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Investigating BESS-based control of over-voltage in stand-alone PV systems

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Abstract. Over-voltage events pose significant challenges to the operation and reliability of stand-alone solar photovoltaic (PV) systems, particularly in rural off-grid communities. This research investigates Battery Energy Storage System (BESS)-based control as a voltage regulation strategy for mitigating over-voltage conditions in stand-alone PV systems. The study addresses the critical problem of DC bus voltage instability occurring when solar power generation exceeds load consumption during periods of high irradiance, resulting in voltage levels exceeding 110% of nominal values as defined by IEEE/IEC power quality standards. To carry out the investigation, this study encompasses the design and simulation of a 3.12 kW stand-alone PV system in MATLAB Live Editor, incorporating Canadian Solar CS6P-260P modules in a 4S×3P array, a DC-DC boost converter with Perturb and Observe (P&O) MPPT, and a lithium-ion battery system with PI-controlled bidirectional converter. Three simulation scenarios were evaluated: baseline under Standard Test Conditions without BESS, varying irradiance (0-1800 W/m²) without BESS, and varying irradiance with integrated BESS control. The scenario without BESS considered resulted in peak voltages reaching 2,433.16 V with over-voltage lasting 149.996 s. With BESS-based control enabled, the DC bus voltage was maintained at 370 V (±0.10% stability), within the required 340-400 V range, thereby eliminating the over-voltage condition entirely. The findings of this investigation validate BESS-based control as an efficient, loss-free solution compared to Active Power Curtailment, with direct application to rural electrification in Namibia.

1 Introduction

The application of stand-alone solar photovoltaic (PV) systems has gained momentum in rural areas such as Ehafo village (situated in Omuthiyagwiipundi Constituency, Oshikoto region, northern Namibia; coordinates 18°14'30.81"S, 16°30'57.34"E) owing to their ability to supply reliable power, thereby reducing reliance on national grids. Stand-alone photovoltaic (PV) systems normally consist of PV panels, battery energy storage systems (BESS), converters, and loads as illustrated in Fig. 1 [1].

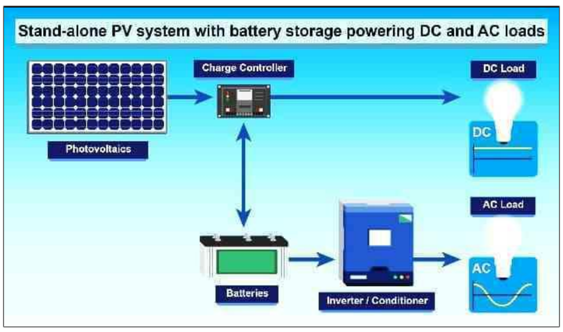

Fig.1. System layout of stand-alone PV system

Solar PV systems are prone to voltage instabilities during operation. The principal challenge is over-voltage, which occurs when generation surpasses consumption, especially during high irradiance and low energy demand periods [2]. Over-voltage is defined as a sustained Root Mean Square (RMS) voltage exceeding 110% of the system's nominal voltage for longer than one minute, in accordance with IEEE/IEC power-quality standards [2]. Over-voltage conditions can lead to inverter disconnection, battery degradation, and reduced system reliability [2].

Several over-voltage mitigation approaches for PV systems have been explored, including Active Power Curtailment (APC), Reactive Power Control (RPC), and Demand-Side Management (DSM) [3]. However, these approaches may not be fully effective or economical in stand-alone configurations. BESS offers a better alternative by storing surplus PV energy in real time and releasing it when generation is low-without wasting energy-while simultaneously stabilizing voltage [4, 5]. Despite growing interest in hybrid PV-BESS systems, a research gap exists in applying BESS-based control specifically to small-scale, stand-alone DC PV systems. Most literature focuses on grid-connected or large-scale microgrid configurations[5]. This project addressed that gap by investigating BESS-based over-voltage control in a stand-alone PV system using MATLAB Live Editor. The study was realized through the following key tasks:

- Reviewed the over-voltage phenomenon in stand-alone PV systems and exploring the role of BESS in voltage regulation.

