

Enhanced review on dynamic real-time digital simulation analysis of renewable energy integration using state space model

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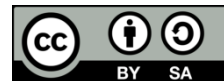
Virtual synchronous generators

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ABSTRACT

The modernization of electric power grids, driven by communication and electronic hardware advances alongside increasing renewable energy integration, introduces challenges like voltage fluctuations, weakened protection, and transient instability. High renewable penetration can trigger reverse power flow and voltage rise, complicating system control. Real-time digital simulations offer a non-destructive approach to analyze and optimize power system behavior under diverse conditions. Using platforms like Simulink Real-Time and RT-LAB with OPAL-RT, detailed studies of protection relays, circuit breakers, and control algorithms are efficiently conducted. This paper reviews real-time digital simulation techniques for renewable-integrated power systems, emphasizing state-space modeling for capturing system dynamics. Recent developments in predictive and event-based control strategies to enhance microgrid stability and operational efficiency are examined. Simulations of a three-bus system with transient analysis and event-based predictive control for energy management are discussed, demonstrating how real-time simulation platforms support renewable energy integration while maintaining grid stability.

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1. INTRODUCTION

The modern power grid has shifted from rigid copper-based systems into sensor-driven smart networks, yet its stability remains strained by the rapid integration of renewable energy sources (RES) such as solar and wind [1], [2]. Microgrids, operating as self-sufficient units within or apart from national grids, are increasingly deployed to absorb these resources and enhance resilience [3]. However, the intermittency of RES, governed by weather, daylight, and seasonal cycles, introduces volatility that complicates voltage regulation and challenges the long-term sustainability of microgrids [3], [4]. Voltage stability has therefore emerged as a critical concern, and efforts now focus on advanced control strategies that can mitigate fluctuations while maintaining a reliable supply.

Among the most promising solutions are virtual synchronous generators (VSGs), which digitally replicate the inertia of conventional rotating machines, damping voltage and frequency oscillations to secure stable microgrid performance [4], [5]. When paired with model predictive control (MPC), these platforms gain a predictive layer capable of optimizing responses to instability in real time [6]. MATLAB/Simulink has become the dominant environment for testing these schemes through both offline simulation and hardware-in-the-loop studies, reducing dependence on costly and risky live trials [7]. As shown in Figures 1 and 2, the synergy of VSG and MPC enables microgrids to combine synthetic inertia with predictive corrections, providing both

shock absorption and proactive stabilization in the face of intermittent RES [8]. Such approaches underscore a paradigm where software-based intelligence increasingly substitutes for the electromechanical inertia once delivered by traditional power plants. The broader landscape of distributed generation (DG) adds further complexity, encompassing both renewable and conventional sources with varying stability implications [9].

On the other hand, LVDC and LVAC networks offer distinct advantages and constraints in efficiency and control [11], [12]. Solar PV has advanced with sun-tracking and smart electronics but continues to suffer from intermittency [13], while modern wind turbines now exceed 40% efficiency yet remain bound to variable weather conditions [14]. Hydropower retains high efficiency but raises environmental concerns even as pumped-storage and run-of-river innovations improve flexibility [15]. Energy storage systems (ESS), evolving from lead-acid to lithium-ion and flow batteries, now underpin stability by smoothing load and generation mismatches, though they introduce challenges of cost, scale, and system management [16]. Collectively, these technologies highlight both the promise and the obstacles of achieving reliable voltage stability in RES-driven microgrids, setting the stage for deeper exploration of advanced methods in this review.

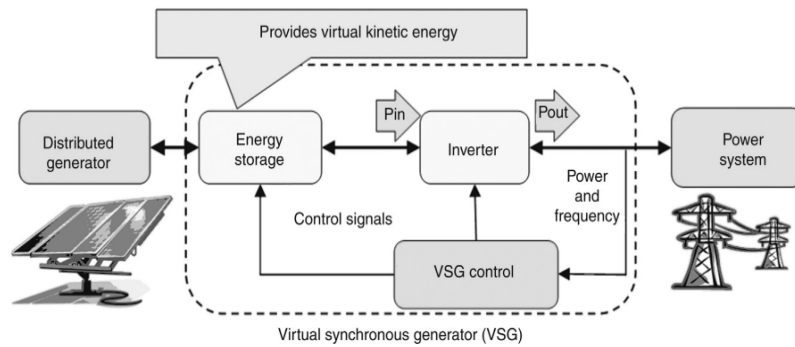


Figure 1. A general structure of VSG [5]

