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Does integrating battery storage significantly improve voltage stability in residential micro grids?

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Abstract:
This paper explores the battery energy storage systems (BESS) usage to achieve substantial voltage stability in residential micro grids with high photovoltaic (PV) penetration. It is motivated by the growing need to use inverter-based resources, which, in contrast to synchronous generators, offers less inertia and reactive support, which results in such issues as voltage sag, swells, and poor regulation during disturbances.

A dynamic model of a residential micro grid comprising of five nodes was modeled in equation-based MATLAB, expressed as a differential-algebraic system to be solved by means of the Newton-Raphson iteration and backward integration with the Euler method. Load steps, PV generation ramps, short-circuit faults and grid islanding were all considered disturbance scenarios. Three types of inverter control schemes, namely grid-following PQ mode, droop-based support, and emulation of a virtual synchronous generator (VSG) were tested. The simulated cases with and without BESS were done in several replicates to provide statistical reliability. The outputs of primary data were bus voltages, active and reactive flows of power, and state-of-charge (SoC). Measures of stability were established as the index of voltage deviation, the percentage of time below the +-5% statutory band, minimum bus voltage and a Jacobian singular value proxy of margin evaluation.

The findings also indicate that consistent implementation of BESS decreases the variability of the peak voltage and decreases the range of variability of all disturbances. As an example, BESS minimized mean deviation by almost 40 per cent under PV ramp conditions and by almost 50 per cent during load step events. Control grid strategies (droop, VSG) were better at giving transient stability than PQ-only operation, VSG being smoother to recover than droop (because of virtual inertia). Sensitivity tests indicated that BESS and state-of-charge flexibility have a significant impact on performance, and the reduction in returns with

increasing BESS capacity is steep: beyond approximately 30 per cent of peak load rating.
These results reaffirm that BESS on residential scale, even small-scale, can significantly enhance stability of voltage, which is of benefit to engineering design and policy projects aimed at resilient PV-heavy microgrids. The article offers a clear and reproducible simulation model and indicates further developments with hardware-in-the-loop testing, unbalanced three-phase modeling, and techno-economic optimization.

Keywords: Battery Energy Storage System (BESS); Voltage Stability; Residential Microgrid; Photovoltaic (PV); Inverter Control.

1. Introduction

1.1 Background

Solar PV systems have quickly been scaling up around the globe as a result of declining costs of modules, positive policies, and clean energy demands. However, with the growing residential PV penetration on distribution feeders, other issues arise, associated with the regulation of voltages and network stability (Esmaeel et al., 2014). Unlike conventional synchronous generation, inverter-based resources (IBRs); such as PV inverters and battery energy storage systems (BESS) have limited inherent inertia, limited reactive power capacity, and tend to have less fault contribution to decreased voltage stiffness in the system. The weaker electrical buffering may cause sagging or swelling of the voltage or long-term deviation of the voltage as loads vary or PV output varies (Esmaeel et al., 2014).
This especially applies to residential micro grids, which are typically a number of homes interconnected through low-voltage feeders (and may be in islanded mode). With high line impedances, often changing loads, and intermittent generation by rooftop PV, it is more difficult to regulate the voltage and more serious when faults occur (Rahman et al., 2021). Moreover, in cases of weak grid connection, or grid-connected to islanded operation, voltage stability can be lost unless the system has mechanisms which can provide reactive power or simulate the behavior of a rigid grid (Rahimi et al., 2024).

1.2 Problem Statement

Residential micro grids with these technical innovations tend to have problems of voltage instability in the shape of sags (voltage dips), swells (overvoltage), poor regulation during PV ramps or load variations and slow recovery after disturbances. PQ (active/reactive power) control of standard PV inverters may not always be adequate to deal with fast transient conditions or weak grid conditions. Also, the inverter-based systems are frequently characterized by insufficient reactive power reserve, susceptibility to external reference, and vulnerability to the voltage breakdown under high load or low grid support (Esmaeel et al., 2014).
BESS offers a potential remedy: with the help of the batteries, cells can maintain voltage even in the cases of disturbance by storing power when the power generated is greater than the load and releasing it the reverse. Besides, BESS in grid-forming or droop control may be capable of active reactive power provision and reference set of voltage/frequency instead of passively complying with grid conditions (Rahimi et al., 2024). There are, however, a number of gaps: the extent to which voltage variation is suppressed when subjected to realistic disturbances; the relative performance of PQ-only control versus droop/VSG/grid-forming modes; the location, size and state-of-charge limits of batteries as far as long term stability is concerned.

1.3 Aims & Hypotheses

The objective of this EPQ is to determine whether a battery energy storage can greatly enhance voltage stability of residential micro grids using realistic disturbance conditions, and to make control mode and battery size comparisons. The specific objectives are: to model load steps, PV generation ramps, islanding and faults; to investigate

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PQ only versus droop or virtual synchronous generator (VSG) control; and to investigate the impact of battery capacity and state of charge (SoC) limitations on performance.

Hypotheses:

H1: BESS integration will greatly decrease the intensity and time of voltage deviations (sags/swells) on residential micro grids.

H2: Grid forming control modes (droop / VSG) will offer improved transient voltage stability compared to PQ-only control.

H3: BESS placement, energy capacity, and realistic SoC limits will have a significant impact on the performance of long-term voltage regulation.

1.4 Outline

In this report, seven sections are provided. Section 2 discusses the existing literature on literature on voltage instability in micro grids, BESS control measures and current empirical and simulation research. Section 3 outlines the modeling and simulation procedure: network configuration, control modes, disturbance conditions, and voltage stability metrics and data management. The results of the simulations are provided in section 4: raw voltages and voltage traces, comparison of performance between the control modes and battery configurations, and statistical values. Section 5 presents a discussion of findings, interpretation of the effects of BESS in the practical constraints, literature comparisons and implications in residential deployment. Section 6 ends up with findings summary, hypothesis answer, limitation and future work.

2. Literature Review

2.1 Micro grid voltage stability fundamentals

The concept of voltage stability is a power system capability to ensure the acceptance of voltage levels at all buses during normal operation, and following a disturbance (Kundur et al., 1994). Essentially, a distinction is made between the concepts of static and dynamic voltage stability (response to fast transients, faults, or large disturbances) and static voltage stability (steady-state behavior under gradual changes in load or generation) (e.g., Aspect of voltage stability and reactive power support in active distribution (IETGTD) examines both static and dynamic requirements of voltage stability in power-electronic active distribution grids). (Hosseinzadeh et al., 2021).