- Developed a stand-alone PV system exhibiting over-voltage and subsequently integrating BESS-based control logic in MATLAB.
- Analysed the performance of BESS-based control in stabilizing over-voltage using simulation results.

2 Literature review

2.1 Overview of stand-alone solar PV systems

Stand-alone photovoltaic (PV) systems, also referred to as off-grid solar plants, are self-contained electrical power generation and storage units designed to operate independently of a utility grid. They are vital for providing energy access in remote areas or during emergencies[6].

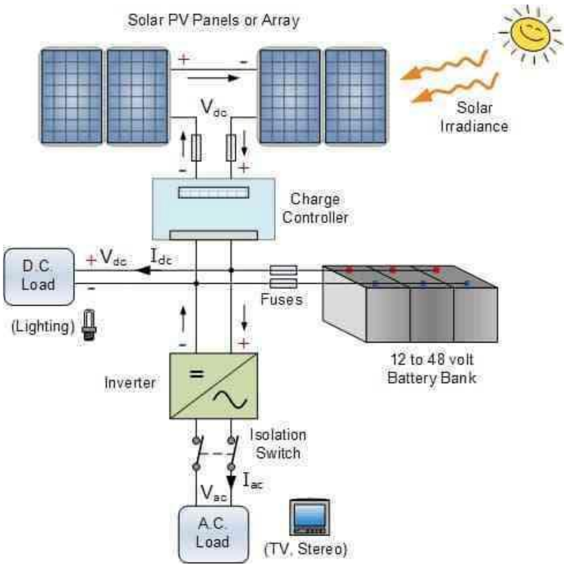

Fig. 2. Typical stand-alone PV system with both DC and AC loads [6]

The fundamental architecture comprises several interconnected components as shown above in Fig. 2

- Photovoltaic Modules: convert solar irradiance into DC electricity. Multiple modules are combined into an array to achieve the desired power output.
- Battery Energy Storage Systems (BESS): store generated DC electricity, ensuring consistent power supply during periods of low or no sunlight.
- Charge Controller: interfaces the solar array with the batteries and regulates power flow, preventing overcharging and over-discharging.
- Inverter: converts DC power into AC electricity compatible with household appliances.
- Ancillary elements: fuses, isolation switches, wiring, and mounting structures.

Operation is regulated by the interaction of the PV array, power-electronic interfaces (MPPT controllers and inverters), energy storage, and the electrical load.

The MPPT algorithm dynamically adjusts the converter duty cycle to extract maximum power as irradiance and temperature change.

2.2 Causes of over-voltage

Over-voltage conditions arise from a confluence of factors:

2.2.1 Excessive power generation

A predominant cause occurs when solar panels generate more electricity than the connected loads can consume and the batteries are nearly charged to full capacity. The surplus power has no immediate pathway, causing bus voltage to rise toward the panel open-circuit voltage (VoC). Without corrective action this stresses other system components.

2.2.2 System design flaws

Improper panel stringing: connecting an excessive number of modules in series can result in a PV input voltage exceeding the maximum MPPT input of the inverter or HV DC bus, causing over-voltage and component damage.

2.2.3 Environmental influence

Solar panel voltage exhibits an inverse relationship with temperature. On cold and sunny days, the operating voltage can increase substantially - approximately 7% at 5°C compared to the nameplate 25°C value - further contributing to over-voltage risk.

2.2.4 External events

Lightning strikes and power surges can induce transient currents and substantial over-voltages within the system's wiring loops, leading to insulation failure and damage to panels, inverters, and communication equipment.

2.3 An Overview of control techniques

2.3.1 Active power curtailment (APC)

APC limits PV output during excess generation to keep voltage within acceptable bounds. While effective, its most significant drawback is energy loss due to intentional curtailment, which is particularly problematic in off-grid contexts where every watt is valuable[7, 8].

2.3.2 Reactive power control (RPC)

Smart PV inverters equipped with RPC absorb or inject reactive power to stabilize voltage using Volt-Var and Volt-Watt control strategies standardized under IEEE 1547[3, 9].

In low-voltage networks, RPC may increase power losses due to the high *R/X* ratio and can lead to inverter over-sizing.

