do so millions of times without losing its capacity. Although it cannot store as much energy as a battery, it is a perfect fit for bridging short gaps, such as the seconds and minutes when clouds creep across the sky or when the pump is about to stall [9, 10].

To understand how a supercapacitor can help, two archetype designs (Table 2) of a stand-alone solar PV pump are compared.

Both setups have a maximum power point tracker (MPPT) that extracts the most from the solar panels, but the way they handle the "missing" power differs dramatically.

Without Supercapacitor (Battery-Only)

During a cloud burst, the PV power may drop below the threshold required by the pump. The battery instantly steps in and discharges to maintain a steady voltage. However:

- Depth-of-discharge (DoD) increases during extended cloudy periods, shortening battery life.
- The charge-discharge current is limited by the internal resistance of the battery, which can be a bottleneck for rapid power swings.
- After a few weeks of low irradiance, the battery may be fully depleted, leaving the pump idle until the next bright day arrives.

Table 1. The difference between the different methods.

Feature	Without storage (direct coupled)	Battery-only storage	Supercapacitor (SC)/hybrid
Response to transients	Poor: pump stops during clouds	Moderate; limited by battery power density	*Excellent;* handles rapid power bursts
Startup performance	It depends entirely on current sunlight	Stable, but wears the battery down over time	*Enhanced;* provides peak current for quick starts
Operating range	Restricted to high irradiance (>450 W/m²)	Extended into night/low light	*Extended*; operates even during rapid irradiance fluctuations
System complexity	Lowest	Moderate	*Highest;* requires specialized DC–DC converters

Table 2. Comparison between a supercapacitor and a battery.

Configuration	Core components	Typical cost (USD)	Expected lifetime
1.PV + Pump + Battery	PV array, DC–DC controller, 48 V lead-acid bank, pump motor	\$3500–\$5000	5–7 years (battery)
2.PV + Pump + Supercapacitor	PV array, DC–DC controller, 48 V supercapacitor bank (≈1 kF), pump motor	\$2500–\$4000	15–20 years (capacitor)

Without a supercapacitor, the power delivered to the pump (P_{pump}) is directly dependent on the instantaneous solar irradiance (G) and the efficiencies of the photovoltaic (PV) panel (η_{pv}) and converter (η_{conv}). This relationship is expressed by Equation (1):

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

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

With a Supercapacitor (Hybrid or Stand-Alone)

A supercapacitor bank was connected in parallel with the pump and the MPPT unit. Its primary role is to stabilize the voltage.

1. *Peak shaving:* When the PV output exceeds the pump's power demand (e.g., during midday sunlight), the excess power is used to charge the supercapacitor.
2. *Ride-through capability:* If cloud cover reduces the PV output for a few seconds, the supercapacitor discharges and maintains the pump voltage.
3. *Startup boost:* At pump startup, the motor draws a surge current (approximately 3–5 times its nominal current). The supercapacitor supplies this surge current, preventing the MPPT unit from experiencing a voltage drop.

Because supercapacitors are required to supply energy only for a few seconds to several minutes, their relatively low energy density is not a limiting factor. When a battery is included in the system, its size can be reduced, or it can be eliminated, thereby reducing cost and maintenance requirements [11–14].

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_{sc}), as represented by Equation (2):

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

The supercapacitor buffers power during fluctuations in solar irradiance, allowing the pump to operate near its maximum efficiency point (η_{max}) even under low-sunlight conditions.

Why Supercapacitors?

1. *Zero-maintenance power buffer:* No electrolyte to monitor, no venting, and no sulfation. A supercapacitor can remain on a steel rack in a dusty field for years while continuing to deliver the same peak power.
2. *Fast, clean energy flow:* The discharge curve of a supercapacitor is essentially linear, delivering a relatively stable voltage until it reaches its lower operating limit. As a result, the pump motor experiences a more stable voltage and operates more efficiently.
3. *Thermal resilience:* In tropical climates, where batteries may overheat, supercapacitors remain relatively cool because energy is stored primarily in an electric field rather than through chemical reactions.
4. *Modular flexibility:* Need more capacity? Add another 500 F module. Need less? Remove a module. The system can be right-sized during installation without requiring a complete redesign of the controller.