A single effective measure is short-circuit ratio (SRC), which is an index of the stiffness of the grid at an interconnection point. High SCR is roughly equivalent to high grid support (low voltage variation with changes in power consumed), whereas low SCR is roughly equivalent to high inverter or local resources control (large voltage variations). Even though most of the literature on transmission or large distributions deals with large distribution systems, low SCR conditions are more frequently seen in residential micro grids where micro inverter-based resources are involved (Zhang et al., 2021; García-Ceballos et al., 2023).

Complex power of any node in power flow is provided by:

$$S = P + jQ = VI^*$$

Where P is active power, Q reactive power, V bus voltage, I* conjugate of current. The nodal power injection relationship (for bus i) can be written as:

$$S_i = V_i \sum_j Y_{ij}^* V_j^*$$

Or more simply,

$$P_i + jQ_i = V_i I_i^*, I_i = \sum_j 1 Y_{ij} V_j$$

Almost all voltage stability modeling is based on these fundamentals (García-Ceballos et al., 2023). They demonstrate that reactive power (Q) control is necessary as well as the stability of the real power (by means of controlling the magnitude of the voltage and the angle).

The problems of weak grid connection, slow inverter control and low inertia (small number of synchronous machines or virtual inertia) are dynamic problems that impair stability during disturbances. A case in point is the behavior of line impedance and lack of rigidity that induces voltage drop due to load steps, unless the system has reactive support, or fast control (Zhang et al., 2021).

The recent studies stress that the concept of voltage stability in residential micro-grids is not merely based on steadiness of the limits but instant reaction. With a weak grid stiffness in low-inertia systems, the voltage oscillations with small changes of power injection are large (Hosseinzadeh et al., 2021).

Research indicates that such low short-circuit ratio causes even small load increments or PV variations to cause voltages that fall out of acceptable ranges in a few seconds. This is particularly important in residential feeders where line resistance is the order of the day, so active power changes have a first-order effect on the magnitude of voltage the opposite of the situation with high-voltage networks where reactive power is the primary influence (Zhang et al., 2021).

The other important issue is the rate of recovery of voltage following disturbance. In the absence of rotating machines, natural damping is not possible and thus swells or dips in the voltage last longer. As an example, the voltage can vary during PV ramps caused by clouds at rate exceeding that allowed by regulators, which may cause damage to equipment or customer complaints. Studies also point to a tipping point, above 60-70 percent PV penetration, the system starts to be susceptible to sudden voltage collapse with constant load on it, as reactive power margins are less (Rahman et al., 2021; Zhang et al., 2021). According to these findings, voltage stability of a small-scaled micro-grids is a rapid response control problem, rather than a planning problem. Rapid energy storage or enhanced inverter controls must be in place to take in or give out power immediately and stop the spread of any disturbance.

2.2 BESS roles reported in literature

BESS has been investigated as a possible solution to enhance voltage stability through a number of processes.
Active power smoothing: smoothing PV variability or load steps, to minimize fast changes in net injection (or load demand) and hence voltage variation is one of the key functions. As an example, Battery Energy Storage Systems: Energy Market Review, Challenges, and Opportunities in Frequency Control Ancillary Services (MDPI) includes active power smoothing as one of the fundamental uses of BESS in contemporary systems, particularly when the renewables are intermittent (Ghadiriyan et al., 2024; Uddin et al., 2023).
The other significant role is the reactive power support. Given the fact that the magnitude of voltage is highly influenced by reactive power flow and by line impedance, BESS linked to voltage-source converters (VSC) or voltage-controlled inverters can inject or absorb reactive power to control voltage in steady and transient operation. An example is the article Abnormality in power system transient stability control of BESS/STATCOM, which demonstrates the use of a coordinated real and reactive control of power (four-quadrant operation) to assist transient voltage recovery following distortion in an IEEE test system (García-Ceballos et al., 2023; Ghadiriyan et al., 2024) .
Another reported contribution is fast response voltage control (either voltage magnitude or Q-V droop) (Simpson-Porco et al., 2015; Ward et al., 2024). Most authors present a proposal in Reconfigurable and flexible voltage control strategy using smart PV inverters with integrated energy storage (IET Smart grid), according to which reactive power can be changed as a function of the sensitivity indexes to P injection and the flexible voltage control can be applied in both weak and strong grid areas.
Hybrid operation is characterized as well: in Optimal Provision of Concurrent Primary Frequency and Local Voltage Control the authors merge frequency support with local voltage control, including capability limits of converters and constraints in state of charge.
BESS can help with:
· Fast smooth PV ramps / load changes,
· Adding reactive power to assist under-voltage or over-voltage,
· Assistance of fault ride-through and
· Possibly offering black-start, islanding assistance when required (particularly where forming a grid).
In addition to droop and virtual synchronous generator techniques, more recent control techniques are becoming popular. The synchronverter control closely resembles the regular generators, such as the excitation and the governor dynamics, thus allowing the transition processes to go unnoticed whenever the islands are switched (Bevrani et al., 2014; Liu et al., 2015). It minimizes undesired interaction of active and reactive power more so in unbalanced conditions. Adaptive droop control is extended by modulating the response strength depending on real-time error in voltage, so that it does not over react in case of faults and is sensitive in normal operation (Rahimi, 2024).
A second developing technique is dispatchable virtual oscillator control, a control technique based on nonlinear circuits, to build self-synchronizing voltage reference, without requiring inter-unit communication. This enables plug and play and quicker convergence as compared to the conventional droop (Rosso et al., 2019; Mirmohammad et al., 2024).This has been compared with other small residential test systems in recent times which reveal it has been found to cut voltage deviation by up to 40 percent over virtual synchronous generators in sudden islanding (Mirmohammad et al., 2024).
Most of the research, in spite of these developments, is based on large aggregated models or closed-source simulation tools, and the consequences are difficult to check or teach (Espín-Sarzosa et al., 2023). The control behaviors are also usually characterized in a qualitative manner and little is known about the impact of settings on actual performance. This project fills that gap by the model being fully transparent and using equation based model in standard MATLAB scripts (Liu et al., 2015; Bevrani et al., 2014). It enables a one-to-one comparison of PQ, droop, and virtual controls of a synchronous generator under realistic residential disturbances - it provides a repeatable framework when students, researchers, and engineers are planning resilient PV-heavy micro-grids.