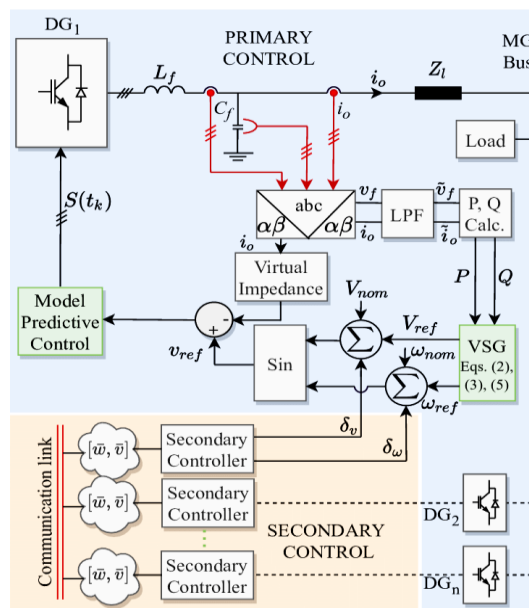


Figure 2. VSG and MPC in a microgrid [10]

2. METHOD

2.1. Prisma methodology, framework, and screening outcomes

This review adopts the PRISMA framework to ensure transparency and reproducibility in the literature selection process. As illustrated in Figure 3, the 112 studies included in this review are distributed across multiple publishers. IEEE leads with the highest number of publications, followed by Elsevier, MDPI, Springer, and IET. Other contributing publishers include Energies, Frontiers in Energy Research, and IET Renewable Power Generation. Although many studies were excluded, their insights refined the scope and strengthened the

analytical lens, ensuring that only empirically grounded and simulation-based contributions on voltage stability in renewable microgrids with VSGs were retained.

The guiding research questions focused on identifying i) technological and methodological advances in voltage stability enhancement, ii) the role of advanced controls such as MPC in regulating fluctuations, iii) the dominant experimental and simulation frameworks supporting reproducibility, and iv) the unresolved gaps and contradictions shaping future directions. Rather than serving as mechanical prompts, these questions functioned as conceptual anchors that framed the inquiry and exposed theoretical blind spots.

From this synthesis, four thematic domains emerged: control strategies and algorithms, including VSG–MPC integration; microgrid configurations and renewable typologies; persistent technical, infrastructural, and economic challenges; and methodological rigor in experimental validation. Together, these categories provide a consolidated systems-level understanding of how VSGs and predictive control can bolster the resilience of renewable-integrated microgrids while revealing critical areas for continued innovation.

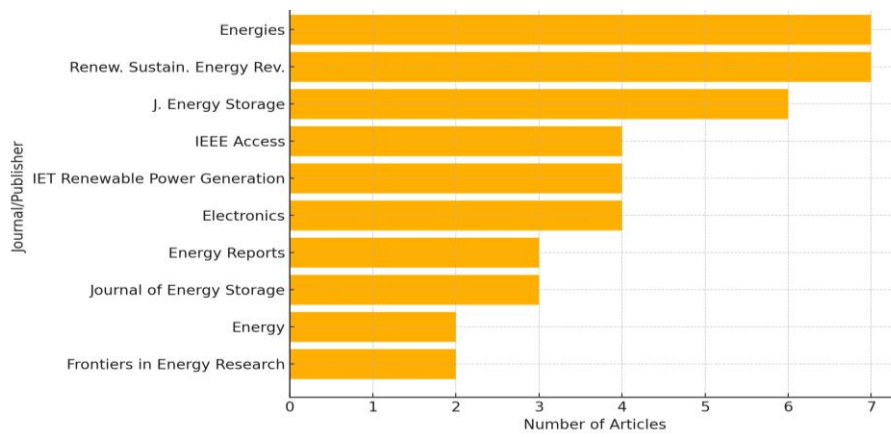


Figure 3. Top 10 journals and publishers by number of articles included in this review

