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

Ahmad Supawi Osman, Aidil Azwin Zainul Abidin
College of Engineering, Putrajaya Campus, University of Tenaga Nasional, Selangor, Malaysia

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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.

Corresponding Author:

Ahmad Supawi Osman
College of Engineering, Putrajaya Campus, University of Tenaga Nasional
Selangor, Malaysia
Email: ahmadsupawi@yahoo.com

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.

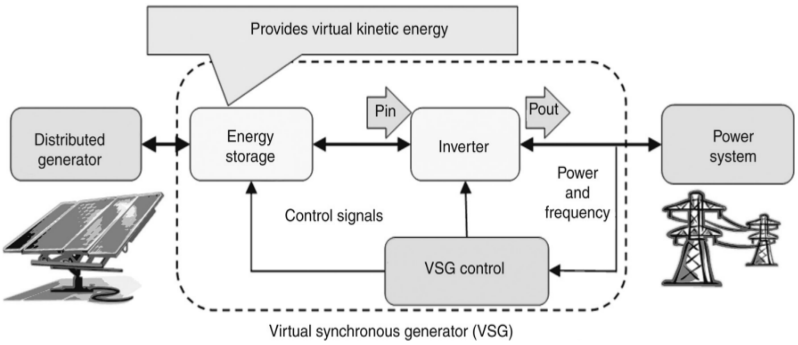


Figure 1. A general structure of VSG [5]

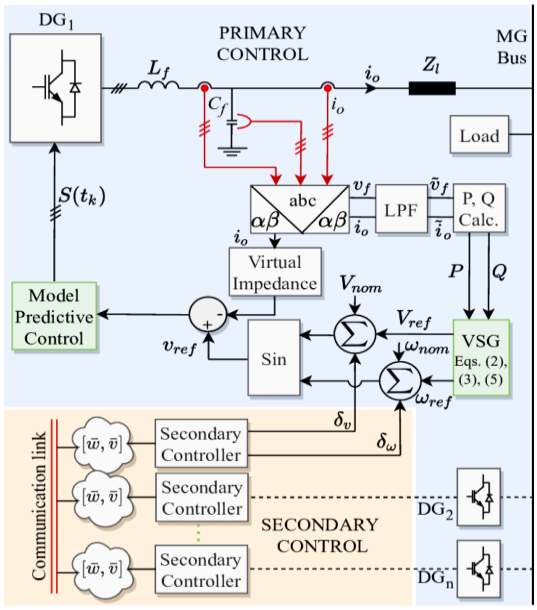


Figure 2. VSG and MPC in a microgrid [10]

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.

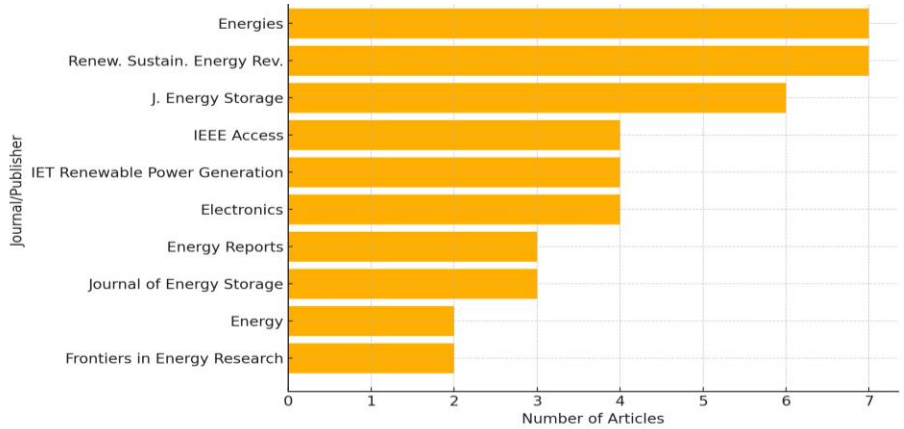


Figure 3. Top 10 journals and publishers by number of articles included in this review

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.

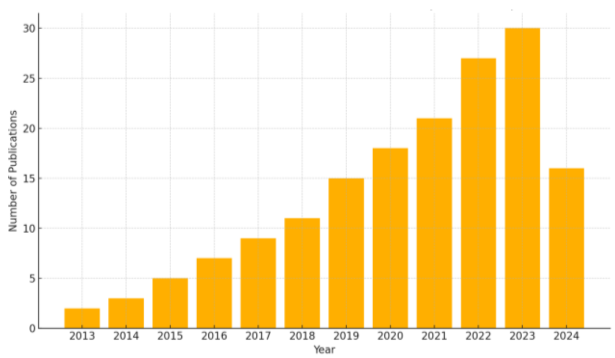


Figure 4. Annual distribution of VSG-related publications from 2013 to 2024

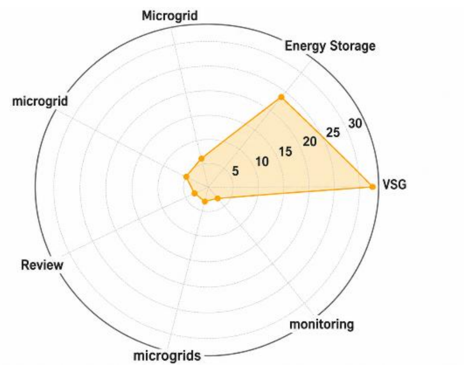


Figure 5. Thematic coverage of VSG-related research based on a systematic review dataset

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.