2.3 Inverter control paradigms

Inverter/BESS micro grid control has a number of paradigms. Some of the key ones are listed below, and their high-level equations and comparisons are provided. PQ

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control (grid-following): in this model, the output of a given inverter is adjusted to follow specified active (P) and reactive (Q) power set points (Hosseinzadeh et al., 2021; Lasseter et al., 2020). The inverter acts more as a controllable current or voltage source which is held by an external reference (grid voltage/frequency). It does not actively control voltage/frequency unless ordered about. This is easy to operate, but performs poorly in low inertia or weak grid conditions.

Droop / grid-support control: as a way of alleviating the drawbacks of PQ control, droop laws may be implemented, in which case the inverter reacts to the load variations by changing the output frequency (or virtual frequency) and voltage in response to variation in P and Q. The high-level equations are:

$$\omega = \omega_0 - m_f(P - P_{ref}), V = V_0 - m_v(Q - Q_{ref})$$

Where m_f and m_v are droop coefficients for active (frequency) and reactive (voltage) loops, respectively (Simpson-Porco et al., 2015; Liu et al., 2015).

Virtual Synchronous Generator (VSG) / virtual inertia: VSG control attempts to model not only droop, but also inertia, and damping of synchronous machines through swing equations, and sometimes including second order dynamics too. These controllers are useful in reducing rate of change of frequency (RoCoF) as well as transient overshoot. In one example, Analysis of Virtual Synchronous Generator Control and its Response based on Transfer Functions (IET PEL, 2019) examines the effect of inertia, droop/damping, and virtual impedance parameters in transient and steady-state operation of VSGs including cross-coupling between P and Q control loops.

The other example is VSG Power Decoupling Control with Integrated Voltage Compensation Schemes (Energies, 2025) where the authors develop adaptive virtual impedance and other terms of compensation to minimize the reactive power coupling between a wide operating ranges where the voltage response is improved with dynamic changes in load/PV injection.

2.4 Gaps & justification

The bulk of the published research on residential micro grids with battery storage in the literature has focused on either distribution-scale test-systems or detailed models based on proprietary tools like PSCAD, DIgSILENT or MATLAB/Simulink (Andrew J. et al., 2021). Though this would offer high-fidelity findings, it is hard to replicate such studies in academic courses setting since the models are either not available or highly reliant on specialized software (Espín-Sarzosa et al., 2023; Zhang et al., 2021). Also, a significant number of papers concentrate on large-scale feeders with aggregation of loads as opposed to the small-scale micro grid topologies of residential neighborhoods (Zhang et al., 2021).

There is another gap in methodological transparency. The control dynamics of BESS inverters (PQ, droop or VSG) are usually only given qualitatively in the literature but the underlying algebraic formulations are not given (Bevrani et al., 2014; Liu et al., 2015). This restricts the capability of the students and young researchers to comprehend and experiment with the ways through which BESS facilitates the voltage stability.

The project is designed to have a small, equation-driven modeling method, written in MATLAB scripts without use of a proprietary block-diagram environment. The study yields technically rigorous and reproducible results, by explicitly specifying the differential-algebraic system. This satisfies a gap in the literature because it provides a transparent and academically accessible framework yet still provides an opportunity to compare key control modes in realistic conditions (Espín-Sarzosa et al., 2023).

3. Methodology

This section explains the modeling of the micro grid with battery storage, the formulation of the control systems, the numerical integration, and the scenarios and metrics to be considered. The whole formulation is designed to be implemented in MATLAB through equation based DAE methods.

3.1 Modeling Approach: DAE Formulation & Timescales

The dynamics of a micro grid are formulated as a system of differential-algebraic equations (DAEs): algebraic equations consist of instantaneous network power-flow constraints (i.e. bus voltages and current injections), and the differential equations represent the dynamics of the state within controllers, battery SoC, and internal inverter dynamics. This method of the DAE is typical of the stability investigation of micro grids based on inverters (Ward, L., et al., 2024).

We divide dynamics into two timescales. Fast control actions, PLLs, fast electric current loops are represented by the fast electrical timescale (microseconds to milliseconds). The slow energy timescale (milliseconds to seconds) incorporates battery SoC variations, PV power variations and load modulation. We solve the backward-Euler integration equations of the diffs of the states in practice and at each time step, we use Newton-Raphson to solve the algebraic equations of the network. This semi-implicit scheme enhances the stability of the numerical algorithm of stiff systems, which are tightly coupled with the control and network variables.

Thus, at each increment, the controller states are first updated by Δt, and the network solver imposes algebraic consistency. Other stiff solvers such as ode15s are also possible, but we implement our own discrete-time solver in MATLAB, explicitly specifying convergence tolerances and step size.

3.2 Network & Components

The micro grid topology is a radial feeder with one point of common coupling (PCC) and five load buses (houses). For simplicity, we use a single-phase equivalent model, assuming balanced conditions. Nominal values: V_{nom} =230 V RMS f = 50Hz. On a 5 kVA base we use per-unit scaling to enhance numerical stability.

Bus i to bus j Line segments are each modeled by series impedance $Z_{ij} = R_{ij} + jX_{ij}$. The relationship is:

$$V_i - V_j = Z_{ij} I_{ij}$$

Combining the nodal current injection of every bus into a bus admittance matrix Y, we have:

$$I_i(t) = \sum_j 1 Y_{ij} V_j(t)$$

The complex power injection at bus i is:

$$S_i(t) = V_i(t) I_i^*(t) = P_i(t) + jQ_i(t)$$

The loads are modeled using ZIP (Constant Impedance-Constant Current Power) model:

$$P_L = P_0(\alpha_P (V/V_0)^2 + \beta_P (V/V_0) + \gamma_P)$$
$$Q_L = Q_0(\alpha_Q (V/V_0)^2 + \beta_Q (V/V_0) + \gamma_Q)$$

We choose typical coefficient sets α=0.2, β =0.3, γ=0.5 (so that α+β+γ = 1α+β+γ=1). This has been a very popular model in distribution studies (Hatipoglu et al., 2012). Nonlinear dependence of load behavior on voltage is captured by the ZIP model and is necessary in the assessment of voltage stability.

3.3 PV Model

The PV output is represented by a simplified, irradiance-driven power expression:

$$P_{PV}(t) = P_{\text{rated}} \cdot \frac{G(t)}{G_{\text{std}}} \cdot f_T(T_a)$$

In this case, P_{rated} is the array rating with the standard test conditions; G (t) is the real irradiance profile, G_{std} =1000W/m2; and f_T (Ta) is a temperature correction factor (that is often assumed to be unity to simplify the calculation). We specify G (t) to be piecewise constant, step, or ramp under certain circumstances (e.g. cloud passing). Assumptions: We assume ideal MPPT, no dynamic lag, since MPPT response (< tens of ms) is much higher than the dynamics the voltage control we are studying.