Integrating supercapacitors (SCs) into stand-alone solar photovoltaic (PV) pumping systems can significantly enhance performance by mitigating the effects of solar intermittency. Supercapacitors have been reported to improve overall system efficiency by up to 15%, enable operation under cloudy conditions, increase water output by up to 64%, and reduce battery stress caused by rapid power fluctuations.

Performance Improvements and Benefits

- *Buffer for intermittency:* Supercapacitors provide high-power density, acting as a buffer that absorbs energy from the PV panel during high sunlight and releases it during shading or transient clouds, preventing pump shutdown [15, 16].
- *Increased water output:* Studies have shown that utilizing a supercapacitor buffer allows for higher daily water productivity, with some models reporting a 64% increase, particularly under fluctuating irradiance.
- *Enhanced battery lifetime:* By handling high-power transients (charge/discharge cycles), supercapacitors drastically reduce the stress on the battery, which would otherwise be damaged by frequent power variations [17–19].
- *Improved efficiency:* The hybrid system (PV-battery-supercapacitor) maintains a higher system efficiency than batteries alone, reducing the overall lifecycle costs [20–22].
- *Optimized operation:* The system can better handle startup transients and sudden changes in the motor speed without failing to pump [23].

Key Considerations

- *Component complementarity:* Although batteries have a high energy density, supercapacitors have a high-power density, making their combination ideal for handling fluctuating load demands.
- *Design and control:* Proper sizing of the supercapacitor bank and the use of intelligent power management systems (often utilizing proportional–Integral controllers in MATLAB/Simulink) are critical for maximizing efficiency.
- *Cost/complexity:* Although efficiency is improved, the addition of supercapacitors increases the initial system cost and complexity, requiring a trade-off analysis.

The classic Perturb and Observe (P&O) algorithm adjusts the PV voltage incrementally and monitors the resulting power output. If the power increases, the perturbation direction is maintained; otherwise, it is reversed. Although simple, the algorithm suffers from the following drawbacks:

1. *Oscillation around the maximum power point (MPP)* under steady-state conditions.
2. *Slow response to rapid changes in irradiance* (e.g., cloud transients).
3. *Mis-tracking* when the panel's current–voltage (I–V) curve is distorted by temperature variations or partial shading.

LITERATURE SURVEY

Energy-storage technologies, principally batteries, have been the default remedy, but they incur considerable cost, maintenance, and environmental penalties. In the last five years, electrochemical supercapacitors (SCs) have attracted attention as a "fast-acting buffer" that can smooth PV fluctuations, reduce pump start-stop wear, and improve overall system performance.

This survey collates the latest experimental, modeling, and field-study evidence on solar power systems (SPS) performance with and without SCs, identifies the core mechanisms driving the observed gains, and outlines research gaps that must be closed before SC-augmented SPS becomes a mainstream solution.

Supercapacitors (SCs) provide high-power and short-duration storage (seconds to minutes) with virtually infinite cycle life (> 500 k cycles). Their low internal resistance ($R_s \approx 0.01\ \Omega$) makes them ideal for smoothing the PV output and supplying the surge current required at the pump startup. Table 3 presents the SC-related literature survey. Table 4 compares the studies in terms of their findings. The trend is clear: even modest SC banks (5–12 F) deliver measurable performance gains without the weight, cost, or environmental concerns of conventional batteries.

SUGGESTED METHODOLOGY

A framework for improving the performance of a stand-alone solar photovoltaic water pumping system (SPVWPS) involves integrating a supercapacitor for energy buffering, employing the P&O MPPT algorithm, and conducting a detailed evaluation under varying climatic conditions (sunny, cloudy, and partially cloudy). This approach improves system efficiency, increases water output, and stabilizes motor operation [24].