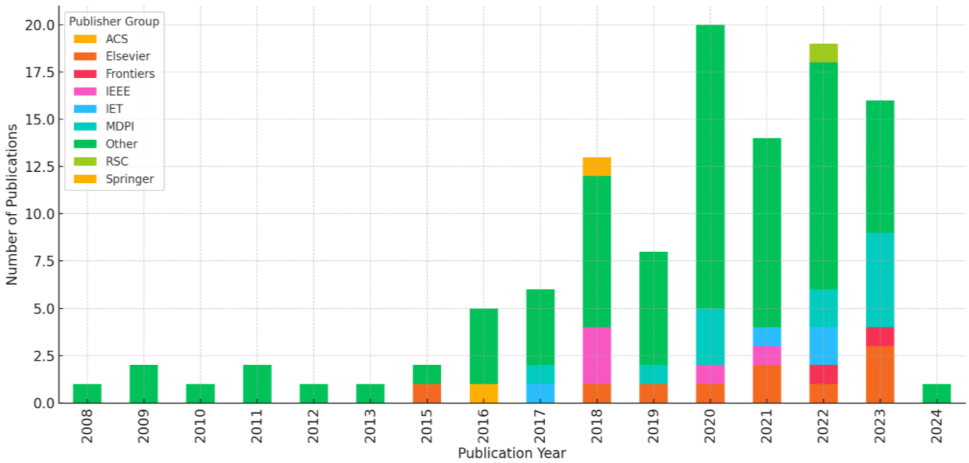


Figure 6. Publication distribution by publisher over time (2008–2024)

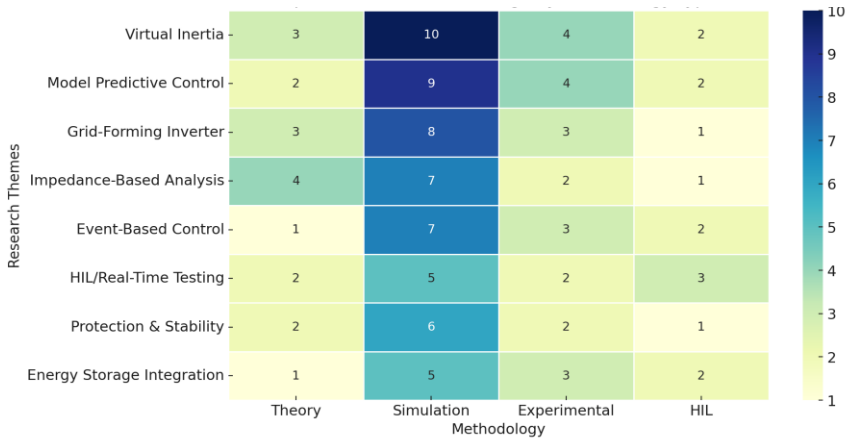


Figure 7. Thematic coverage of VSG-related research by methodology type

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].

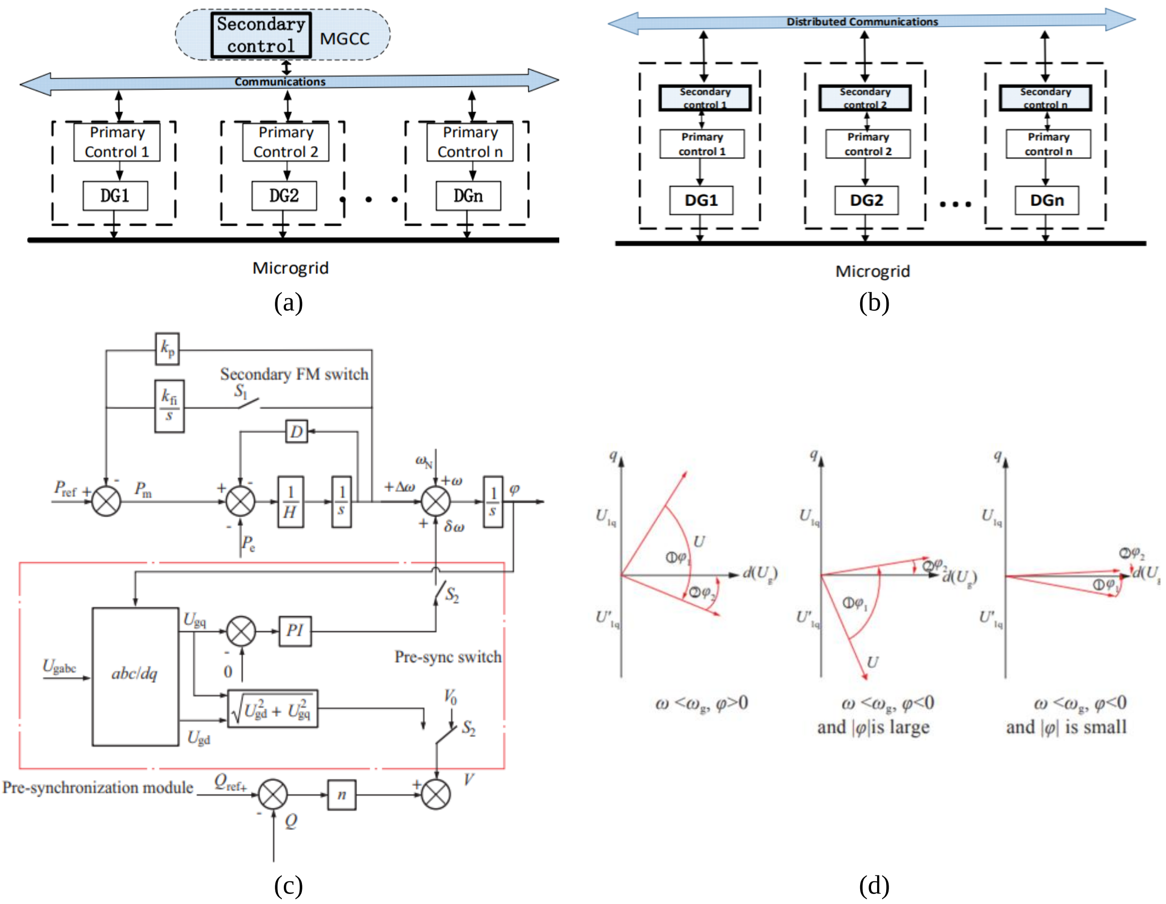
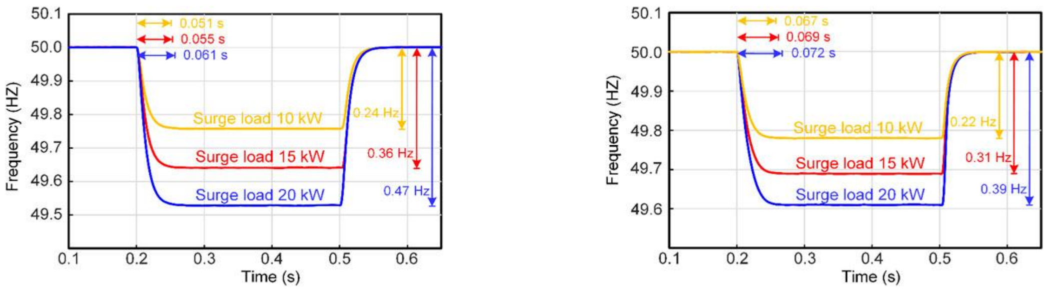