2.3.3 Demand-side management (DSM)

DSM shifts energy consumption to periods of excess PV generation, reducing curtailment losses and inverter stress[10]. However, it depends on consumer participation infrastructure that is difficult to implement in rural stand-alone systems.

2.3.4 Battery energy storage system (BESS)

BESS is highly effective in managing over-voltage by absorbing excess solar power during high-generation, low-demand periods, preventing voltage surges [4]. A systematic review by Rana et al. [4] analyzed over 150 hybrid PV-BESS studies and demonstrated how timed battery charging strategies absorb surplus energy, maintaining system voltage within safe thresholds. Battery cycling between 20% and 90% SoC protects battery health while ensuring voltage stability. However, a specific research gap still exists: a detailed simulation-based study with BESS control logic, specifically for over-voltage mitigation as a main control objective in a small-scale, stand-alone DC system, which is addressed in this study.

3 Methodology

3.1 Research design

A quantitative simulation-based design has been adopted in this study, whereby MATLAB/Simulink software tool has been used to develop and simulate a stand-alone PV system with battery storage under three scenarios to evaluate the applicability of BESS-based control for voltage regulation. The performance of the developed system has been assessed using DC bus voltage stability, peak voltage, over-voltage duration, and battery State of Charge (SoC).

3.2 System design and sizing

3.2.1 Load estimation

The study area for this investigation is a remote rural area in Namibia, named Ehafo village in the Omuthiyagwiipundi constituency in the Oshikoto region in northern Namibia, comprises approximately 59 households, 25 small businesses, and one church. The geographical coordinates of the village are 18°14′30.81″S, 16°30′57.34″E. Currently, the village does not have access to grid-connected power. However, some forms of power are available for agro-processing activities such as milling, although the power is diesel-based. Ehafo village was chosen for this research due to its representation of off-grid communities in Namibia.

Thus, it is a suitable area for testing a standalone photovoltaic power system for energy access and sustainability. The amount of power required for Ehafo village is approximately E_{load} = 10,715 Wh/day[11]:

$$E_{\text{PV,req}} = \frac{E_{\text{load}}}{0.8} = \frac{10{,}715}{0.8} = 13{,}393.75 \text{ Wh/day} \quad (1)$$

A loss factor of 20% is assumed to account for the inefficiencies of power conversion, battery storage, wiring losses [12], and is consistent with the normal approach to the design of stand-alone PV systems.

3.2.2 PV array sizing

Using site-specific peak-sun hours of *6.694 h/day*, the required array power is determined as follows:

$$P_{\text{array,req}} = \frac{E_{\text{PV,req}}}{H_{\text{sun}}} = \frac{13{,}393.75}{6.694} \approx 2.0 \text{ kW} \quad (2)$$

The Canadian Solar CS6P-260P modules of ratings ($P_m = 260$ W, $V_{mp} = 30.4$ V, $I_{mp} = 8.56$ A) were selected for its proven reliability, high efficiency of up to 16.47%, and robust performance under diverse environmental conditions, making it suitable for stand-alone PV applications[13]. For simulation flexibility, the array was scaled to 4S×3P (12 modules):

$$V_{mpp,array} = 4 \times 30.4 = 121.6\ V$$
$$I_{mpp,array} = 3 \times 8.56 = 25.68\ A, P_{array} = 3.12\ kW \quad (3)$$

3.2.3 DC-DC boost converter

In this investigation, a DC-DC boost converter was employed to step up the PV voltage to the required 370 V DC bus. Considering V_{pv}= 121.6 V and V_{out} = 370 V, the duty cycle is obtained as:

$$\text{D} = 1 - \frac{Vpv}{Vout} = 1 - \frac{121.6}{370} \approx 0.67 \quad (4)$$

The inductor (*L = 380 μH*) was sized for Continuous Conduction Mode (CCM) operation, which is preferred for better efficiency, reduced current ripple, and better dynamic performance. To always guarantee CCM mode under varying load conditions, the inductor is designed for a light-load condition (20% of full load). This worst-case scenario always guarantees CCM mode, even at low loads when discontinuous conduction mode is likely to occur[14]. The output capacitor (*C = 220 μF*) was sized for <2% voltage ripple, as illustrated in Table 1.

