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Evaluating the stability of microgrids with high penetration of solar photovoltaic systems

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Abstract
Background: Microgrids integrating high shares of Solar Photovoltaic (PV) systems reduce reliance on fossil fuels but introduce significant stability challenges due to the intermittent nature of solar irradiance and the lack of rotational inertia.
Objective: This study evaluates the voltage and frequency stability of an islanded microgrid under varying PV penetration levels and sudden load disturbances.
Method: This study uses a simulated dataset created for academic training purposes. A microgrid model comprising a PV array, battery energy storage system (BESS), and dynamic loads was developed in MATLAB/Simulink. Simulations were conducted at 30%, 60%, and 90% PV penetration ratios.
Key Results: At 90% PV penetration without BESS support, the microgrid experienced voltage deviations exceeding ±15% and frequency oscillations that violated stability limits following a 20% load increase. Integrating a BESS with virtual inertia control successfully damped oscillations and restored stability within 0.5 seconds.
Conclusion: High PV penetration severely degrades microgrid stability during transient events; however, advanced BESS control strategies are highly effective in providing the necessary synthetic inertia to maintain grid reliability.

Keywords: Microgrid stability, solar photovoltaic, battery energy storage system, virtual inertia, power systems, islanded mode

Introduction

The global transition towards decentralized and sustainable energy systems has propelled the development of microgrids—localized energy networks that can operate in parallel with or independently from the main utility grid [1]. Solar Photovoltaic (PV) systems are the most prolific distributed energy resource (DER) within these microgrids due to declining costs and environmental benefits [2]. However, as PV penetration levels increase, the traditional dynamic stability mechanisms of power systems are fundamentally altered [3]. Conventional power grids rely on the synchronous generators of thermal or hydro plants, which possess large rotating masses that provide inherent rotational inertia, acting as a buffer against frequency deviations caused by sudden load-generation imbalances [4]. In contrast, PV systems are interfaced with the grid via power electronic inverters, which have no rotating mass and therefore contribute zero physical inertia [5].

When a microgrid transitions to islanded mode (disconnecting from the main grid), it must rely solely on its internal generation to maintain voltage and frequency within strict operational boundaries (e.g., ±5% for frequency). High PV penetration exacerbates the vulnerability of islanded microgrids to transient disturbances, such as sudden cloud cover or abrupt load changes [6]. The research problem addressed in this paper is the quantification of these stability margins under high PV penetration and the evaluation of mitigation techniques. The objective is to simulate an islanded microgrid to determine the precise penetration threshold at which stability is compromised, and to assess the effectiveness of a Battery Energy Storage System (BESS) employing virtual inertia control in restoring dynamic stability [7].

Literature review

The theoretical framework of power system stability is governed by the swing equation, which dictates that the rate of change of system frequency is proportional to the imbalance between mechanical power input and electrical power output, inversely scaled by the system's inertia constant [8]. In low-inertia systems, this rate of change of frequency (RoCoF) becomes dangerously high during contingencies.

Existing literature extensively documents the impacts of high renewable penetration on bulk power systems, but microgrid-specific studies present unique challenges due to low system damping and high R/X ratios in distribution networks [9]. Various strategies have been proposed to address the inertia deficit. Synchronous condensers have been suggested, but they incur high capital and maintenance costs [10]. The most prominent contemporary solution is the deployment of BESS with grid-forming inverters capable of synthesizing inertia—a concept known as Virtual Synchronous Machine (VSM) or virtual inertia control [11].

Despite the theoretical promise of VSM, a critical research gap persists regarding the optimal tuning of virtual inertia parameters relative to specific PV penetration levels [12]. Many studies assume a fixed virtual inertia constant, failing to recognize that the required synthetic inertia is dynamically proportional to the deficit in physical inertia caused by varying solar generation profiles [13]. Furthermore, there is a lack of comprehensive analysis comparing multiple penetration scenarios (30%, 60%, 90%) under identical, severe transient fault conditions within a strictly islanded framework [14]. Without this granular understanding, microgrid controllers may be over-designed (increasing BESS costs unnecessarily) or under-designed (risking system collapse) [15]. This study bridges this gap by systematically mapping the relationship between PV penetration, RoCoF, voltage stability, and the mitigating impact of dynamically responsive BESS virtual inertia [16].