Figure 8. Comparison of VSG configurations and pre-synchronization process: (a) centralized, (b) distributed VSG [26], (c) VSG pre-synchronization control schematic, and (d) the vector diagram of the pre-synchronization process [37]

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].



(a) (b)

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.

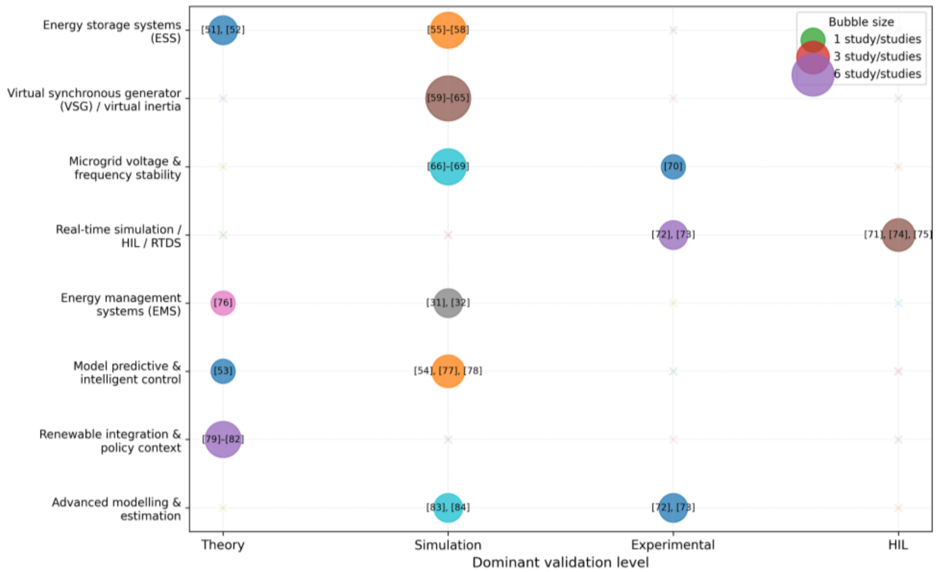


Figure 10. Evidence maps of unused but relevant studies: bubble size = number of studies and labels show representative IDs

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.