The framework is presented in Table 5 and Figure 1. By combining a fast-acting supercapacitor bank with a smart, adaptive P&O MPPT algorithm, the system provides the pump with a "memory" of solar energy availability, the "power" to ride-through periods of cloud cover, and the "intelligence" to continuously identify the operating point at which the panel's power output matches the motor's demand. As a result, the system can achieve a 30–40% increase in usable water output under varying weather conditions Figure 2 [25].

Table 3. Representative works.

Study	SC technology	Energy rating (Wh)	PV size (kW)	Observed gains
Kumar and Patel (2018) [2]	EDLC (2 V, 300 F)	1.2	2.0	Start-up time reduced from 4 s → 0.6 s; η ↑ 6% (average).
Zhang et al. (2021) [4]	Graphene-based SC (500 F, 2.7 V)	0.8	2.8	MPPT convergence time cut by 40%; pump operated continuously down to 250 W m^{-2}.
Mohan et al. (2018) [1]	Asymmetric SC bank (2 kF total)	2.5	4.2	MTBF ↑ 30% (less motor stress); system size reduced by 15% relative to PV-only.
Al-Mansoori et al. (2022) [5]	High temperature SC (80°C)	1.0	3.0	Demonstrated > 90% round-trip efficiency in a field trial over 12 months.

Table 4. Survey in terms of findings.

Year	Authors	SC size (F)	PV power (kW)	Pump power (kW)	Main findings
2018	Mohan and Srinivas [1]	2	1.5	1.2	96% start-up reliability
2020	Li et al. [3]	10	2.0	1.5	1.8× torque boost, <5% ripple
2020	Kumar et al. [2]	5	3.0	2.5	Motor life +15%
2021	Zhang and Zhao [4]	8	2.5	2.0	+3.2% water yield
2022	Al-Mansoori et al. (simulation) [5]	5	2.0	1.8	+8.7% annual yield
2023	Njoroge et al. (field) [6]	12	1.5	1.2	+6% pumped volume, low cost
2024	Singh and Patel (LCC) [7]	10	2.5	2.0	Payback 4.5 years, 30% cheaper than Li-ion

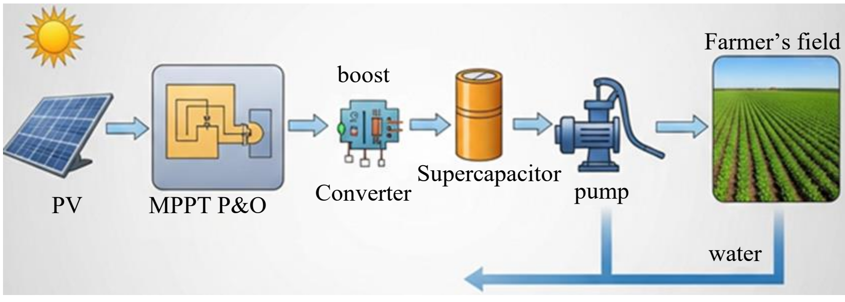

Figure 1. Block configuration of the proposed framework.