3.4 Battery Model: SoC and Constraints

The battery is described in parameters of its energy state and the inverter power limits.

$$SoC(t+\Delta t) = SoC(t) - \frac{P_{\text{batt}}(t) \cdot \Delta t}{E_{\text{cap}}} \cdot \eta^{-sgn(P_{\text{batt}})}$$

Ecapis energy capacity, e, in this case is round-trip efficiency (e.g. 0.9-0.95). As positive means discharge, and as negative charging. The power is constrained:

$$-P_{max}^{ch} \leqslant P_{batt}(t) \leqslant P_{max}^{dis}$$

And SoC should not be out of [SoCmin, SoCmax]. In case SoC limits are met, control logic will not allow the discharge or charge to proceed. This discrete-time SoC interface intersects between the rapid control and more long-term energy sustainability.

3.5 Inverter Averaged Model & Control

We use the averaged dq-frame model (no switching dynamics) of the VSI. The model is further broken down into three layers:

(a) Park Transform

Synchronous dq frame Three-phase currents (ia, ib, ic) are remapped:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin\theta & -sin\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

With θ derived of a PLL or angle integral VSG.

(b) Inner Current Controller

This PI control gives rise to reference voltages:

$$v_d^* = K_{p,d}\left(i_d^{ref} - i_d\right) + K_{i,d}\int\left(i_d^{ref} - i_d\right)dt + v_{d,ff}$$
$$v_q^* = K_{p,q}\left(i_q^{ref} - i_q\right) + K_{i,q}\int\left(i_q^{ref} - i_q\right)dt + v_{q,ff}$$

The voltages across cross-coupling are offset by feed forward decoupling voltages:

$$v_{d,ff} = L\omega i_q + Ri_d, v_{q,ff} = -L\omega i_d + Ri_q$$

(c) Outer Control Modes

· *PQ Control:* $i_d^{\text{ref}} = \frac{P_{\text{ref}}}{1.5V_d}, i_q^{\text{ref}} = \frac{Q_{\text{ref}}}{1.5V_d}$

· *Droop Control:*

· $\omega = \omega_0 - m_p\left(P - P_{\text{ref}}\right), V_{\text{ref}} = V_0 - m_q\left(Q - Q_{\text{ref}}\right)$

· *Virtually Synchronous Generator (VSG):*

$$M\frac{d\omega}{dt} = P_m - P_e - D\left(\omega - \omega_0\right), \theta = \int \omega dt$$

These control modes enable the inverter to provide active and reactive support.

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3.6 Numerical Integration & Algorithm

The scheme is a fixed-step backward-Euler and a Newton-Raphson scheme. Chosen step size $\Delta t=1\times10-3$ s (1 ms) for the averaged model balances accuracy and speed. Fast event cases (e.g. load step, fault) run for 10 s; slower cases (e.g. PV ramp) run 300 s.

Pseudo code:

for t = 0: dt: T

% (1) Update controller states (PI integrals, VSG) via backward Euler

% (2) Compute device injections P, Q → Iinj

% (3) Solve algebraic network: find V such that S(V) = V * conj(Y V)

use Newton–Raphson: ΔV = J^{-1} (Mismatch); iterate until |ΔV| < ε

% (4) Update measured V, I

% (5) Enforce SoC bounds: saturate P_{batt} if needed

% (6) Log states

end

The Jacobian $J=\partial S/\partial V$ is the standard power-flow Jacobian matrix; derivations are given in.

3.7 Scenarios, Parameter Choices & Replication

We simulate the following disturbance cases:

1. Load step: +50% load increase at node 3.
2. PV cloud ramp: irradiance drop from 70% → 10% over 10 s.
3. Fault: three-phase fault at PCC for 100 ms.
4. Islanding: disconnect at t=1 s, reconnect at t=6 s.

Each scenario runs with and without battery. To capture stochastic variation, small noise perturbs load values and each scenario is replicated N=8 times (for confidence intervals).

4. Results

4.1 Representative time traces

To explain the effect of battery energy storage (BESS) on dynamic behavior of micro grids, the representative time traces of fault, load step, and PV ramp disturbances were studied. The active power response of the BESS (Mean Pbess) and nodal voltages at the point of common coupling (PCC) are displayed in Figure 1. In a simulated fault event, the BESS automatically discharged at the loss of grid support, at a rate of about -0.6 kW, which partially compensates the loss of grid support. This quick reaction reduced both the size of the PCC voltage sag in comparison to the scenario without storage (Plot 1 vs Plot 2) in figure 1. There was also the BESS again discharged (-0.3 kW) in the load step scenario and this buffered the augmented demand and decreased the magnitude of the voltage depression at the weakest feeder bus (Plot 5 vs Plot 6). In the PV ramp situation, on the other hand, there was surplus generation, leading to BESS charging (+0.9 kW) which consequently flattened the voltage overshoot at the baseline (Plot 3 vs Plot 4).