Table 1. Non-datasheet parameters for the DC-DC converter

Component	Parameter	Value	Justification
Inductor	Inductance	380 μH	CCM at 20% load
Capacitor	Capacitance	220 μF	<2% ripple; margin for transients
Diode	Forward Voltage	0.8 V	Typical power diode
IGBT	*On* Resistance	0.001 Ω	Minimise conduction losses
Snubber R	Resistance	100 kΩ	Minimise snubber losses

3.2.4 MPPT algorithm

The Perturb and Observe (P&O) algorithm was selected due to its low computational complexity, ease of implementation, and suitability for real-time control in MATLAB/Simulink environments[15]. These advantages make it a promising algorithm for implementing real-time control for a DC-DC converter in a stand-alone PV system. dynamically adjusts the converter duty cycle to track the maximum power point. Fig. 3 illustrates the Perturb and Observe (P&O) algorithm flowchart. The P&O algorithm operates by injecting a small signal into the voltage of the PV cell and measuring the response in terms of power. If the power increases, the signal continues in the same manner; otherwise, the signal reverses. This allows the tracker to continuously track the MPP, with small oscillations in steady state.

The parameters for the P&O were set at: $V_{refinit}$ = 125 V, V_{refmax} = 145 V (≈ 4 × V_{oc} × 0.975), V_{refmin} = 0 V, ΔV_{ref} = 1 V (corresponding to approximately 0.8% of the nominal operating voltage, selected to achieve a balance between fast tracking response and minimal steady-state oscillations around the MPP).

3.2.5 DC bus and resistive load

The DC bus target range is 340-400 V, compatible with a standard 230 V AC single-phase inverter. Considering an average daily load power P_{avg} = 10,715 / 24 ≈ 446 W, the resistive load is determined to be;

$$R_{\min} = \frac{340^2}{446} \approx 259\ \Omega \qquad (5)$$

3.2.6 BESS sizing

In this investigation, a lithium-ion battery was sized for 1 day of autonomy, whose SoC range is 20-90%, and with a battery efficiency η_{bat} = 0.9. The storage capacity is determined to be;

$$C_{\text{bat,Wh}} = \frac{E_{\text{load}} \times DOA}{DoD \times \eta_{bat}} = \frac{10{,}715 \times 1}{0.7 \times 0.9} \approx 17{,}000\ \text{Wh} \qquad (6)$$

For a nominal voltage V_{nom} of 288 V, $C_{bat,Ah}$ ≈ 59 Ah. A slightly larger capacity of 21,430 Wh (74.4 Ah) was used in the model to provide a margin for dynamic over-voltage control and battery cycling.

3.3 Operating scenarios

Three case scenarios were executed in the MATLAB/Simulink simulation model to evaluate the performance and operation of the model:

- **Case 1** – Baseline: 1000 W/m² at 25°C, with no battery energy storage system (BESS), for a duration of 6 s.
- **Case 2** – Over-voltage demonstration: varying irradiance 0–1800 W/m² at 25°C, with no BESS, for a duration of 150 s.
- **Case 3** – BESS control: same irradiance as Case 2, BESS integrated, for a duration of 10 s.

4 BESS-based control logic

4.1 Supervisory control strategy

In this study, the supervisory controller was implemented to monitor three critical parameters and Fig. 4 shows the flowchart of the control:

- DC Bus Voltage (V_{DC}): serving as the primary indicator of power imbalance. A rising bus voltage signals surplus power, whereas a falling voltage indicates deficit.
- Battery State of Charge (SoC): maintained between 20% and 90% to protect battery health and extend its service life.
- PV Power Output (P_{PV}): assists in guiding the control decisions during rapidly varying irradiance.