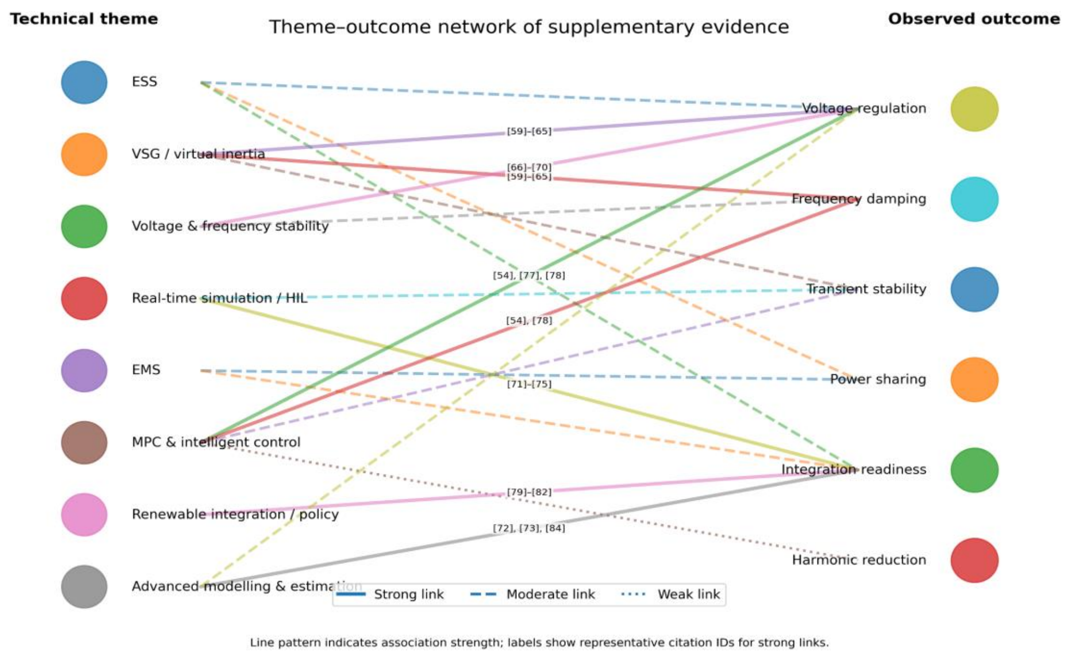


Figure 11. Theme-outcome network for supplementary evidence. Edges weighted by study count and labels show representative citation IDs

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

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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 : **C**onceptualization
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So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding 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.

REFERENCES

[1] M. Abuagreb, M. F. Allehyani, and B. K. Johnson, "Overview of virtual synchronous generators: existing projects, challenges, and future trends," *Electronics*, vol. 11, no. 18, p. 2843, Sep. 2022, doi: 10.3390/electronics11182843.

[2] D. Razmi, O. Babayomi, A. Davari, T. Rahimi, Y. Miao, and Z. Zhang, "Review of model predictive control of distributed energy resources in microgrids," *Symmetry*, vol. 14, no. 8, p. 1735, Aug. 2022, doi: 10.3390/sym14081735.

[3] Z. Lu, L. Wang, and P. Wang, "Review of voltage control strategies for DC microgrids," *Energies*, vol. 16, no. 17, p. 6158, Aug. 2023, doi: 10.3390/en16176158.

[4] Y. Dong, S. Ma, Z. Han, H. Dong, and X. Li, "A comprehensive virtual synchronous generator control strategy for harmonic and imbalance voltage suppression of multi-inverter parallel microgrid," *Electronics*, vol. 11, no. 3, p. 492, Feb. 2022, doi: 10.3390/electronics11030492.

[5] C. Ma, J. Sun, J. Huang, and K. Wang, "Transient stability enhancement strategy for islanded microgrids based on energy storage–virtual synchronous machine control," *Energies*, vol. 16, no. 17, p. 6390, Sep. 2023, doi: 10.3390/en16176390.

[6] X. Yang, R. Wang, N. Jin, J. Zhao, Y. Cui, and Y. Li, "Parameter adaptive model predictive control strategy of NPC three-level virtual synchronous generator," *Frontiers in Energy Research*, vol. 11, Sep. 2023, doi: 10.3389/fenrg.2023.1236646.

[7] D. Dougherty and D. Cooper, "A practical multiple model adaptive strategy for multivariable model predictive control," *Control Engineering Practice*, vol. 11, no. 6, pp. 649–664, Jun. 2003, doi: 10.1016/S0967-0661(02)00170-3.

[8] T. Ise and H. Bevrani, "Virtual synchronous generators and their applications in microgrids," in *Integration of Distributed Energy Resources in Power Systems*, Elsevier, 2016, pp. 282–294. doi: 10.1016/B978-0-12-803212-1.00012-X.

[9] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical control of droop-controlled AC and DC Microgrids—a general approach toward standardization," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, Jan. 2011, doi: 10.1109/TIE.2010.2066534.

[10] A. Elnady and M. M. A. Salama, "Unified approach for mitigating voltage sag and voltage flicker using the DSTATCOM," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 992–1000, Apr. 2005, doi: 10.1109/TPWRD.2004.837670.

[11] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 387–405, Aug. 2013, doi: 10.1016/j.rser.2013.03.067.

[12] N. Kumari, B. Tran, A. Sharma, and D. Alahakoon, “A comprehensive review on stability analysis of hybrid energy system,” *Sensors*, vol. 25, no. 10, p. 2974, May 2025, doi: 10.3390/s25102974.

[13] S. Rawat, B. K. Shukla, P. Sihag, Y. Srivastav, and H. K. Singh, “Environmental effects and sustainable hydropower development: A review of deployment research, environmental valuation and IoT sensors integration,” in *AIP Conference Proceedings*, 2024, p. 040008. doi: 10.1063/5.0193662.

[14] M. Y. Worku, “Recent advances in energy storage systems for renewable source grid integration: a comprehensive review,” *Sustainability*, vol. 14, no. 10, p. 5985, May 2022, doi: 10.3390/su14105985.

[15] L. Meng, E. R. Sanseverino, A. Luna, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, “Microgrid supervisory controllers and energy management systems: A literature review,” *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1263–1273, Jul. 2016, doi: 10.1016/j.rser.2016.03.003.

[16] S. P. Bihari *et al.*, “A comprehensive review of microgrid control mechanism and impact assessment for hybrid renewable energy integration,” *IEEE Access*, vol. 9, pp. 88942–88958, 2021, doi: 10.1109/ACCESS.2021.3090266.