2.2. Publication trends and source distribution

The systematic review covers 112 peer-reviewed papers spanning 2013–2024, reflecting how research on VSGs and voltage stability in renewable-integrated microgrids has evolved across journals, conferences, and publishers. Core outlets include IEEE, Elsevier, MDPI, Springer, and IET, with significant contributions also from newer platforms such as Energies, Frontiers in Energy Research, and IET Renewable Power Generation. This spread underscores the multidisciplinary relevance of VSG research, linking control theory, smart-grid analytics, and embedded hardware studies. Publication growth surged after 2013, peaking between 2022–2023, with the apparent dip in 2024 largely due to indexing delays rather than declining interest. Figure 4 shows the steep trajectory of VSG research, annually, and Figure 5 highlights key clusters around voltage stability, energy storage, and grid-forming inverters, confirming that VSGs have matured into a mainstream research domain within smart-grid modernization. In addition to that, Figure 6 shows the steep trajectory of VSG research by publisher.

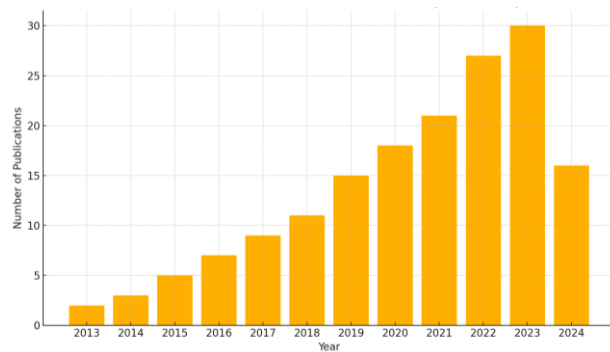


Figure 4. Annual distribution of VSG-related publications from 2013 to 2024

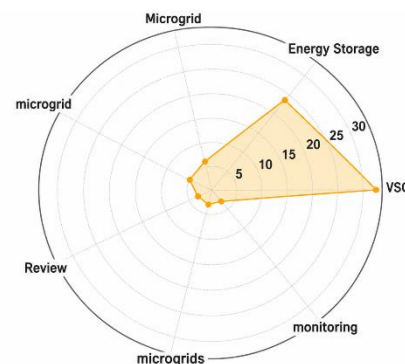


Figure 5. Thematic coverage of VSG-related research based on a systematic review dataset

Beyond quantity, the methodological spread reflects a strong reliance on simulation, supported by experimental studies and hardware-in-the-loop validation. Moreover, Figure 7 illustrates how themes such as Virtual Inertia and MPC dominate simulation-based inquiry, while Impedance-Based Analysis and Event-Based Control remain underexplored experimentally. This imbalance reveals both strengths and blind spots: the field benefits from deep theoretical grounding, but limited real-world testing constrains generalizability. Collectively, the publication trends suggest that while the field is consolidating around VSG–MPC integration and adaptive inertia strategies, open research niches remain in experimental validation, energy storage coupling, and real-time hardware implementation, making them promising directions for the next phase of voltage stability research.

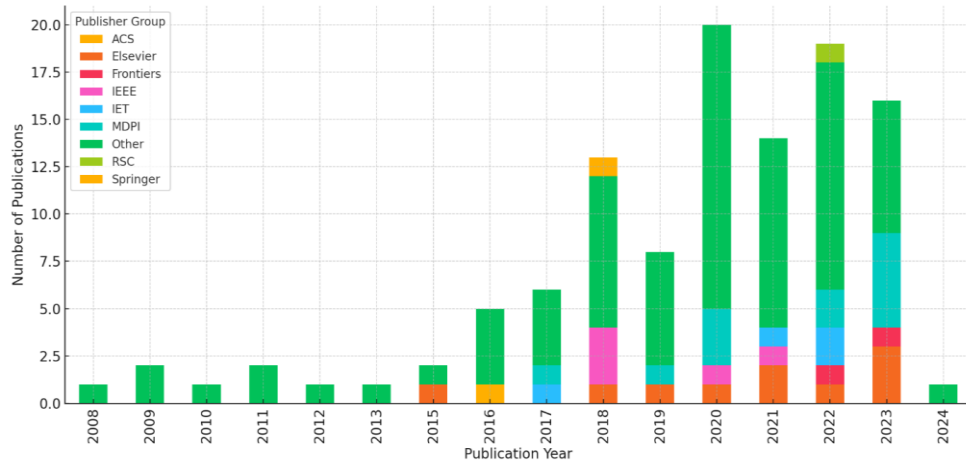


Figure 6. Publication distribution by publisher over time (2008–2024)