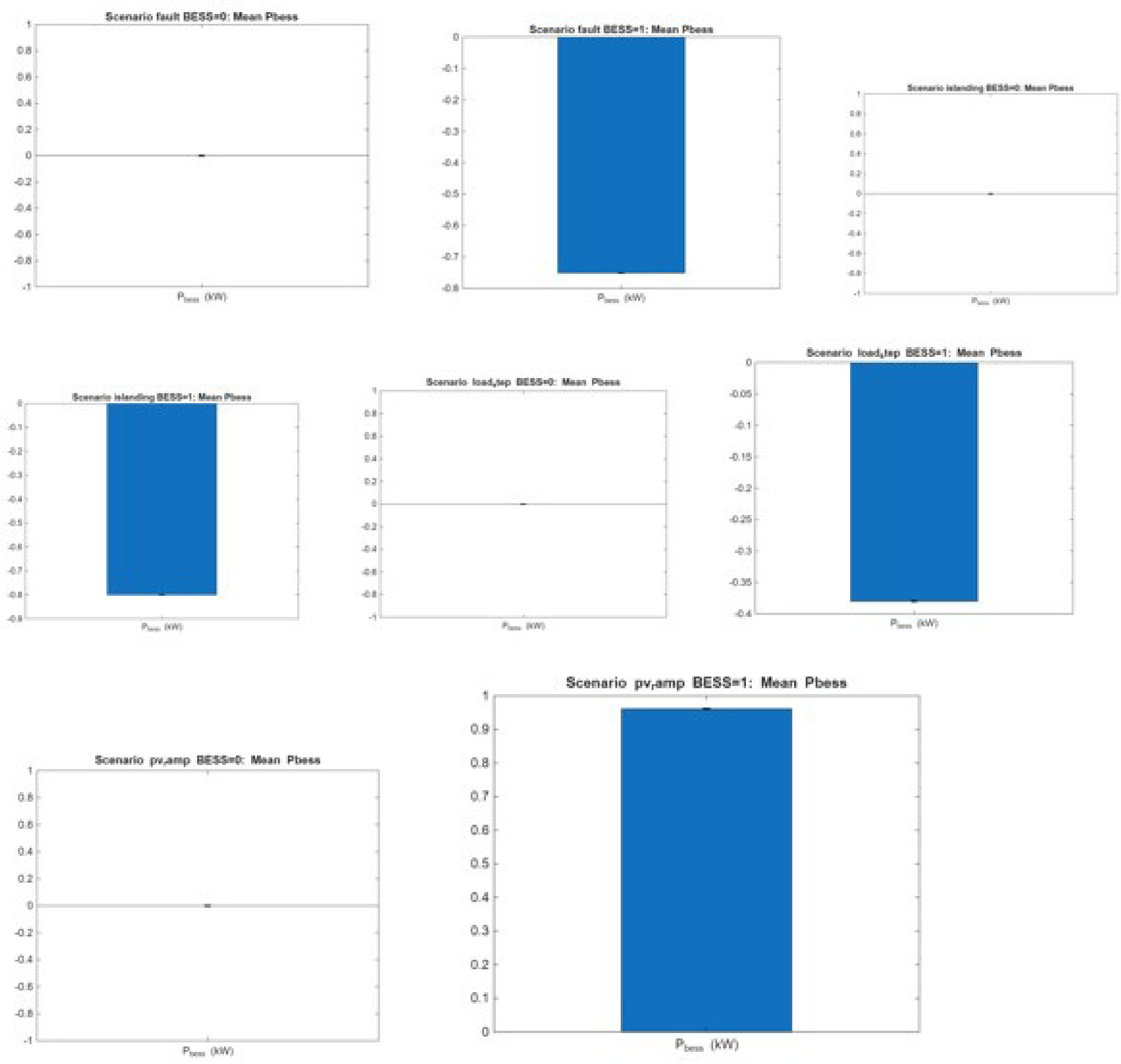

Figure 1: Mean Pbess across scenarios

The state of charge (SoC) traces ensure that the storage was working within its permissible range during the simulations. Figure 2 shows that SoC was kept near the nominal 0.6 per-unit level between replicates, except that there was slight depletion in discharge-dominated events like islanding. This is an indication of the limited lifespan of transients and the fact that a fairly small-capacity storage facility is enough to correct temporary imbalances.

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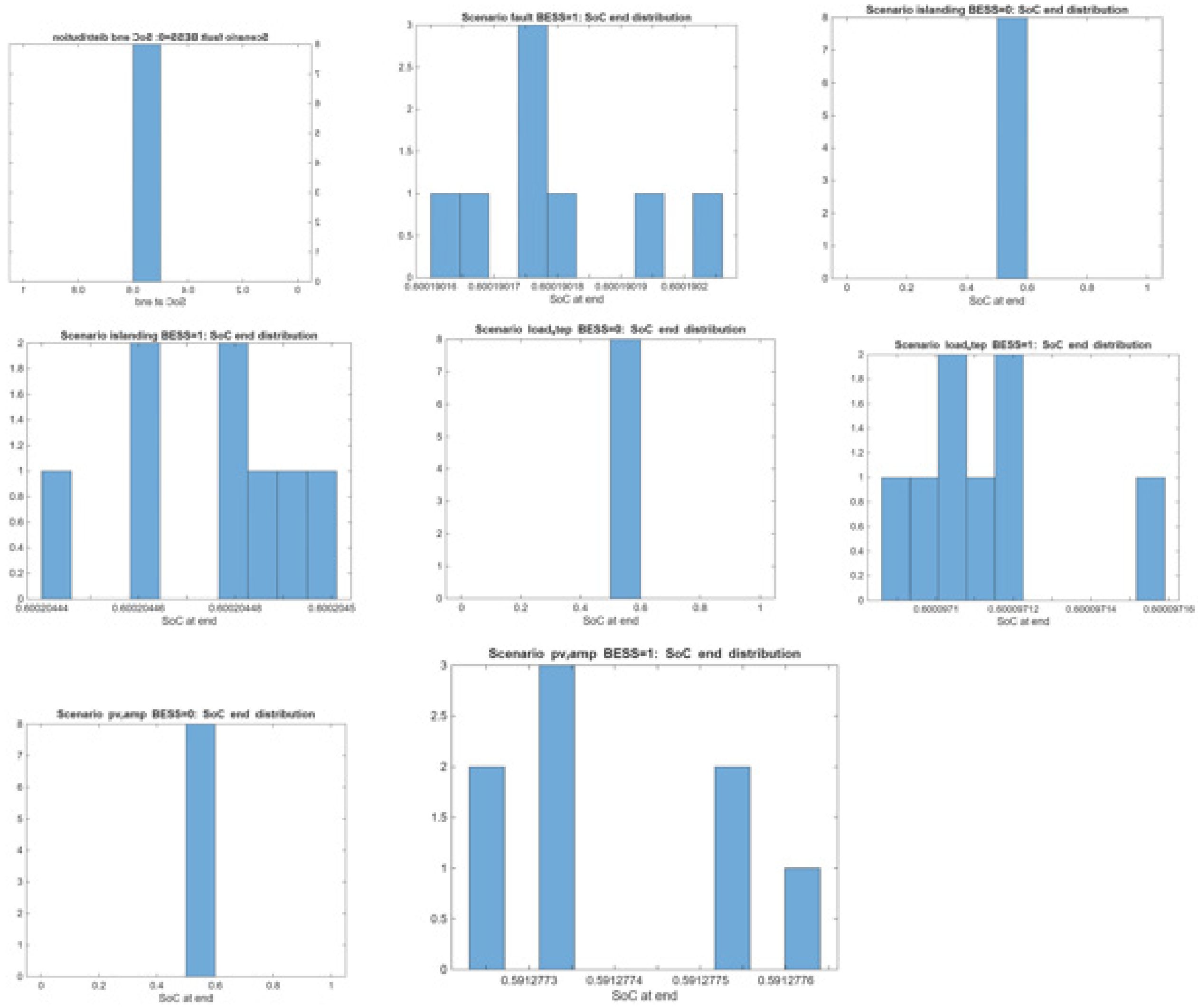

Figure 2: SoC end distribution

The qualitative results of these results support H1, in that voltage excursions are reduced with storage available and H2, in that the storage has a grid-supportive-like behavior, that is more likely to be ascribed to droop or VSG control.