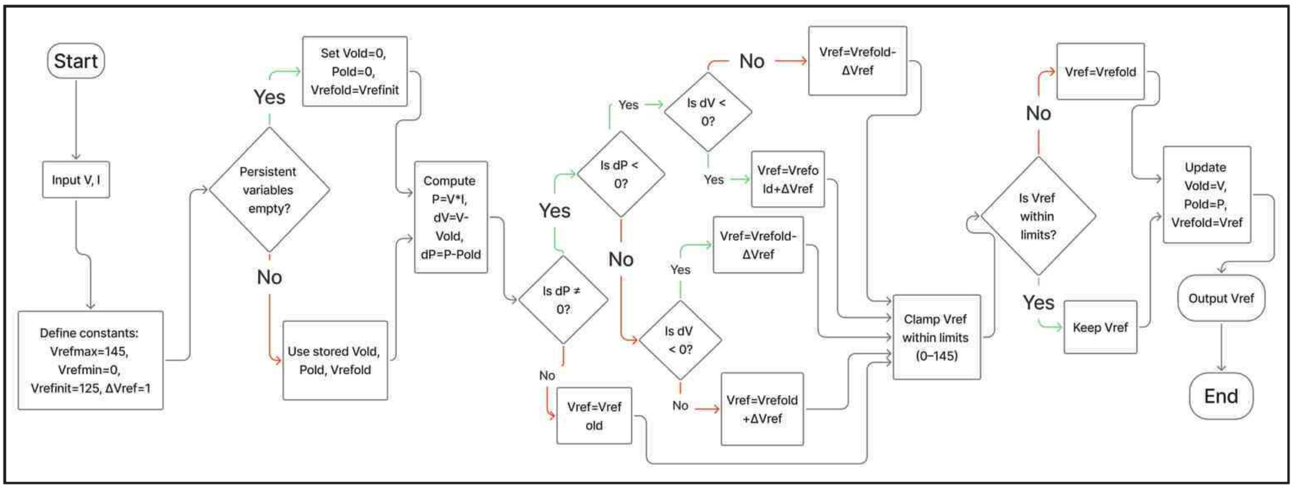

Fig. 3. Flowchart of the Perturb and Observe (P&O) MPPT algorithm

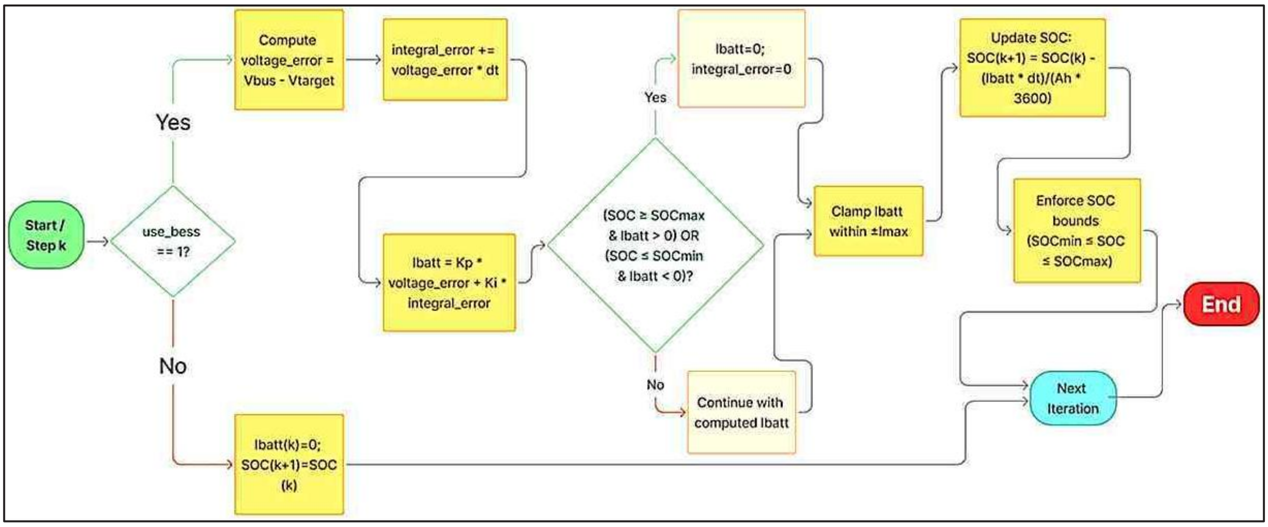

Fig. 4. BESS-based control

4.2 PI-based charging/discharging logic

The charging and discharging logic is as follows: when V_{bus} exceeds the upper threshold (400 V) and SoC < 90%, the PI controller commands the bidirectional converter to charge the battery, absorbing the excess power. Conversely, when V_{bus} falls below the lower threshold (340 V) and SoC > 20%, the battery discharges to support the bus. The PI controller equation is as follows:

$$I_{batt} = K_p \times Voltage_{error} + K_i \times Integral_{error} \quad (7)$$