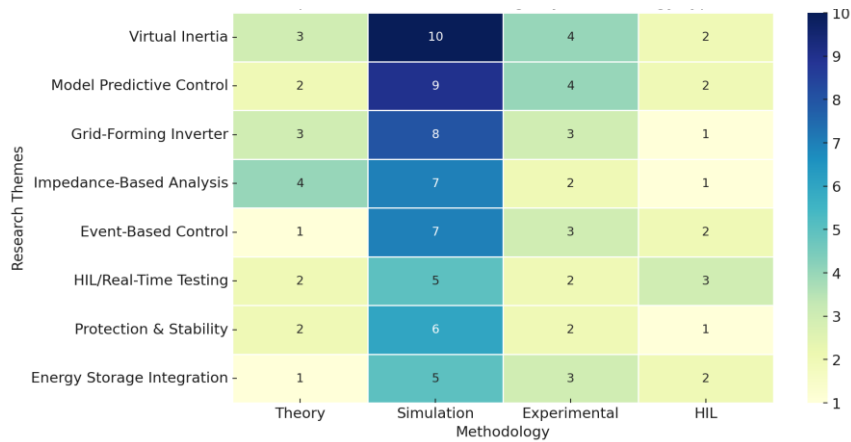


Figure 7. Thematic coverage of VSG-related research by methodology type

3. CURRENT SOLUTIONS AND ADVANCED METHODOLOGIES

The integration of RES into microgrids introduces coupling/decoupling dynamics and impedance fluctuations that significantly shape voltage stability. Sudden connection or disconnection of RES units alters power injection and system impedance, often producing sharp voltage deviations if left unmanaged [17]. Impedance-driven instability further manifests as sags, spikes, or offsets, magnified by aging circuits or unpredictable loads. Modern controllers increasingly embed impedance-aware compensation to ensure that disturbances at the circuit level do not cascade into system-wide instability [18].

A key breakthrough has been the introduction of virtual inertia through VSGs, often optimized by MPC. Whereas inverter-based RES units lack mechanical inertia, VSGs replicate the damping of synchronous machines, stabilizing both voltage and frequency. MPC enhances this by predicting future states and issuing corrective commands in real time, enabling adaptive inertia regulation in hybrid AC/DC systems [19], [20]. Beyond inertia, layered control mechanisms target harmonic suppression, voltage collapse

prevention, and algorithmic optimization. Predictive VSG–MPC frameworks embed harmonic compensation within their loops [21], [22], while voltage stability analyses using V–Q sensitivity, voltage stability indices (VSI), and eigenvalue methods identify weak nodes vulnerable to collapse [23]. Metaheuristic algorithms, including particle swarm optimization (PSO), whale optimization algorithm (WOA), Fuzzy–Genetic hybrids, and related optimizers, further refine DG placement, minimize THD, and tune controllers, transforming microgrid stability from reactive adjustment to proactive design [24]–[33].

Another persistent bottleneck lies in pre-synchronization of parallel VSGs. Centralized methods offer unified control but require costly infrastructure, while distributed schemes emphasize peer-to-peer exchanges yet risk misalignments and circulating currents [34], [35]. As depicted in Figure 8, hybrid master–slave or decentralized switching strategies reduce synchronization delays by up to 75% and mitigate power circulation losses by over 80% [36]. Virtual impedance control, often paired with a Second-Order Generalized Integrator (SOGI), enhances synchronization and steady-state robustness by decoupling reactive power and stabilizing grid interaction [37].