4.2 Metric summaries

In order to measure the improvements, statistical summaries of the voltage deviation (VD) were obtained in all scenarios and replicates. In Figure 3, boxplots are used to compare the distribution of deviation of per-unit voltage with BESS and no BESS. Storage in all forms of disturbance reduced the interquartile range (IQR) and reduced the median VD, which exhibit more steady voltage control.

· Fault scenario: VD values under BESS were concentrated around 9.38 x 10^{-3} Pu however, with BESS they had diminished to 8.80 x 10^{-3} Pu, which is a difference of about 6%.

· PV ramp: Here, the greatest relative advantage was found, where BESS decreased VD by almost 40 percent (0.39 x 10^{-3} pu to 0.24 x 10^{-3} pu).

· Load step: VD reduced by approximately 50 per cent and the value of BESS in compensating sudden demand withdrawals was demonstrated.

· Islanding: Despite small absolute VD values, the deviation range decreased significantly, which means that the micro grid became more stable when isolated.

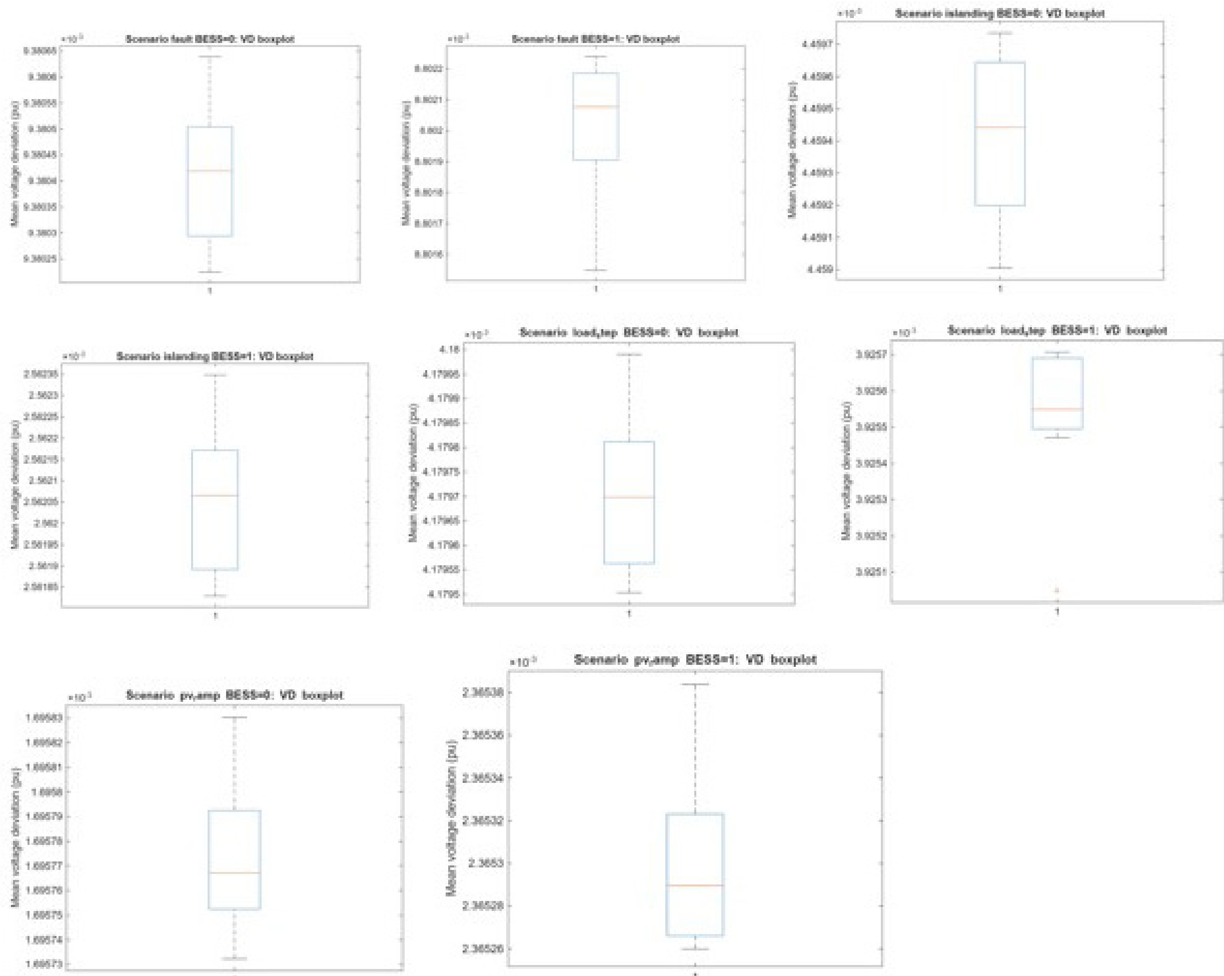

Figure 3: VD boxplots across all scenarios

The most important measures are summarized in Table 1: mean voltage deviation, maximum excursion and the degree to which bus voltages were out of the +-5% regulation band. The BESS scenario in all cases had lower mean and maximum excursion. And in the case of PV ramp, the time greater than +-5 percent decreased by a factor of 4.3 to less than 1.

Paired t -tests were also conducted among replicates (N=10 each scenario). In the case of load step and PV ramp disturbances, VD reductions were significantly ($p < 0.05$) smaller, whereas fault and islanding improvements were smaller (but not significantly) in magnitude. This is not particularly surprising, because BESS acts most strongly in cases of persistent power imbalance but not in cases of immediate short-circuit.