Where: *voltage_error* = *Vbus* − *Vtarget* (*Vtarget* = 370 V), proportional gain K_p = 1.0 and integral gain K_i = 50.0. Battery current is clamped within ±*Imax* = ±15 A and SoC bounds are enforced at every time step. The SoC update follows the algorithm;

$$SoC(k+1) = SoC(k) - (I_{batt} \times dt)/(Ah \times 3600) \quad (8)$$

5 Results and discussion

5.1 Case 1: Baseline under STC

Fig. 5 illustrates the system under the base case scenario.

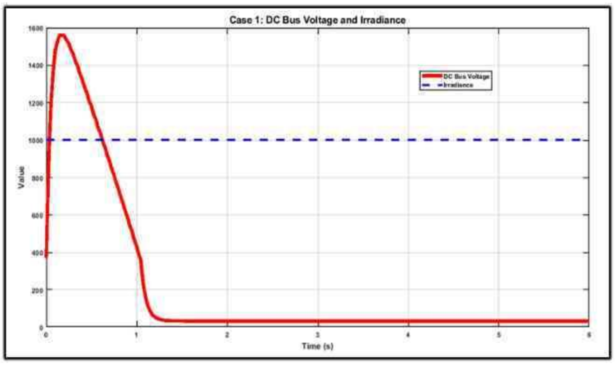

Fig. 5. DC Bus voltage and Irradiances under STCs after 6 s

It is observed from Fig. 5 that, under constant 1000 W/m² irradiance with no BESS, the DC bus voltage exhibited severe instability despite steady irradiance. The peak voltage reached 1,560.76 V and the average settled at only 213.54 V - far below the target 370 V, which demonstrates the inherent instability of an unbuffered stand-alone PV system. The results further highlight that the P&O MPPT controller was unable to hold the bus at its reference point without an energy buffer.

5.2 Case 2: varying irradiance without BESS

Fig. 6 illustrates the system to varying irradiance (0-1800 W/m²) without BESS resulted in severe voltage instability and persistent over-voltage conditions.

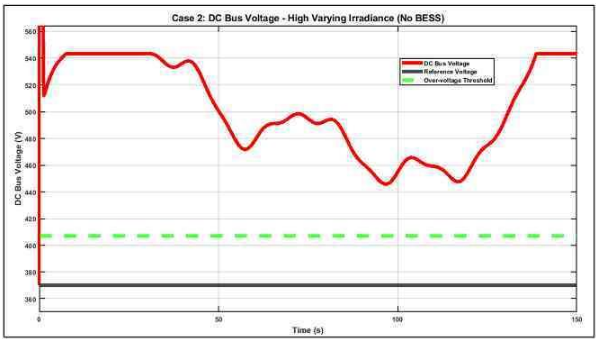

Fig. 6. DC Bus voltage under over-voltage conditions

Table 2 summarises the key indicators as follows.

Table 2. Key Performance Metrics - Case 2

Metric	Value	Remark
Average Voltage	509.76 V	Significantly above nominal (370 V)
Maximum Voltage	2,433.16 V	Severe over-voltage; no control action

Over-voltage duration (>407 V)	149.96 s	Exceeds IEEE/IEC 1-min threshold
Voltage Stability	±29.45%	Extremely poor regulation

These results confirm that irradiance variation leads to extreme over-voltage when no regulation technique is applied. Voltages sustained above 407 V (110% of the 370 V nominal) for nearly the entire 150 s simulation clearly exceeds the IEEE/IEC power-quality threshold [2].

5.3 Case 3: BESS-based control

Fig. 7 shows the integration of the PI-controlled BESS dramatically transformed system performance.