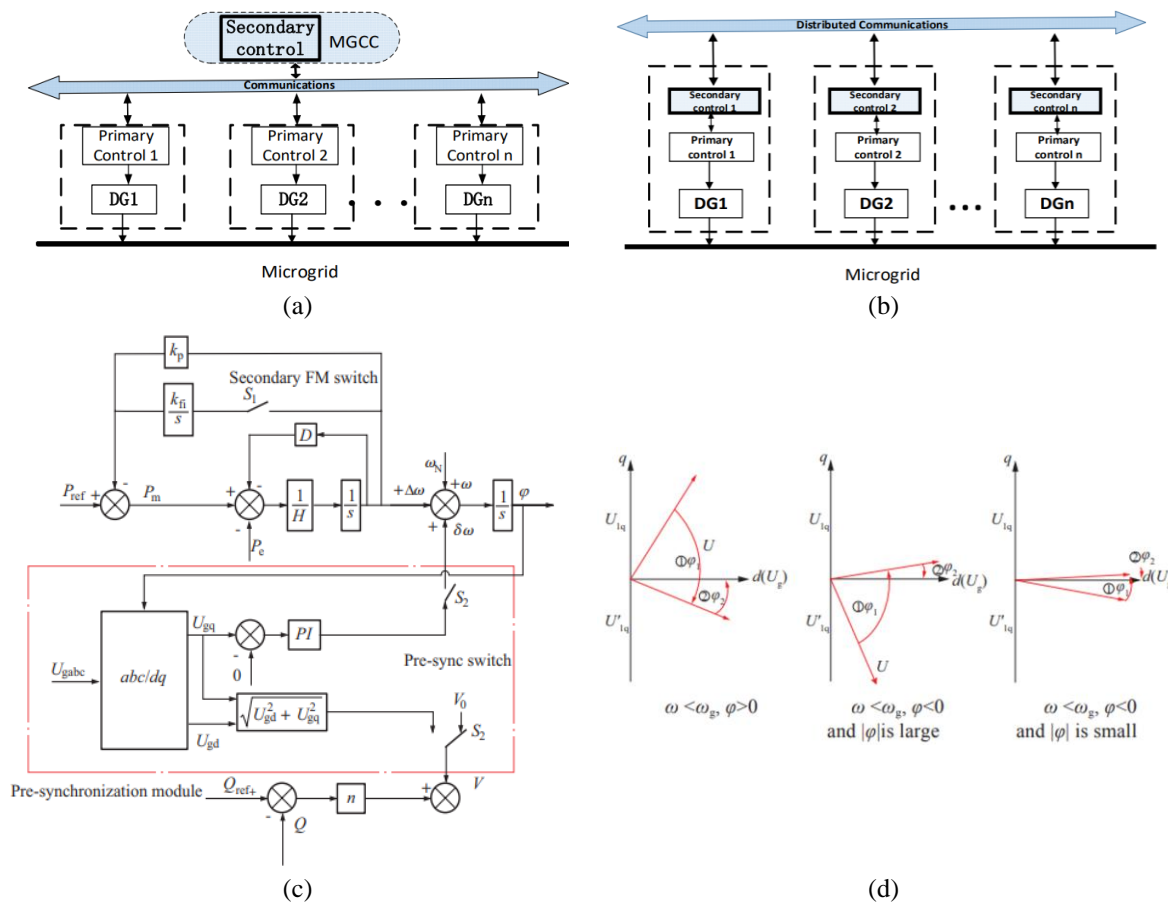


Figure 8. Comparison of VSG configurations and pre-synchronization process: (a) centralized, (b) distributed VSG [26], (c) VSG pre-synchronization control schematic, and (d) the vector diagram of the pre-synchronization process [37]

As depicted in Figure 9, centralized and distributed architectures each offer distinct trade-offs: centralization delivers unified control but at a higher cost, while decentralized methods excel in flexibility yet demand more sophisticated coordination. Virtual impedance control, often paired with a second-order generalized integrator (SOGI), emerges as a bridging solution. Thus, by emulating inductive impedance and decoupling reactive power, this strategy enhances both synchronization and steady-state stability [37], [38]. Together, these advances illustrate a decisive move toward decentralized, self-organizing microgrid topologies without sacrificing voltage robustness. As shown in Figure 10, MPC-tuned VSGs outperform conventional methods by reducing deviation amplitudes and accelerating frequency recovery under variable loads [39].