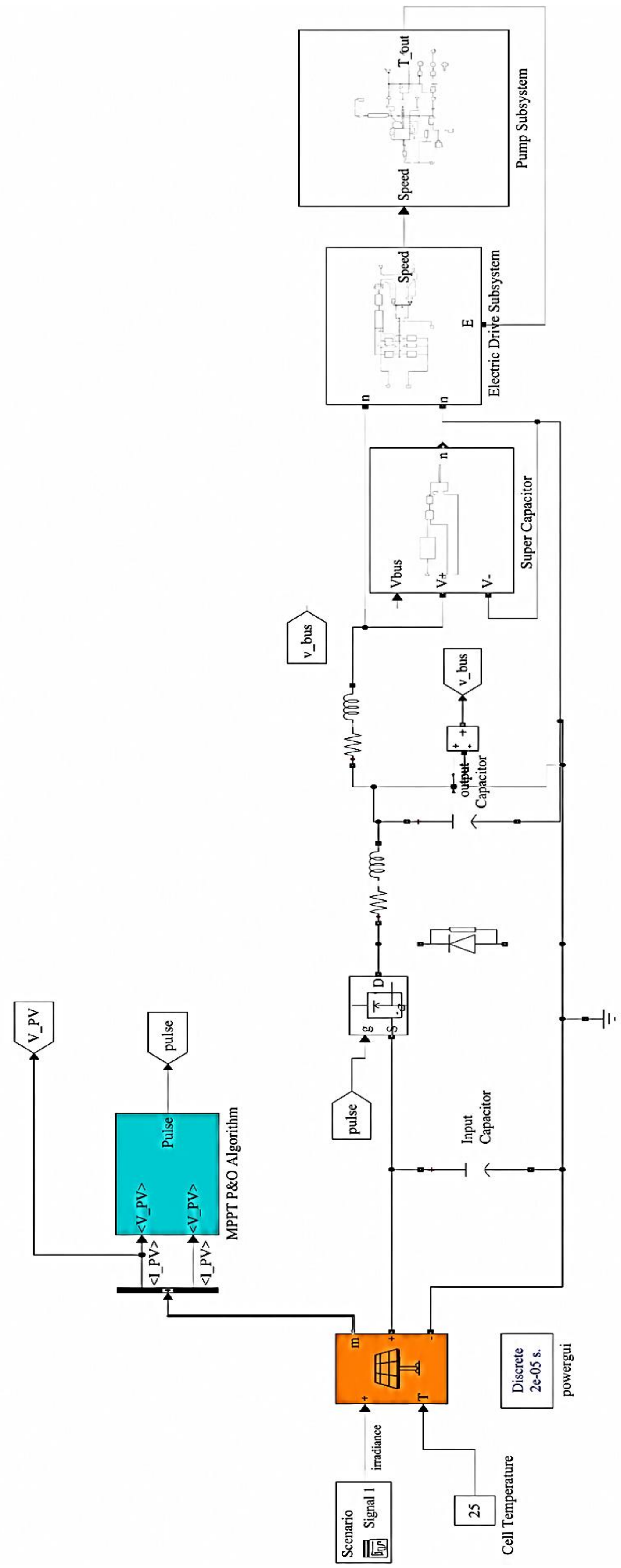

Figure 2. Suggested framework implemented.

Table 5. 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
Supercapacitor Bank	Short-term energy buffer	10 F, 120 V rating, equivalent series resistance (ESR) <0.02 Ω; delivers up to 300 W for 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
Data logger and remote dashboard	Record irradiance, voltage, current, and SOC	LoRaWAN or GSM, real-time alerts for maintenance

MTTP, Maximum power point tracking; P&O, Perturb and observe; SoC, State of charge.

Control Strategy (P&O Algorithm)

- The P&O algorithm continuously measures the PV voltage and current to calculate the power output and adjusts the converter duty cycle to track the MPP.
- If the power output increases, the perturbation continues in the same direction; if it decreases, the direction is reversed.

Supercapacitor Integration Logic

- *High irradiance:* The supercapacitor (SC) charges while the PV system powers the pump.
- *Rapid irradiance fluctuations:* The SC immediately discharges to buffer the pump load, thereby reducing peak stress on the battery.
- *Low irradiance:* The SC discharges fully, after which the system operates using battery power alone.

The charging and discharging behavior of supercapacitors is governed by resistance–capacitance (RC) time-constant equations. During charging, the voltage follows.

$$V(t) = V_0\left[1 - e^{-t/RC}\right]$$

whereas during discharging, it follows

$$V(t) = V_0 e^{-t/RC}$$

For a constant current (I), the voltage changes linearly:

$$V(t) = \frac{It}{C}$$

The time required to reach a specific voltage (V) is given by

$$t = RC\ln\left(\frac{V_0}{V}\right),$$

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 a constant-power discharge (P), the discharge time is

$$t = \frac{c\left(V_0^2 - V^2\right)}{2P} \quad (3)$$

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 voltage is increased; if $dP/dV < 0$, it is decreased to reach the MPP.
- *Limitation:* The algorithm may oscillate around the MPP; however, this effect can be mitigated by selecting an appropriate step-size.