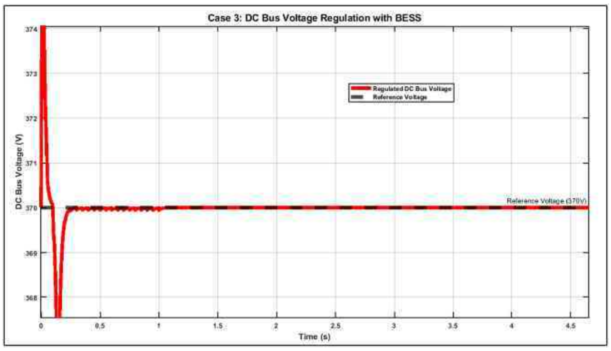

Fig. 7. Regulated DC Bus Voltage value (zoomed) under varying irradiances with BESS-based control

Table 3 presents the key metrics as follows.

Table 3. Key performance metrics - Case 3.

Metric	Value	Remark
Average Voltage	370.00 V	Target achieved exactly
Maximum Voltage	376.72 V	Within acceptable 340–400 V range
Over-voltage Duration	0.0000 s	Over-voltage eliminated entirely
Average SoC	50.00%	Stable within safe 20–90% range
SoC Change	0.00%	Battery acting as pure buffer (10 s run)
Voltage Stability	±0.10%	Excellent regulation

The average SoC remained at its initialized value of 50% with zero change because the 10-second simulation window was too short to observe net SoC drift. Over longer day-scale simulations, charging during peak irradiance and discharging in the evening would produce visible SoC cycling. The PI controller maintained the bus voltage at 370 V with a transient overshoot of only 6.72 V before settling, confirming excellent closed-loop regulation.

5.4 Comparative performance analysis

Table 4. Comparing standard benchmarks and design targets

Performance Metric	Bench mark	Result (Case 3)	Assessment
Nominal DC bus voltage	370 V (design)	370.00 V	Target achieved
DC bus voltage range	340–400 V	340–376.72 V	Within range
Voltage stability	±1% (typical)	±0.10%	Excellent
Over-voltage time	>1 min (IEEE/IEC)	0.0 s	Eliminated
Battery SoC	20-90% (safe)	50% (stable)	Safe

These results indicate that BESS-based control offers a loss-free, technically sound alternative to APC. Unlike APC, no available solar energy is wasted; instead, surplus energy is stored and returned when required.

6 Conclusions

This study investigated the Battery Energy Storage System (BESS)-based control as a voltage regulation strategy for mitigating over-voltage conditions in stand-alone PV systems. To enable the assessment of the strategy, a 3.12 kW solar PV/BESS system was modelled in MATLAB/Simulink, incorporating Canadian Solar CS6P-260P modules, a P&O MPPT boost converter, and a PI-controlled bidirectional BESS interface. The system was simulated under three case scenarios, for system evaluation: (1) Baseline: 1000 W/m² at 25°C, with no battery energy storage system (BESS), (2) over-voltage condition by varying irradiance 0 - 1800 W/m² at 25°C, with no BESS, and (3) BESS control: same irradiance as Case 2, with BESS integrated.

The findings of this study demonstrated that BESS-based control effectively mitigates over-voltage in stand-alone PV systems. The key findings under each case scenario are; (1) without BESS, the peak DC bus voltages reached 2,433.16 V under varying irradiance, far exceeding IEEE/IEC thresholds; (2) BESS-based control maintained the bus strictly within 340 - 400 V (±0.10%

stability) at a reference of 370 V, eliminating all over-voltage events; and (3) battery SoC was maintained within the safe 20 - 90% window, protecting battery health. These results confirm that BESS-based control is superior to APC because no solar energy was curtailed in all scenarios.

Future work is proposed to focus on extended day-long simulations to capture full SoC cycling; hardware-in-the-loop or physical prototype validation; advanced control techniques (fuzzy logic, model-predictive control, ANN-based MPPT); hybrid storage configurations combining BESS with supercapacitors; and an economic feasibility analysis is crucial, in the deployment of these systems in rural electrification processes.

The data used to support the findings of this study are available from the corresponding author upon request. The first author developed the model, conducted simulations, analysed results, and prepared the manuscript. The second author supervised the research, reviewed the manuscript, and provided technical guidance.

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