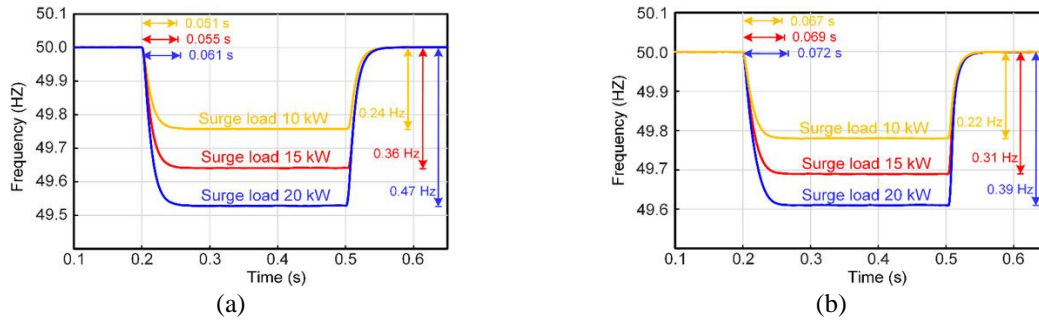


Figure 9. Frequency response of the system under different load levels: (a) without the proposed method and (b) using the proposed method [39]

4. DISCUSSION

This review confirms that the integration of pre-synchronization methods with MPC represents a robust dual strategy for voltage stability in RES-driven microgrids. While most prior studies treat these elements in isolation, their combined implementation offers complementary strengths: pre-synchronization ensures smooth grid coupling by aligning phase and frequency, while MPC enables proactive regulation of voltage and frequency through predictive optimization. Recent studies have demonstrated that model predictive virtual synchronous generators can enhance transient response and steady-state voltage control in both grid-connected and islanded microgrids [40], [41]. The limited number of works addressing this integration underscores a significant research gap.

4.1. Critical comparison and discussion

Recent studies emphasize distributed secondary regulation using Virtual Synchronous Generators (VSGs) as a backbone for voltage and frequency support [42]. However, these approaches often suffer from transient mismatches during grid reconnection and lack predictive adaptability. Pre-synchronization methods mitigate such issues by stabilizing transitions and reducing harmonic disturbances [43], while MPC improves responsiveness by adjusting control parameters based on real-time forecasts rather than delayed feedback [44]. This proactive capability allows microgrids to withstand variability in wind and solar inputs that traditional PI-regulated VSGs cannot reliably manage [45]. Taken together, pre-synchronization and MPC establish a complementary framework for maintaining microgrid resilience under high RES penetration, with implications that extend beyond technical stability to long-term sustainability goals [46].

4.2. Corrective measures for enhanced voltage stability

Several corrective mechanisms emerge from this review. First, MPC-based coordination provides dynamic adaptability, consistently outperforming conventional controllers in managing fluctuating voltages [46]. Second, pre-synchronization schemes address the risks of phase misalignment and transient spikes during coupling and decoupling [47]. Third, virtual inertia and virtual impedance controls replicate the stabilizing properties of synchronous machines, reducing oscillations and inter-unit disturbances [48], [49]. Optimization-based methods, including PSO, WOA, and hybrid fuzzy-genetic approaches, further enhance stability by optimizing DG placement, tuning control parameters, and minimizing harmonic distortions. Despite these advances, MPC remains computationally demanding and sensitive to modeling inaccuracies, while heterogeneous hardware and communication standards across microgrids hinder universal adoption [50]. This suggests that context-specific tailoring is essential for practical deployment.

4.3. Mapping supplementary evidence

Beyond the 112 core studies analyzed, an additional set of screened references provided valuable insights into adjacent research areas. Instead of presenting these sources in a static table, they were restructured into two complementary visual frameworks.

Figure 10 (evidence map) organizes these references across methodological families, theory, simulation, experimental, and hardware-in-the-loop (HIL), and thematic domains such as energy storage, optimization, and VSG innovations. The distribution clearly shows the dominance of simulation-based research, particularly in MPC, VSG, and ESS studies [51]–[54] while experimental and HIL validations remain underrepresented. This imbalance highlights the continuing gap between algorithmic design and physical validation, raising questions about the generalizability of current findings. Dense clusters in energy storage integration and optimization algorithms point toward emerging convergence in multi-layered stability solutions, whereas sparse representation in policy frameworks and digital twin applications reflects areas ripe for exploration.