[17] K. S. Joshal and N. Gupta, “Microgrids with model predictive control: a critical review,” *Energies*, vol. 16, no. 13, p. 4851, Jun. 2023, doi: 10.3390/en16134851.

[18] M. Shadoul, R. Ahshan, R. S. AlAbri, A. Al-Badi, M. Albadi, and M. Jamil, “A comprehensive review on a virtual-synchronous generator: topologies, control orders and techniques, energy storages, and applications,” *Energies*, vol. 15, no. 22, p. 8406, Nov. 2022, doi: 10.3390/en15228406.

[19] H. Fakham, D. Lu, and B. Francois, “Power control design of a battery charger in a hybrid active PV generator for load-following applications,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 85–94, Jan. 2011, doi: 10.1109/TIE.2010.2062475.

[20] Y. Han, H. Li, P. Shen, E. A. A. Coelho, and J. M. Guerrero, “Review of active and reactive power sharing strategies in hierarchical controlled microgrids,” *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2427–2451, Mar. 2017, doi: 10.1109/TPEL.2016.2569597.

[21] B. Adineh, R. Keypour, P. Davari, and F. Blaabjerg, “Review of harmonic mitigation methods in microgrid: from a hierarchical control perspective,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 3, pp. 3044–3060, Jun. 2021, doi: 10.1109/JESTPE.2020.3001971.

[22] M. G. M. Almihat and J. L. Munda, “Review on recent control system strategies in microgrid,” *Edelweiss Applied Science and Technology*, vol. 8, no. 6, pp. 5089–5111, Nov. 2024, doi: 10.55214/25768484.v8i6.3116.

[23] Y. Naderi, S. H. Hosseini, S. G. Zadeh, M. Savaghebi, M. Dahidah, and J. M. Guerrero, “Multi-objective model predictive control for microgrid applications,” *International Journal of Electrical Power & Energy Systems*, vol. 154, p. 109441, Dec. 2023, doi: 10.1016/j.ijepes.2023.109441.

[24] K. Nassereddine, M. Turzynski, H. Bielokha, and R. Strzelecki, “Simulation of energy management system using model predictive control in AC/DC microgrid,” *Scientific Reports*, vol. 15, no. 1, p. 5388, Feb. 2025, doi: 10.1038/s41598-025-89036-7.

[25] W. C. Clarke, M. J. Brear, and C. Manzie, “Control of an isolated microgrid using hierarchical economic model predictive control,” *Applied Energy*, vol. 280, p. 115960, Dec. 2020, doi: 10.1016/j.apenergy.2020.115960.

[26] A. Elmouatamid, R. Ouladsine, M. Bakhouya, N. El Kamoun, M. Khaidar, and K. Zine-Dine, “Review of control and energy management approaches in micro-grid systems,” *Energies*, vol. 14, no. 1, p. 168, Dec. 2020, doi: 10.3390/en14010168.

[27] K. Liu *et al.*, “Review on small-signal stability of multiple virtual synchronous generators,” *Renewable and Sustainable Energy Reviews*, vol. 215, p. 115543, Jun. 2025, doi: 10.1016/j.rser.2025.115543.

[28] J. Hu, Y. Shan, K. W. Cheng, and S. Islam, “Overview of power converter control in microgrids—challenges, advances, and future trends,” *IEEE Transactions on Power Electronics*, vol. 37, no. 8, pp. 9907–9922, Aug. 2022, doi: 10.1109/TPEL.2022.3159828.

[29] X. Yang, H. Li, W. Jia, Z. Liu, Y. Pan, and F. Qian, “Adaptive virtual synchronous generator based on model predictive control with improved frequency stability,” *Energies*, vol. 15, no. 22, p. 8385, Nov. 2022, doi: 10.3390/en15228385.

[30] J. Hu *et al.*, “Economic model predictive control for microgrid optimization: a review,” *IEEE Transactions on Smart Grid*, vol. 15, no. 1, pp. 472–484, Jan. 2024, doi: 10.1109/TSG.2023.3266253.

[31] M. M. Elwakil, H. M. El Zoghaby, S. M. Sharaf, and M. A. Mosa, “‘Adaptive virtual synchronous generator control using optimized bang-bang for Islanded microgrid stability improvement,’” *Protection and Control of Modern Power Systems*, vol. 8, no. 1, p. 57, Dec. 2023, doi: 10.1186/s41601-023-00333-7.

[32] W. Zhou, B. Wang, J. Gu, Y. Zhang, S. Wang, and Y. Wu, “Power stability control of wind-PV-battery AC microgrid based on two-parameters fuzzy VSG,” *Frontiers in Energy Research*, vol. 11, Nov. 2023, doi: 10.3389/fenrg.2023.1298033.

[33] M. R. Khan, Z. M. Haider, F. H. Malik, F. M. Almasoudi, K. S. S. Alatawi, and M. S. Bhutta, “A comprehensive review of microgrid energy management strategies considering electric vehicles, energy storage systems, and AI techniques,” *Processes*, vol. 12, no. 2, p. 270, Jan. 2024, doi: 10.3390/pr12020270.

[34] J. Pahasa, P. Potejana, and I. Ngamroo, “Multi-objective decentralized model predictive control for inverter air conditioner control of indoor temperature and frequency stabilization in microgrid,” *Energies*, vol. 14, no. 21, p. 6969, Oct. 2021, doi: 10.3390/en14216969.