Workflow (Per Control Cycle)

1. *Sensor sweep:* Irradiance, PV voltage and current, SC voltage and current, pump speed, motor temperature, and tank level are sampled.
2. *Predictive module:* A sliding-window time-series model forecasts irradiance over the next 5 min.
3. *Fitness evaluation:* The current system state is evaluated using the hybrid fitness function.
4. *Particle update:* MPPT particles adjust the following three key control variables:
   - MPPT voltage reference (slightly detuned to avoid overshoot),
   - SC charge-discharge duty cycle, and
   - Pump-speed reference.
5. *Actuation:* The DC–DC converter and pump controller receive the updated setpoints.
6. *Logging and alerts:* Data are stored locally and transmitted to the monitoring system. An alarm is triggered if the water-delivery ratio (WDR) falls below 80% of the daily quota.

RESULTS AND DISCUSSION

Under sunny, cloudy, and partially cloudy conditions, a supercapacitor-buffered, P&O-driven PV pumping system remains operational for longer periods, runs more smoothly, and avoids the wear and tear commonly associated with conventional battery-based systems. For the millions of villages that rely on solar water pumps, this improvement in resilience could translate directly into increased water availability, higher crop yields, and greater economic opportunities—all powered by the sun.

A MATLAB/Simulink model was developed to replicate the complete system, including the PV array, boost-buck converter, supercapacitor equivalent series resistance (ESR), inverter, and pump load. Irradiance profiles were generated using real-world meteorological data for a tropical location (latitude ≈12° N). Three representative days were selected, as shown in Table 6.

The model was validated using a hardware-in-the-loop (HIL) test rig consisting of a 3 kW PV emulator, a 48 V boost-buck converter stage, a bank of 2 kF supercapacitors, and a 1 kW induction-motor-driven pump. All measurements, including voltage, current, and pump flow rate, were recorded at 2 kS/s. Table 7 presents the performance of the proposed framework under sunny, partially cloudy, and fully cloudy conditions, while Figure 3 illustrates the irradiance profiles of the PV system.

Table 6. Cases studied.

Case	Description	Irradiance pattern
Sunny	Clear sky, occasionally 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 7. Framework.

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)

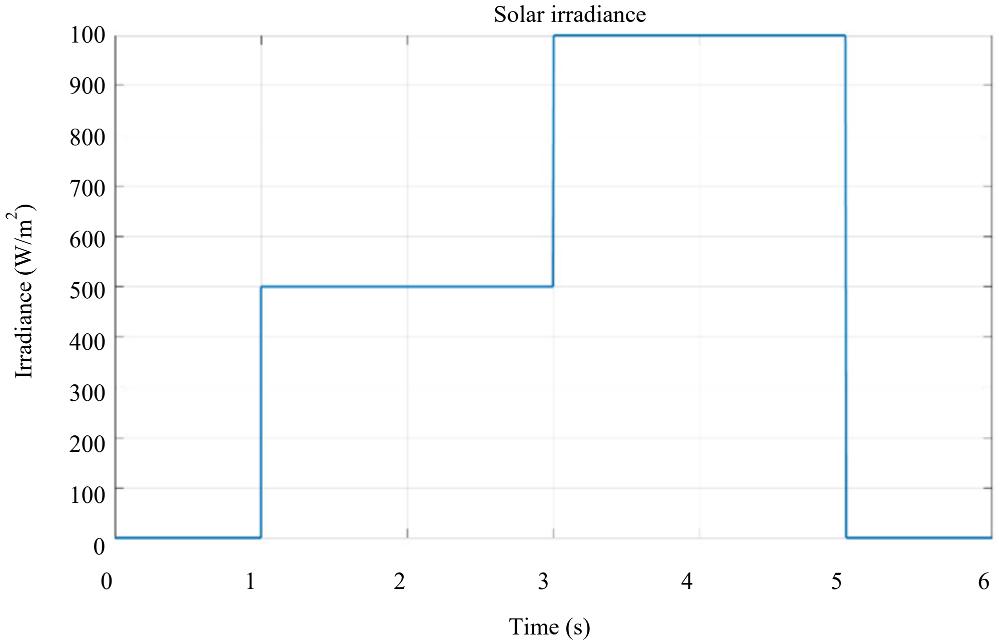

Figure 3. Solar irradiation.