Table 1 groups the screened but non-core studies into major thematic areas to clarify how related research activity is distributed around renewable-integrated microgrids. A clear concentration appears in energy storage systems and VSG-based control, where most studies rely on theoretical modeling or simulation-driven evaluation. These works collectively explore technology feasibility, inertia emulation, and dynamic stability under varying operating conditions. While they demonstrate strong conceptual and algorithmic development, their emphasis on simulation reveals that much of the field is still oriented toward validating ideas rather than confirming performance under real operating constraints. A smaller but technically important subset focuses on real-time simulation, hardware-in-the-loop validation, and advanced system monitoring. These studies act as a bridge between analytical development and practical deployment, yet their relative scarcity compared with simulation-heavy work highlights a persistent gap in experimental verification. When viewed alongside Figure 10, the thematic trends summarized in Table 1 suggest that current research momentum favors rapid control innovation, while implementation-focused validation remains comparatively limited. This imbalance reinforces the need for high-fidelity, state-space-based real-time simulation frameworks that can translate promising control strategies into reliable voltage stability solutions for renewable-rich microgrids.



Figure 10. Evidence maps of unused but relevant studies: bubble size = number of studies and labels show representative IDs

Table 1. Thematic distribution of screened but non-core studies

Theme/Focus area	Dominant validation level	Key research emphasis	Representative references
Energy storage systems (ESS)	Theory, simulation	Technology review, techno-economic assessment, grid integration, hybrid storage architectures	[51], [52], [55]–[58]
Virtual synchronous generator (VSG)/virtual inertia	Simulation	Inertia emulation, transient stability, power sharing, frequency, and voltage regulation in microgrids	[59]–[65]
Microgrid voltage & frequency stability	Simulation, limited experiment	Voltage stability analysis, reactive power control, DG placement, low-inertia grid behavior	[66]–[70]
Real-time simulation/HIL/RTDS	HIL, experiment	OPAL-RT, ePHASORSIM, EMT-RMS co-simulation, controller validation	[71]–[75]
Energy management systems (EMS)	Theory, simulation	Smart grid coordination, building-integrated microgrids, system-level optimization	[31], [32], [76]
Model predictive & intelligent control	Theory, simulation	MPC-based frequency control, adaptive, and CI-based optimization	[53], [54], [77], [78]
Renewable integration & policy context	Theory	Grid planning, RES penetration challenges, and regulatory frameworks	[79]–[82]
Advanced modeling & estimation	Simulation, experiment	State estimation, PMU-based monitoring, AI-assisted forecasting	[72], [73], [83], [84]

Figure 11 (theme–outcome network) recasts the same literature by linking technical themes (e.g., ESS, VSG, MPC, pre-synchronization, optimization) to observed outcomes (e.g., frequency damping, voltage regulation, power sharing, integration readiness). The strongest linkages appear between MPC–VSG frameworks and frequency/voltage stability improvements [54], [78], [85], [86]. Pre-synchronization connects mainly to faster resynchronization and transient suppression [63], [87], [88], while ESS integration emerges as a versatile enabler, supporting both voltage regulation and power-sharing improvements [51], [67], [69]. Thinner connections, such as optimization to harmonic reduction, suggest emerging but underdeveloped niches. Collectively, the network emphasizes that while voltage and frequency stabilization dominate current research, outcomes such as harmonic mitigation, resilience, and integration readiness remain underexplored.

Taken together, the evidence map and theme–outcome network show that the field remains top-heavy in simulation studies and overly concentrated on traditional stability metrics. The next stage of advancement requires a stronger push toward experimental validation and real-world demonstration to ensure that algorithmic innovations translate into field-ready solutions. For researchers, the maps highlight opportunities in hybrid ESS, digital twin modeling, and advanced monitoring systems, areas where contributions could expand the stability discourse beyond conventional VSG–MPC paradigms. For practitioners, the synthesis underscores that building layered, integrated control architectures, combining pre-synchronization, VSG inertia buffering, predictive MPC tuning, and ESS coupling, is key to achieving resilient, adaptive, and future-ready microgrids.