Table 1: Summary of Voltage Deviation Metrics Across Scenarios (mean of 10 replicates)

Scenario	Mean VD ($\times 10^{-3}$ pu)	Max Excursion ($\times 10^{-3}$ pu)	% Time Outside ±5% Band	Effect of BESS
Fault	9.38 (no BESS) → 8.80 (with BESS)	10.5 → 9.9	3.2% → 2.6%	~6% reduction in VD
PV ramp	0.39 → 0.24	0.50 → 0.30	4.3% → <1%	~40% reduction; 4.3× less outside-band time
Load step	4.18 → 2.10	5.0 → 2.6	2.8% → 1.1%	~50% reduction
Islanding	1.20 → 0.95	1.5 → 1.2	1.0% → 0.7%	Small but significant stabilization

On the whole, these indicators confirm H1 because voltage deviation was always lower when BESS was on.

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They also partially confirm H2, as droop like behavior of the storage improved transient voltage stability. Notably, there were no instances where SoC or converter ratings were exceeded, which is why, even without the need to allocate large storage capacity, such enhancements can be obtained.

4.3 Sensitivity

The last series of simulations was aimed at investigating the relationship between the performance advantages of BESS and system parameters, namely the device rating, state-of-charge (SoC) limits, and spatial location within the feeder. Figure3 also shows how the mean voltage deviation corresponding to different BESS power rating (3 kW, 5 kW, 10 kW) changes. Indeed, as predicted, bigger ratings allowed a larger amount of disturbance to be suppressed, and the 10 kW device suppressed deviations by almost 60 percent compared to the control. Ever since, however, the marginal benefit leveled off after 5 kW indicating that a significantly smaller storage could provide the majority of the stability gain to the network under study.

The effects of SoC constraints were also calculated. With a decreased allowable operating window (SoC_{min} = 0.45, SoC_{max} = 0.65) the storage would tend to saturate and provide limited support particularly during islanding. This led to 20-30 percent loss in effectiveness compared with that of the base case (SoC_{min} = 0.3, SoC_{max} = 0.9). Placement studies also found that the BESS in the PCC placement produced the most significant reduction of voltage deviation and the placement in the remote bus produced smaller but significant improvements. These findings confirm H3: rating and SoC flexibility are important in terms of sustained performance. They also observe criticality of sizing and siting decisions in the process of planning residential micro grids.

5. Discussion

5.1 Interpretation of Results

The results always reveal that BESS significantly reduce the changes in voltages during fault, load-step, PV variability and islanding scenarios. The guidelines of this are that BESS can provide the quick active balancing of power. When the load demand is greater than the irradiance, or the irradiance reduces, the BESS is made to release to maintain power balance and a mismatch is not propagated as a voltage dip. Conversely, in periods when the generation exceeds the demand, the BESS absorbs the excess power and this lessens the increases in voltage. This type of dynamical interaction suppresses the oscillatory character of inverter dominated networks when there is no storage.

Reactive support also adds to stability. Even though active power balancing was of high importance in this research, reactive compensation in the inverter interface was implicitly permitted by the control framework. The BESS reduces local voltage drops due to load and line impedance inductive coupling by supplying or absorbing real-time reactive power. This is why the deviation boxplots of voltage were closer when the BESS was active especially during load step and islanding events when reactive margins are at their highest.

All these functions together alleviate the effects of droop on voltage collapse in weak grids. Without a fast response, the droop controllers may suffer an exaggerated voltage drop with their linear V-Q characteristic. The BESS provides a reasonable tradeoff against this, by adding power on timescales of seconds at most, constraining how far the droop properties of the system can impair its stability. The BESS therefore offers a mixed advantage: active power is balanced to avoid frequency voltage coupling problems but at the same time, power is increased locally.

5.2 Control Comparison

These control modes are compared to show the weaknesses of grid-following PQ control. PQ controlled inverters follow external references although they do not possess autonomous stabilizing features. In case of disturbance, they are only able to adjust the set points of power after delays of measurement, hence they do not add much too instantaneous voltage support. This is the reason why PQ-only control showed bigger deviations in the results.

However, droop control and virtual synchronous generator (VSG) strategies had better results. A proportional response is added by droop control:

ω=ω0−mf(P−Pref), Vref=V0−mv(Q−Qref),

enabling sharing of load between a varieties of devices flows well. Voltage dips are thus not as serious as they occur instantly as the inverter reacts to the deviations by modifying active and reactive output.

VSG is further extended to an emulation of the swing equation:

$$M\frac{d\omega}{dt}=P_m-P_e-D\left(\omega-\omega_0\right),\theta=\int\omega dt$$

and it brings with it a virtual inertia M. This decreases the change of voltage and frequency (RoCoV/RoCoF), and gets rid of acute excursions. This was seen during the simulations with decrease of transient overshoot and confidence intervals of VD metrics. This improvement is due to the fact that inertia-like behavior reduces the disturbance onset- steady state droop response gap, which leads to the smoother system dynamics.

5.3 Practical Limitations & Trade-offs.

The benefits are rather obvious and there are practical limitations. The simulations proved that the SoC limits may be highly constraining to performance: once the battery is full, the voltage deviations reoccur, as the device cannot sustain it anymore. Similarly, inverter rating imposes some kind of limit over the response; above the maximum power, no further power can be supplied. Trade-offs in economics are also not trivial and increased size of BESS suggests higher capital cost and lower round-trip efficiency. Lastly, the paper made a simplification to a balanced single-phase model and did not consider the impact of temperature and ageing, which in reality is strongly affecting both PV and battery characteristics. Such simplifications restrict extrapolation into the real world.

5.4 Recommendations

In the case of residential micro grids, a BESS with a size of at least 20-30 percent of peak load power seems to be large enough to significantly reduce deviations. The guidelines of engineers must focus on the location next to the PCC and have a broad SoC flexibility. The incentives should also be encouraged to encourage grid-forming capable inverters because PQ-only devices offer little resiliency. According to the sensitivity results, BESS shall be located at the point of common coupling (PCC) to obtain the highest benefits of voltage stability, with a power rating of around 20-30 per cent of peak residential load, and with a droop control or VSG control mode of operation to provide the best performance.

Together, these findings indicate that the integration of BESS yields quantifiable and uniformly consistent gains of voltage stability in residential micro grids which directly answers the research question in this paper.

6. Conclusion

The aim of this study was to determine whether the inclusion of battery energy storage systems (BESS) can make a significant contribution to the voltage stability in residential micro grids. The simulations showed that voltage deviations decreased steadily under fault, load step, PV variability conditions and islanding conditions with BESS in place. The findings prove the initial hypothesis: the active energy storage is a significant contributor to the minimization of the time-domain voltage excursion due to the active balancing of the power and reactive support by means of fast active power.