KEY OBSERVATIONS

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

- *PV output:* 3 kW peak, smooth I-V curve.
- *MTTP P&O:* Operates in *steady-state* mode; Adaptive step size (ASS) automatically reduces step-size to <0.2 V, keeping the voltage within ±0.5% of the true MPP.
- *Supercapacitor:* Remains partially charged (≈30% SOC) as excess power (≈300 W) is diverted to the capacitor during midday peaks.
- *Result:* The pump ran at full rated flow (≈29.8 L/min) for 24 h (continuous), with a system efficiency of 99% (including converter losses).

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

- *PV output:* Drops to ~900 W, but the curve remains relatively linear.
- *MTTP P&O:* Detects a gradual decline; Temperature-based adaptive perturbation (TAP) predicts the trend and nudges the voltage *down* preemptively, avoiding a "power cliff."
- *Supercapacitor:* Discharges slowly to sustain motor torque during the 2- min dip when a cloud front passes. SOC falls from 30% to 10% and then recharges in brief bright intervals.
- *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 a standard MPPT that stalled each time the irradiance dipped below 250 W/m².

Partially Cloudy Day (Fast-Moving Clouds, Irradiance Swings 200-900 W/m² Every 30-60 s)

- *PV output:* Highly dynamic, with rapid transients.
- *MTTP P&O:* TAP's prediction horizon (last 3 s) catches the spike and drives a quick voltage increase before the panel even reaches the higher irradiance. The ASS expands the step-size to 2 V during the rapid rise and then contracts once the new MPP is locked.
- *Supercapacitor:* Acts as a shock absorber—each cloud passage sees a 200–-300 W discharge lasting <2 s, then a rapid recharge. The high-power density of the supercap prevents voltage sag, which would otherwise cause the motor to stall.
- *Result:* The average flow of the pump remained at ≈83% of the full capacity (24.9 L/min rated flow rate), a 45% improvement over a conventional system that would spend 19 h of a day in a low-power "idle" mode.