[35] R. Fabián Espinoza, G. Justino, R. B. Otto, and R. Ramos, “Real-time RMS-EMT co-simulation and its application in HIL testing of protective relays,” *Electric Power Systems Research*, vol. 197, p. 107326, Aug. 2021, doi: 10.1016/j.epsr.2021.107326.

[36] G. G. Farivar *et al.*, “Grid-connected energy storage systems: state-of-the-art and emerging technologies,” *Proceedings of the IEEE*, vol. 111, no. 4, pp. 397–420, Apr. 2023, doi: 10.1109/JPROC.2022.3183289.

[37] M. Tang and X. Liu, “A control strategy for a grid-connected virtual synchronous generator with virtual impedance,” *Energy Reports*, vol. 9, pp. 132–142, Mar. 2023, doi: 10.1016/j.egyr.2022.10.381.

[38] G. Li *et al.*, “Analysis and mitigation of subsynchronous resonance in series-compensated grid-connected system controlled by a virtual synchronous generator,” *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 11096–11107, Oct. 2020, doi: 10.1109/TPEL.2020.2977981.

[39] M. Khan, W. Wu, and L. Li, “Grid-forming control for inverter-based resources in power systems: A review on its operation, system stability, and prospective,” *IET Renewable Power Generation*, vol. 18, no. 6, pp. 887–907, Apr. 2024, doi: 10.1049/rpg2.12991.

[40] K. Shi, H. Ye, W. Song, and G. Zhou, “Virtual inertia control strategy in microgrid based on virtual synchronous generator technology,” *IEEE Access*, vol. 6, pp. 27949–27957, 2018, doi: 10.1109/ACCESS.2018.2839737.

[41] J. Wang, N. Ramli, and N. H. A. Aziz, “Pre synchronization control strategy of virtual synchronous generator (VSG) in micro-grid,” *IEEE Access*, vol. 11, pp. 139004–139016, 2023, doi: 10.1109/ACCESS.2023.3341102.

[42] N. Hatziargyriou *et al.*, “Definition and classification of power system stability – revisited & extended,” *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 3271–3281, Jul. 2021, doi: 10.1109/TPWRS.2020.3041774.

[43] Z. Huang, Z. Liu, G. Shen, K. Li, Y. Song, and B. Su, "A virtual synchronous generator-based control strategy and pre-synchronization method for a four-leg inverter under unbalanced loads," *Symmetry*, vol. 16, no. 9, p. 1116, Aug. 2024, doi: 10.3390/sym16091116.

[44] J. M. Guerrero, P. C. Loh, T.-L. Lee, and M. Chandorkar, "Advanced control architectures for intelligent microgrids—part ii: power quality, energy storage, and AC/DC microgrids," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1263–1270, Apr. 2013, doi: 10.1109/TIE.2012.2196889.

[45] E. Espina, J. Llanos, C. Burgos-Mellado, R. Cardenas-Dobson, M. Martinez-Gomez, and D. Saez, "Distributed control strategies for microgrids: an overview," *IEEE Access*, vol. 8, pp. 193412–193448, 2020, doi: 10.1109/ACCESS.2020.3032378.

[46] B. C. Moura *et al.*, "Comparative analysis of virtual impedance control techniques for improved stability in DC microgrids," *IEEE Access*, vol. 13, pp. 99077–99091, 2025, doi: 10.1109/ACCESS.2025.3576476.

[47] Y. Kuang, F. Ma, C. Yang, Q. Peng, and G. Huang, "Pre-synchronization control strategy for virtual synchronous generator grid connection based on voltage mathematical relationships," *IEEE Access*, vol. 12, pp. 135854–135863, 2024, doi: 10.1109/ACCESS.2024.3457683.

[48] P. Utkarsha, N. K. S. Naidu, B. Sivaprasad, and K. A. Singh, "A flexible virtual inertia and damping control strategy for virtual synchronous generator for effective utilization of energy storage," *IEEE Access*, vol. 11, pp. 124068–124080, 2023, doi: 10.1109/ACCESS.2023.3330237.

[49] F. Garcia-Torres, A. Zafra-Cabeza, C. Silva, S. Grieu, T. Darure, and A. Estanqueiro, "Model predictive control for microgrid functionalities: review and future challenges," *Energies*, vol. 14, no. 5, p. 1296, Feb. 2021, doi: 10.3390/en14051296.

[50] A. A. Kebede, T. Kalogiannis, J. Van Mierlo, and M. Berecibar, "A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration," *Renewable and Sustainable Energy Reviews*, vol. 159, p. 112213, May 2022, doi: 10.1016/j.rser.2022.112213.

[51] A. G. Olabi, C. Onumaegbu, T. Wilberforce, M. Ramadan, M. A. Abdelkareem, and A. H. Al – Alami, "Critical review of energy storage systems," *Energy*, vol. 214, p. 118987, Jan. 2021, doi: 10.1016/j.energy.2020.118987.

[52] D. A. Elalfy, E. Gouda, M. F. Kotb, V. Bureš, and B. E. Sedhom, "Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends," *Energy Strategy Reviews*, vol. 54, p. 101482, Jul. 2024, doi: 10.1016/j.esr.2024.101482.

[53] H. Bevrani and T. Hiyama, *Intelligent Automatic Generation Control*. CRC Press, 2017. doi: 10.1201/b10869.