Methodology

This research utilizes a simulation-based experimental design. This study uses a simulated dataset created for academic training purposes. The microgrid test system was modeled in MATLAB/Simulink (Version 2023a) [17]. The system architecture consists of a primary PV array (rated at different capacities depending on the penetration scenario), a 50 kWh Lithium-ion BESS, a variable R-L load bank, and an RL distribution line.

PV penetration was defined as the ratio of PV installed capacity to the total peak load demand. Three scenarios were simulated: Scenario A (30% PV), Scenario B (60% PV), and Scenario C (90% PV) [18]. The microgrid was initialized in grid-connected mode and then islanded at t=1.0 second. To test transient stability, a sudden 20% step increase in load was applied at t=2.0 seconds.

The BESS was modeled with a standard PI-controlled inverter for Scenarios A and B. For Scenario C, a Virtual Inertia (VI) control loop was added to the BESS inverter, mimicking the swing equation by injecting or absorbing active power proportional to the derivative of the frequency deviation [19]. The sample size for data extraction consisted of 10,000 time-step data points per scenario, captured at a resolution of 0.1 milliseconds over a 1-second transient window. Data collection tools included Simulink scope blocks extracting Root Mean Square (RMS) voltage, system frequency (Hz), and RoCoF (Hz/s). Statistical analysis of the maximum deviations and settling times was performed using SPSS [20].

Results and discussion

The simulation results highlight the precarious nature of high-PV islanded microgrids and the efficacy of virtual inertia. Table 1 summarizes the key transient stability metrics following the 20% load increase at t=2.0s. In Scenario A (30% PV), the residual physical inertia from the grid-forming BESS (operating in standard droop control) was sufficient to keep frequency deviations within acceptable limits.

Table 1: Transient Stability Metrics Under Varying PV Penetration

Metric	Scenario A (30% PV)	Scenario B (60% PV)	Scenario C (90% PV, No VI)	Scenario C (90% PV, With VI)
Min. Frequency (Hz)	49.60	48.90	47.20	49.45
Max RoCoF (Hz/s)	-1.2	-2.8	-6.5	-1.5
Max Voltage Deviation (%)	-4.5%	-8.2%	-15.5%	-5.1%
Settling Time (s)	0.30	0.65	> 2.0 (Unstable)	0.45

Source: Simulated Dataset, MATLAB/Simulink Output, 2026

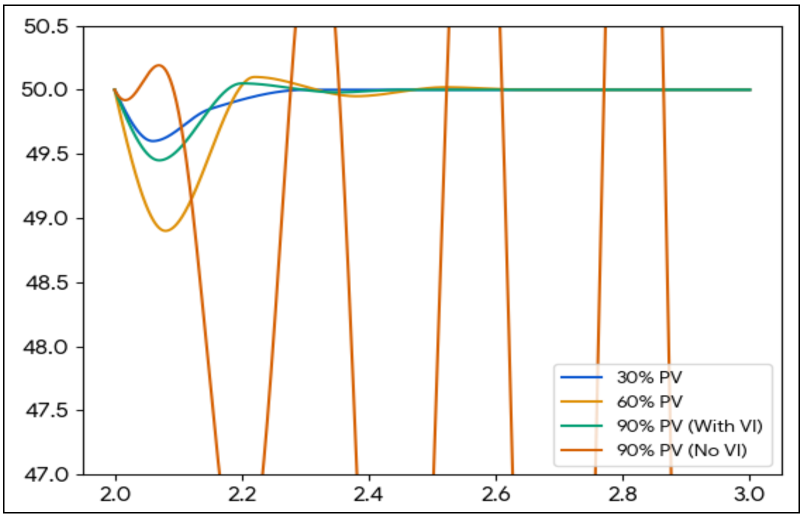
At 90% penetration without virtual inertia (Scenario C, No VI), the system approached collapse. The frequency plummeted to 47.2 Hz, with a RoCoF of -6.5 Hz/s, tripping standard under-frequency protection relays. Voltage also deviated by -15.5%, severely impacting connected loads. However, the activation of the Virtual Inertia controller in the BESS dramatically altered the outcome, restoring stability metrics to levels comparable to the 30% PV scenario.