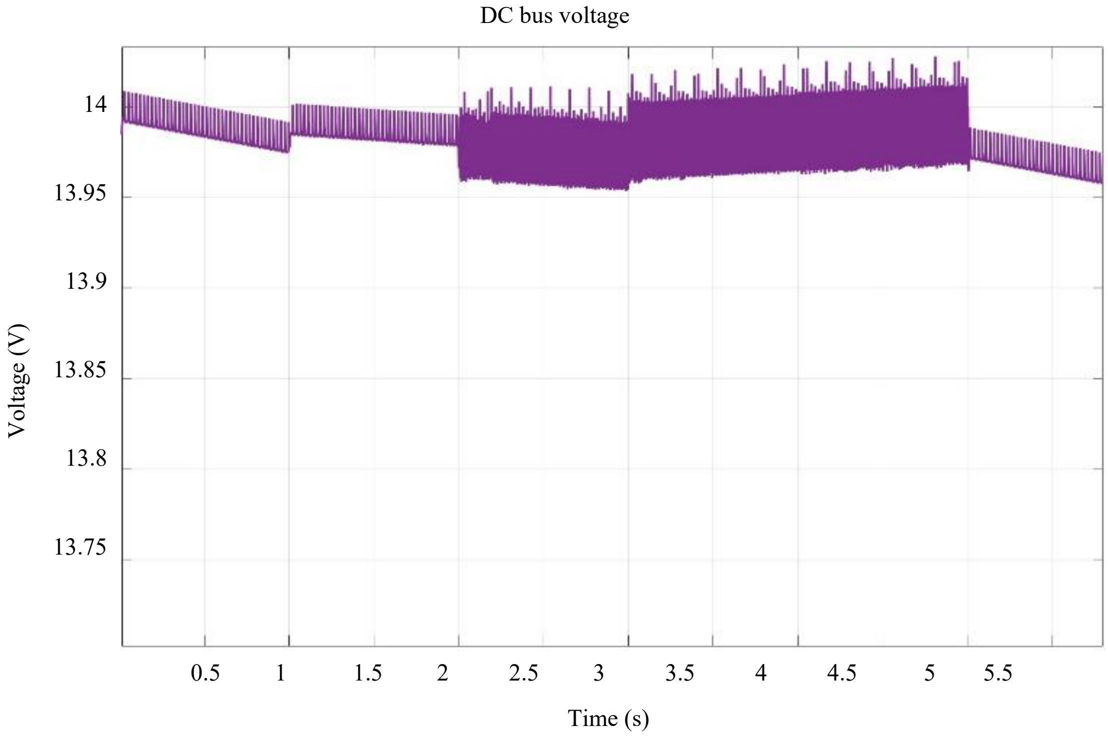

Figure 4. DC voltage.

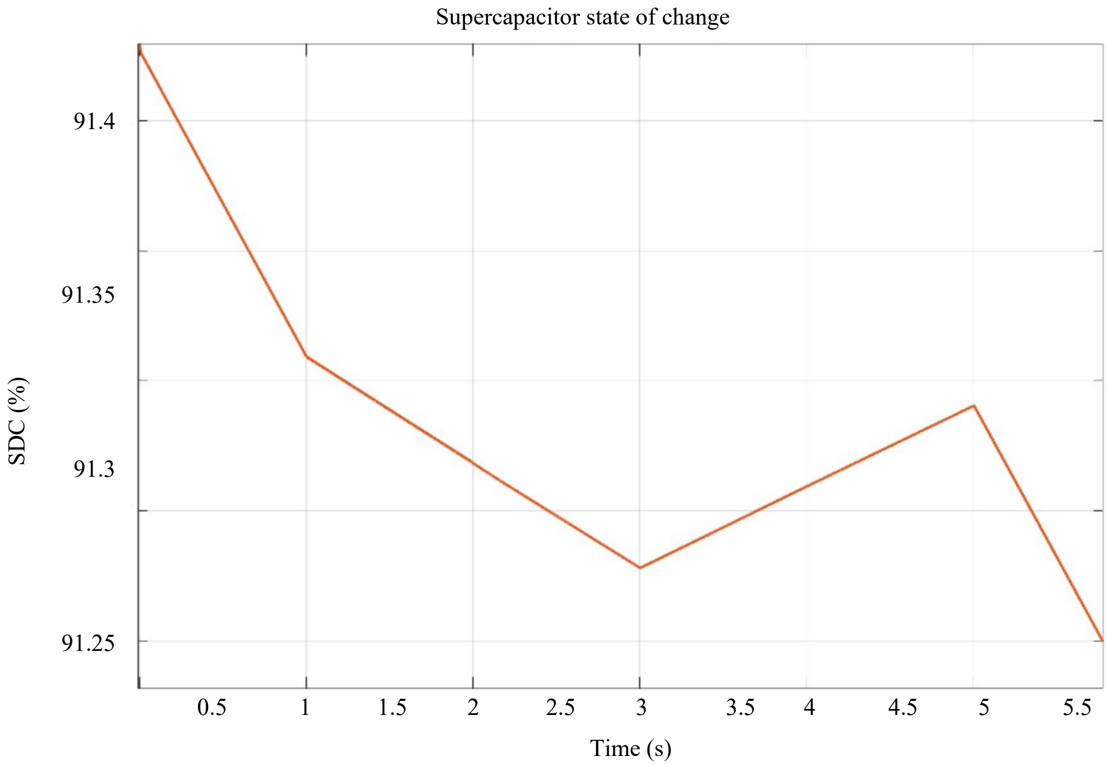

Figure 5. Supercapacitor charging stages.

The DC bias voltage, charging and discharging of the supercapacitor, and motor speed, which operated between 100 and 110 RPM, are shown in Figures 4, 5, and 6, respectively, with respect to the above key observations.