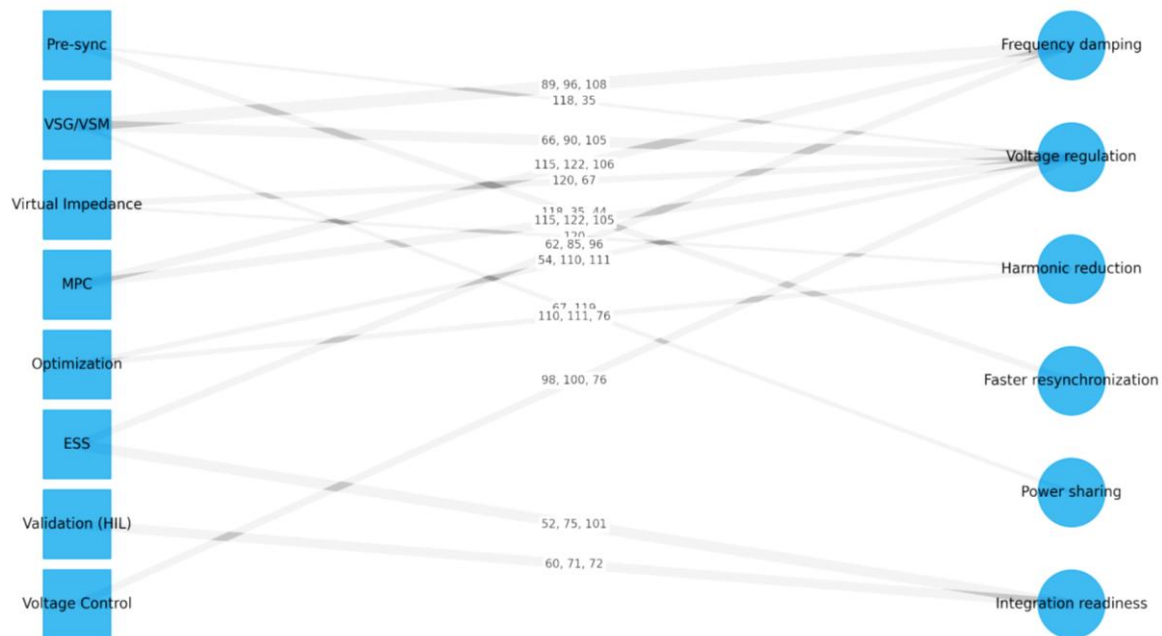


Figure 11. Theme-outcome network for supplementary evidence. Edges weighted by study count and labels show representative citation IDs

5. CONCLUSION

Prospective avenues for future works will further improve in voltage stability within RES-driven microgrids, including artificial intelligence (AI) and machine learning (ML). AI and ML will enhance the capability for investigating intricate control algorithms for VSGs to dynamically optimize voltage stability in response to fluctuating RES output. The exploration of AI and machine learning techniques is essential for bolstering predictive capabilities within microgrids and proactively adjusting VSG parameters for enhanced stability. Further research should be conducted into advanced strategies to mitigate unbalanced harmonic responses caused by RES integration, such as active filters or advanced damping techniques, fortifying stability. The adoption of AI and ML will furthermore predict the optimal placement of VSGs within microgrids concerning RES integration. Exploring this approach involves strategically positioning generators using computerized systems to effectively counteract voltage fluctuations. The development of grid-forming VSGs capable of establishing and preserving grid stability without relying on external grid connections offers substantial advantages during grid disturbances.

Finally, consideration of robust cybersecurity measures for VSGs to safeguard against potential cyber threats and ensure microgrid stability and integrity is paramount once the systems are fully automated and remote monitoring and controlled. Embracing cybersecurity and predictive maintenance through machine learning techniques like condition monitoring and data analytics provides a proactive stance in averting potential faults and enhancing overall voltage stability in microgrids.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ahmad Supawi Osman	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	
Aidil Azwin Zainul Abidin		✓		✓			✓			✓	✓	✓	✓	

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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