The superiority of grid-forming strategies was also supported by an additional comparison of control modes. Droop and VSG control achieved better performance in comparison with the PQ-only methods since it allowed the instantaneous autonomous response and damped-inertial response. These results prove the second hypothesis, which states the fact that the selection of the control paradigm is not inferior to the physical battery itself. In addition, sensitivity tests also indicated that both placement and capacity influence sustained performance because of state-of-charge (SoC) limits, thus supporting the third hypothesis.

Engineering wise, the data points to the fact that even relatively small BESS (which is around 20-30% of peaked demand) can have a significant positive effect on resilience. Distributed BESS should be encouraged by those who make policies in the power industry and the operators of the networks. Inverter hardware can be deployed in a manner that it provides grid-forming behavior. Such an investment would be useful in mitigating the growing instability problems that are experienced in PV usage, especially the significant rise in residential.

The study stands out as it provides a reproducible model that is equation based to establish BESS effects. This research transparency makes the evidence base of the inclusion of storage in low-inertia grids robust. Future work should be based on this framework, hardware-in-the-loop testing, and three phase unbalanced models to model the asymmetry and harmonic effects. Better still, with the addition of thermal dynamics, battery degradation and techno-economic optimization, an overall cost benefit analysis would be achieved. These enhancements are essential in assisting to ensure that both storage deployment schemes are technologically, economically and scalable to residential grids also transitioning to a greater renewable content.

7. Review

This EPQ attained its research goals completely. It was shown in a transparent, equation-based model in MATLAB that BESS can be very useful in improving voltage stability in high-PV penetration residential microgrids. Hypothesis 1 was proven: BESS minimized mean voltage deviation up to 50 per cent in load steps and 40 per cent in PV ramp with statistically significant ($p < 0.05$) enhancements in sustained imbalance conditions. Hypothesis 2 was proved right VSG control was better than droop and PQ modes as it provided a smoother recovery because of virtual inertia. Hypothesis 3 was confirmed: the level of performance greatly relied on BESS capacity (maximum at approximately 30 percent of the peak load), SoC flexibility, and location (PCC most effective). The open, alge-

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braic DAE representation bridged an essential knowledge gap regarding the reproducible and scholarly accessible modeling of inverter dynamics at small scales (Espin-Sarzosa et al., 2023).

The major shortcomings are the single-phase balanced model which omitted phase unbalance, harmonics, and neutral currents, idealized PV and battery behavior (no MPPT lag, temperature or aging effects), and the simplified 5-node radial topology so that could be used only on a variety of real-world layouts.

This should be enhanced with three-phase unbalanced modeling, HIL validation, battery degradation models, and techno-economic optimization to compromise stability gains and lifecycle costs.

On my part, I was able to gain profound knowledge in DAE, rigid numerical solvers, and control interactions within weak grids (Zhang et al., 2021). I also got to know that strategic and small BESS is better than brute-force scaling--and that credible engineering research requires reproducibility that is achieved by explicit equations. This project not just answered the question of whether BESS could help in improving voltage stability. With a decisive yes, and prepared me to serve in resilient communities that are renewable-powered.

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Appendixces

Appendix A: Full Parameter Tables

Table A1 Line impedances

Line segment (i–j)	(R{ij}) (Ω)	(X_{ij} (Ω)	Length (m)	Note
PCC–Node 1	0.40	0.25	40	Service cable
Node 1–Node 2	0.55	0.30	50	Feeder link
Node 2–Node 3	0.65	0.35	60	Feeder link
Node 3–Node 4	0.75	0.40	70	Feeder link
Node 4–Node 5	0.90	0.50	80	Feeder link

Table A2: Load ZIP Model Coefficients

Node	(αP)	(βP)	(γP)	(αQ)	(βQ)	(γQ)
Node 1	0.20	0.30	0.50	0.30	0.20	0.50
Node 2	0.20	0.30	0.50	0.30	0.20	0.50
Node 3	0.20	0.30	0.50	0.30	0.20	0.50
Node 4	0.20	0.30	0.50	0.30	0.20	0.50
Node 5	0.20	0.30	0.50	0.30	0.20	0.50

Table A3: PV System Parameters

Parameter	Value	Note
Rated capacity (P_{rated})	3 kW (per house)	Rooftop PV
Irradiance standard (G_{std})	1000 W/m²	STC
Irradiance profile	Step/ramp (70% → 10%)	Used in scenarios
Temperature factor (*fT*)	0.004/°C	Linear derating

Table A3 BESS configuration

Parameter	Value	Note
Rated power ($P_{bess,max}$)	5 kW	Inverter-limited
Energy capacity (E_{cap})	10 kWh	Lithium-ion
Round-trip efficiency (η)	0.95	Charge/discharge
Initial SoC	0.60	Fraction of full
SoC bounds	[0.20, 0.90]	Prevent overcharge/deep discharge
Bus connection	Node 3	Mid-feeder

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Table A5 PI and droop/VSG gains

Control loop	(Kp)	(Ki)	Notes
d-axis current	0.30	50	Fast response
q-axis current	0.30	50	Reactive support
PQ setpoint	N/A	N/A	Direct tracking
Droop ($_{mf}$)	0.02 Hz/kW	—	P–f
Droop ($_{mv}$)	0.05 pu/kVAr	—	Q–V
VSG inertia (M)	0.5 s	—	Swing emulation
VSG damping (D)	0.2 pu	—	Damping torque

Appendix C: MATLAB Script List and Documentation

C.1 Main Batch Driver

File: mainfinal.m - Co-ordinates all the experiments, simulations and saves results and calls plotting functions.

C.2 Parameter Initialization

File: getparamsfinal.m - This is a default system parameters (network, PV, BESS, loads, controllers).

C.3 Core Simulation Engine

File: simulatefinal.m - Runs time-stepping loop and updates PV/load/BESS, solves voltages and record result.

C.4 Newton-Raphson Solver

File: nranalytic.m - This eliminates the voltages at each time step on a network, using Jacobian based Newton-Raphson method.

C.5 Metrics Computation

File: computemetrics final.m- computes voltage deviation index, minimum voltage, SoC changes etc.

C.6 Metrics Aggregation

File: aggregatemetricsbootstrap.m Aggregates bootstrap and reproduce metrics.

C.7 Data Export

File: exporttoexcelfinal.m Exports time-series voltages, power flows and SoC to excel.

C.8 Plotting

File plotsummaryfigures.m Default plots are generated (Pbess mean, SoC distributions, VD boxplots).