[54] Z. Zhao, X. Zhang, and C. Zhong, "Model predictive secondary frequency control for islanded microgrid under wind and solar stochastics," *Electronics*, vol. 12, no. 18, p. 3972, Sep. 2023, doi: 10.3390/electronics12183972.

[55] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 569–596, Feb. 2015, doi: 10.1016/j.rser.2014.10.011.

[56] F. Nadeem, S. M. S. Hussain, P. K. Tiwari, A. K. Goswami, and T. S. Ustun, "Comparative review of energy storage systems, their roles, and impacts on future power systems," *IEEE Access*, vol. 7, pp. 4555–4585, 2019, doi: 10.1109/ACCESS.2018.2888497.

[57] H. A. Behabtu *et al.*, "A review of energy storage technologies' application potentials in renewable energy sources grid integration," *Sustainability*, vol. 12, no. 24, p. 10511, Dec. 2020, doi: 10.3390/su122410511.

[58] S. Choudhury, "Review of energy storage system technologies integration to microgrid: Types, control strategies, issues, and future prospects," *Journal of Energy Storage*, vol. 48, p. 103966, Apr. 2022, doi: 10.1016/j.est.2022.103966.

[59] B. Li, L. Zhou, X. Yu, C. Zheng, and J. Liu, "Improved power decoupling control strategy based on virtual synchronous generator," *IET Power Electronics*, vol. 10, no. 4, pp. 462–470, Mar. 2017, doi: 10.1049/iet-pel.2016.0608.

[60] C. Gao, Y. Sun, W. Zheng, and W. Wang, "Transient power equalization control strategy of virtual synchronous generator in isolated island microgrid with heterogeneous power supply," *Scientific Reports*, vol. 13, no. 1, p. 12598, Aug. 2023, doi: 10.1038/s41598-023-39121-6.

[61] Yong Chen, Ralf Hesse, Dirk Turschner, and Hans-Peter Beck, "Comparison of methods for implementing virtual synchronous machine on inverters," *RE&PQJ*, vol. 10, no. 6, Jan. 2024, doi: 10.24084/repqj10.453.

[62] B. Gao, C. Xia, N. Chen, K. Cheema, L. Yang, and C. Li, "Virtual synchronous generator based auxiliary damping control design for the power system with renewable generation," *Energies*, vol. 10, no. 8, p. 1146, Aug. 2017, doi: 10.3390/en10081146.

[63] M. S. Haritha and D. S. Nair, "Review on virtual synchronous generator (VSG) for enhancing performance of microgrid," in *2018 International Conference on Power, Signals, Control and Computation (EPSCICON)*, IEEE, Jan. 2018, pp. 1–5. doi: 10.1109/EPSCICON.2018.8379587.

[64] Z. Ke *et al.*, "VSG control strategy incorporating voltage inertia and virtual impedance for microgrids," *Energies*, vol. 13, no. 16, p. 4263, Aug. 2020, doi: 10.3390/en13164263.

[65] L. Zhang, H. Zheng, T. Wan, D. Shi, L. Lyu, and G. Cai, "An integrated control algorithm of power distribution for islanded microgrid based on improved virtual synchronous generator," *IET Renewable Power Generation*, vol. 15, no. 12, pp. 2674–2685, Sep. 2021, doi: 10.1049/rpg2.12191.

[66] A. Selim, S. Kamel, L. S. Nasrat, and F. Jurado, "Voltage stability assessment of radial distribution systems including optimal allocation of distributed generators," *International Journal of Interactive Multimedia and Artificial Intelligence*, vol. 6, no. 1, pp. 32–40, Mar. 2020, doi: 10.9781/ijimai.2020.02.004.

[67] J. Kweon, H. Jing, Y. Li, and V. Monga, "Small-signal stability enhancement of islanded microgrids via domain-enriched optimization," *Applied Energy*, vol. 353, p. 122172, Jan. 2024, doi: 10.1016/j.apenergy.2023.122172.

[68] F. Ruiz-Tipan, C. Barrera-Singana, and A. Valenzuela, "Reactive power compensation using power flow sensitivity analysis and QV curves," in *2020 IEEE ANDESCON*, IEEE, Oct. 2020, pp. 1–6. doi: 10.1109/ANDESCON50619.2020.9272113.

[69] J. Liu, D. Yang, W. Yao, R. Fang, H. Zhao, and B. Wang, "PV-based virtual synchronous generator with variable inertia to enhance power system transient stability utilizing the energy storage system," *Protection and Control of Modern Power Systems*, vol. 2, no. 1, p. 39, Dec. 2017, doi: 10.1186/s41601-017-0070-0.

[70] L. Petersen, F. Kryezi, and F. Iov, "Design and tuning of wind power plant voltage controller with embedded application of wind turbines and STATCOMs," *IET Renewable Power Generation*, vol. 11, no. 3, pp. 216–225, Feb. 2017, doi: 10.1049/iet-rpg.2016.0199.

[71] G. R. Bharati, S. Chakraborty, C. Duan, and T. Nishikawa, "An Integrated transmission-distribution modeling for phasor-domain dynamic analysis in real-time," in *2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, IEEE, Feb. 2020, pp. 1–5. doi: 10.1109/ISGT45199.2020.9087705.

[72] A. Chandra, A. K. Pradhan, and A. K. Sinha, "PMU based real time power system state estimation using ePHASORsim," in *2016 National Power Systems Conference (NPSC)*, IEEE, Dec. 2016, pp. 1–6. doi: 10.1109/NPSC.2016.7858967.