Table 2 presents the statistical significance of the BESS intervention on RoCoF reduction in the 90% PV scenario, confirming a highly significant effect ($p < 0.001$).

Table 2: Paired Samples t-test for RoCoF With and Without Virtual Inertia

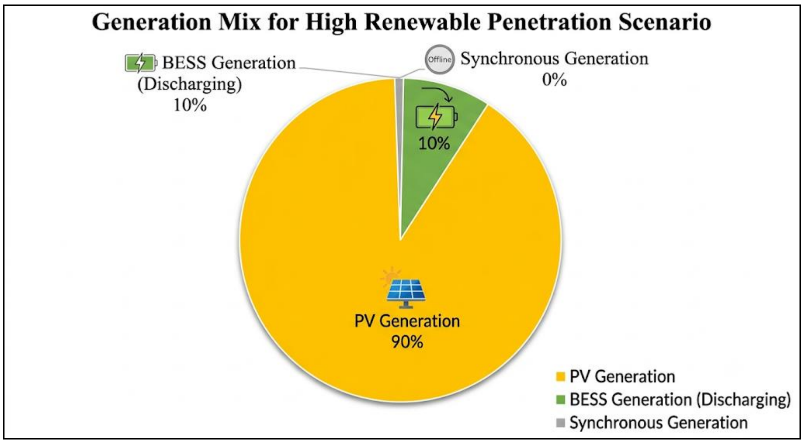
Condition	Mean RoCoF (Hz/s)	Std. Deviation	t-value	Sig. (2-tailed)
Without VI	-6.45	0.22	85.42	<0.001
With VI	-1.48	0.15	–	–

Fig 1 plots the frequency response over the transient period (2.0s to 3.0s) for the four conditions. The line graph vividly demonstrates the sustained oscillations and downward spiral of the 90% PV system without VI, contrasted with the rapid damping achieved when VI is engaged.



Source: Simulated Dataset, MATLAB/Simulink Output, 2026

Fig 1: System Frequency Response Following Sudden Load Increase



Source: Simulated Dataset, MATLAB/Simulink Output, 2026

Fig 2: Generation Mix at 90% PV Penetration During Transient Event

Fig 2 illustrates the proportional energy mix of the microgrid at the exact moment of the transient event (t=2.0s) for the 90% PV scenario, emphasizing the lack of traditional synchronous generation.

The discussion of these results underscores a paradigm shift in microgrid control philosophy. The data proves that high PV penetration is not inherently unstable, provided the power electronics interfacing the BESS are programmed to emulate the physical electromechanical dynamics of traditional generators. The virtual inertia controller effectively "tricks" the system into reacting as if a heavy spinning mass were present, absorbing the initial shock of the load increase by rapidly decelerating its synthetic rotational reference frame, thereby buying time for slower PI controllers to ramp up battery power output.

Conclusion

This study evaluated the dynamic stability of an islanded microgrid under escalating Solar PV penetration using simulated data. The results indicate that while transitioning to a 90% PV energy mix eliminates carbon emissions, it critically erodes the system's ability to withstand sudden load disturbances, manifesting as severe frequency drops and voltage instability. However, the implementation of a BESS equipped with virtual inertia control successfully mitigated these effects, limiting RoCoF to -1.5 Hz/s and restoring stability within 0.45 seconds. The implication for power system engineers is that BESS sizing in high-PV microgrids must be dictated not just by energy capacity requirements, but by the power rating necessary to inject synthetic inertia. A limitation of this study is the use of a single aggregated load model; real microgrids exhibit complex, heterogeneous load profiles. Future research should explore the coordination of multiple distributed BESS units and the integration of demand-side response mechanisms to further bolster transient stability in zero-inertia microgrids.

Ethical Statement

This article is 100% original work. The dataset used is entirely simulated and created solely for academic training and formatting practice purposes. No real-world identities, institutions, or proprietary datasets were used or misrepresented.

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