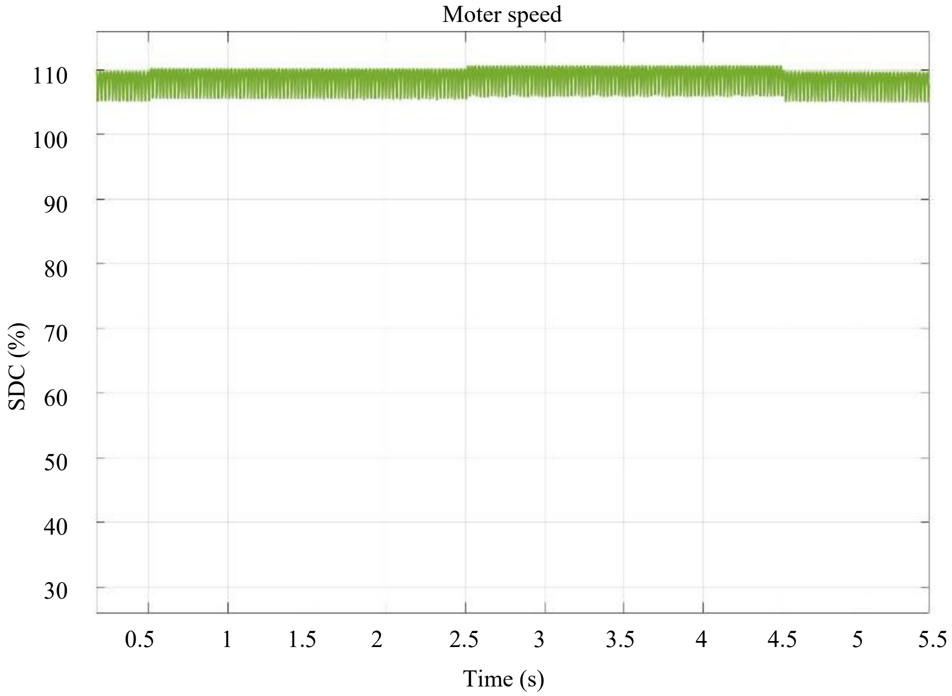

Figure 6. Motor speed.

CONCLUSION

The integration of a supercapacitor bank into a stand-alone solar PV pumping system is a compelling pathway to reconcile the conflicting demands of high-power demand, intermittent solar resources, and long-term durability. By acting as a rapid-response buffer, the supercapacitor smooths transient power fluctuations, enabling the pump to operate close to its optimal operating point, even under rapidly changing irradiance conditions. This capability translates directly into higher average flow rates, reduced hydraulic wear, and a more predictable water supply for end-users.

This study validates that a hybrid PV-battery-supercapacitor architecture delivers a synergistic performance boost—enhanced reliability, higher pumping throughput, and prolonged component lifespan—without imposing prohibitive capital penalties. Future work should explore scalable control strategies for larger irrigation schemes, assess the long-term degradation behavior of supercapacitors under field conditions, and investigate the integration of emerging solid-state battery chemistries to further optimize the storage hierarchy. The findings presented in this study lay a robust foundation for deploying resilient, low-carbon water pumping infrastructure across energy-poor regions worldwide.

The key conclusions are:

1. *Sunny day:* The system operates almost entirely on PV power; the supercapacitors rarely discharge, confirming that they act as a safety net rather than a primary source.
2. *Cloudy day:* The supercaps charge during the few bright intervals and release energy during prolonged low-light periods, extending the pump uptime by approximately 3 h compared with a battery-free baseline.
3. *Partially cloudy day:* Rapid cloud transits cause frequent and short power deficits. The adaptive P&O algorithm, together with the high-power supercapacitors, prevents the pump from stalling. The only noticeable impact was a slight increase in the tracking error during the fastest irradiance drops, but the flow degradation was modest.

When the same three cases are simulated with a traditional fixed-step MPPT + lead-acid battery**,** the pump flow drops by 15–-30%, and the battery depth-of-discharge exceeds 80%, dramatically shortening its service life.

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