[73] A. Dubey, S. Chakrabarti, and V. Terzija, “Testing and validation of a dynamic estimator of states in OPAL-RT real time simulator,” in *2017 IEEE Power & Energy Society General Meeting*, IEEE, Jul. 2017, pp. 1–5. doi: 10.1109/PESGM.2017.8273954.

[74] M. Ibrar, “Real time flight simulator data communication for co-simulation,” *Kurdish Studies*, pp. 1377–1387, May 2024, doi: 10.53555/ks.v12i5.3482.

[75] C. Zhang *et al.*, “Implementation and hardware-in-the-loop testing of a wide-area damping controller based on measurement-driven models,” in *2021 IEEE Power & Energy Society General Meeting (PESGM)*, IEEE, Jul. 2021, pp. 1–5. doi: 10.1109/PESGM46819.2021.9638055.

[76] S. A. Ghorashi Khalil Abadi, S. I. Habibi, T. Khalili, and A. Bidram, “A model predictive control strategy for performance improvement of hybrid energy storage systems in DC microgrids,” *IEEE Access*, vol. 10, pp. 25400–25421, 2022, doi: 10.1109/ACCESS.2022.3155668.

[77] T. A. Jumani *et al.*, “Computational intelligence-based optimization methods for power quality and dynamic response enhancement of ac microgrids,” *Energies*, vol. 13, no. 16, p. 4063, Aug. 2020, doi: 10.3390/en13164063.

[78] V. Pandey, P. Kaur, and P. Kumar, “Load frequency control of single area power system with microgrid using fuzzy logic and virtual inertia control,” *International Journal of Science and Research (IJSR)*, vol. 10, no. 6, pp. 785–790, Jun. 2021, doi: 10.21275/SR21610104714.

[79] J. Hu, Y. Shan, J. M. Guerrero, A. Ioinovici, K. W. Chan, and J. Rodriguez, “Model predictive control of microgrids – An overview,” *Renewable and Sustainable Energy Reviews*, vol. 136, p. 110422, Feb. 2021, doi: 10.1016/j.rser.2020.110422.

[80] G. Fearn, “Electricity decarbonisation targets and the distribution dilemma,” *Energy Policy*, vol. 203, p. 114625, Aug. 2025, doi: 10.1016/j.enpol.2025.114625.

[81] J. Liu, J. Wang, and J. Cardinal, “Evolution and reform of UK electricity market,” *Renewable and Sustainable Energy Reviews*, vol. 161, p. 112317, Jun. 2022, doi: 10.1016/j.rser.2022.112317.

[82] R. Shah, N. Mithulananthan, R. C. Bansal, and V. K. Ramachandaramurthy, “A review of key power system stability challenges for large-scale PV integration,” *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1423–1436, Jan. 2015, doi: 10.1016/j.rser.2014.09.027.

[83] S. Rao and Y. Yuan, “Online monitoring of power grid intelligent voltage stability considering potential factors,” *Mobile Information Systems*, vol. 2022, pp. 1–9, Aug. 2022, doi: 10.1155/2022/8760582.

[84] L. Zhang, G. Wang, and G. B. Giannakis, “Real-time power system state estimation and forecasting via deep unrolled neural networks,” *IEEE Transactions on Signal Processing*, vol. 67, no. 15, pp. 4069–4077, Aug. 2019, doi: 10.1109/TSP.2019.2926023.

[85] Y. Chen, R. Hesse, D. Turschner, and H.-P. Beck, “Improving the grid power quality using virtual synchronous machines,” in *2011 International Conference on Power Engineering, Energy and Electrical Drives*, IEEE, May 2011, pp. 1–6. doi: 10.1109/PowerEng.2011.6036498.

[86] S. Lin, L. Lin, and B. Wen, “A voltage control strategy of VSG based on self-adaptive inertia coefficient and droop coefficient,” *Mathematical Problems in Engineering*, vol. 2021, pp. 1–12, Apr. 2021, doi: 10.1155/2021/5567826.

[87] O. Babayomi, Z. Zhang, and J. Kang, “High-bandwidth distributed virtual-inertia converters for AC microgrids,” in *2020 IEEE PES/IAS PowerAfrica*, IEEE, Aug. 2020, pp. 1–5. doi: 10.1109/PowerAfrica49420.2020.9219843.

[88] T. H. Elmenfy, “Gain schedule PI Fuzzy load frequency control for two-area electric power system,” *International Journal of Energy Optimization and Engineering*, vol. 9, no. 3, pp. 39–50, Jul. 2020, doi: 10.4018/IJEOE.2020070103.

BIOGRAPHIES OF AUTHORS

Ahmad Supawi Osman believes in having excellent potential and ability to actively contribute towards fully utilizing skills, knowledge, and abilities in the technical and management field that offers professional growth while being dependable, resourceful, innovative, and flexible, thus contributing to the development of the organization and nation. He can be contacted at email: ahmadsupawi@yahoo.com.

Aidil Azwin Zainul Abidin is an expert in power system simulations that involve real-time simulators such as OPAL-RT and Speedgoat. These simulators utilize hardware-in-the-loop (HIL) techniques, allowing him to test protection relays in a controlled environment instead of the field. This method enables the testing of a broader range of operational scenarios. Additionally, he is actively involved in modeling protection relays within the Simulink environment as part of his research and simulation efforts. He can be contacted at email: Aidilazwin@uniten.edu.my.